10 PRIMARY MIRROR SEGMENTS

10.1 Overview

The design, manufacture and support of the primary mirror segments build on the successful primary mirror systems of the MMT, Magellan and Large Binocular telescopes. The GMT mirror system is based on a proven design, and the experience gained in the existing telescopes has led to several significant refinements that will provide even better performance in the GMT. This experience gives the project a tremendous head start in the design of the mirror system, including the active support. The conceptual design is well established and attention is now focused on the details. Fabrication of the first segment, shown in Figure 10-1, is well underway.

Figure 10-1. First GMT segment resting on the furnace hearth after a successful casting.

The honeycomb sandwich mirror is much stiffer, yet lighter, than a comparable solid mirror. Gravitational deflections are reduced, and sensitivity to wind and actuator errors are greatly reduced. The lightweight structure and thin glass sections, combined with forced-air ventilation, reduce the mirror’s thermal time constant to less than one hour, so that neither thermo-elastic deflections nor mirror seeing make a significant contribution to image blurring.

The active support system controls the mirror’s shape to high accuracy with relatively simple pneumatic actuators. The support system follows the same principles used for the MMT, Magellan and LBT mirrors. It is a synthetic floatation system with 6 defining points and 165 actuators. The defining points sense the net forces and moments on the mirror and distribute compensating forces to the actuators. The bandwidth of this outer control loop is about 1 Hz, so it provides excellent resistance to wind in terms of rigid body motion as well as bending.
10.2 Requirements for primary mirror segments

10.2.1 General requirements

There are two general requirements for the primary mirror segments, including their support systems and thermal control systems. The first is that wavefront errors caused by the segments should be a modest fraction of those caused by the atmosphere in the best seeing that will be encountered. For seeing-limited observations, the segment’s contribution to image blurring will be small compared with the seeing limit. When adaptive optics are used, correction of wavefront errors due to the primary segments will use a small fraction of the stroke of the deformable mirror. The errors allocated to different sources are specified by their contributions to image size. For certain errors we specify or at least track the wavefront structure function, a measure of error as a function of spatial scale.

The second general requirement can be summed up as “Don’t break the glass.” This translates to quantitative limits on tensile stress in the glass for all load cases, including those that occur during manufacture, handling, transport, standard operation, failure of the active support system, and rare seismic events. Internal stresses are calculated for all of these cases, and equipment and procedures are designed to keep the maximum tensile stress below 1030 kPa (150 psi) at all times, and below 690 kPa (100 psi) for durations of more than 5 minutes.

10.2.2 Error budget for primary mirror segments

The telescope error budget presented in Chapter 12 is given in terms of the image diameter $\theta_{80}$ containing 80% of the energy at a wavelength of 500 nm. The terms in this error budget related to the primary mirror segments are listed in Table 10-1. The values apply to a zenith-pointing telescope. Errors that depend on zenith angle $z$ are allowed to increase as the seeing increases, i.e. $\theta_{80}$ may increase in proportion to $(\sec z)^{3/5}$.

Table 10-1. Error budget for primary mirror segments.

<table>
<thead>
<tr>
<th>source of error</th>
<th>specification for $\theta_{80}$ (arcsec)</th>
<th>goal for $\theta_{80}$ (arcsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>polishing and measuring</td>
<td>0.166</td>
<td>0.054</td>
</tr>
<tr>
<td>gravity and actuator force errors</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>wind</td>
<td>0.075</td>
<td>0.075</td>
</tr>
<tr>
<td>temperature gradients</td>
<td>0.089</td>
<td>0.045</td>
</tr>
<tr>
<td>mirror seeing</td>
<td>0.053</td>
<td>0.036</td>
</tr>
</tbody>
</table>

Additional specifications are set for polishing and measuring as described in Section 10.5.2. These include specifications for mirror geometry, i.e. radius of curvature, off-axis distance, and clocking angle.
The ability to meet the specifications in the error budget is addressed for different sources of errors in this chapter. Sections 10.5 and 10.6 include estimates of the errors due to polishing and measurement. Section 10.8 on the support system includes estimates of the image blurring due to gravity sag, actuator force errors, wind, and temperature gradients in the segment. Section 10.9 on thermal control includes estimates of the image blurring due to mirror seeing. Based on experience and analysis, we are confident of meeting all of the specifications.

10.2.3 Use of structure functions

In many cases we are interested in wavefront errors on all spatial scales, not simply the overall rms wavefront error or the overall image size. For this purpose we use the wavefront structure function, a statistical characterization of wavefront accuracy as a function of spatial scale.

The structure function is the mean square wavefront difference \( D \) between pairs of points in the aperture as a function of their separation \( s \). It is commonly used to describe the wavefront error due to the atmosphere. In the standard Kolmogorov model of seeing, the wavefront structure function corresponding to the long-exposure image is

\[
D_{\text{long}}(s) = \left( \frac{\lambda}{2\pi} \right)^2 6.88 \left( \frac{s}{r_0} \right)^{5/3},
\]

where the coherence length \( r_0 \) is related to the image full width at half-maximum \( \theta_{FW} \) and the image size \( \theta_{80} \) as

\[
\theta_{FW} = 0.98 \frac{\lambda}{r_0},
\]

\[
\theta_{80} = 1.84 \frac{\lambda}{r_0}.
\]

The long-exposure structure function includes wavefront tilt, or image motion. When active guiding is used, the short-exposure image is a better measure of the quality of the atmosphere and leads to a tighter specification for wavefront errors. The structure function corresponding to the short-exposure image for an aperture diameter \( d \) is approximately (Ref. 1)

\[
D_{\text{short}}(s) = \left( \frac{\lambda}{2\pi} \right)^2 6.88 \left( \frac{s}{r_0} \right)^{5/3} \left[ 1 - \left( \frac{s}{d} \right)^{1/3} \right].
\]

Several sources of wavefront error related to the primary mirror segments will be evaluated in terms of the wavefront structure function, and compared with the short-exposure atmospheric structure function for the specified image size \( \theta_{80} \). A wavelength of 500 nm is assumed. An estimated structure function that is less than \( D_{\text{short}}(s) \) for most separations \( s \) will generally meet the specification for image size. Future analysis of wavefront errors will evaluate the image size directly.

Errors due to polishing and measuring are specified contractually in terms of the complete structure function for \( \theta_{80} = 0.166^\circ \). For this source of error only, the structure function is
modified to provide an allowance for small-scale errors that have an insignificant effect on the image but exceed the small-scale smoothness of the atmospheric wavefront. The allowance is defined by the fraction of light \( L \) (for loss) that is scattered outside the seeing disk. The loss \( L \) is related to the small-scale rms wavefront error \( \sigma \) by
\[
L = 1 - e^{-\left(\frac{2\pi \sigma}{\lambda}\right)^2},
\]
and the modified structure function is
\[
D'_{\text{short}}(s) = \left(\frac{\lambda}{2\pi}\right)^2 6.88 \left(\frac{s}{r_0}\right)^{5/3} \left[1 - \left(\frac{s}{d}\right)^{1/3}\right] + 2\sigma^2.
\]
For polishing and measuring errors, the specified scattering loss \( L \) is 2\% and the goal is 1.5\%, both at \( \lambda = 500 \) nm. In addition to the specified structure function, the error budget includes a goal of \( \theta_{80} = 0.054'' \) for polishing and measuring. This does not imply a complete structure function, but simply the image size resulting from errors due to polishing and measuring. The value chosen as a goal is the image size calculated from figure measurements of the second LBT primary mirror (Section 10.5.6).

We generally calculate and display the square root of the structure function, the rms wavefront difference. For sources of error for which we can estimate the rms surface error and the spatial scale of the error (or a lower limit to the spatial scale), we use the approximation that the rms wavefront difference for a given separation is roughly \( 2\sqrt{2} \) times the rms surface error at the corresponding spatial scale.

### 10.3 Active optics

For errors that are constant over periods of minutes or longer, we assume that large-scale errors are corrected with the active optics system. Correction forces must remain within the range of the actuators, and specific limits are set on forces used to correct errors in polishing and measurement. In the analysis of different sources of error, we simulate active correction through finite-element calculations. Active correction plays a major role in the analysis of errors presented in this chapter, so we will describe the process here.

We start with calculations of the actuator influence functions, such as those shown in Figure 10-2. An influence function is the deflection of the segment’s optical surface caused by a unit force at one actuator. The calculations constrain rigid-body motion of the segment in the same way the real active support system does: forces are distributed over all 165 actuators to cancel the net force and moments due to the one actuator with the unit force. The influence functions are therefore broad deflections rather than local bumps. These influence functions can be fit to any figure error to determine the actuator forces that would correct that error, and the residual error after corrections.
For most uses of active optics it is not practical to fit all 165 actuator forces. This would result in high correction forces as the actuators try to correct insignificant small-scale errors. Furthermore, wavefront measurements made with integration times of a few minutes or less would have poor signal-to-noise ratios for the small-amplitude, small-scale errors. We therefore use a modal fit, applying combinations of actuators in patterns that induce the segment’s natural bending modes. The correction is typically limited to the first, most flexible, 20-30 bending modes. These modes and the force patterns that produce them are calculated by singular value decomposition of the actuator interaction matrix (the matrix whose columns are the influence functions). A few of the most flexible modes are shown in Figure 10-3. The mode stiffness increases rapidly toward higher modes; mode 20 is 75 times stiffer than mode 1.

The active optics systems for the MMT, Magellan and LBT are based on similar calculations for those mirrors. We have verified the accuracy of the calculations by inducing real bending modes on the mirrors and measuring them to high accuracy in the lab. (Ref. 2) The shapes of measured modes agree remarkably well with the calculated shapes. The amplitudes of measured modes are typically larger than the calculated amplitudes by 5-10%, indicating that the real mirrors are more flexible than the models. The calculations are then scaled to match the measured amplitudes.
10.4 Design of the segment

All aspects of the segment structure, shown in Figure 10-4, are optimized for image quality. The 28 mm facesheet thickness is about the maximum that will keep the thermal time constant under one hour and virtually eliminate mirror seeing. The honeycomb cell spacing of 192 mm sets the gravitational print-through of the honeycomb structure at a level of less than 10 nm peak-to-valley. (Gravitational print-through is polished out zenith-pointing but its negative shows up at horizon pointing.) The overall segment thickness is chosen to minimize deflections due to wind while keeping the segment flexible enough that manufacturing errors at low spatial frequency can be corrected with the active support system. The GMT mirror segments are somewhat thinner and more flexible than LBT mirrors because the optical test of the off-axis segments has significant uncertainties in several low-order aberrations. The selected maximum thickness of 704 mm gives a mirror whose deflections due to wind are insignificant (Section 10.8.10) but whose shape can be adjusted to correct low-order aberrations over the range of uncertainty of the optical test (Section 10.6).

Figure 10-4. Half of plan view and cross section of the GMT off-axis segment.

The segment is made of Ohara’s E6 borosilicate glass, the best material that can be cast into the complex honeycomb structure. Its expansion coefficient of 2.9 ppm/K is significant, but thermal effects are controlled by the forced-air ventilation (Section 10.8.12) and correction by the active supports. Its homogeneity in expansion coefficient, 0.005 ppm/K rms, is similar to that of ULE and Zerodur, and yields insignificant deflections over the operating temperature range of +4 to +17°C.

The designed mass of the segment is 16,200 kg.
10.5 Fabrication

10.5.1 Overview

Fabrication of the mirror segments follows the same strategy used for the MMT, Magellan and LBT primary mirrors. Spin-casting creates the honeycomb sandwich structure with an accuracy of a few mm. The mirror is generated (machined) to define all critical external surfaces and bring the optical surface within about 10 μm rms accuracy. The load spreaders are attached to the rear surface before work starts on the optical surface. Loose-abrasive grinding and polishing of the optical surface are done with a stressed-lap polishing tool that actively conforms to the aspheric surface, augmented by small tools for local figuring.

The off-axis segments are more challenging to make than previous symmetric mirrors. The greatest challenge is accurate measurement of the off-axis surface, discussed in Section 10.6. Polishing is not expected to be significantly more difficult; although the GMT segments are much more aspheric than the MMT, Magellan and LBT mirrors, the aspheric departure under the polishing lap is about the same. The entire fabrication process, including the optical test, is being demonstrated through the fabrication of a 1.7 m off-axis mirror that is approximately a 1/5 scale model of the GMT segment. This mirror is the primary mirror for the New Solar Telescope (NST) at Big Bear Solar Observatory.

Manufacture of eight GMT segments (including one spare) requires an efficient pipeline processing system that goes beyond that required for primary mirrors produced to date at the Mirror Lab. The Lab has recently expanded its facility to support this kind of processing. With the addition of a second 8.4 m polishing machine in 2004, the Lab has three stations for parallel processing of 8.4 m mirrors: the casting furnace, the generator, and the polisher. With each segment spending 10-12 months at each station, the Lab can produce finished segments at a rate exceeding one per year after an initial ramp-up. The Lab has also expanded its integration facility, shown in Figure 10-5, where mirror support cells are assembled and mirrors are integrated with their support systems.

Figure 10-5. Expanded integration facility at the Mirror Lab. The enclosure for the optical test tower is seen in the background.
10.5.2 Requirements

Optical specifications for the GMT segments are listed in Table 10-2. These specifications apply to the combination of polishing and measuring errors, after active correction of low-order aberrations within the specified limits on correction forces. The structure function for the figure specification is plotted in Figure 10-6. The specified coherence length is equivalent to $\theta_{\text{Spec}} = 0.166^\circ$.

**Table 10-2.** Optical specifications for the first GMT segment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of curvature $R$</td>
<td>$36,000.0 \pm 1.0 \text{ mm}$</td>
<td>$\pm 0.3 \text{ mm}$</td>
</tr>
<tr>
<td>Measurement accuracy for $R$</td>
<td>$\pm 0.5 \text{ mm}$</td>
<td>$\pm 0.3 \text{ mm}$</td>
</tr>
<tr>
<td>Conic constant $k$</td>
<td>-0.998286</td>
<td></td>
</tr>
<tr>
<td>Clear aperture</td>
<td>8.365 m</td>
<td></td>
</tr>
<tr>
<td>Off-axis distance</td>
<td>$8710 \pm 2 \text{ mm}$</td>
<td>$\pm 1 \text{ mm}$</td>
</tr>
<tr>
<td>Clocking angle</td>
<td>$\pm 50 \text{ arcseconds}$</td>
<td></td>
</tr>
<tr>
<td>Coherence length $r_0$</td>
<td>91.9 cm</td>
<td></td>
</tr>
<tr>
<td>Scattering loss $L$ at $\lambda = 500 \text{ nm}$</td>
<td>$&lt; 2.0%$</td>
<td>$&lt; 1.5%$</td>
</tr>
<tr>
<td>Actuator correction forces</td>
<td>$&lt; 30 \text{ N rms}$</td>
<td></td>
</tr>
<tr>
<td>Microroughness</td>
<td>$&lt; 20 \text{ A rms}$</td>
<td>$&lt; 10 \text{ A rms}$</td>
</tr>
</tbody>
</table>

**Figure 10-6.** Figure specification for the GMT segment. The curve is the square root of the structure function. The goal of 1.5% scattering loss is also shown.
The specification includes tight tolerances on off-axis distance and clocking angle (rotation of the segment about its mechanical axis) in order to limit displacements of the segments relative to their cells, which are fixed in the telescope. There is also a tight requirement for matching radius of curvature among all seven segments, primarily to provide equal plate scales for imaging over the 20’ field. The segments’ radii must match well enough in the lab that they can be adjusted to give essentially a perfect match in the telescope.

The LBT mirrors meet the figure accuracy requirements specified for the GMT segments, as described in Section 10.5.6. Polishing the GMT segments is not significantly more difficult than polishing the LBT mirrors, and there is little doubt that the same accuracy can be achieved. Measuring the off-axis segments, however, is new territory. Compared with measurement of the LBT mirrors, the measurement of the off-axis segment has significant uncertainty in several low-order aberrations. Ultimately, these aberrations will be measured to high accuracy in the telescope with the wavefront sensor, and the aberrations can be adjusted both by shifting the position of the segment in the telescope and by bending it with the active supports. The fundamental requirement for the lab measurement is therefore to measure all aberrations to sufficient accuracy that the errors can be corrected in the telescope by a combination of shifting the position of the segment and bending it. The design and tolerance analysis of the GMT measurement presented in Section 10.6.3 shows that the measurement meets this requirement. The specification places constraints on the allowed displacements of the segments and the allowed correction forces. The tolerance analysis shows that the corrections in the telescope will be within these constraints.

The tolerance analysis takes account of the interaction between uncertainty in the lab measurements of low-order aberrations, adjustment of the segment’s position in the telescope, and active correction of the segment’s shape. Only focus, astigmatism and coma depend strongly on the position of the segment. Their sensitivities to lateral displacement and rotation (clocking) are listed in Table 10-3. These displacements are in local segment coordinates with the origin at the center of the segment’s surface and the z axis normal to the surface. Lateral displacement is along the x axis that intersects the optical axis of the parent. Clocking is rotation around the z axis. Translation in the y direction is equivalent to a combination of lateral displacement and clocking.

<table>
<thead>
<tr>
<th>aberration</th>
<th>rms surface error (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 mm lateral displacement</td>
</tr>
<tr>
<td>focus</td>
<td>799</td>
</tr>
<tr>
<td>astigmatism</td>
<td>539</td>
</tr>
<tr>
<td>coma</td>
<td>49</td>
</tr>
</tbody>
</table>

The sensitivities of these aberrations to segment position are coupled, so they cannot be corrected independently. For any combination of aberrations, however, there is an optimum
adjustment of the segment position that minimizes the actuator forces required to correct the residual error.

Table 10-4 gives the relationship between surface error and correction force for a number of low-order aberrations. It also lists the residual surface errors after correction. For each aberration, the residual error is the difference between the pure aberration and the best fit obtained by adding several bending modes. The number of modes used in the fit can be adjusted to balance correction force (which increases with the number of modes) and residual error (which decreases). Residual errors will be on medium scales, on the order of 1-2 m, where the structure function specification allows errors of 50-70 nm rms surface.

Table 10-4. Correction forces and residual errors for some low-order aberrations. Aberrations are defined as Zernike polynomials with amplitude of 1 μm rms surface.

<table>
<thead>
<tr>
<th>aberration</th>
<th>astigmatism</th>
<th>focus</th>
<th>coma</th>
<th>trefoil</th>
<th>spherical aberration</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of modes</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>rms force (N)</td>
<td>13</td>
<td>38</td>
<td>150</td>
<td>60</td>
<td>420</td>
</tr>
<tr>
<td>rms residual (nm)</td>
<td>19</td>
<td>54</td>
<td>140</td>
<td>45</td>
<td>290</td>
</tr>
</tbody>
</table>

Large amounts of astigmatism can be corrected with low forces and residual errors. Focus is a relatively flexible aberration while coma is much stiffer. Spherical aberration is very stiff, but the tolerance analysis will show that the measurement of the off-axis segment contains no significant source of error in the form of spherical aberration. (The types of errors that would cause spherical aberration in a symmetric mirror cause astigmatism and coma in the off-axis segments.)

The optical specification in Table 10-2 sets a limit of 30 N rms correction force. This is the rms over the 165 axial support actuators. An additional correction force of 40 N rms is reserved to correct for the uncertainty in radius of curvature, which is specified as 0.5 mm (equivalent to 1.0 μm rms surface error in focus) with a goal of 0.3 mm. The tolerance analysis for the optical test treats focus like any other aberration, to be corrected by a combination of lateral translation and bending. With this approach there is no need for a separate force allowance to correct an error in radius of curvature, so the force allowances are combined in quadrature for a total of 50 N rms correction force. (This allowance can be compared with the average axial force of 1070 N per actuator at zenith.) The allowed correction force must accommodate not only uncertainty in the lab measurements, but also figure errors that are measured in the lab but not polished out of the segment. This use of active optics to relax the fabrication tolerance on low-order aberrations is standard practice for large optics. As a preliminary budget for correction force, we allocate 30 N rms to relax the fabrication tolerance and 40 N rms to allow for uncertainties in the measurement.

10.5.3 Casting procedures

The first GMT segment was successfully cast in July 2005. The casting process used the same procedures and equipment used previously for the MMT, Magellan and LBT mirrors. The most
significant refinement for GMT was designing and machining the ceramic fiber boxes that form the cavities in the honeycomb structure. These cavities follow the off-axis aspheric shape of the optical surface in order to produce a uniform facesheet thickness of 28 mm in the finished segment.

The mold is a tub of hard silicon carbide that is lined with soft ceramic fiber (alumina-silica fiber) and filled with hexagonal boxes of the same ceramic fiber. The silicon carbide provides strength while the ceramic fiber defines the geometry of the mirror, including the honeycomb structure. The ceramic fiber maintains sufficient strength at high temperature to resist the hydrostatic pressure of molten glass, but is soft and weak enough to be separated from the solid glass without causing high stress.

The silicon carbide tub is assembled first. An array of floor tiles, one for each hexagonal box, are placed on the furnace hearth to form the floor of the tub. Each tile has a hole in its center to take a bolt and nut, both silicon carbide, which will bolt the hexagonal boxes to the floor. The tub wall is then installed in sections. Inconel steel bands are wrapped around the tub wall in 90° sections to restrain the mold. Pneumatic cylinders are attached to each end of the inconel bands to maintain constant tension as the band expands thermally during the casting. The furnace is then closed and heated to 1160°C to seat the inconel bands securely to the tub walls (the band seat firing).

After the band seat firing, the wall and floor of the tub are lined with ceramic fiber. A machining arm is installed above the mold, the floor is machined flat and the wall is machined cylindrical. The 1681 hexagonal boxes, or cores, are machined on a CNC mill in parallel with assembly of the tub. The height of each core, and the slope of its lid, follow the shape of the off-axis mirror surface. No two cores are alike, but the two halves of the mold have mirror symmetry.

The cores are now installed, initially with open tops in order to give access for bolting them to the floor. A jig is used to locate each core precisely using the floor tiles as reference. Each core sits on a ceramic fiber collar that serves as a stand-off for the core (defining the cast back plate thickness at 30 mm). The silicon carbide bolt is inserted through the collar and through the hole in the floor tile, and threaded into the nut. A set of 38 mm diameter ceramic fiber pins are installed between neighboring cores for lateral stability. A lid is then glued on top of each core. After all the cores are installed, the mold is cleaned, inspected and prepared for a second firing to 1160°C. This firing serves to set the glue used to install all the ceramic fiber parts, and to thermally stress the mold to ensure that no damage will occur during the casting.

The mold is then re-inspected and cleaned. The glass is loaded on top of the cores, 18 metric tons of Ohara E6 glass in the form of irregular, roughly 5 kg blocks. Each block is inspected for impurities and stress concentrations. The furnace is closed and prepared for casting. A generator is rented for emergency power during the 3-month melting and cooling process. The furnace is heated to peak temperature over a 5-day period, including tests of temperature control and rotation. As the temperature reaches 750°C, the furnace starts rotating. For the outer GMT segment the rotation rate is 0.51 rad/s to create a parabolic surface with a radius of curvature equal to 37 m. At the peak temperature, 1160°C, the glass has the consistency of room-temperature honey. The mold is held at this temperature for about 4 hours, giving the glass time
to flow down through the 12 mm gaps between the cores (forming the ribs of the honeycomb) and under the cores (forming the back plate), and allowing trapped air to rise to the surface as bubbles. The level of the glass surface is monitored through cameras mounted in the ceiling of the furnace.

The blank is quickly cooled to below its melting point, at which time rapid rotation of the furnace ends. The blank is then cooled slowly over a 3-month period. Over the annealing range of 530°C to 450°C, when atoms are frozen in place, temperature gradients are minimized by cooling at 2.4 K/day. When the blank reaches room temperature, the furnace is opened, the outer portions of the mold are removed, and the blank is prepared for cleanout.

Figure 10-7 shows the lifting fixture attached to the GMT blank, with its 36 steel pads bonded to the facesheet with a compliant silicone adhesive. The silicone cures for 5 weeks and the blank is then ready to be lifted off the furnace hearth. A 45 ton bridge crane lifts the blank and places it into a 10 m steel ring that serves to stiffen the lifting fixture when the blank is brought into a vertical plane. The blank is rotated vertical and positioned for cleanout. The silicone carbide tiles are unbolted from the cores and removed. A high-pressure water jet is used to break down the ceramic fiber boxes inside the blank and wash out the ceramic fiber. Once the mirror blank is clean, it is inspected for any flaws that may need to be repaired. The blank is then ready to be generated and polished.

![Figure 10-7. First GMT segment on the furnace hearth after casting. The lifting fixture rests on the blank as the adhesive cures.](image)

**10.5.4 Generating procedures**

The segments will be machined, or generated, to near net shape using a computer-controlled mill (the Large Optical Generator, LOG, shown in Figure 10-8) that has been used to generate all large aspheric mirrors at the Mirror Lab. The front and rear surfaces will be generated and the rear surface will be lapped and polished during this phase of fabrication. The cylindrical surfaces at the outer diameter of the front and rear surfaces will be generated and polished, as
well as bevels where the front and rear surfaces intersect the edge. The bosses on the outer cylinder, where edge sensors will be mounted, will be machined but otherwise the outer cylinder will be left with its cast surface. The 50 mm center hole (a drain hole for polishing) will be machined.

Figure 10-8. Large Optical Generator, polishing one of the Magellan mirrors. Before the installation of a new polishing machine, the LOG was used for both generating and polishing.

The segment remains bonded to the lifting fixture while the rear surface is machined and polished. The load spreaders that serve as interface between the segment and the actuators are then attached to the back plate. The segment is then turned right-side-up, the lifting fixture is removed from the front surface, and the segment is mounted on its polishing support for machining, lapping and figuring of the front surface.

The off-axis shape of the front surface requires some modifications of the generating technique. The LOG has computer control of 3 axes: rotation of the segment, $\theta$, and horizontal and vertical position of the tool, $r$ and $z$. The standard procedure for generating a symmetric surface is to cut on a tight spiral, with the tool following the desired path $z(r)$ as the mirror rotates. The most straightforward modification for the off-axis surface is to vary the vertical position $z(r,\theta)$ while following the standard spiral path in $r$ and $\theta$. This would lead to large errors due to backlash of the vertical motion. Horizontal backlash causes much smaller errors because the slope of the surface is less than 1 in 9 everywhere. We will therefore maintain a monotonic vertical motion and weave in the horizontal direction instead. The tool will follow contours of constant height on the aspheric surface, superposed on the spiral path. We expect to achieve an accuracy of about 10 $\mu$m rms, more than adequate for the transition to loose-abrasive grinding.

Initial cuts of both surfaces are made with a coarse diamond cup wheel that removes about 0.5 mm per pass. Final cuts are made with fine diamond bowl wheels (convex spherical cutting surfaces) removing about 0.1 mm per pass. Each pass over the full surface takes about 8 hours.
We use the LOG as a profilometer to measure symmetric mirrors during generating. Subsequent comparison with optical measurements confirms the accuracy of better than 10 μm rms. We have not tested the LOG’s accuracy as a 2-D profilometer, and the principal measurement of the GMT surface during generating will be with a laser tracker. This measurement, described in Section 10.6.5, will also support loose-abrasive grinding of the optical surface and is expected to be accurate to better than 10 μm rms.

10.5.5 Polishing procedures

The final stage of fabrication, loosely known as polishing, includes loose-abrasive grinding, polishing, and figuring. All are lapping processes in which a tool with a large contact area (100 mm to 1.2 m diameter) rests on the surface under a controlled load rather than a controlled position. This stage of work is performed with the Large Polishing Machine (LPM) that was first used to polish the second LBT mirror.

We use a variety of lapping tools but rely heavily on a pair of 1.2 m stressed laps, shown in Figure 10-9. The stressed-lap system was developed at the Mirror Lab to lap, polish and figure extremely aspheric surfaces, and it works well for off-axis as well as symmetric aspheres. The stressed lap’s aluminum plate is bent elastically by computer-controlled actuators to follow the changing curvature of the aspheric surface as it moves over that surface. This allows use of a large, stiff tool with a strong smoothing action. The bending of the stressed lap required for a GMT segment, proportional to local changes in curvature of the mirror surface, is similar to that required for the Magellan and LBT mirrors, and the bending forces are somewhat less for GMT.

![Figure 10-9.](image)

The first lapping process, loose-abrasive grinding, will remove subsurface damage (microscopic fractures) from generating, and bring the surface to an accuracy of about 2 μm rms surface error. The surface will be measured with the laser tracker during this phase. Loose-abrasive grinding will be done entirely with the stressed laps, faced with glass or ceramic tiles. We go through a
sequence of abrasives from about 40 μm to 10 μm particle size. The surface will then be polished to a specular finish, using the stressed laps faced with pitch and optionally synthetic polishing pads.

As soon as the surface is polished we will begin optical measurements using an interferometer and a null corrector described in Section 10.6.3. We will also use a scanning pentaprism system to measure slope errors as described in Section 10.6.4. We do not know whether the laser tracker measurements will be accurate enough for a transition directly from them to visible-wavelength interferometry. If not, we will rely on the pentaprism measurements to guide the initial figuring until slope errors are small enough that interference fringes can be resolved over most of the surface.

We will bring the segment’s figure to its specified accuracy using a combination of stressed-lap polishing and local figuring with small tools. Both of these techniques will behave essentially the same on the GMT segments as on the LBT mirrors, so we expect to be able to control the segment’s figure to similar accuracy.

### 10.5.6 Results for 8.4 m LBT primary mirrors

The two LBT primary mirrors were figured to an accuracy similar to the specification for the GMT segments. The second LBT mirror is slightly better than the first because some uncertainties in the optical test were not resolved before completion of the first mirror. We present here the results for the second LBT mirror, which is representative of the accuracy of the figuring process, as opposed to the measurement accuracy. Measurement accuracy for the GMT segment is discussed in detail in Section 10.6. We also present the figure measurements after integrating the second LBT mirror on its active support in the lab.

Polishing of the second LBT primary mirror was completed in May 2005. The polished figure is shown in Figure 10-10. The mirror’s figure is shown with astigmatism and spherical aberration subtracted, and with some additional aberrations subtracted. Astigmatism is affected by small changes in support forces and will be determined in the telescope by support forces. Spherical aberration is within tolerance and will be determined by airspaces in the telescope. With only these two aberrations subtracted, the rms surface error is 32 nm. With all Zernike polynomials through 4th degree in radius removed, the rms surface error is 15 nm. These aberrations are also strongly affected by support forces and therefore easily corrected by support forces in the telescope.
Figure 10-10. Measured figure of the second LBT mirror at completion of polishing. Left: with astigmatism and spherical aberration removed, the rms surface error is 32 nm. Right: with all Zernike polynomials through 4th degree in radius removed, the rms surface error is 15 nm. The color bars are labeled in nm of surface. The images cover the full 8.4 m aperture. Some defects in the interferometer have been masked off.

Figure 10-11 shows the square root of the structure function, along with the specification which is identical to that for the GMT segment. The structure function is calculated over the clear aperture, defined as the region $463 \, \text{mm} < r < 4181 \, \text{mm}$. Figure 10-12 shows the encircled energy at 500 nm for the actual mirror and for a perfect mirror, in perfect seeing. It is calculated over the clear aperture. With the easily corrected aberrations removed, $\theta_{00} = 0.054^\circ$. This is the basis for the goal listed for the GMT segment in Table 10-2. Figure 10-13 shows the encircled energy in 0.25" FWHM seeing.

Figure 10-11. Square root of the structure function of the measured figure with astigmatism and spherical aberration removed, and with all Zernike polynomials through 4th degree in radius removed.
Figure 10-12. Encircled energy at 500 nm for the actual mirror (with and without removal of additional low-order aberrations) and a perfect mirror. With the easily corrected aberrations removed, 80% of the light is contained in a diameter of 0.054".

Figure 10-13. Encircled energy at 500 nm for the actual mirror and a perfect mirror, in 0.25" FWHM seeing. The 2 curves for the real mirror with different aberrations removed are indistinguishable.

We installed the LBT mirrors in their active support cells in the lab, and optimized the support forces on the basis of figure measurements with the interferometer. The mirror was not
ventilated as it is in the telescope, but the mirror cell was vented to remove most of the actuator heat. The force optimization uses the mirror’s natural bending modes as described in Section 10.3. We optimized the figure with successively larger numbers of modes. The best results were obtained with 43 modes and 51 modes, and these are summarized in Table 10-5. Results of these two optimizations are almost indistinguishable apart from residual astigmatism and other low-order aberrations. These have nothing to do with the number of modes used, but are caused by small errors in support forces and variations in temperature gradients. A 43 mode correction is preferred because it uses smaller correction forces. Figure 10-14 shows the optimized figure for this case. Figure 10-15 through Figure 10-17 show the structure function and encircled energy.

Table 10-5. Summary of results for optimization of support forces with 43 and 51 bending modes, and comparison with the mirror figure on the polishing support.

<table>
<thead>
<tr>
<th>aberrations removed</th>
<th>rms surface error (nm)</th>
<th>( \theta_{50} ) (arcsec)</th>
<th>correction force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>none</td>
<td>astig &amp; spherical</td>
<td>through r^4</td>
</tr>
<tr>
<td>polishing support</td>
<td>32</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>43-mode correction</td>
<td>25</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>51-mode correction</td>
<td>20</td>
<td>19</td>
<td>17</td>
</tr>
</tbody>
</table>

Figure 10-14. Measured figure with support forces optimized using 43 bending modes. Left: with only alignment aberrations (focus and coma) removed, the rms surface error is 25 nm. Right: with astigmatism and spherical aberration removed, the rms surface error is 19 nm.
Figure 10-15. Square root of the structure function after optimizing support forces using 43 bending modes. The goal shown is the same curve shown for measurements on the polishing support although this does not apply as a specification for measurements on the active telescope support.

Figure 10-16. Encircled energy at 500 nm, perfect seeing, for the 43 mode correction (with and without removal of low-order aberrations) and a perfect mirror. With the easily corrected aberrations removed, $\theta_{\text{st}} = 0.065^\circ$. 
Figure 10-17. Encircled energy at 500 nm in 0.25" FWHM seeing. There is no perceptible difference between the 43-mode and 51-mode corrections, nor for removal of residual low-order aberrations.

10.5.7 Production schedule

Figure 10-18 shows the Mirror Lab’s production schedule for the primary mirror segments. Seven segments plus one spare outer segment will be produced by 2016. The schedule includes prior Mirror Lab commitments to produce the combined primary-tertiary mirror of the Large Synoptic Survey Telescope (LSST) and a 6.5 m primary mirror for a telescope on San Pedro Martir (SPM) in Mexico. For each segment, the block labeled “casting” includes mold fabrication, casting, and cleaning out ceramic fiber mold material. The block labeled “polishing” includes generating, installation of load spreaders, and polishing. The first segment is scheduled to be completed by the end of 2008. This allows a full 2 years to generate and polish the optical surface, about 30% longer than the same processes for the LBT primary mirrors. The critical optical test systems are required by the middle of 2007. The second segment is to be completed by the end of 2010 following the LSST and SPM mirrors, and the remaining segments will be completed at 10-11 month intervals.
Measurement of the off-axis surface is the greatest challenge in optical fabrication for the GMT. The test system draws on all the experience gained in the successful measurements of MMT, Magellan and LBT mirrors, but the off-axis geometry calls for major innovations. A set of three tests has been defined and the concepts have been developed in some detail. Errors in the measurement have been analyzed and shown to be acceptable. The most critical parts of the tests have been demonstrated in the measurement of the off-axis 1.7 m mirror.

The principal optical test is a full-aperture, high-resolution measurement of the figure, made by phase-shifting interferometry with a null corrector to compensate for the aspheric surface. The null corrector compensates for 14 mm of aspheric departure in the off-axis segment, ten times the departure of the LBT primary which is the most aspheric primary mirror in a telescope today. This results in additional uncertainty in low-order aberrations. The accuracy of the principal test is specified so that these aberrations can be corrected in the telescope using a combination of small displacements of the segment and bending with the active supports. An independent measurement of low-order aberrations—the scanning pentaprism test—is provided in order to guard against the possibility of a mistake in the implementation of the principal test. A third test—the laser tracker measurement—will support generating and loose-abrasive grinding and provide a meaningful independent measurement of radius of curvature and astigmatism.

Figure 10-19 shows the layout of the principal test. The null corrector comprises two spherical mirrors and a computer-generated hologram, that together transform the interferometer’s
spherical wavefront into a test wavefront matching the surface of the segment. Most of the compensation is made by an oblique reflection off a 3.75 m spherical mirror. A similar reflection off a 0.75 m sphere makes further compensation, and the hologram is designed to eliminate the residual error.

Figure 10-19. Layout of the principal optical test.

The scanning pentaprism test measures slope errors in a number of one-dimensional scans across the surface. It does not cover the entire surface but provides a sensitive measurement of low-order aberrations. The third test uses a laser tracker to scan the surface with a retroreflector whose position is measured from a fixed platform above the mirror.

For the symmetric mirrors made for MMT, Magellan and LBT, we were able to verify the accuracy of the interferometric measurement and, in particular, the null corrector by measuring a computer-generated hologram that mimicked a perfect primary mirror. An apparent wavefront error in that measurement would imply an error in either the null corrector or the hologram, but in any case an error that must be resolved. In the principal test of the GMT segment, the test wavefront is almost 4 m in diameter before it leaves the null corrector, so a verification hologram for the full null corrector is not practical. We have independent measurements of important components of the test wavefront: we will use a small verification hologram to measure and calibrate the wavefront produced by the interferometer, test hologram, and 0.75 m spherical mirror; and we will measure the figure of the 3.75 m sphere in situ from its center of curvature. We do not, however, have a direct measurement of wavefront errors due to misalignment of the 3.75 m sphere. The necessary redundancy is provided by the scanning pentaprism test, which verifies the null corrector by independently measuring low-order aberrations of the GMT segment.
The measurements of the GMT segment require a test tower slightly larger than the existing Mirror Lab tower. The upper part of the tower must be wider to accommodate the light cone for the principal optical test, and stiff enough to support the 3.75 m spherical mirror. The complete measurement system is being developed and assembled for the fabrication of the first GMT segment.

10.6.2 Requirements

The measurements have several high-level requirements:

1. measure large-scale errors accurately enough that they can be corrected in the telescope with a combination of segment displacements within the specified position tolerance, and bending using correction forces within the specified limit;

2. measure small-scale errors to an accuracy that represents a small fraction of the specification for figure errors;

3. measure the mirror’s geometry (radius of curvature, off-axis distance, and clocking angle) within the specified tolerances;

4. include sufficient redundancy to make it very unlikely that a mistake in implementing one of the tests could cause a serious figure error;

5. support all 3 stages of fabrication: generating, loose-abrasive grinding and polishing.

The set of three measurements planned for the GMT segment meets these requirements. The principal optical test measures both large- and small-scale errors, and mirror geometry, within the required accuracy. The scanning pentaprism test measures large-scale errors and mirror geometry within the required accuracy, providing the desired redundancy. The laser tracker measures the ground surface with sufficient accuracy to guide the figuring in the early stages, and provides a useful independent measurement of radius of curvature and astigmatism.

The accuracy requirements for the measurements are given separately for large-scale errors and small-scale errors. A convenient dividing line is a period of 1 m. The segment’s structure-function specification allows rms wavefront differences of 200-300 nm at separations greater than 1 m. For the principal test, the only measurement errors that will contribute at that level are the aberrations due to misalignment of the test optics, and these are all large-scale errors. The alignment accuracy is specified so that these aberrations are small enough to be correctable within the budget for segment position and correction forces. Other errors in the principal test, such as errors related to the hologram and the figure of the fold sphere, may have magnitudes of nanometers to tens of nanometers on scales of 0.1 m or less, where they may use up a significant fraction of the error budget. These errors are specified in terms of the structure function.

The budget for small-scale errors in the principal test is based on the fact that the apparent error in the GMT segment is the sum of the real error in the GMT segment and the systematic error in the test. Because the mirror is figured according to the test, systematic errors in the test become real errors in the GMT segment. (Random errors in the test simply make the GMT segment look worse than it really is, and do not need to be constrained by the error budget, although it is in our
interest to minimize them.) Table 10-6 gives the budget for small-scale errors in the measurement of the GMT segment. The apparent figure error in the GMT segment, and each source of error in the test, are allocated a fraction of the structure-function specification shown in Figure 10-6. The fractions add to 1 in quadrature because the various errors are spatially uncorrelated.

Table 10-6. Budget for small-scale errors in the principal test of the GMT segment.

<table>
<thead>
<tr>
<th>type of error</th>
<th>fraction of GMT segment spec</th>
</tr>
</thead>
<tbody>
<tr>
<td>apparent figure errors in GMT segment</td>
<td>0.8</td>
</tr>
<tr>
<td>systematic errors in hologram, including manufacturing errors</td>
<td>0.4</td>
</tr>
<tr>
<td>systematic errors due to figure of fold sphere</td>
<td>0.4</td>
</tr>
<tr>
<td>other systematic errors, including small fold sphere, fold flat, and interferometer</td>
<td>0.2</td>
</tr>
</tbody>
</table>

10.6.3 Optical figure measurement

The principal optical test uses a null corrector to transform an interferometer’s spherical wavefront into the off-axis aspheric wavefront that matches the surface of the GMT segment. Figure 10-20 shows the segment’s aspheric departure. Achieving such a large compensation, 14 mm peak-to-valley surface, is challenging and requires great attention to the alignment of all parts of the test. Figure errors in the 3.75 m sphere would cause significant errors in the GMT test, so the sphere will be measured from its center of curvature simultaneously with the measurement of the GMT segment and its errors will be subtracted from the GMT measurement.

Figure 10-20. Contour map of the segment’s aspheric departure, in mm.
The computer-generated hologram compensates for the aspheric departure not produced by the reflections off the two spherical mirrors. The hologram diffracts a fraction of the incident light into a wavefront of the desired shape. It may be an amplitude hologram with opaque fringes on a transparent flat glass window, or a phase hologram with etched fringes. Phase holograms are more efficient, giving a brighter return, while amplitude holograms allow a more straightforward correction for errors in the substrate as described below. Figure 10-21 shows the wavefront change to be induced by the hologram, a representation of its fringe pattern, and a photograph of the similar hologram used to measure the 1.7 m NST mirror.

Figure 10-21. Left: wavefront change introduced by the hologram, in μm. Center: representation of the line pattern, where each fringe in the drawing represents 400 fringes on the real hologram. Right: photograph of the NST hologram. The small circular and rectangular patterns outside the main pattern produce reference wavefronts used for alignment.

The manufacturing group at the University of Arizona has developed a great deal of experience with holograms in optical testing, using more than 20 holograms over a period of 15 years. (Ref. 3) The potential errors and methods of controlling them are well understood.

Errors in the hologram can come from three sources: design error, substrate error, and writing error. The desired phase pattern for the hologram is designed in optical design software. This design is translated into a program to control the writing machine. There is always a chance of a mistake in the modeling or the translation. For every hologram that we design, we make an end-to-end test of the final machine-code pattern that will be written. Using this procedure, we have never had a design error.

The hologram is used in transmission, so surface errors or refractive index variations in the glass will cause errors in the diffracted wavefront, primarily on large scales. These errors can be measured directly using the zero order of diffraction (the ordinary transmitted wavefront) and removed from the data. For amplitude holograms, the accuracy of this correction is limited only by the accuracy of measurement, better than 3 nm rms. Second-order effects come in for phase holograms, but we have developed a method of removing the errors to an accuracy of better than 5 nm rms. The stated accuracy applies to the measurement of the surface of the GMT segment.

Distortion in the fringe pattern, which can come from manufacturing limitations, will cause an error in the wavefront. The coupling of pattern distortion to wavefront error depends on the line spacing. The GMT hologram has a nominal line spacing of about 20 μm. We plan to have it fabricated using electron beam lithography, which is accurate to 0.1 μm. (The standard quality-
control check for e-beam patterns includes a measurement to prove that the pattern is accurate to 0.1 µm.) Pattern distortion of 0.1 µm will cause λ/200 wavefront error for each pass through the hologram, so the test accuracy for the GMT surface will be degraded by 3 nm rms.

We expect the net error in the hologram to contribute less than 10 nm rms error in the surface of the GMT segment. Most of the error will be on scales greater than 1 m on the GMT segment, where the allocation for hologram errors (40% of the GMT structure-function specification) is at least 20 nm rms surface error. While we do not have a way to verify independently the wavefront accuracy of the hologram for the GMT test, we will have one or more holograms made that have similar specifications (such as size and line spacing) but which convert a spherical wavefront to a different spherical wavefront that can be measured directly. We have used this practice for several aspheric holograms in the past and confirmed the accuracy of the process.

The 3.75 m spherical mirror is a major investment but a necessary part of the most accurate measurement that can be made. The sphere folds the test beam down to an accessible point as well as making most of the aspheric compensation. A test from the mirror’s center of curvature, with no fold mirror, would require an extension of the test tower from 27 m to 40 m, and a large asymmetric null lens that would be difficult to validate. This option was rejected in favor of the folded test.

The large sphere is a borosilicate honeycomb sandwich mirror, being fabricated at the Mirror Lab. The mirror, shown in Figure 10-22, is 455 mm thick at its edge and weighs 3300 kg. A comparison between the honeycomb and a solid mirror, 200 mm thick and weighing 6000 kg, showed similar performance, and the honeycomb mirror requires less development by the Mirror Lab.

![Figure 10-22. Cross section of the 3.75 m fold sphere for the principal optical test.](image)

The figure of the sphere will be measured in situ from its center of curvature, and the measured error will be removed from the measurement of the GMT segment. This correction cannot be assumed to be perfect, and it is allocated 40% of the structure function specification for the GMT segment. An accurate correction requires accurate mapping from the image of the sphere seen from its center of curvature to the distorted image of the sphere seen in the test of the GMT segment. A mapping error produces a wavefront error roughly equal to the product of the mapping error and the slope error in the figure of the sphere. An analysis of errors related to the sphere shows that the measurement error will be less than 40% of the GMT specification if the surface slope errors on the sphere are less than 4 nm/cm rms and the mapping error is less than 1.5 cm rms. (Both quantities represent magnitude, combining the x and y components, and are measured at the fold sphere, not at its projection onto the GMT segment).
On the smallest scales, subtracting the measured figure of the sphere would add noise to the GMT measurement, so a smoothed version of the measured figure will be subtracted. The 4 nm/cm limit on slope errors applies to the smoothed version, but any real small-scale figure errors in the sphere that are not included in the smoothed version must also meet the structure function spec, corresponding to 40% of the GMT spec. These specifications can be achieved. The second LBT primary mirror approximately meets them and a smoother surface is expected for a smaller spherical mirror.

The 3.75 m sphere will be mounted from an adjustable 48-actuator support. Print-through of the supports, including the change from zenith-pointing during manufacture to nearly nadir-pointing in use, will cause slope errors of 2.4 nm/cm rms, which is significant but within the budget. Temperature gradients and support force errors have been analyzed and shown to induce slope errors less than 1 nm/cm rms.

The smaller spherical mirror will also be measured from its center of curvature in situ, but its figure error will be much smaller and much more stable than that of the large sphere. The interferometer is a commercial high-power simultaneous phase-shifting Twyman-Green interferometer that is nearly immune to vibration. Wavefront errors due to the interferometer, fold flat and small sphere, including those due to internal alignment of these components, will be measured by a reference hologram that can be inserted at the intermediate focus between the two spherical mirrors. This reference hologram contains several patterns on a flat glass substrate. The primary pattern is designed to return a null wavefront to the interferometer if the interferometer, test hologram and small spherical mirror are perfect and perfectly aligned. The reference hologram thus serves to calibrate this part of the null corrector. Residual errors in this calibration are allocated 20% of the GMT specification.

Misalignment of components of the test—the interferometer, hologram, spherical mirrors, and GMT segment—will cause low-order aberrations. A tolerance analysis shows that these aberrations are acceptable provided the alignment is held within the tolerances listed in Table 10-7. This list of tolerances and the tolerance analysis that follows ignores the calibration of certain wavefront errors with the reference hologram. The calibration can only improve the wavefront accuracy.

The alignment accuracy depends on measurement of the relative positions of the components. The shorter dimensions, with tolerances on the order of 10 μm, will be set with metering rods using techniques developed and demonstrated in the measurement of the 1.7 m mirror (Section 10.7). The longer dimensions, with tolerances on the order of 100 μm, will be set using a laser tracker. The tolerances are within the accuracy specifications for the tracker’s absolute distance mode, in which the tracker measures the 3-dimensional position of fixed retroreflectors. The reference hologram at the intermediate focus serves as a mechanical reference for alignment of the 3.75 m sphere with respect to the smaller elements.
Table 10-7. Preliminary tolerances for alignment of the test optics in the principal test. Tilt is measured across the diameter of the element.

<table>
<thead>
<tr>
<th>element</th>
<th>parameter</th>
<th>tolerance (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hologram</td>
<td>axial displacement</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>tilt</td>
<td>10</td>
</tr>
<tr>
<td>3.75 m sphere</td>
<td>axial displacement</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>tilt</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>radius of curvature</td>
<td>500</td>
</tr>
<tr>
<td>0.75 m sphere</td>
<td>axial displacement</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>tilt</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>radius of curvature</td>
<td>20</td>
</tr>
<tr>
<td>GMT segment</td>
<td>axial displacement</td>
<td>250</td>
</tr>
</tbody>
</table>

The tolerance analysis for alignment of the test optics is based on the procedure that will be carried out after the segment is installed in the telescope and its wavefront errors measured with the wavefront sensor. The segment’s position will be adjusted within its allowed range of travel to minimize aberrations that are sensitive to position. More precisely, the optimum position will minimize the actuator forces needed to correct the residual aberrations. Thus the optimization places a higher weight on coma than astigmatism because coma requires much greater correction forces. Once the segment is moved to the optimum position, the actuator forces are adjusted within specified limits to minimize the residual wavefront error. The sensitivities of low-order aberrations to segment position and correction force were listed in Table 10-3 and Table 10-4 in Section 10.5.2.

The tolerance analysis simulates this procedure as follows. For each misalignment, say a tilt of the large fold sphere, we calculate the resulting wavefront error, keeping track of aberrations through 4\(^{th}\) degree and the rms wavefront error due to higher aberrations. We then compensate the errors in focus, astigmatism and coma by adjusting the off-axis distance and clocking angle, weighting aberrations in proportion to the rms correction force from Table 10-4. Finally we correct the remaining aberrations through 4\(^{th}\) degree using bending modes, keeping track of the rms correction forces and rms residual errors. We record the rms force, rms residual error, and shift in off-axis distance and clocking angle. We repeat this process for all components of alignment error listed in Table 10-7, and add the results in quadrature. The results are listed in Table 10-8. All of the net compensations—correction force, off-axis distance and clocking angle—are within tolerance and the residual surface error is small compared with the structure function on the relevant scales of 1-2 m.
Table 10-8. Tolerance analysis showing the contribution of each component of misalignment to the shifts in off-axis distance and clocking angle, rms correction force, and rms residual surface error. Tilt is measured across the diameter. The x axis is the axis of symmetry that intersects the optical axis.

<table>
<thead>
<tr>
<th>element</th>
<th>parameter</th>
<th>tolerance (μm)</th>
<th>radial shift (mm)</th>
<th>clocking (arcsec)</th>
<th>correction force (N rms)</th>
<th>residual surface (nm rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hologram</td>
<td>axial displacement</td>
<td>20</td>
<td>0.04</td>
<td>0.70</td>
<td>7.2</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>tilt about y</td>
<td>10</td>
<td>0.02</td>
<td>0.00</td>
<td>3.8</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>tilt about x</td>
<td>10</td>
<td>0.00</td>
<td>0.50</td>
<td>1.3</td>
<td>2.1</td>
</tr>
<tr>
<td>3.75 m sphere</td>
<td>axial displacement</td>
<td>100</td>
<td>1.17</td>
<td>0.00</td>
<td>11.0</td>
<td>13.9</td>
</tr>
<tr>
<td></td>
<td>tilt about y</td>
<td>100</td>
<td>0.97</td>
<td>0.00</td>
<td>12.0</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>tilt about x</td>
<td>100</td>
<td>0.00</td>
<td>1.27</td>
<td>6.3</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>radius</td>
<td>500</td>
<td>0.77</td>
<td>0.00</td>
<td>4.6</td>
<td>6.4</td>
</tr>
<tr>
<td>0.75 m sphere</td>
<td>axial displacement</td>
<td>20</td>
<td>0.47</td>
<td>0.00</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>tilt about y</td>
<td>10</td>
<td>0.13</td>
<td>0.00</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>tilt about x</td>
<td>10</td>
<td>0.00</td>
<td>2.88</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>radius</td>
<td>20</td>
<td>0.46</td>
<td>0.00</td>
<td>5.7</td>
<td>6.7</td>
</tr>
<tr>
<td>GMT segment</td>
<td>axial displacement</td>
<td>250</td>
<td>0.47</td>
<td>0.00</td>
<td>6.7</td>
<td>8.0</td>
</tr>
<tr>
<td>sum in quadrature</td>
<td></td>
<td></td>
<td>1.89</td>
<td>3.24</td>
<td>23.0</td>
<td>26.4</td>
</tr>
</tbody>
</table>

The tolerance analysis treats focus like any other aberration. Focus is not ignored as it is in some optical tests. An error in radius of curvature is equivalent to a focus error, so the principal test of the GMT segment controls radius of curvature. If we hold the alignment tolerances listed in Table 10-8, the error in radius of curvature can be eliminated in the telescope by displacements and correction forces within the limits shown in Table 10-8, leaving only residual surface error also within the limits shown in Table 10-8.

The alignment tolerance analysis presented above is based on distance measurements with metering rods and a laser tracker. It shows that a system aligned by these methods will meet all requirements for wavefront accuracy, correction force, and displacement of the GMT segment. Use of the reference hologram at the intermediate focus will eliminate all errors related to the test hologram and small sphere, and replace them with a single wavefront error due to the reference hologram. This is expected to improve the accuracy for these components by a factor of 1.5 or more. We expect an additional improvement by measuring the location of the center of curvature of the large sphere, which is very sensitive to tilt of the sphere. In summary, the tolerance analysis presented in Table 10-8 is conservative yet shows that we will meet the requirements for measuring the GMT segment.
The large fold sphere will be the mechanical reference for alignment. It generally will not be moved after its initial adjustment. The small test optics—the interferometer, hologram and small fold sphere—will be mounted on a platform with 6-axis adjustment. These components will be aligned relative to each other, and the platform will be adjusted relative to the large fold sphere. The required frequency of adjustments is not known yet, but we expect these alignments to be stable within tolerances for periods covering many measurements of the GMT segment. The segment itself must be realigned with respect to the large fold sphere for every measurement. It will be mounted on a 6-axis positioner with sufficient resolution to position it within the 250 μm axial tolerance listed in Table 10-7 and similar accuracy in off-axis distance and clocking, as measured by the laser tracker. This meets the wavefront accuracy requirements but is not sufficient to null the interference fringes for an optical test. Nulling the fringes requires sub-micron resolution in tilt, but there is no tight accuracy requirement. The mirror positioner will have the required resolution in all axes.

10.6.4 Scanning pentaprism measurement

The analysis of the principal optical test shows that it can measure the figure and geometry of the GMT segment to the required accuracy in all respects. We feel that it is necessary to have an independent measurement of certain aberrations that would be affected by a mistake in the implementation of the optical test. The scanning pentaprism test meets this need.

The pentaprism test, illustrated in Figure 10-23, measures slope errors in a series of one-dimensional scans across the segment. It does this by projecting a collimated beam parallel to the optical axis of the parent asphere and measuring the position of the focused spot on a detector at the focus of the parent. A beam projector introduces the beam perpendicular to the axis, and the pentaprism deflects it by 90°.

The properties of the pentaprism make the surface slope measurement nearly immune to errors in motion of the pentaprism. Figure 10-24 illustrates these properties. The beam’s deflection in the pitch direction is independent of small rotations of the pentaprism, so high accuracy is maintained as the pentaprism scans across the surface. This accuracy holds for the component of slope parallel to the scan direction; slope in the perpendicular direction is ignored. The measurement is sensitive to changes in the pitch of the beam projector, so we mount a fixed pentaprism beamsplitter in front of the beam projector and measure the relative positions of the spots formed by the two pentaprisms.

A single scan of the surface will measure slope errors in one direction along one diameter of the segment. We combine scans taken at several angles to determine the global shape errors in the surface. A least-squares fit provides the surface error as a set of Zernike polynomials.

The scanning pentaprism system will measure the low-order aberrations that are most sensitive to alignment errors in the principal optical test. A system with 4 rails positioned at 45° intervals would measure focus, astigmatism, coma, trefoil and spherical aberration, and this is the baseline plan. Accuracy requirements are based on the same criterion as those for the principal optical test. Residual errors in the segment must be correctable by translating and bending the segment, using displacements and correction forces within the allowed limits.
Figure 10-23. Schematic view of the scanning pentaprism measurement of the GMT segment. The surface of the full parent primary mirror is sketched in order to clarify the concept. A beam projector and moving pentaprism illuminate the mirror segment with collimated light that is always parallel to the optical axis. Reflection from the mirror brings the light to focus at a CCD placed at the prime focus of the parent. Motion of the focused spot in the CCD is used to determine slope errors in the mirror surface.

Figure 10-24. Definition of degrees of freedom for the scanning pentaprism. The measurement is sensitive to errors in pitch of the scanning beam, which is to first order independent of pitch, roll and yaw of the pentaprism.

Because focus, astigmatism and coma are sensitive to the segment’s position relative to the optical axis, the pentaprism test includes a laser tracker measurement of the position of the segment relative to the detector at the focus. The test thus measures the geometry of the segment—radius of curvature, off-axis distance, and clocking angle—independently of the principal optical test.
The scanning pentaprism test gives a null result (no spot motion) for a perfect paraboloid. For the slightly ellipsoidal GMT segment, we would measure 10 µrad or 183 µm rms spot motion for a perfect mirror. This desired spot motion is subtracted from the measured motion.

Steward Observatory has developed a similar scanning pentaprism system, with 3 fixed rails, for a 6.5 m collimator. The accuracy requirements for the 6.5 m system are several times tighter than those for the GMT segment because no active correction of aberrations is assumed. The GMT system is therefore a simplified version of the 6.5 m system. Some components of the 6.5 m system are shown in Figure 10-25.

![Figure 10-25. Scanning pentaprism system built by Steward Observatory for a 6.5 m collimator. The beam projector is shown at left and a set of 3 pentaprisms on a rail are shown at right. This system is designed to measure absolute wavefront with 60 nm rms accuracy, about an order of magnitude tighter than required by GMT.](image)

We have performed a thorough analysis of errors in the 6.5 m pentaprism system and predict an error of 150 nrad rms per sampled point. (Ref. 6) The system for GMT has significantly relaxed requirements, allowing about 1 µrad rms wavefront slope error in the data. Table 10-9 gives a preliminary error budget for the GMT system, based on a net error of 1 µrad rms per sampled point. Table 10-9 also lists the corresponding terms in the error budget for the existing 6.5 m pentaprism system.

**Table 10-9.** Preliminary error budget for the scanning pentaprism test, along with the corresponding budget for a 6.5 m scanning pentaprism system. Values are rms wavefront slope error in nrad.

<table>
<thead>
<tr>
<th>source of error</th>
<th>6.5 m</th>
<th>GMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>determination of spot position</td>
<td>30</td>
<td>600</td>
</tr>
<tr>
<td>aliasing of mirror figure error</td>
<td>125</td>
<td>500</td>
</tr>
<tr>
<td>optical alignment</td>
<td>61</td>
<td>500</td>
</tr>
<tr>
<td>thermal effects</td>
<td>35</td>
<td>300</td>
</tr>
<tr>
<td>sum in quadrature</td>
<td>147</td>
<td>975</td>
</tr>
</tbody>
</table>
For a given rms wavefront slope error for each sample, the accuracy with which the aberrations can be measured depends on the number of sample points per scan, the number of scans, and the extent to which errors are correlated among sample points and scans. We have determined the measurement accuracy for each aberration by simulating a complete measurement of 4 scans and uncorrelated noise of 1 µrad rms per point. If we assume sampling of 20 points per scan, we will measure the low order aberrations to the accuracies listed in Table 10-10. The accuracies listed for astigmatism, coma and trefoil are the net errors, combining both components of each aberration.

Table 10-10. Predicted error in measurement of low-order aberrations with the scanning pentaprism test. The table also lists the rms correction force and rms surface error after correction, obtained from Table 10-4.

<table>
<thead>
<tr>
<th>aberration</th>
<th>rms surface error (nm)</th>
<th>rms correction force (N)</th>
<th>rms residual error (nm surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td>focus</td>
<td>68</td>
<td>2.6</td>
<td>3.7</td>
</tr>
<tr>
<td>astigmatism</td>
<td>170</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>coma</td>
<td>60</td>
<td>9.0</td>
<td>8.4</td>
</tr>
<tr>
<td>trefoil</td>
<td>120</td>
<td>7.2</td>
<td>5.4</td>
</tr>
<tr>
<td>spherical aberration</td>
<td>30</td>
<td>12.6</td>
<td>8.7</td>
</tr>
<tr>
<td>sum in quadrature</td>
<td></td>
<td>17.4</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Table 10-10 also lists the rms force required to correct each aberration with the active support, and the residual error after correction. The correction forces and residual errors are within the budget. This analysis is conservative in that it ignores the partial correction of focus, coma and astigmatism by displacing the segment in the telescope. It does not, however, include the uncertainties in measuring the position of the focal point (where the spot motion is measured) relative to the segment. This position, in 3 dimensions, determines the off-axis distance, clocking angle, and focal length of the segment. It will be measured with a laser tracker after both the scanning rail angle and the position of the detector have been adjusted to minimize alignment aberrations. By measuring positions to an accuracy of 200 µm with the laser tracker, we expect to determine the focal length and off-axis distance to 200 µm, and clocking angle to 10".

The implementation of the scanning pentaprism test requires some large support hardware. An 8.4 m long carriage must be supported above the segment and rotated to 4 different angles. Alternatively a single frame with 4 rails can be placed over the segment. A CCD detector must be placed 18 m from the segment at the focal point of the parent. This geometry is shown in Figure 10-26.
10.6.5 Laser tracker measurement

While we generate the surface of the segment and perform loose-abrasive grinding and initial polishing, we will measure the surface with a laser tracker. This is a commercial device that combines a distance-measuring interferometer with angular encoders and servo-controlled pointing so it can follow a moving retroreflector and measure its position in 3 dimensions. The tracker will be mounted about 20 m above the GMT segment. We will scan the surface of the segment with the spherical retroreflector (the tracker ball).

The laser tracker measures the shape of the segment’s surface but it is also sensitive to rigid-body motion of the segment and to motion of the tracker relative to the segment. Significant motion is likely to occur during the duration of a measurement, probably 15 minutes or longer. We will therefore augment the tracker measurements with simultaneous interferometric measurements of the distances to 4 fixed retroreflectors at the edge of the segment, as shown in Figure 10-27. These distance readings will be used to correct for relative motion between the segment and the laser tracker, as well as large-scale variations in refractive index that affect all the distance measurements.

Figure 10-26. Layout of scanning pentaprism test in the new test tower.
Figure 10-27. Concept of laser tracker and separate distance-measuring interferometers, that will be used to measure the surface of the segment

The tracker’s distance measurement is sensitive to displacements of less than 1 μm and the angular encoders are accurate to about 1" without any special calibration. For typical applications of a laser tracker, measuring points or surfaces over a distance $d$, the 1" angular accuracy limits position accuracy to the order of $10^{-5}d$, or about 80 μm for the GMT segment. Much better accuracy can be achieved with a favorable geometry in which the critical dimensions are nearly along the tracker’s line of sight, as in the measurement of a mirror surface from near its center of curvature. We measured the 1.7 m NST mirror (Section 10.7) with a laser tracker mounted 2 m above the mirror. This is not very near the center of curvature ($R = 7.7$ m) but the maximum angle of incidence for the tracker beam is only 17”, reducing the sensitivity to angular errors by about a factor of 3. We compared the tracker measurement with an optical measurement. Apart from aberrations that are sensitive to alignment in the optical test, the difference between the two measurements was 0.5 μm rms surface. We achieved similar agreement in measurements of a 1.8 m spherical mirror.

The primary purpose of the laser tracker measurement is to guide the figuring until the surface is polished and accurate enough to allow an interferometric measurement with visible light. This essentially means that interference fringes must be resolved, or—assuming 20 mm pixels—the surface slope errors must be less than 8 μrad. We achieved this with considerable margin for the NST mirror. Figure 10-28 shows the first interference fringes recorded for the NST mirror, after figuring entirely on the basis of laser tracker measurements.
Figure 10-28. Interference pattern for the first optical measurement of the NST mirror. Fringes are easily resolved over the full surface. Note the distorted image of the round mirror due to the geometry of the off-axis measurement, and the additional patterns on the hologram outside the measurement area.

Some effort will be required to achieve similar accuracy with a laser tracker measuring the larger GMT segment, and we are developing methods that will improve the accuracy. The first is the set of auxiliary distance measurements to fixed retroreflectors described above, which were not part of the NST measurement. We are also developing calibration techniques specific to the geometry of the GMT measurement. We can measure and correct systematic errors that are repeatable functions of the tracker’s azimuth and elevation angles $\theta$ and $\phi$. We saw such systematic errors at a level of 3 $\mu$m rms in the NST measurements and reduced them by measuring with the mirror at different orientations. The calibration is made by measuring a small spherical mirror from its center of curvature, where the measurement is sensitive only to errors in distance $\Delta r(\theta,\phi)$, and from positions displaced from its center of curvature, where the measurement is sensitive to angular errors $\Delta \theta(\theta,\phi)$ and $\Delta \phi(\theta,\phi)$ as well as distance errors. These errors, once separated, are fit to a polynomial representation that can be used to correct future measurements covering a similar range in $\theta$ and $\phi$.

With these techniques we hope to reach an accuracy that will not only allow a hand-off to optical measurements, but also measure focus and astigmatism at levels that provide a meaningful confirmation of the principal optical test and the pentaprism measurement. From Table 10-4, errors of roughly 3 $\mu$m rms in astigmatism or 1 $\mu$m rms in focus are correctable by bending the mirror, and somewhat larger errors could be corrected by a combination of displacement and bending. A tracker measurement of these aberrations accurate to 1 $\mu$m rms provides a valuable independent check.

An important part of the system that remains to be designed is a method of moving the tracker ball across the surface. For the smaller NST mirror we were able to do this safely with hand-held tools. For the GMT segment we are exploring options including a robotic positioner and a system of cables attached to winches located off the mirror. Safety for the mirror is the primary consideration.
10.6.6 Test tower

The Mirror Lab’s 24 m test tower, used for center-of-curvature tests of the LBT primary mirrors as well as the MMT and Magellan 6.5 m mirrors, is not quite large enough for the principal optical test of the GMT segment. It is being replaced by a new tower shown in Figure 10-29 whose upper levels are wide enough to accommodate the test beam and which is stiff enough to support the 3.75 m spherical mirror and minimize vibration.

![Figure 10-29. Design of the new test tower, showing the optics for the principal optical test of the GMT off-axis segment. Left: view from north, showing the light cone for the GMT test in beige and that for the simultaneous measurement of the 3.75 m fold sphere from its center of curvature in green. Right: close-up showing the interferometer, hologram and 0.75 mm spherical mirror for the GMT principal test.](image)

The new tower will provide all of the measurements of the GMT off-axis segments: principal optical test, pentaprism measurement, and laser tracker measurement. It will support the equipment for these measurements and provide clear light paths. It will also support the measurement of the GMT center segment (Section 10.6.8), as well as other 6.5 m and 8.4 m mirrors that may be made at the Mirror Lab. The laser tracker and distance-measuring interferometer for the surface measurement (Section 10.6.5) will be mounted on a stage that can be positioned under the 3.75 m sphere and directly over the GMT segment. A station is provided for an additional laser tracker that will measure the long dimensions that are critical to the alignment of the measurements. It has a direct view of the full GMT segment, the 3.75 m fold sphere, the reference hologram, the center of curvature of the 3.75 m sphere, the pentaprism rail, and the pentaprism detector.

The steel tower has been analyzed and designed to have stiffness and stability equivalent to those of the present test tower. The finite-element model shown in Figure 10-30 contains the 3.75 m sphere and its support cell with a combined mass of 5500 kg, and a total mass of 5500 kg in steel platforms and 4800 kg in equipment. The steel beams are designed so that the lowest resonant frequency is greater than 5 Hz.
10.6.7 Other tests

The symmetry of the segment with respect to rotation about the telescope’s optical axis can be exploited to verify the accuracy of the optical test in important respects. The GMT primary mirror is an ellipsoid of revolution, symmetric about the optical axis of the telescope. Each segment possesses this same symmetry about the parent axis. An ideal segment can be rotated about this axis and the apparent shape of the mirror will not change. Viewed in fixed coordinates that do not rotate with the segment, any changes in the apparent shape are due to figure errors that are not symmetric about this axis. This change is independent of errors in the test system.

While we cannot rotate the segment around the parent axis by large angles, a 60 mrad rotation will provide a sensitive verification of the optical test. A 60 mrad rotation can be made by shifting the segment laterally by 500 mm, clocking it by 60 mrad, and tilting it by 14 mrad (±60 mm across the 8.4 m diameter). The in-plane displacements will be made by moving the segment positioner before parking the segment on it. The positioner is designed with enough vertical travel at each connection to the segment to produce the 14 mrad tilt. The segment’s lateral support will take 1.4% of the weight of the segment, about 250 kg. The lateral support in the polishing cell routinely takes much larger loads from the lap and distributes them to 6 load spreaders at the back of the segment. The surface distortion resulting from the 250 kg lateral load will be calculated and subtracted from the measured figure change.

A preliminary analysis of this shear test indicates that it can provide fully redundant information for intermediate scale shape errors, limited only by the few nm random noise in the data. The test has very poor sensitivity for astigmatism, power, coma, and trefoil, but these are the aberrations measured accurately by the pentaprism system.

We have explored an alternative laser tracker measurement that would use a set of four trackers that measure the distance to a retroreflector on the surface on the segment. This determines the
surface from distance measurements alone, unlike the laser tracker measurement described in Section 10.6.5 that relies partly on angular measurements. The UK National Physical Laboratory (NPL) has developed such a “multilateration” system and applied it to smaller surfaces. We commissioned a study by NPL to develop a conceptual design and estimate the accuracy of a multilateration measurement of the GMT segment. The predicted accuracy is excellent, better than 1 µm uncertainty in the surface. Our current plan is to use the system described in Section 10.6.5, which is expected to be accurate enough and cost less than the multilateration system.

10.6.8 Measurement of the center segment

The center segment can be measured much more easily than the others. The test uses the 3.75 m sphere, but tilted so it is nadir pointing. This folds the light path and also compensates most of the aspheric departure. The small residual aspheric departure is corrected by a small computer-generated hologram, which also produces alignment references. Since this segment is axisymmetric, it can be rotated by a full 180° to check for errors in the test optics. The shadow of the interferometer and hologram falls inside the large center hole, and the only obscuration will be from narrow beams supporting them. The effect of this obscuration will be eliminated by rotating the mirror.

10.7 1.7 m off-axis demonstration

Many of the techniques that we will use for the GMT mirrors are being demonstrated on a smaller scale with the 1.7 m off-axis primary mirror for the New Solar Telescope at Big Bear Solar Observatory. (Refs. 4,5) Its dimensions are listed in Table 10-11. The optical surface is nearly a 1/5 scale model of the GMT surface, with 2.7 mm peak-to-valley asphericity.

<table>
<thead>
<tr>
<th>Table 10-11. Dimensions of the NST off-axis mirror.</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius of curvature</td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td>7.7 m</td>
</tr>
</tbody>
</table>

The mirror is 100 mm thick, solid Zerodur. The aspheric surface was generated to an accuracy of 14 µm rms by ITT Industries. We are polishing it with a 2 m polishing machine equipped with a 30 cm diameter stressed lap. As is the case for the GMT segments, the asphericity of the NST mirror has a large amplitude but is dominated by astigmatism and coma, so the bending of the stressed lap is actually less than the bending required for several secondary mirrors that have been figured to high accuracy using the same equipment.

The optical test of the NST mirror, shown in Figure 10-31, is roughly a scaled-down version of the GMT test. Only one folding sphere is used because it produces a beam diameter for the hologram that can fit on a standard substrate. Its alignment tolerances are about 10 µm in distance and tilt relative to the hologram, similar to the tolerances for the small fold sphere in the GMT test. We developed methods for aligning these optics using carbon-fiber metering rods and tooling balls, and will use similar methods to align the smaller optics for the GMT test. Four metering rods measure the distance between a tooling ball near the hologram and 4 balls on the surface of the fold sphere; the 4 measurements define the distance and tilt with redundancy.
Special alignment patterns on the hologram define the position of the balls on the surface of the fold sphere. The rods are calibrated at their nominal distances using a distance-measuring interferometer.

![Diagram of optical test](image)

**Figure 10-31.** Layout of the optical test for the 1.7 m NST off-axis mirror.

Initial measurements of the ground surface were made with a laser tracker mounted 2 m above the mirror. The tracker measurements were not enhanced by additional stability measurements or any special calibration, but they still agreed with the optical test of the NST mirror within 0.5 μm rms surface, ignoring aberrations that depend on the alignment of the optical test.

We are figuring the NST mirror with a combination of stressed-lap polishing and local figuring with passive tools. The figure as of December 2005 is shown in Figure 10-32.

![Figure of the NST mirror as of December 2005](image)

**Figure 10-32.** Figure of the NST mirror as of December 2005. Color bar is labeled in nm of surface. The rms surface error is 32 nm after removal of several low-order bending modes as allowed.
10.8 Support system

10.8.1 Overview

The support system follows the same principles used for the MMT, Magellan and LBT mirrors. It is a synthetic floatation system with 6 hard points and 165 actuators (for the off-axis segments), as shown in Figure 10-33. The hard points sense the net forces and moments on the segment, and the actuators apply compensating forces. The bandwidth of this outer control loop is about 1 Hz, so it provides excellent resistance to wind in terms of rigid body motion as well as bending.

Figure 10-33. Layout of the segment support system.

All 165 actuators have axial components (perpendicular to the back of the segment) and 85 have lateral components (parallel to the back) as well. Four of the off-axis segments tilt around both axes, so they require two components of lateral force. The 85 actuators with lateral components therefore have 3 axes. The off-axis segments and their support cells are identical and interchangeable, so all have the same arrangement of single-axis and 3-axis actuators.
When the active support system is not operating, the mirror is supported by a set of springs, the static support system. These springs do not contact the mirror during operation. The force actuators and the static support springs act on the mirror through load spreaders that are permanently attached to the mirror and distribute the force to enough points that support print-through is insignificant. The hard points connect to the mirror through glass blocks bonded to the rear surface.

The actuators are actively controlled to take the force of the mirror—weight, wind load, and inertia—and to bend out low-order distortion measured by the wavefront sensor. The forces applied by the hard points are measured and resolved into three net forces and three net moments. For each component of net force or moment there is a set of actuator forces that compensates it while minimizing deformation of the optical surface. These force patterns—including axial and both lateral components—are applied through an outer control loop operating with a bandwidth of about 1 Hz. Additional axial force patterns are applied to correct distortions detected by the wavefront sensor at intervals of 30 seconds to several minutes. The resulting force set is checked against safety criteria to ensure that commanded forces will not result in excessive stress in the mirror.

Lengths of the hard points are actively controlled to maintain segment alignment, raise the mirror to its operating position, and lower it onto the static supports on shut-down.

The overall design closely follows the designs of the MMT, Magellan and LBT support systems. One significant change is the addition of the second lateral axis to the actuators. A second is modification of the load spreaders so that they attach mechanically to the back plate, relying only on compression rather than shear or tension through adhesive.

10.8.2 Requirements

Requirements for the mirror support system include both wavefront accuracy and safety. The general safety criterion is to limit tensile stress in the glass to 1030 kPa (150 psi) at all times, and to 690 kPa (100 psi) for durations of more than 5 minutes. (Ref. 7) The tighter criterion is applied to long-term stresses in order to limit slow growth of fractures for at least 50 years. All anticipated load cases have been analyzed against these criteria and the support system keeps stresses within the stated limits.

Wavefront accuracy requirements for the support system were listed in Table 10-1. The following support-related errors are described in this section:

1. deflections due to gravity and actuator force errors;
2. deflections due to wind;
3. deflections due to temperature gradients, after active correction.

For some sources of error, we estimate the structure function and compare it with the short-exposure atmospheric structure function corresponding to the image size specified in Table 10-1. In most cases, the estimated structure function is flatter than the atmospheric structure function, i.e. it does not increase as rapidly toward larger scales. If the estimated structure function is less
than or equal to the atmospheric structure function at small scales, the estimated contribution to image size will be less than the specified image size.

Actuator forces that minimize gravity deflections are calculated by finite-element analysis. In addition to these forces, actuators must apply axial forces to resist wind and to correct figure errors measured by the wavefront sensor. The additional force capability is specified as ±150 N (for actuators with a single attachment point) to ±600 N (for actuators acting through 4-point load spreaders).

Wind loads are taken initially by the hard points, which must be stiff enough to resist the high-frequency component of wind. The outer control loop distributes the compensating force to the full set of actuators for wind variations slower than about 1 Hz. The wind force is insignificant in comparison with gravity, so the low-frequency component resisted by the actuators causes a negligible deflection. The high-frequency component resisted by the hard points causes a deflection that must meet the specification listed in Table 10-1 for wind speeds up to 9.5 m/s (75th percentile). Image motion due to rigid-body motion of the segments is analyzed separately as part of the model of the telescope structure in wind, presented in Chapter 7. Motion of the primary mirror segments is small compared with misalignment of the secondary mirror in the wind.

The support system must allow a certain range of motion of the mirror segment relative to its cell. The actuators, static supports and hard points must have sufficient travel to accommodate uncertainty in optical alignment of the segment, installation tolerances for the hardware, and deflections of the telescope and cell under gravity and temperature changes. These allowances define the operational range of motion, over which the system must meet the wavefront accuracy requirements. The operational range for the actuators is ±8 mm in the axial direction and ±10 mm laterally. An additional range of ±4 mm axial and ±6 mm lateral motion is specified for seismic events with acceleration up to ±0.4 g. The segments must not be subjected to stress outside the specified limit (1030 kPa tensile stress) for seismic loads.

10.8.3 Optimization of support forces

In keeping with the design of the MMT, Magellan and LBT support systems, axial and lateral support forces are applied to the back plate of the segment. This arrangement is mechanically simpler and safer than applying forces inside the honeycomb structure near the neutral surface. The lateral forces at the back plate apply an unwanted moment to the segment, but it is easily compensated with axial forces. The axial forces therefore have a component proportional to the cosine of the segment’s zenith angle (the standard axial component) and a component proportional to the sine of that angle (the compensation for lateral forces). Both components are optimized to minimize deflections of the optical surface.

Axial forces are applied under rib intersections of the honeycomb structure, where the local strength and stiffness are greatest. A spacing of 384 mm, or two honeycomb cells, between support points reduces support print-through (shear deflections under gravity) to an insignificant level. This results in about 400 axial support points, more than the number of actuators needed to control the shape of the mirror. Most support points are therefore connected in groups of 2, 3, or 4 by load spreaders, reducing the number of actuators to 165.
Because the axial forces are optimized for all orientations, the distribution of lateral forces can be chosen for simplicity and to minimize local stress in the glass. Lateral forces are applied only at the locations of axial actuators that have 3- or 4-point loadspreaders. We use equal lateral forces at 85 locations covering most of the back plate. Applying lateral forces near the edge of the segment increases the required axial compensation forces, so lateral forces are not applied within about 0.5 m of the edge. Lateral forces are applied directly in the plane of the back plate, at the edges of the holes of the back plate. Each load spreader distributes the lateral force over 3 holes.

Table 10-12 lists the range of axial and lateral forces for the outer segments, for the extreme telescope zenith angles of 0° and 60°. Some axial forces go negative when a segment’s zenith angle exceeds 70°. Lateral forces, equal for all lateral actuators within a segment, would reach a maximum of 2073 N for a horizon-pointing segment (a situation that does not occur). The lateral forces differ among the segments when the telescope is not pointed at zenith.

Table 10-12. Minimum and maximum support forces for telescope zenith angles of 0° and 60°.

<table>
<thead>
<tr>
<th>telescope zenith angle</th>
<th>axial force (N)</th>
<th>lateral force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>minimum</td>
<td>maximum</td>
</tr>
<tr>
<td>0°</td>
<td>321</td>
<td>1878</td>
</tr>
<tr>
<td>60°</td>
<td>-117</td>
<td>1376</td>
</tr>
</tbody>
</table>

10.8.4 Load spreaders

The standard load spreader is a triangular metal frame that takes the force from one actuator, distributes the axial force equally to 3 points in the segment’s back plate, and distributes the lateral force equally also to 3 points in the back plate. A number of custom load spreaders are used near the edge of the segment, where the honeycomb geometry is irregular, and along the centerline. In all cases the axial support points are at rib intersections, where the structure is strongest and glass stresses are minimized, and the lateral support points are at the surfaces of holes in the back plate.

The load spreaders used on the MMT, Magellan and LBT mirrors are attached to the back plate through three 100 mm steel pucks bonded to the glass with compliant adhesive (RTV). Long-term load tests have raised concern about the lifetime of the RTV due to the shear stress caused by lateral support forces. The GMT load spreaders will therefore be attached mechanically to the back plate, with all loads in compression rather than tension or shear.

There are several constraints on the load-spreader geometry. Axial forces can be positive or negative due to the compensation for lateral force and active correction of figure errors. Applying axial loads to the unsupported back plate—away from the ribs—causes unacceptable stress, so the internal attachments for axial forces must be at the intersections of ribs and back plate. This requires a mechanism resembling a C-clamp reaching through a hole for each axial support point. For the lateral forces, the available surface area on each hole is insufficient to take the full load with acceptable stress, so the force from each actuator is distributed over 3 holes. We explored a number of load spreader geometries, calculating local stress in the glass.
due to axial and lateral support forces. We found that the design shown in Figure 10-34 satisfies the limit of 690 kPa tensile stress at any point in the glass. Results of a representative stress calculation are shown in Figure 10-35.

![Conceptual design of a standard 3-point load spreader](image1)

**Figure 10-34.** Conceptual design of a standard 3-point load spreader, viewed from the actuator toward the rear surface of the segment. The actuator attaches to the central triangle on the load spreader. The pucks are bonded to the rear surface of the segment, the cylinders interface with the surfaces of holes in the segment’s back plate, and the internal pucks are bonded to the inner surface of the back plate.

![Distribution of stress in the glass](image2)

**Figure 10-35.** Distribution of stress in the glass (tensile is positive) for a near-worst-case condition with a segment tilted 70° from horizontal. The locations of 2 pucks of a standard 3-point load spreader are indicated. (The third puck is outside the view.) Stress is labeled in psi. The maximum tensile stress is 32 psi, or 220 kPa.

The inner surfaces of the cast honeycomb mirror are irregular, so they require a compliant layer between the steel load spreader and the glass. The design calls for RTV at the inner surfaces where axial forces are applied, and a thin elastomeric ring bonded to the surface of each hole for
lateral forces. In order to accommodate local variations in the hole pattern, the steel cylinders that transfer lateral load will be attached to the load spreader frame after being fit into the holes.

10.8.5 Support actuators

The actuators are pneumatic force actuators. They apply axial and lateral forces in any direction. We use the term “actuator” for a unit that applies force in any desired direction at one point on the segment. An “axis” of an actuator is a pair of opposed pneumatic cylinders that applies force (positive or negative) in one direction. Each segment has 80 single-axis actuators that apply only axial force. The center segment tilts only in one direction, so most of the rest of its actuators have two axes. (A few have an additional cross-lateral axis for stability.) Four of the six outer segments require 2 components of lateral force, so the 85 actuators that apply lateral force have 3 axes. The six outer segments are interchangeable, so all have the same set of 3-axis actuators.

We explored several 3-axis actuator geometries, and determined that the geometry shown in Figure 10-36 is the simplest one that meets all requirements. It includes one axis perpendicular to the back plate and two axes at 45° to the back plate. A net force in any direction can be produced by a combination of the 3 forces. This force vector must be applied to the same point on the mirror and have the same direction even when the mirror is translated relative to the actuator by any amount within the operational range (±8 mm of axial motion and ±10 mm of lateral motion). The constant vector is achieved by transferring force from each axis to the load spreader through a ball decoupler, a translating bearing. The ball decoupler, combined with the travel of the pneumatic cylinders, allows the full operating range of motion with no loss of accuracy and without engaging the static supports. The cylinders and ball decouplers allow additional travel of at least 6 mm after the load spreaders contact the static supports.

Each axis has two opposed pneumatic cylinders to provide push and pull forces. The cylinders are essentially the same commercial, low-friction cylinders used for the LBT support system. The major change is to add "cushions", or restrictions of the outlet orifices at the end of travel, a standard option. Cushions increase safety by adding to the stiffness of the static supports before the actuator runs out of travel.

The force of each axis is measured by a load cell and controlled by a pair of proportional control valves, one for each cylinder. The load cells for all 3 actuators are connected to a common plate attached to the load spreader. The plate and its sliding washer serve as a ventilation seal to the top plate of the mirror cell, which is needed because the forced-air ventilation of the mirror requires positive pressure in the cell.

The specification for air consumption is a maximum of 40 scfm per segment at a supply pressure of 120-140 psi. This is the same as the specification for an LBT mirror. The GMT segment has more cylinders because of the 3-axis actuators, but the consumption per cylinder is expected to be lower because of improved control valves. The controls, valves, and load cells inside the cell may use up to 300 W of DC power per segment. An additional 2 kW of AC power is needed for the cell computer and other equipment located out of the cell.
Figure 10-36. Conceptual design of 3-axis actuator. Each axis consists of a pair of opposed pneumatic cylinders applying force to the load spreader through a cylindrical ball decoupler and a load cell. The actuator case is attached to the upper plate of the cell, while the moving parts attach to the load spreader.

The actuators are designed for simple and rapid installation and removal. Actuators are always installed and removed from inside the cell, with the mirror on the static supports. The fixed case that holds the cylinders has 3 slots that slide over 3 bolts in the top plate of the cell. The plate that attaches to the load spreader has two captive screws.

Before being installed, each actuator will be tested and calibrated in a fixture containing 6 load cells that measure all components of force and moment applied by the actuator. We will use this test stand to determine an offset and gain for each desired component of force, and to measure unwanted components of force and moment at the force application point. Measurements will be made over the full range of required forces and the full range of motion of the actuator relative to the mirror segment.

10.8.6 Static supports

Static supports are stiff springs that support the mirror evenly when the active support system is not operating, and limit the motion of the mirror during handling and seismic events. They provide support and constraint in the axial and both lateral directions. We will use the same static supports used for the Magellan and LBT mirrors. Each unit is a commercial cable isolator with 6 wire ropes holding a cylinder. Three static supports interface to each 3-point load spreader as shown in Figure 10-37. The static support’s cylinder captivates a bolt and flange attached to the load spreader, with sufficient clearance to allow the operational range of motion. The static supports restrain the segment for motion beyond the operating range.

The static support has approximately the same stiffness in all directions. It takes the maximum specified load of 1 g gravity and 0.4 g seismic, with a deflection of less than 6 mm.
10.8.7 Hard points

The hard points are motorized struts that determine the position of the segment. In operation, they apply nominally zero force. The hard-point geometry is a truncated hexapod—the legs do not meet at a common point but attach to 6 points each on the segment and cell—that completely defines the position of the segment relative to the cell. Each hard point contains a load cell to measure the force parallel to the leg. The 6 forces are combined to obtain the net force and net moment on the segment. The outer control loop adjusts the forces on the 165 actuators to eliminate the net force and moment.

Each hard point attaches to the back plate of the segment through a glass wedge, bonded to the rear surface with epoxy, that provides a surface normal to the hard point. Flexures at both ends allow free motion over the operational range of segment position, with the position determined by the lengths of the hard points. The hard points include breakaway mechanisms that cause the hard point to collapse or extend freely if the force exceeds 1300 N. The breakaway mechanism involves a piston that is preloaded with air pressure against a stiff contact area at each end.

The GMT hard point is similar to the LBT hard point, shown in Figure 10-38, with refinements to improve stiffness and breakaway behavior. The stiffness is specified as at least 115 N/μm. The locations and orientations of the hard points have been optimized to minimize mirror deflections and rigid body motion under wind load. For the optimized geometry with the specified hard-point stiffness, the lowest resonant frequency for rigid-body motion is 13 Hz. The deflection of the mirror surface due to wind is shown in Section 10.8.10.

The lengths of the hard points are actively controlled to maintain segment alignment, raise the mirror to its operating position, and lower it onto the static supports on shut-down. Movement is accomplished by a roller screw with a motor and gear, and is based on feedback from a displacement sensor. The resolution of motion is about 1 μm, adequate to limit image motion to about 0.2". The secondary mirror segments will compensate for small pistons and tilts of the primary segments, and the primary mirror segments will be moved only as needed to reduce stroke for the secondary segment’s positioning actuators.
10.8.8 Control of the support system

The functions of the control system are to control the support forces on the mirror; control the mirror position; perform diagnostic checks on the mirror cell subsystems; and report status information. The block diagram for the control system is shown in Figure 10-39. It uses 4 types of control computers or processors:

1. The cell computer, the main computer for the cell, functions as a user interface, safety supervisor, development environment, and boot host for the controllers in the cell. It will be a power PC or Intel based computer running standard Linux.

2. The hard-point controller controls all six hard points and runs the outer control loop that distributes force commands to the actuators. It will use low-power digital signal processors (DSPs) running a commercial real-time operating system (RTOS).

3. 335 axis controllers execute the inner control loops on the axes of the actuators. They will use the same DSPs and RTOS as the hard-point controller.

4. The air controller controls air supply and monitors the cell computer via a watchdog signal from the cell computer. If the watchdog signal is not present, the air controller will cause the mirror segment to be lowered onto the static supports by venting the air supply. The air controller also uses the same DSPs and RTOS as the hard-point controller.

All communication among the control computers and processors will be by Ethernet.
The forces measured by the hard points provide feedback to the outer control loop, which minimizes the hard-point forces by distributing force commands to the actuators so as to apply the same net force and moment. The outer loop also uses feed-forward from an inclinometer measuring the orientation of the mirror cell, which gives an estimate of the vector force and moment required to support the segment. The hard-point forces are fed into a PID algorithm to produce differential terms to be summed with the force and moment vector derived from the inclinometer. The hard-point controller sends the 6-element force-moment vector $J$ to all 335 axis controllers. It also sends to all the axis controllers a 335-element vector of correction forces $b$ based on wavefront measurements. The correction forces are defined to have zero net force and moment.

Each axis controller converts the force-moment vector and correction force vector to a single scalar force $F_i = k_i \cdot J + b_i$, where $k_i$ is a constant vector appropriate to the axis. This local computation of forces by the axis controllers reduces the real-time communication by a factor of about 50, compared with central computation of all forces by the hard-point controller.

The axis controller runs one force control loop with feedback from the load cell, and two pressure control loops (one for each cylinder) with feedback from two pressure sensors. The axis controller controls the cylinder pressures through proportional control valves. Figure 10-40 is a schematic of the axis control. A small local accumulator provides high-frequency isolation from the air supply system. The pressure loops will include compensation for the dead-band of the control valve.
10.8.9 Gravity and support errors

Deflections due to gravity and actuator force errors are grouped together in the image error budget. The error budget allows $\theta_{80} = 0.036^\circ$ for segment distortion due to gravity and actuator force errors when the telescope points at zenith. The allowance increases with zenith distance as the seeing-limited image size does, $\theta_{80} \propto (\sec z)^{3/5}$, to $\theta_{80} = 0.055^\circ$ at $z = 60^\circ$. A segment’s zenith distance $z'$ is not identical to $z$, but the distinction is not significant for this discussion of figure errors.

Axial forces are optimized to minimize gravity deflections for a zenith-pointing segment and a horizon-pointing segment. The horizon-pointing lateral forces are defined to be equal over all 85 lateral actuators as described in Section 10.8.3. Gravitational deflections have been computed for zenith-pointing, $d_z$, and horizon-pointing, $d_h$. The deflection at a zenith distance $z'$ is a weighted sum of the two, $d = d_z \cos z' + d_h \sin z'$. During manufacture, the segment will be measured zenith-pointing with a set of axial forces nominally identical to the operational forces. The gravity deflections will be polished out, causing the figure error to be zero at zenith-pointing. The net figure error at any zenith distance is $\delta = d_z (\cos z' - 1) + d_h \sin z'$.

Figure 10-41 shows the gravity deflections with the segment zenith-pointing, $d_z$, and the gravity deflections $d_h$ with the segment horizon-pointing in both directions with respect to the support pattern. These deflections would never be seen as figure errors in the telescope, but they are the patterns that are combined to calculate the deflection that would be seen at any zenith angle. The rms deflection is 7 nm zenith pointing, and 11 nm and 12 nm for the two horizon-pointing cases. Figure 10-42 shows the figure error $\delta$ that would result at a segment zenith angle $z' = 60^\circ$ in both directions. The rms surface error is 10 nm and 11 nm for the two cases.
Figure 10-41. Maps of gravity deflections for a segment zenith-pointing (left) and horizon-pointing in both directions with respect to the support layout. These deflections would not be seen as figure errors. The color bar is labeled in nm of surface.

Figure 10-42. Maps of the figure error due to gravity deflections for a segment zenith angle of 60° in both directions with respect to the support layout.

The actuators have force errors, primarily due to misalignment during assembly and friction in the bearings. The stiff honeycomb segment is relatively insensitive to force errors, but they must be accounted for in the error budget. Errors will appear in all 6 components of force and moment for each actuator. (The moments are nominally zero.) Some errors will be repeating while others, including those due to friction, will not repeat. Repeating force errors will have a repeating effect on the segment figure, and the resulting low-order aberrations will be corrected by the active optics system, leaving only residual high-order aberrations. Non-repeating errors are not correctable.

We estimate the magnitudes of errors from tests of the LBT support actuators, which are similar to the GMT actuators. We estimate the net errors for GMT 3-axis actuators as $\sqrt{3}/2$ times the measured errors for LBT 2-axis actuators, under the assumption that contributions of the axes are uncorrelated. Repeating and non-repeating errors were determined by commanding each actuator through a set of force levels 4 times. The estimated force and moment errors for GMT actuators are listed in Table 10-13.
Table 10-13. Estimated force and moment errors for GMT actuators, based on tests of LBT actuators. The $z$ axis is perpendicular to the segment’s rear surface.

<table>
<thead>
<tr>
<th>component</th>
<th>units</th>
<th>repeating</th>
<th>non-repeating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3-axis</td>
<td>single axis</td>
</tr>
<tr>
<td>$F_x$</td>
<td>N</td>
<td>6.9</td>
<td>2.2</td>
</tr>
<tr>
<td>$F_y$</td>
<td>N</td>
<td>5.1</td>
<td>2.4</td>
</tr>
<tr>
<td>$F_z$</td>
<td>N</td>
<td>5.2</td>
<td>1.5</td>
</tr>
<tr>
<td>$M_x$</td>
<td>N-m</td>
<td>4.7</td>
<td>1.6</td>
</tr>
<tr>
<td>$M_y$</td>
<td>N-m</td>
<td>3.7</td>
<td>1.6</td>
</tr>
<tr>
<td>$M_z$</td>
<td>N-m</td>
<td>2.9</td>
<td>0.1</td>
</tr>
</tbody>
</table>

In order to estimate the deflection of the optical surface due to actuator errors, we first calculate the deflections due to a representative set of actuators (e.g., one at the edge, one near the center, and one at an intermediate radius). We assume that the deflections due to other actuators are statistically equal to those of the representative actuators at similar locations. We then add the contributions of all actuators in quadrature. While this process is adequate for uncorrelated actuator errors, there may also be systematically distributed force errors, for example due to translation of the segment. We therefore assume additional errors in axial force with patterns corresponding to the segment’s 4 most flexible bending modes, astigmatism and trefoil (2 orthogonal modes each). The magnitude of force error for each systematic pattern is taken as $\frac{1}{4}$ of the randomly distributed error. This procedure is applied to both repeating and non-repeating errors.

For repeating errors, we simulate the active optics correction by fitting and removing the 28 most flexible bending modes from the computed deflection. For non-repeating errors, no correction is applied. The net effect of all actuator errors is 21 nm rms surface error. The dominant error (15 nm rms) is in the form of astigmatism due to the non-repeating, systematic error pattern.

Figure 10-43 and Figure 10-44 show the structure functions calculated for gravity deflections and actuator errors for $z' = 0'$ (where the figure error due to gravity is zero) and $z' = 60'$. A structure function corresponding to the allowed image size $\theta_{80}$ is plotted for comparison. This structure function for $\theta_{80}$ is the short-exposure structure function defined in Section 10.2.3, with no allowance for scattering loss. For zenith pointing, $\theta_{80} = 0.036''$ and the corresponding $r_0 = 530$ cm. For $z' = 60'$, $\theta_{80} = 0.055''$ and $r_0 = 350$ cm. For $z' = 60'$ the predicted structure function exceeds the structure function corresponding to $\theta_{80}$ at small separations but lies under the $\theta_{80}$ structure function by about a factor of 2 at larger separations. The net effect is that the image blur due to the gravity deflections and force errors will be less than the specified $\theta_{80}$. We will calculate $\theta_{80}$ explicitly for the predicted error in the next phase of development.
Figure 10-43. Structure function for actuator force errors, compared with the structure function corresponding to $\theta_{90} = 0.036^\circ$.

Figure 10-44. Structure function for gravity deflections and actuator force errors at $z' = 60^\circ$, compared with the structure function corresponding to $\theta_{90} = 0.055^\circ$. 
10.8.10 Wind deflections

An important function of the hard points is to resist the high-frequency components of wind. The low-frequency components, resisted by the full set of actuators, cause an insignificant deflection of the optical surface because the wind pressure is less than 1% of the gravity load. The locations and angles of the hard points are optimized to minimize both rigid-body displacements and deformations due to the high-frequency component. The magnitude of deflection depends on the wind speed and spectrum of fluctuations, and the bandwidth of the outer control loop that transfers reaction forces from the hard points to the actuators.

We computed deflections due to an 8.9 m/s wind with a Kaimal spectrum incident on the mirror. This gives a very conservative approximation of deflections due to wind, because the enclosure will attenuate the wind by a significant factor. The spectrum was filtered according to a 0.95 Hz outer-loop bandwidth, yielding pressure variations of 6 Pa rms for the high-frequency component. Figure 10-45 shows the surface deflection due to this pressure resisted by the hard points. The rms deflection is 31 nm. The structure function is shown in Figure 10-46 along with the structure function corresponding to $\theta_{so} = 0.075''$, the allowance for deflections due to wind. The predicted deflection is well within the error budget.

![Figure 10-45. Deflection due to the high-frequency component of an 8.9 m/s wind resisted by the hard points. The color bar is labeled in nm. Focus is not removed.](image)
10.8.11 Thermal performance

The borosilicate mirror segment, with a thermal expansion coefficient of 2.9 ppm/K, is sensitive to temperature gradients. Gradients are minimized by ventilation of the internal structure of the segment with forced air at controlled temperature (typically ambient temperature). The ventilation system also minimizes mirror seeing by keeping the surface temperature close to ambient. The thermal control system is described in Section 10.9. The present section includes calculated thermo-elastic deflections of the segment and the degree to which they can be corrected with the active support system.

We have calculated the deflections resulting from a number of temperature distributions. For each set of deflections we simulated a correction with the active optics system, using up to 28 bending modes for compensation. Figure 10-47 through Figure 10-49 show the deflections before and after correction for several cases. As the number of bending modes increases, the correction forces increase and the residual deflection decreases. It is necessary to strike a balance between excessive correction forces and excessive figure error. The error budget specifies $\theta_{s0} = 0.089^\circ$ with a goal of $\theta_{s0} = 0.045^\circ$. The structure function corresponding to the specification can accommodate rms surface errors of 35-50 nm on the spatial scales of 1-2 m that will dominate the residual error after active correction. Correction forces may not exceed ±300 N on actuators with 2-point load spreaders, and ±440 N on actuators with 3-point load spreaders. While a small fraction of this range is used to correct low-order aberrations in the optical test and actuator errors, we can allow up to ±200 N on individual actuators to correct thermal deflections. We set a conservative limit of 50 N rms correction force over all actuators.
Table 10-14 lists, for each temperature distribution, the rms figure error before and after correction, and the rms correction force. Tilt of the surface is ignored but power (change of radius of curvature) is not ignored. The table also lists the magnitude of the temperature
difference that can be corrected with correction force less than 50 N rms and residual figure error less than 50 nm rms.

Table 10-14. Deflections due to certain temperature distributions, and correction force. Last column is magnitude of temperature distribution that can be corrected with <50 N rms force and <50 nm rms residual error.

<table>
<thead>
<tr>
<th>temperature distribution</th>
<th>magnitude</th>
<th>rms deflection, uncorrected (nm)</th>
<th>rms deflection, corrected (nm)</th>
<th>number of modes</th>
<th>rms correction force (N)</th>
<th>correctable magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>linear variation across diameter</td>
<td>1 K p-v</td>
<td>1.8</td>
<td>0.5</td>
<td>7</td>
<td>0.1</td>
<td>unlimited</td>
</tr>
<tr>
<td>linear variation with radius</td>
<td>1 K p-v</td>
<td>490</td>
<td>16</td>
<td>28</td>
<td>14</td>
<td>3 K p-v</td>
</tr>
<tr>
<td>quadratic variation with radius</td>
<td>1 K p-v</td>
<td>560</td>
<td>28</td>
<td>28</td>
<td>25</td>
<td>2 K p-v</td>
</tr>
<tr>
<td>uniform change</td>
<td>10 K</td>
<td>2000</td>
<td>108</td>
<td>14</td>
<td>76</td>
<td>5 K</td>
</tr>
<tr>
<td>uniform axial gradient</td>
<td>1 K/m</td>
<td>7600</td>
<td>400</td>
<td>14</td>
<td>280</td>
<td>0.12 K/m</td>
</tr>
<tr>
<td>axial gradient varying linearly with radius (back plate uniform)</td>
<td>1 K/m p-v</td>
<td>660</td>
<td>130</td>
<td>14</td>
<td>82</td>
<td>0.4 K/m p-v</td>
</tr>
<tr>
<td>axial gradient varying linearly across diameter (back plate uniform)</td>
<td>1 K/m p-v</td>
<td>630</td>
<td>85</td>
<td>20</td>
<td>100</td>
<td>0.5 K/m p-v</td>
</tr>
</tbody>
</table>

The most problematic distribution is a uniform axial gradient. According to the analysis it must be kept below 0.12 K/m to avoid exceeding limits on figure error and correction forces. Axial gradients that vary across the radius or diameter are more benign and can be 3-4 times larger. The uniform change applies to the differences among segments, because any change common to all segments will simply cause the primary mirror to grow or shrink and is correctable by refocusing with the secondary.

The result for the axial gradient is a cause for concern, but this may not be representative of temperature gradients that would arise in practice. While most of the deflection is focus, which is easily corrected, there is enough high-order spherical aberration to leave a large residual error after correcting the first two axisymmetric modes (modes 3 and 14, corresponding roughly to focus and the first spherical aberration). Analysis of similar axial gradients in the LBT mirrors does not show nearly as much high-order spherical aberration. The temperature distribution analyzed for LBT was slightly different, and the structure of the LBT mirror is different from
that of the GMT segment. We will continue the analysis to determine whether the result presented here is representative and to understand why the residual error after correction depends so strongly on the details of the temperature distribution or the segment geometry.

10.8.12 Reliability and maintenance

The support actuators are being designed with the goal of minimizing down-time for repair, and minimizing cost for manufacturing, operation and maintenance. The GMT design is the fifth generation of similar actuators used previously in the SOR 3.5 m telescope, MMT, Magellan telescopes, and LBT. Prior experience with these actuators as well as some improved technology will lead to a more robust design for GMT, as is required for a mirror with 1150 actuators.

The specification for actuator reliability is a mean time between failures of 10,000 hours of operation, and the goal is 100,000 hours. The specification would result in an average of 10 failures per week for the telescope while the goal would give one failure per week. Only one component of the present (LBT) generation of actuators has shown reliability that would be problematic for GMT, and that is the pressure regulator. Proportional control valves are now available that are more reliable than the LBT regulators. They have the added advantage of using less compressed air. Their initially higher cost will be recovered during operation by reducing maintenance.

The actuators are designed for ease of installation and removal, as described in Section 10.8.5. The actuator test stand will be designed with the same considerations. The LBT test stand and its software allow a full actuator calibration and characterization in about 45 minutes, including mounting the actuator. This translates to 124 hours for a full set of actuators for one segment, so there is incentive to reduce the time further.

10.9 Thermal control

10.9.1 Ventilation requirements

The purpose of the primary mirror ventilation system is (a) to reduce temperature gradients within the mirror to a level where the thermal deflections satisfy the requirements of the error budget and (b) to maintain the mirror surface temperature near or slightly below the ambient air temperature to reduce mirror seeing. The system is designed to satisfy the image error budget when the outside temperature is changing by up to ±0.5 K/h (20th - 90th percentile conditions).

The technique employed on the 3.5 m, 6.5 m, and 8.4 m telescopes involves blowing air, conditioned to the ambient temperature, into the interior cells of the mirror to promote rapid equilibration of the internal temperatures. This was described in Ref. 8 and has been discussed in a number of papers since. (Refs. 9-12) The air is injected into the cells with typically 25 mm diameter nozzles that come up approximately level with the back surface of the mirror and direct the air into the cell with speeds of 12-16 m/s (6-8 L/s). There are 1681 cores in the off-axis primary mirror segments.

As shown in Section 10.8.11, a front-face to back-face temperature gradient (“uniform axial gradient”) appears to set the tightest tolerances for thermal control. The temperature distribution
for this case induces bending in axisymmetric modes including higher orders of spherical aberration for which the mirror is very stiff and high correction forces are required. The goal is to reduce the internal temperature gradient below 0.12 K/m to control this bending. Experimental results in Ref. 8 for a case relevant to GMT (8 L/s air flow, 0.25 K/h cooling rate) showed a total variation of 0.08 K within a cell and less than 0.02 K front-to-back differences. It remains to be demonstrated that this result scales to the higher cooling rate for GMT. It is likely that for the highest cooling rates the atmospheric seeing will be poor and mirror deflection will not be a limiting factor.

The requirement for mirror seeing is $\theta_{60} = 0.057''$ and the goal is $\theta_{60} = 0.039''$. As shown in Chapter 12, these limits on mirror seeing correspond to temperature differences between the segment and ambient air $\Delta T < 0.4$ K for the requirement and $\Delta T < 0.3$ K for the goal, assuming a 1 m/s wind across the segment’s surface. (The allowed temperature difference depends weakly on wind speed $v$, roughly as $v^{0.5}$.) At the specified cooling rate, 0.5 K/h, we require a thermal time constant $\tau \approx 0.8$ h and our goal is $\tau \approx 0.6$ h. The rate of air flow required to produce these time constants depends on physical properties of the glass and the air, and on the coupling efficiency between air and glass, defined as

$$\eta = \frac{T_{\text{out}} - T_{\text{in}}}{T_{\text{glass}} - T_{\text{in}}},$$

where $T_{\text{in}}$ and $T_{\text{out}}$ are the air temperatures coming into the cell and leaving the cell, and $T_{\text{glass}}$ is the glass temperature. (Thus $\eta = 1$ if the air comes fully to the glass temperature as it passes through the cell.)

The experiments of Ref. 8 found that $\eta \approx 0.6$ for flow rates up to about 10 L/s. With $\eta = 0.6$ one can show that a flow rate of 5.4 L/s should meet the goal of $\tau = 0.6$ h. The Magellan primary mirrors are ventilated with a flow rate of about 5.6 L/s and the time constant is seen to be about 1.0 h, suggesting that the coupling efficiency is closer to 0.4. The GMT ventilation system will be designed to supply 8 L/s per nozzle in order to keep the segment’s front facesheet within 0.3-0.4 K of ambient temperature for ambient temperature changes of at least 0.5 K/h. In addition to one nozzle per cell, about 70 additional nozzles are needed around the perimeter of the mirror to ventilate the outer wall.

10.9.2 Design

The nozzles that direct streams of air into the segment’s honeycomb cells mount in the top plate of the mirror cell, directly below the back of the segment, as shown in Figure 10-50. The volume below the plate is loosely sealed and pressurized to around 90 Pa relative to ambient. This pressure difference drives the flow in the nozzles. The mirror support actuators and hard points penetrate the top plate and must be sealed off to prevent short circuiting the flow. In order to avoid spurious forces on the mirror, the air above the plate is maintained at atmospheric pressure with filtered vents through the side walls of the cell.
There are currently two methods for producing the pressurized air inside the mirror support cell. The first to be developed uses fans with heat exchangers to draw air down from above the top plate and bring it to the set-point temperature close to ambient. This method is used by the 3.5 m telescopes and Magellan. The heat exchangers are supplied with liquid coolant from chillers off the telescope.

In the second method, the air is pressurized and conditioned by one or more remote compressors, heat exchangers and filters, and brought onto the telescope with large ducts. The pressurized air is fed into flow amplifiers (“jet ejectors”) in the mirror cell that boost the flow volume by a factor of 10 to pressurize the plenum. MMT and LBT use jet ejectors.

The on-board fans have the advantage that they use less than half the power of the jet ejectors and require much smaller supply lines coming onto the telescope. Air in the system is recirculated so cleanliness is less an issue. The disadvantages are in having coolant in the cell, vibration from the fan and coolant pump, and power dissipation from the fans.

The jet ejectors have the advantage of having no moving parts or power electronics in the cell and no fan vibration, although there may be acoustic noise generated by the jets. The disadvantages are the large, stiff ducting to get the air onto the telescope, the introduction of external air with potential contaminants, and power consumption.

The baseline ventilator concept selected for GMT is a modification of the Magellan on-board fan/heat exchanger design, Figure 10-51. Each unit supplies 18-20 nozzles at 94 Pa for the target flow rate of 8 L/s per nozzle. AC and DC versions of the fans are available with similar performance characteristics. Magellan uses DC fans. GMT will require about 95 ventilators per segment including the provision for 70 nozzles at the side walls.

Figure 10-50. Nozzles exhausting pressurized air into the cells of the honeycomb mirror segment.
The fan/heat exchanger assembly is supported from the top plate by a pair of C-channels. A double layer of rubber mounts provide vibration isolation. The fan assembly is coupled to the fitting through the top plate by a flexible duct.

Supply and return lines for coolant attach to the heat exchanger. A coolant loop for each cell supplies glycol to the ventilators at a set temperature. The flow in the loop is about 6.4 L/s. The temperature in the loop is controlled by a valve that mixes glycol from a chiller off the telescope into the loop circuit. The circulating pump and mixing valve are located in the C-ring structure.

The heat exchangers will be supplied with glycol all at the same temperature. Turbulent mixing of the air in the lower plenum will eliminate air temperature variations due to temperature variation in the return air from the mirror and surrounding cell, differences in efficiency of heat exchangers, and local heat sources such as actuators. The system will have a single set-point temperature determined from an array of thermocouples that measure the difference between the air temperature averaged throughout the cell and the ambient air above the mirror. All temperatures are measured relative to a copper block. This technique was first developed on the WIYN 3.5 m telescope and later used on Magellan. The accuracy achieved is better than 0.01 K. The temperature readings are recorded with an Agilent Model 34970A data logger connected to the mirror thermal control computer.

Vibration must be considered in the design of the fan assemblies. In all of the systems currently deployed, the fans are mounted on very compliant vibration isolators to reduce coupling to the cell structure. In the cases of Magellan and GMT two stages of isolation are provided. The individual fans are dynamically balanced before being installed in the ventilators.

Interferograms taken with the fans running on the Magellan 1 mirror under the test tower at the Mirror Lab showed no discernible fringe motion in the real-time image nor any increase in the rms error in the measured wavefront. Similarly, during testing of the WIYN primary mirror assembly, no degradation was apparent in scatter-plate interferograms taken with the fans.
running nor was any motion detected down to the level of 0.05" in an inspection of point-source images produced by the mirror and viewed with an auto-collimating microscope. The WIYN ventilation system used a fan arrangement different from Magellan’s but with the same design flow rates.

The estimated cooling loads and power requirements per segment are given in Table 10-15 and Table 10-16. The chiller system will use staged compressors to supply all seven mirror cells with parallel redundant circulating pumps.

**Table 10-15. Cooling load for the ventilation system, for one primary mirror segment.**

<table>
<thead>
<tr>
<th>source of heat</th>
<th>steady-state load (kW)</th>
<th>transient load at 2 K/h (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fans (101 x 65 W)</td>
<td>6.7</td>
<td>6.7</td>
</tr>
<tr>
<td>coolant pump (6.4 l/s @ 0.15MPa)</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>thermal mass glass (16.2 t @ 740 J/kg/K)</td>
<td>0</td>
<td>6.7</td>
</tr>
<tr>
<td>thermal mass steel (36 t @ 434 J/kg/K)</td>
<td>0</td>
<td>8.7</td>
</tr>
<tr>
<td>total</td>
<td>8.0</td>
<td>23.4</td>
</tr>
</tbody>
</table>

**Table 10-16. Power requirement for the ventilation system, for one primary mirror segment.**

<table>
<thead>
<tr>
<th>component</th>
<th>steady-state load (kW)</th>
<th>transient load at 2 K/h (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fans</td>
<td>6.7</td>
<td>6.7</td>
</tr>
<tr>
<td>coolant pump</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>chiller system (cooling load/COP = 3)</td>
<td>2.7</td>
<td>7.8</td>
</tr>
<tr>
<td>booster pump</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>total</td>
<td>12.2</td>
<td>17.3</td>
</tr>
</tbody>
</table>

The fans on Magellan have been very reliable with only a two failures in 5 years of service on two telescopes (112 fans). The other failure points have been occasional leaks at the fluid connectors to the heat exchangers and problems early on with the DC power supplies which have since been addressed.

The mirror ventilation system will be thoroughly reviewed during the detailed design phase of the project. Jet ejectors and alternative concepts as well as the baseline concept remain under consideration. Alternative concepts currently under discussion include separating the heat exchangers from the main set of fans and moving them out of the cell. The advantages are higher flow through the fans due to less restriction and fewer fluid lines in the cell. The heat exchangers would be provided with a separate set of blowers.
10.10 Mirror transport

The mirror transport system is a mature design that has already transported two 8.4 m LBT mirrors to the telescope. The similar 6.5 m transport system has taken two Magellan mirrors to Las Campanas.

The LBT transport box is shown in Figure 10-52. The mirror is supported and attached to the box through the load spreaders, which are attached in pairs to a spreader beam that is supported on rubber springs. The spring deflections are about 10 mm for the full weight of the mirror in any direction, and the box allows at least 50 mm of travel in all directions. The springs are mounted on a simple steel frame with 5 cross beams and two end beams. The beams are sized to deflect less than 1 mm under the weight of the mirror in any direction. This ensures an even load distribution on the mirror because the spring deflections are 10 times the frame deflection.

The inner frame is surrounded by an outer frame and connected to it with a pneumatic “Air Ride Truck Suspension” bag that gives soft vibration isolation. The soft suspension then requires rubber end stops to limit the travel from large bumps or in case an air bag leaks. The outer frame can be poorly supported or severely deformed without distorting the inner frame. Insulating panels and a light steel armor plate cover the outer frame.

The resonant frequency of the rubber springs is about 5 Hz and that of the pneumatics about 1 Hz. This dual isolation damps all significant vibrations including those near the resonant frequencies that could be amplified by either system alone.

![Figure 10-52. Views of the LBT transport box. Left: mirror being installed onto support frame of transport box. The mirror is suspended by vacuum pads, with a protective coating on the optical surface. Right: closed transport box being loaded onto trailer.](image)

10.11 Cleaning

In order to maintain high reflectivity and low emissivity, routine CO₂ cleaning of the optics is required. Due to the large surface area and minimized access to the primary mirror segments, an automated system is required. Normal soap and water washing will not be done due to the limited access to the segments and the planned frequent aluminizing schedule.
CO₂ cleaning is done by directing a CO₂ snow at the mirror and allowing it to sublime at the mirror’s surface. The sublimation process loosens contamination which is then swept away by the flow of CO₂ snow and gas. The CO₂ snow is generated by expansion of bulk CO₂ liquid through an appropriately sized nozzle. In the case of GMT, multiple nozzles will be used on a common distribution rail to speed the process.

A regular cleaning schedule is required to avoid having the contamination adhere to the mirrors. Current practice is to clean every two weeks. Better results are obtained with shorter intervals and this must be balanced against the manpower overhead and cost even with a semi-automated system. It is important to minimize the mirror surface exposure to high humidity events while the mirror is dirty. High humidity increases the adherence of contamination to the mirror surface, making snow cleaning less effective.

The Magellan 6.5 m mirrors are CO₂ cleaned with the telescopes horizon pointing. This allows the contaminants to fall to the bottom of the cell where they can be removed with a vacuum cleaner. The GMT does not fully reach the horizon so an alternative procedure will be developed for picking up the dust.

10.12 Technical challenges and risks

The major technical risks for the primary mirror segments are seen to be measurement of the off-axis segment, and thermal control. The measurement involves a number of new systems that have not been implemented on a large scale. The risk is being mitigated by a thorough analysis and by prototyping the optical test and the laser tracker measurement with the NST mirror. The analysis shows that a reasonable set of tolerances will meet the accuracy requirements. The prototype is valuable in at least two ways. It serves as a proof of concept and greatly reduces the risk of encountering a fundamental difficulty in the GMT implementation. And it reduces the risk of delays in the GMT implementation by forcing the manufacturing group to develop and practice many of the detailed techniques—such as aligning meter-class optics to 10 µm accuracy—that must come together for the GMT test.

Thermal control appears to be a technical risk because the analysis of the segment shows a surprisingly high sensitivity to an axial temperature gradient. This risk is being addressed by further analysis of the segment’s thermo-elastic deflections and early attention to the ventilation system. In the next phase of the project we will develop a full thermal model of the segment and its cell, and apply realistic heat loads as opposed to simple, defined temperature distributions. Although the GMT analysis to date makes it clear that this issue requires attention, we are encouraged by the fact that the Magellan telescopes—with similar borosilicate honeycomb mirrors and a relatively weak ventilation system—regularly produce excellent images. The Magellan performance is often limited by temperature gradients in the first few hours of the night when the mirrors are farthest from equilibrium with the ambient air. GMT needs to improve on this performance, possibly by increased ventilation flow and pre-conditioning during the daytime. The overall experience with Magellan, however, gives us confidence that the segment design is fundamentally sound and that excellent performance can be obtained without a dramatically different approach to thermal control.
10.13 References


