Manufacture of GMT Primary Mirror Segments

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8.4 m honeycomb sandwich segments

- 8.4 m honeycomb sandwich segments are the best way to guarantee a smooth wavefront over the largest possible area.
- Their excellent imaging performance will carry over from Magellan to GMT.
- They reduce the mechanics of alignment and phasing to control of 7 agile secondary mirror segments.
- They come with a legacy of optimized design for mirror structure, mirror support, and thermal control.
- Manufacturing system and plant for serial production are almost complete.
3 stages of segment fabrication

1. Spin-cast mirror blank, forming honeycomb-sandwich structure.
2. Machine and polish rear surface; bond loadspreaders; generate optical surface.
3. Polish optical surface to specifications.
   - Accurate, redundant measurements are critical.
   - Each stage is performed at a different station.
     - Allows parallel processing of 3 segments.
   - Each stage will take about 12 months in routine operation (1-1.5 shifts).
     - Longer for first segment.
     - First segment includes building complete system of measurements, to be used for all segments.
Stage 1. Casting: mold assembly

Mold consists of tub made of silicon carbide cement, lined with ceramic fiber, filled with 1681 ceramic fiber boxes that form honeycomb structure.

Tops of boxes follow shape of aspheric surface; no two are identical.

Machine and install ceramic fiber boxes.
Casting: glass loading

Inspect, weigh, and load 18 t of Ohara E6 borosilicate glass.

Close furnace, prepare to melt and spin.
Casting: melt and spin

Heat to 1160°C, spin at 4.9 rpm, hold 4 hours to allow glass to fill mold. Cool rapidly to 900°C then slowly for 3 months, 2.4 K/day through annealing (530-450°C).
Lift and removal of mold material

Segment with lifting fixture

Tilted into vertical plane
Rear surface with floor tiles attached

Removal of floor tiles and ceramic fiber
Stage 2. Rear surface preparation

- Machine, lap and polish rear surface, edges.
- Bond 165 loadspreaders.
  - Permanent interface to active support system.

GMT loadspreaders being surveyed and bonded to rear surface
Front surface generating

Generate off-axis aspheric surface by diamond machining with 3-axis mill.
Stage 3. Polishing with stressed lap

Stressed-lap polishing developed for highly aspheric surfaces.
- Polishing disk bends actively to match varying curvature of surface.
- Gives passive smoothing traditionally associated with spherical surfaces.
- Works for off-axis surfaces as well as symmetric aspheres.
Orbital polisher with RC lap

New machine has second spindle for stressed lap or orbital polisher.

- Orbital polisher is good for local figuring, correcting small-scale errors.
- Rigid conformal (RC) lap is stiff on short timescales and compliant through flow on long.
- We are implementing new control and modeling with variable dwell time.
Measurements

Principal optical test
Full-aperture, interferometric test
Also provides SCOTS slope test

Scanning pentaprism test
Measures low-order aberrations via slopes

Laser Tracker Plus
Scans surface with laser tracker
Works on ground or polished surface
Laser Tracker Plus

Stability references:
4 fixed DMIs monitor relative motion out of plane.
4 PSDs monitor relative motion in plane.
Also sense apparent motion due to refractive index.
Principal optical test

Reference CGH is used to align large fold sphere and GMT segment to wavefront from small components. It is currently being upgraded to meet alignment requirements.
Axisymmetric

Test optics at ~20 m
Light from optical test is only 200 mm diameter near the test optics. Allows direct measurement of test wavefront.

No axisymmetry
Light path defined by GMT is much larger: 3.5 m diameter at top of tower.
Shaping of test wavefront

14 mm p-v at GMT surface

6.1 mm p-v at intermediate focus between fold spheres

320 µm p-v between 76 cm sphere and CGH

Difference from sphere (µm)
Principal test in tower

3.75 m spherical mirror
23 m above GMT segment

CGH
vibration-insensitive interferometer
Alignment accuracy

- Alignment errors in the test cause low-order aberrations, correctable with active optics.
  - Active optics is necessary and automatic for all telescopes ~4 m or larger.
  - Wavefront measurement using starlight are more accurate than lab measurements for low-order aberrations.
  - For segmented primary, active optics includes segment alignment as well as bending.
- Analysis of measurements takes account of active optics that will be used in telescope.
  - Consider not only the figure error measured in the lab, but error that will be seen in telescope when active optics are used.
- For every source of error:
  - Estimate wavefront error.
  - Simulate correction of low-order components with active alignment then bending.
  - Keep track of segment displacement, rms actuator force, residual wavefront error
- Add effects of all error sources in quadrature.
- Verify that net displacement and actuator forces do not exceed allowances.
- With new reference hologram, alignment errors are expected to contribute:
  - No error in radius of curvature (after segment alignment and bending)
  - 1.2 mm uncertainty in off-axis distance (spec = 2 mm, goal = 1 mm)
  - 14 N rms actuator force (spec = 30 N)
  - 16 nm rms surface error (meets requirement for figure accuracy)
Scanning pentaprism test

- Scan collimated beam across the pupil.
- Pentaprism ensures deflected beam remains parallel to optical axis of parent.
- Motion of spot at prime focus is proportional to surface slope error.
- Accuracy of 0.5 μrad rms surface slope
  - Immune to rotations of pentaprism to 1st order
  - Differential: reference prism allows rejection of system alignment errors
- Determine low-order aberrations by fitting model to measured slopes.
Implementation for GMT segments

- GMT pentaprism system has rail support beam held at center, suspended from test tower.
- Central hub allows pentaprism to scan any diameter (any rotation angle).
- System stows at side of tower, leaving light path free for principal test.
- Status: Made first set of measurements, working out details of data processing software.
SCOTS slope test

- Software Configurable Optical Test System measures slope of surface.
  - Accurate for small- and mid-scale structure: 1 cm - 2 m
  - Complementary to pentaprism test
  - Together pentaprism and SCOTS tests provide independent confirmation of principal test

- Video monitor displays lines, camera records images through GMT segment and fold sphere.
- Knowledge of coordinates determines slope at each position on segment surface.
- Geometry is not controlled well enough to determine low-order aberrations.
Recent progress in figuring segment

- First 4 months of 2010 are shown. Polishing suspended May 1 for upgrade of reference CGH and first pentaprism test.
- Focus and astigmatism are separated because:
  - Tolerances are loose: $\Delta R = 0.6$ mm for 1 µm rms focus; bend out 1 µm rms astigmatism with only 12 N rms force.
  - They’re sensitive to misalignments in principal test, temperature gradients, support forces.
  - We’ll reduce measured values to ~100 nm rms surface.
- Most important quantity is residual error after subtracting focus and astigmatism.
  - It has improved in parallel with focus correction.
• Map is synthesis of data from principal test (21 low-order polynomials) and SCOTS test (everything else).
• Principal test currently loses some data at edge of segment due to high slopes and temporary lack of vibration isolation.
• Figure error of finished mirror will be around 30 nm rms with focus and astigmatism subtracted.

all aberrations included
2.0 µm rms

focus & astigmatism subtracted
0.44 µm rms
Compare principal test and Laser Tracker Plus

<table>
<thead>
<tr>
<th>Test Type</th>
<th>rms Value</th>
<th>Aberrations Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal test</td>
<td>2.0 µm</td>
<td>all aberrations included</td>
</tr>
<tr>
<td>Laser Tracker Plus</td>
<td>2.6 µm</td>
<td>all aberrations included</td>
</tr>
<tr>
<td>Difference</td>
<td>1.3 µm</td>
<td>all aberrations included</td>
</tr>
</tbody>
</table>

LT+ map is 8-degree polynomial fit to 256 measured points (0.5 m spacing).

Differences in focus (1.0 µm rms) and astigmatism (0.7 µm rms) are close to expected accuracy of LT+, but misalignment of PT probably contributes.

With F&A subtracted, much of difference is small-scale structure LT+ does not resolve.
SCOTS ignores 21 low-order polynomials, so same polynomials are subtracted from principal test.

Excellent agreement. Much of difference is error in principal test at edge of segment.
Summary

• The Mirror Lab has developed a complete system for efficient serial production of GMT segments.
  • Segments can be produced at 1-year intervals after 2\textsuperscript{nd} segment.
• The system includes a powerful suite of tests.
  • Supports all stages of fabrication
  • Measures segment geometry as well as figure, to high accuracy
  • Provides necessary redundancy in all critical parameters
• One set of tests serves to make all segments.
  • Minor modifications of principal test and pentaprism test for center segment
• We are implementing more effective small-tool figuring capability to augment stressed lap.
• First segment’s figure is improving steadily.
Backup slides

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Measurements

- Measurements are critical.
  - We make the mirror to match the test.
  - GMT off-axis segments are difficult to measure, because of large, non-axisymmetric aspheric departure.
  - We provide the necessary redundancy with independent measurements of all critical parameters.

- UA has unique experience in measuring large, highly aspheric surfaces.
  - GMT tests build on experience with four 6.5 m systems, 8.4 m LBT primaries, and 1.7 m NST off-axis mirror.
  - Tests make use of computer-generated holograms and other methods developed by Burge.

- 4 different measurements, supporting all stages of fabrication.
Principal optical test

- Principal test is a full-aperture, high-resolution, interferometric measurement.
  - Produces interferograms, phase maps like everyone uses to guide polishing
- Null corrector designed by Burge is complex because of large, non-axisymmetric aspheric departure.
  - Null corrector produces template wavefront.
  - Surface is polished to match that wavefront.
System accuracy as structure function

- Add alignment errors and component errors to estimate the system accuracy.
- To accommodate measurement errors, spec for measured figure errors in GMT segment is tightened for separations > 100 mm.
- The system meets our goals for accuracy in terms of structure function.