Optical Testing of Mirrors for Giant Telescopes

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Today’s talk

- Introduce giant astronomical telescopes planning to be built in the next decade
- Summarize challenges of testing the mirrors for these telescopes
- Present technologies and capabilities developed at the University of Arizona that enable measurements of the mirrors
The Giant Magellan Telescope

Site in Chile
2018 first light
Consortium with UA
GMT Design

36 meters high, 25.3 meters across

25-m Primary mirror (f/0.7)

3.2-m segmented secondary mirror
corrects for PM position errors
deformable mirror for adaptive optics

Alt-Az structure
~1000 tons moving mass
21.3 m azimuth disk
21 m elevation C-ring

Steel + CFRP secondary support

Instruments mount below primary at the Gregorian focus
GMT Primary mirror segments

- Off-axis asphere with ~15 mm aspheric departure
- Segments must match in radius to work together correctly
- For 25-m diameter parent, 36 m ROC is needed

14.5 mm departure from best fit sphere
GMT segments

- Aspheric polishing with stressed lap
- Shaping relies on feedback from surface measurement
Optical testing of GMT segments

Heritage (LBT)
~1.4 mm aspheric departure

Axisymmetric
Test optics at ~20 meters
Light from optical test is only 200 mm diameter near the test optics – allows direct measurement of test system

No Axisymmetry
Light path defined by GMT is much larger (~3.5 meters across at the top of our tower)
Interferometric surface measurements

interferometer and reflective null corrector with CGH

3.75-m M1 fold sphere tilted 14.2°

75-cm mirror

Axis of parent ellipsoid

M1 center of curvature

Interferometer at M1 center of curvature

Sam

CGH

GMT segment

25 meters
Test tower at Steward Observatory Mirror Lab

New tower

28 meters tall, 80 tons of steel floated on 400 ton concrete pad
accommodates other UA projects (LBT, LSST)
lowest resonance of 4.8 Hz with 9 ton 3.75-m fold sphere + cell

J. H. Burge  University of Arizona
CGH test of small optics system

- CGH inserted into light coming from Sam for alignment test
- Reflection back through system is used to verify wavefront
- CGH mounted on invar plate with other references for M1 alignment
Active system alignment relies on laser tracker

- Reference hologram is aligned to Sam. Then it is used to represent Sam.
- Laser tracker used to measure locations of Sam, fold sphere, GMT
- Fold sphere and GMT actively positioned to ~100 um

Laser tracker

Sphere
Mounted
Retroreflector

Measures $\rho$, $\theta$, $\phi$ to determine position to ~25 $\mu$m
Measurement of center segment

Tilt the fold sphere to nadir

Cone defined by light from outer edge of mirror

Cone defined by light from edge of central hole

50 mm CGH compensates 20µm aspheric departure

Vibration insensitive interferometer
3.75 m fold sphere

- UA produced mirror, mounted at the top of the tower
- Shape is actively controlled based on surface measurements from the center of curvature

Cast in the Mirror Lab spinning oven
Polished, measured at the Mirror Lab
Coated at Kitt Peak
Scanning pentaprism test

Uses the “magic” of the pentaprism

Pentaprism rail lies in plane perpendicular to parent axis.

Scanning pentaprism measures slope errors by producing collimated beams parallel to parent axis. Displacement of focused spot is measured with camera in focal plane.

Scanning pentaprism test as implemented for GMT off-axis segments. Pentaprism rail is suspended from tower.
Pentaprism test of 1.7 m off-axis NST mirror

- 1/5 scale GMT pentaprism test (f/0.7 off axis paraboloid)
- The pentaprism test only samples lowest order aberrations
- The PP results corroborate the results from interferometry!

(Peng Su)

102 nm rms
113 nm rms

interferometric test  pentaprism measurement
Laser Tracker Plus
Guide initial figuring

Sphere-mounted retro-reflector for laser tracker

Laser tracker & distance-measuring interferometers (DMI)

DMI laser and remote receivers

PSD

10% BS

DMI retroreflector

Retroreflector for interferometer and position sensing detector (PSD) assemblies in 4 places at edge of mirror

T. Zobrist
Ball positioning system

GMT segment during a measurement with Laser Tracker Plus system
Comparison of Laser Tracker with Interferometer

Interferometry

Laser Tracker (200 point sample)

Difference

0.44 μm rms
0.53 μm rms
0.48 μm rms
SCOTS: Software Configurable Optical Test System

Concept from Roger Angel for measuring solar reflectors
Applied to GMT measurements (Peng Su, Bob Parks, Tom Zobrist)

Uses simple technology –
LCD screen and CCD camera

UA President Shelton, Congresswoman Giffords and Prof. Angel beside collector

Camera view of grid pattern
Collector slope data

Display grid pattern
Measurement Principle

- SCOTS measures slope variations by looking at the reflection of a screen (computer monitor) from the surface under measurement.
- The measurement brightness variations are used to calculate surface slopes.
- Integrate slope maps to get full surface maps.

**Line scanning**
- Image at CCD

**Fringe projection**
- Monitor image
Implementation for GMT

Uses reflection from large fold sphere
Video monitor and CCD placed upward looking near intermediate focus

Looking down at Sam and SCOTS
SCOTS Comparison with Interferometry

Wow!

All maps show surface error in microns. Circle indicates 8.4 m diameter.
The Giant Magellan Telescope

- Uses proven mirror technology
- Challenges of optical testing has been solved
- Primary segment #1 nearing completion
- The casting of the second primary mirror segment is currently being planned
Large Synoptic Survey Telescope

- 8.4-m aperture
- Uses three-mirror design to attain 3.5° field of view
- 15-sec exposures to survey the sky
- 30TB of data per night!
- Plan for 2016 operation in Chile
- Spin cast blank at UA
- PM curvature from spinning, TM shape cut in with diamond generated
Null test of M1, M3

Separate interferometric optical tests being developed for TM and PM

Each test is aligned to mirror using two methods:
- Laser tracker
- Projected references from computer generated holograms

Configuration for test of M1

$R = 19.8\, \text{m}$

Configuration for test of M3

$R = 8.3\, \text{m}$

Both sets of test optics are deployed on trolleys, can be removed to avoid obscuring views from other test equipment.
The Thirty Meter Telescope

Led by Universities of California
(formerly known as the California Extremely Large Telescope)
Plan for Mauna Kea site
2018 first light
3.1-m convex secondary mirror

3.5-m flat tertiary mirror

30 meter f/1 primary mirror, made of 492 hexagonal segments
The European Extremely Large Telescope

42-m aperture
European Southern Observatories
2018 First light
E-ELT telescope

6 meter convex aspheric secondary mirror

42-meter f/1 segmented primary mirror

(plus other mirrors)
Measurement of large flat mirrors

TMT tertiary:
Flat mirror: 3.5 x 2.5 meter

Conventional test of large flats uses Ritchey-Common test, not practical

Measurement difficulties are solved by technologies developed and proven at UA
1-m vibration insensitive interferometer

- Commercial instantaneous Fizeau interferometer (uses 2 circularly polarized beams)
- Modified to use external 1-m reference
- Demonstrated on 1.6-m flat mirror
- World’s best large flat!

Flat Surface by Stitching Method - power/astigmatism removed

7 nm rms
UA Fizeau test for TMT tertiary

Layout of subapertures

3 nm rms typical measurement noise

Monte Carlo analysis to evaluate coupling of alignment, noise to surface reconstruction

5.5 nm rms measurement accuracy with proven UA hardware!

Mode 1  
2.9 nm rms 

Mode 2  
2.4 nm rms 

Mode 3  
1.4 nm rms 

Mode 4  
1.1 nm rms 

Mode 5  
1.4 nm rms 

Mode 6  
0.8 nm rms 

Mode 7  
0.8 nm rms 

Mode 8  
0.8 nm rms 

Mode 9  
0.5 nm rms 

Mode 10  
0.8 nm rms 

RSS for all modes:  
4.6 nm rms 

Residual from fitting all modes:  
3 nm rms 

4.6 nm rms for all modes

3 nm rms residual 

(C. Zhao)
Scanning pentaprisms test for flat mirrors

- Demonstrated performance is 0.2 µrad rms
- Power measurement for 1.6-m flat was 11 nm rms
Measurement of large convex aspheres

Convex secondary mirrors

TMT secondary: 3.1-m
LSST secondary: 3.4-m
E-ELT secondary: 6-m

Conventional test of such mirrors uses the Hindle test, not practical at these sizes.

LSST SM blank: ULE
Swingarm Optical CMM

- Scans surface with optical displacement probe
- Continuous arc scans create profiles
- Profiles stitched together to give surface maps
- Works for convex or concave surface
Surface maps from SOC data for 1.4-m off axis asphere

Pattern of 64 scans

Repeatability ~ 6 nm rms/scan

Interpolated data
75 nm rms

896 term reconstruction
78 nm rms

Low order terms removed
6 nm rms

Repeatable errors of 34 nm rms are calibrated out

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(P. Su)
Measurement with Swingarm Optical CMM

- Original system built at Optical Sciences was made with 3.8-m capacity.
- This was designed to be integrated with 4-m polishing machine.
- Performance is expected to be < 20 nm rms at this size.
Fizeau interferometry for large secondary mirrors

Reference surface on test plate has concave matching asphere for off axis portion of the secondary mirror

We have also developed concept for using a spherical reference, corrected with CGH
TMT primary mirror

30–m f/1 near paraboloid
492 segments

1.44-m segments, 45 mm thick
Each is supported by 27-point whiffle tree, warped with 21 actuators
Segment tip/tilt/piston adjusted with 3 position actuators, based on edge sensors
E-ELT primary mirror

- 42-m f/1 near paraboloid
- 984 segments

1.43-m segments, 50 mm thick
Each is supported by 18 or 27-point whiffle tree
Segment tip/tilt/piston adjusted with 3 position actuators, based on edge sensors
The challenges of measuring the TMT, E-ELT PM mirror segments

• Off-axis aspheres, with different prescription (curvature changes from center to edge)
• To work together, the radius of curvature must match. Power is treated as a figure error
• Must be efficient, limiting setup, alignment, and test time
• Measurement accuracy of 5 nm rms is required

Other important issues:
• Efficient fabrication of hundreds of mirror segments
• Complex support for each segment
• Active shape and position control for each segment
CGH Fizeau test for primary mirror segments

- **Collimator**
- **Measurement CGH**
- **Projection Lens**
- **CCD camera**
- **Aperture**
- **Reference wavefront**: Zero order from CGH, reflects from segment
- **Test wavefront**: First order from CGH, reflects from segment
- **Return: common path**: Both wavefronts coincide, the difference between these gives the shape error in the segment
- **Common CGH**
- **Convex reference sphere**
- **M = 1** from segment
- **M = 0** from sphere
- **Blocked by aperture**: m = 0 from segment, m = 1 from sphere
- **Reference and test wavefronts come to focus and pass through aperture**
- **All other orders and reflections are blocked**

**Diagram Notes**:
- **Convex reference sphere**
- **Aspherical surface**

**Flow of Light**:
- Laser light enters the system, directed through a diffuser and objective.
- Collimator focuses the light onto the common CGH.
- The measurement CGH projects the wavefront onto the projection lens.
- The wavefront is then detected by the CCD camera.
- The aperture blocks all other orders and reflections.

**Summary**:
- The test wavefront reflects from the segment, while the reference wavefront reflects from the convex reference sphere.
- The difference between these wavefronts provides the shape error in the segment.
CGH Fizeau test

• Common path – low noise
• Radius matching is easy, all segments compared with the same reference
• Detailed engineering analysis for TMT, E-ELT predicts 14 nm rms overall accuracy, 5 nm rms after some low order correction
Full scale demonstration of CGH Fizeau test

Test convex, off axis aspheres by measuring though the substrate,
UA achieved very low noise measurements with CGH Fizeau system

Excellent fringe visibility
Excellent spatial resolution
Overall accuracy of < 4 nm rms
< 1 nm rms noise per measurement (average of 50 maps)
Verified effects of straie in glass to cause < 1 nm rms
Largest sources of error: ghost reflection in CGH, coating irregularity on fold flat
Comparison of Fizeau, SOC for off-axis aspheres

- The Fizeau test was budgeted as < 3.3 nm rms uncertainty, after correction for low order terms.
- SOC measurements of the OAPs are consistent with this.

Raw data

<table>
<thead>
<tr>
<th>Fizeau</th>
<th>SOC</th>
</tr>
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<tbody>
<tr>
<td>109 nm rms</td>
<td>117 nm rms</td>
</tr>
<tr>
<td>14 nm rms</td>
<td>16 nm rms</td>
</tr>
</tbody>
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Largest errors in Fizeau came from:
- coating defect on large fold flat 1 nm rms
- ghost fringes 1 nm rms

Astigmatism and coma from alignment were not needed to be controlled accurately
What next?

Combine several elements:

• Fizeau interferometry with spherical reference, corrected by CGH

• Vibration insensitive interferometry using polarization

Design for such a test for LSST was presented last summer. Prototype work is underway.

(M. Dubin)
Conclusion

• University of Arizona technology is enabling the Giant Magellan Telescope and the Large Synoptic Survey Telescope
• We are prepared to support TMT and E-ELT if those projects move forward.