Optical Testing of Mirrors for Giant Telescopes

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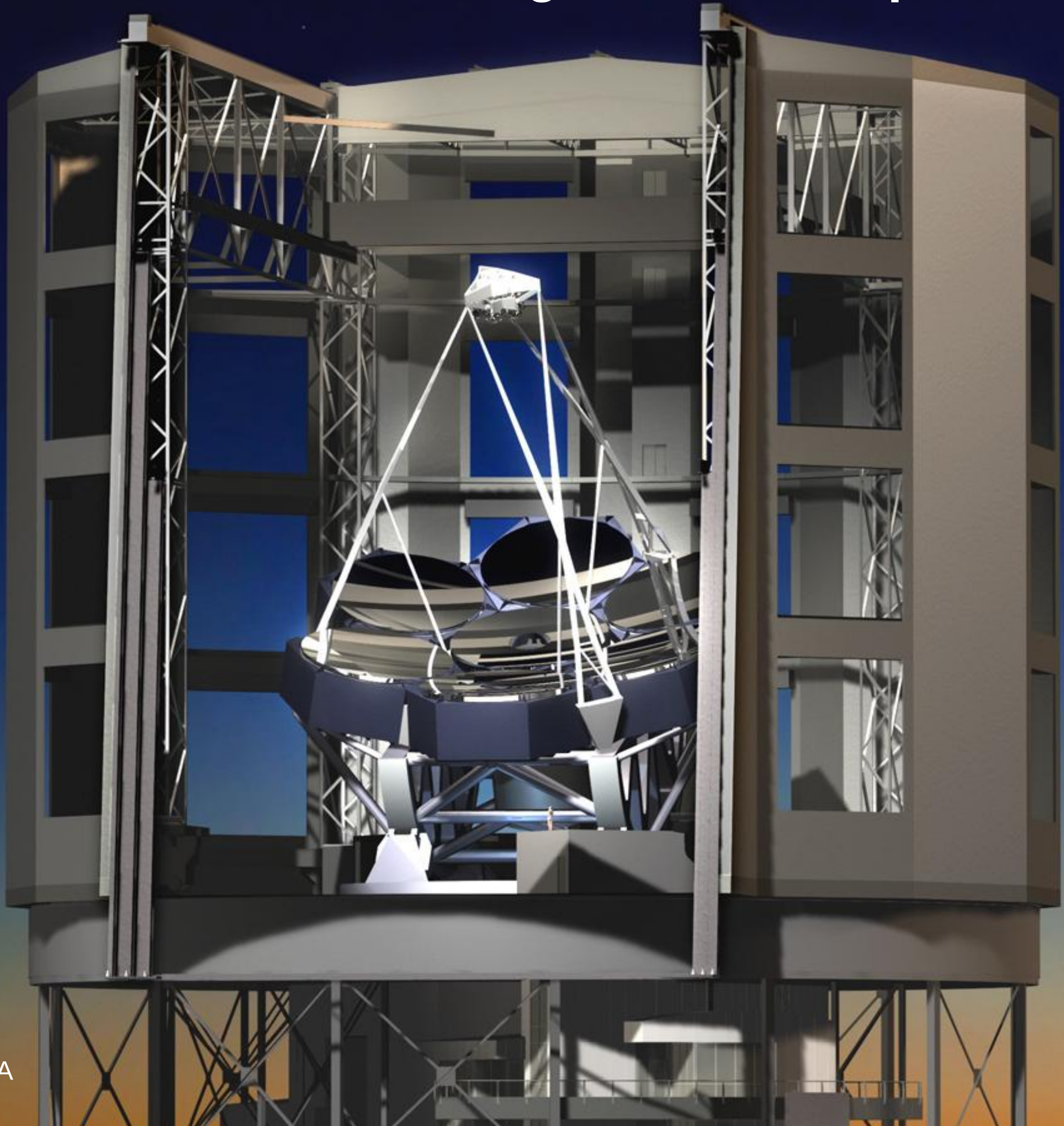
Today's talk

- 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

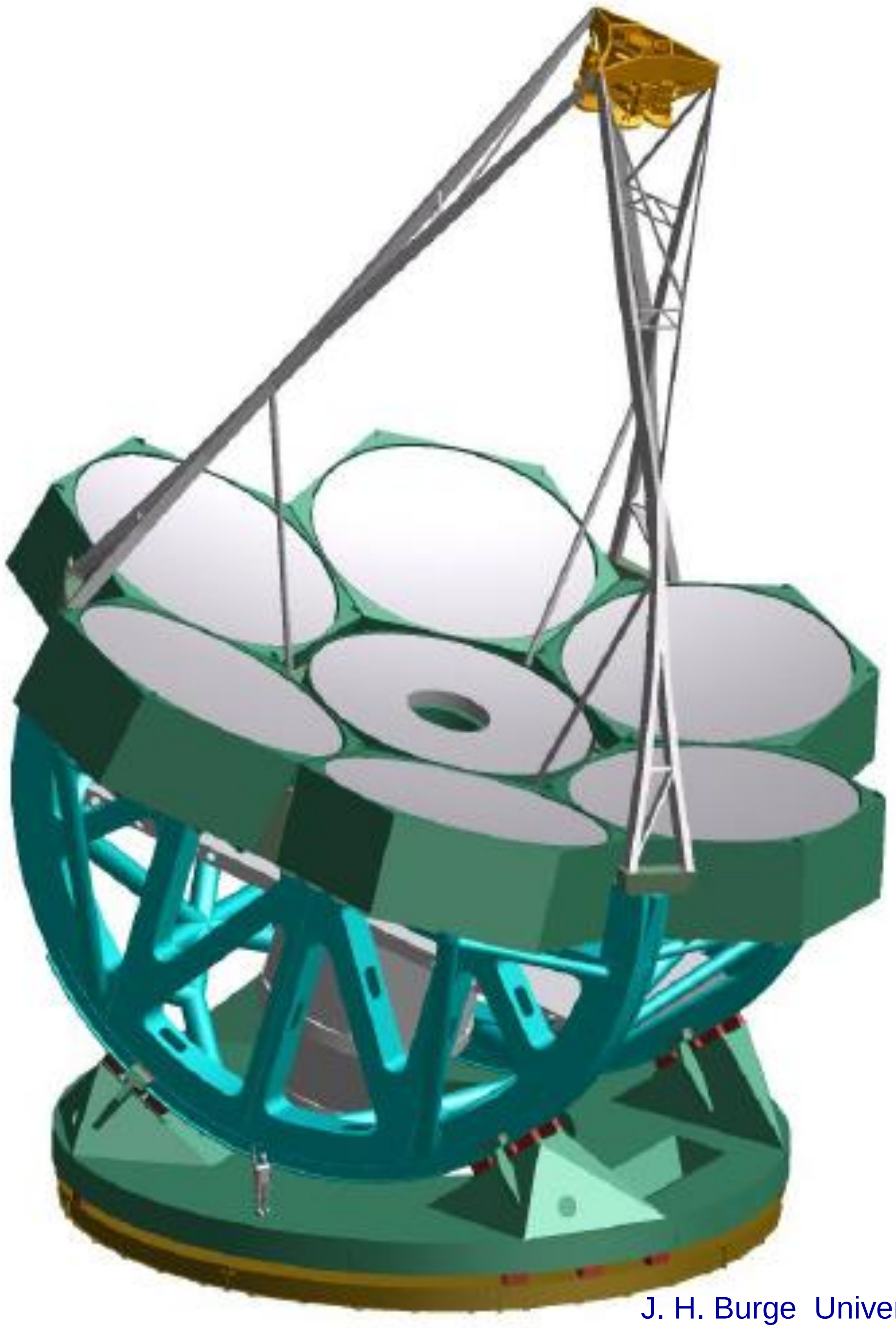
The Giant Magellan Telescope



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

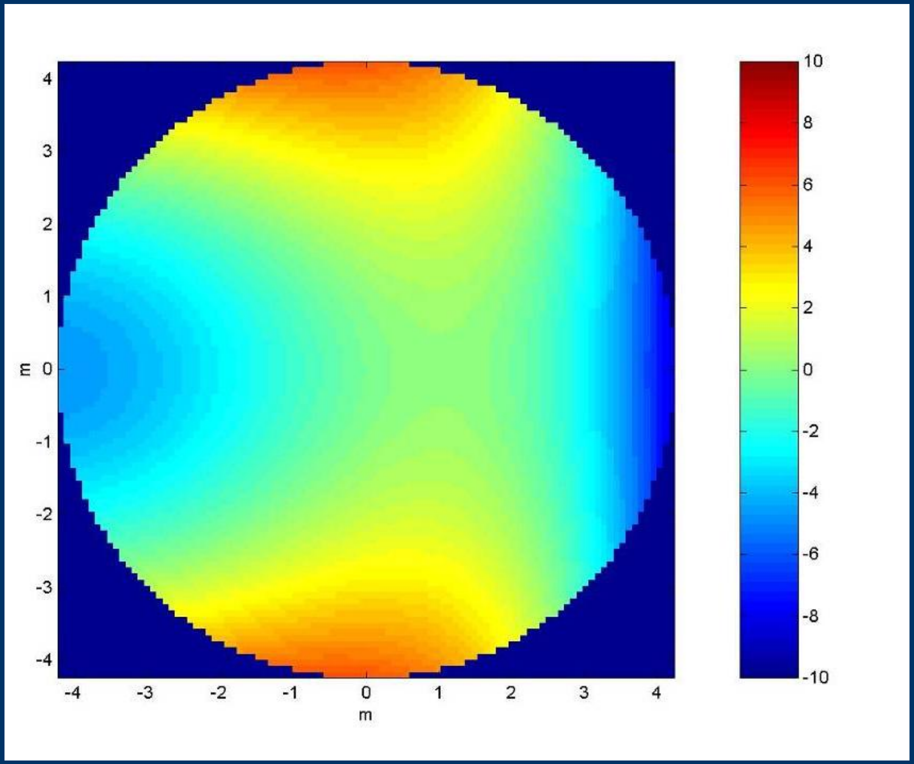
Instruments mount below primary at the Gregorian focus

Key optical testing challenges for GMT primary mirrors

GMT Primary mirror segments

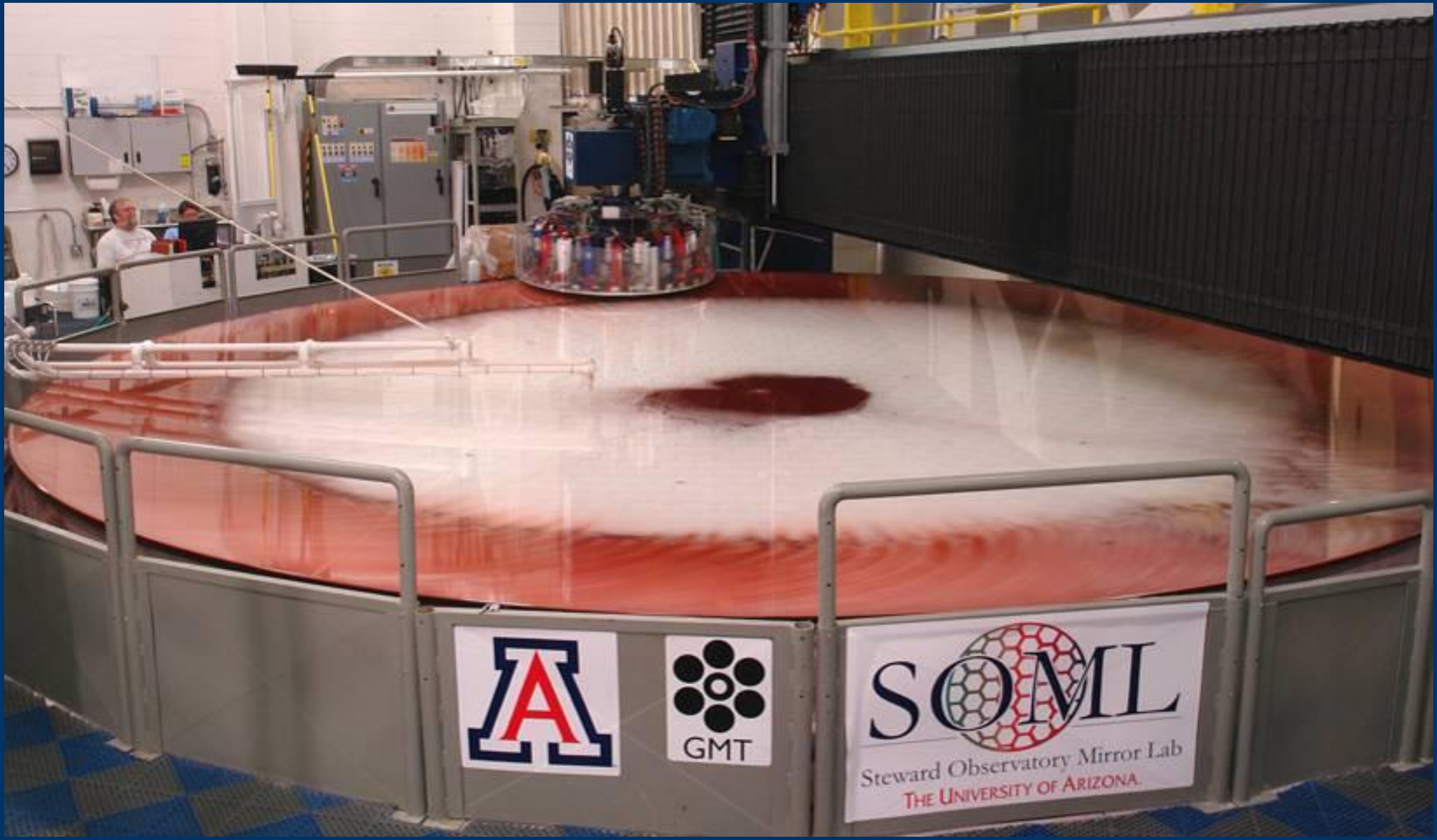
- Off-axis asphere with ~15 mm aspheric departure
- Segments must match in radius to work together correctly
- For 25-m diameter parent, 36 m ROC is needed

14.5 mm departure from best fit sphere



GMT segments

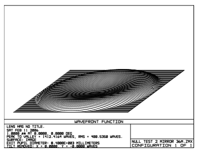
- Aspheric polishing with stressed lap
- Shaping relies on feedback from surface measurement



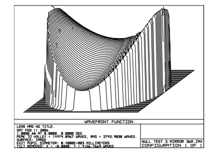
Optical testing of GMT segments

Heritage (LBT)

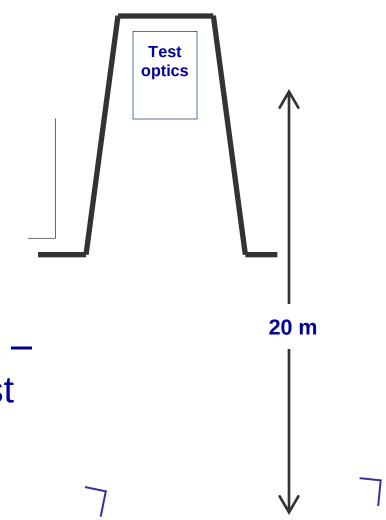
~1.4 mm aspheric departure



~14.5 mm aspheric departure



Test wavefront defined to match aspheric shape of mirror



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

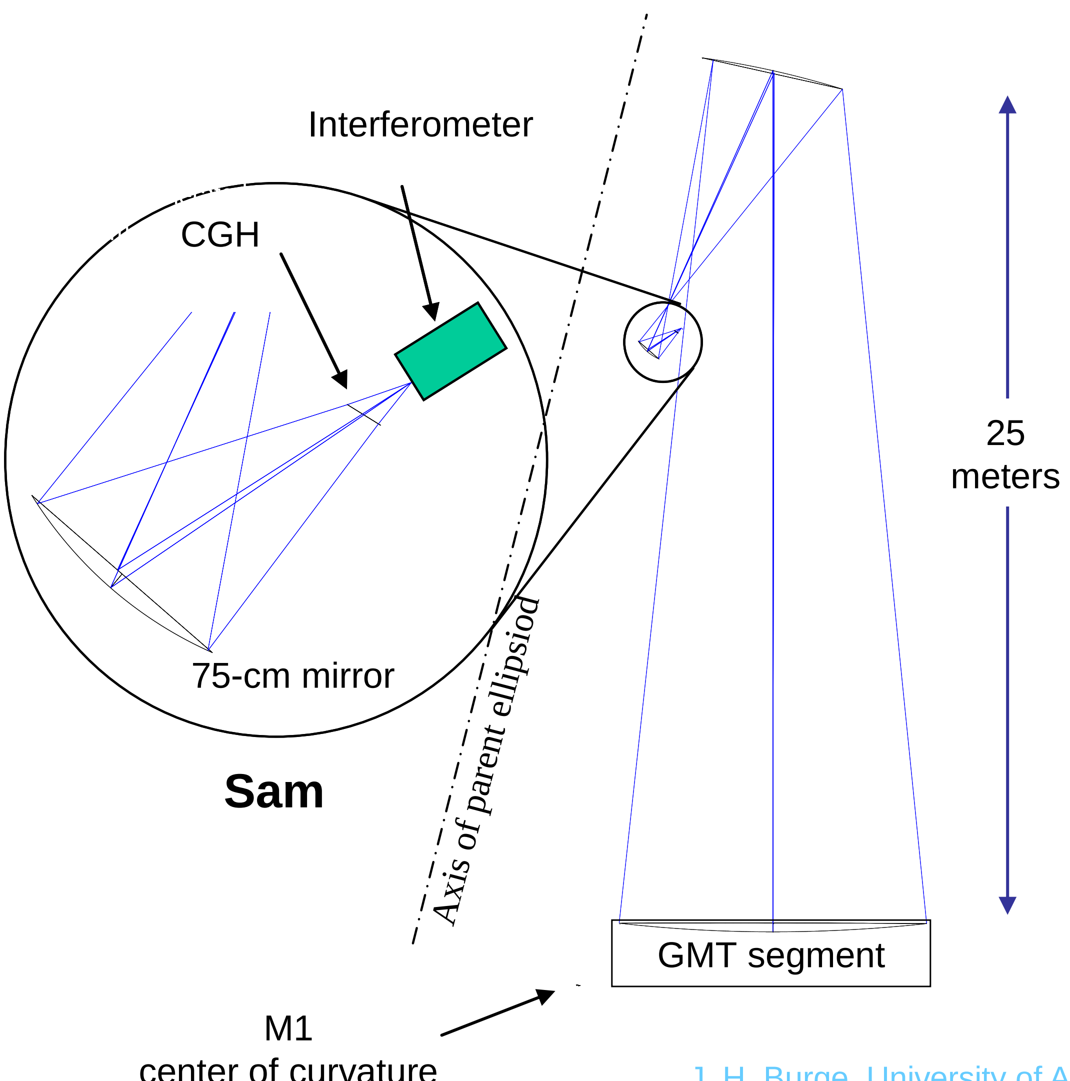
No Axisymmetry

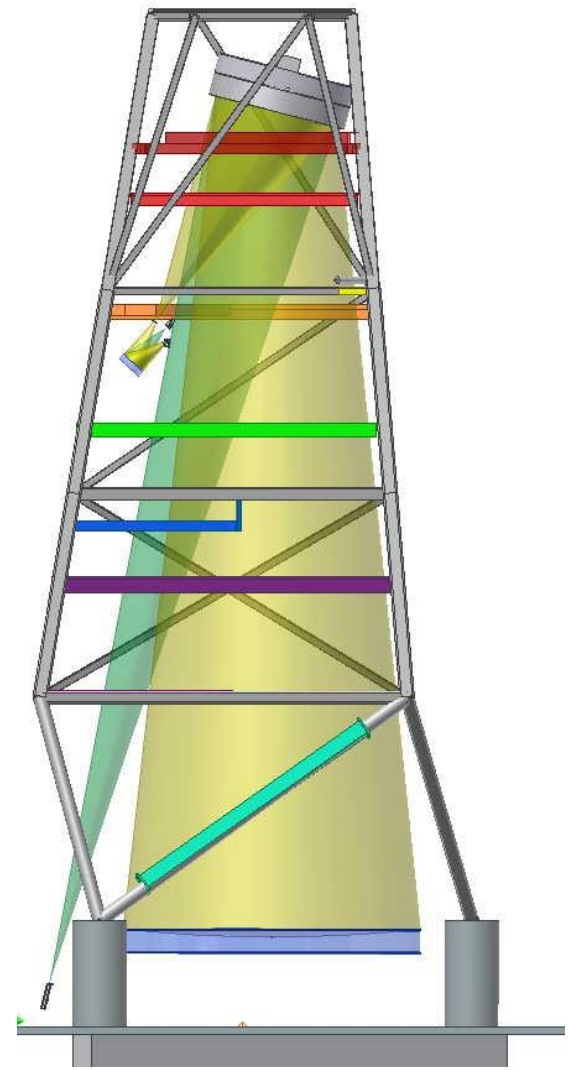
Light path defined by GMT is much larger

(~3.5 meters across at the top of our tower)

Interferometric surface measurements

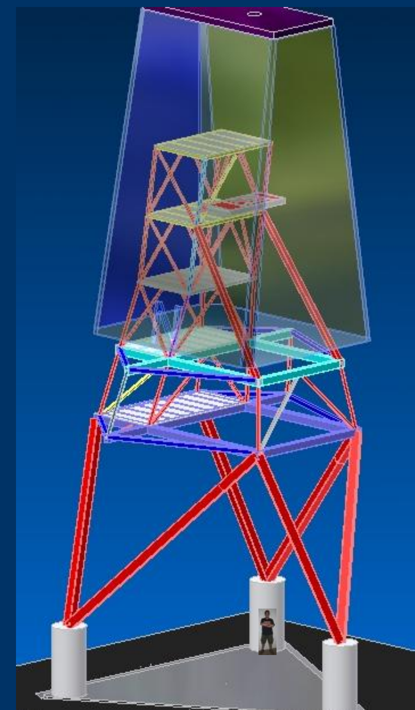
interferometer and reflective null corrector with CGH





Test tower at Steward Observatory Mirror Lab

Original tower



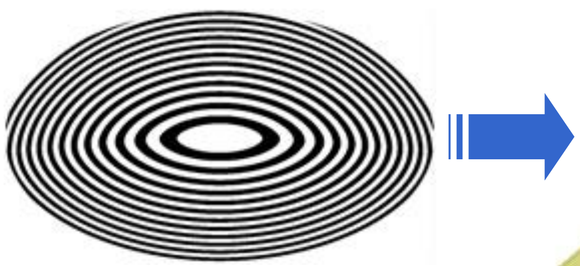
New tower

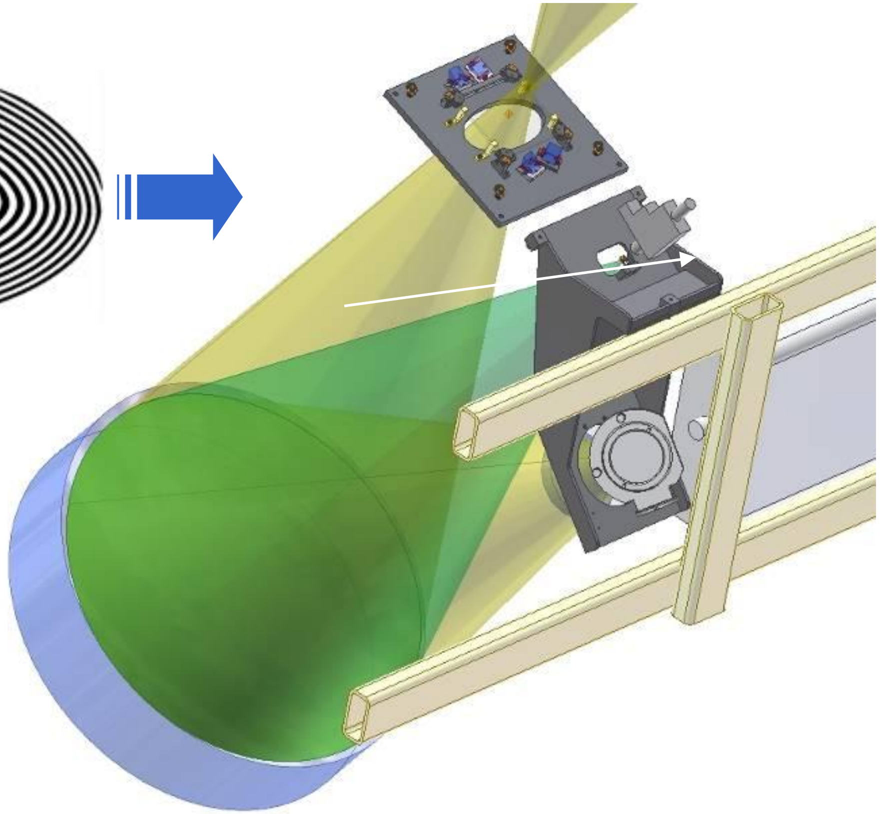
New tower

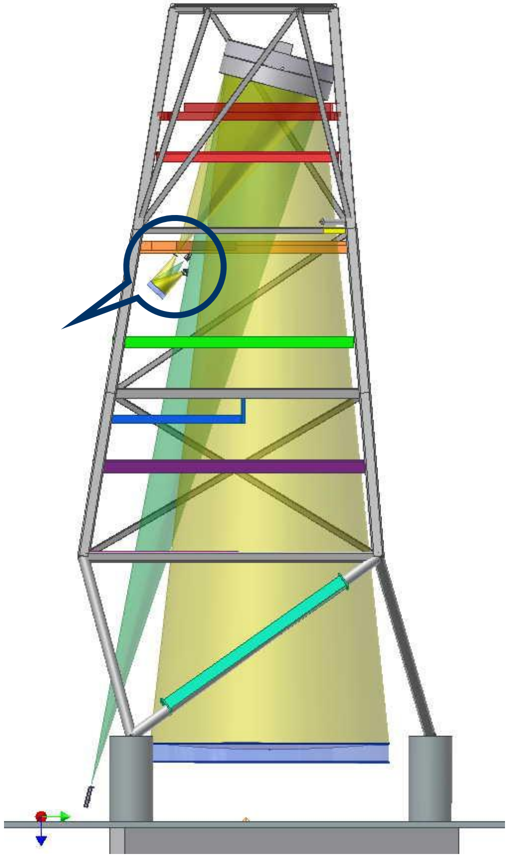
- 28 meters tall, 80 tons of steel
- floated on 400 ton concrete pad
- accommodates other UA projects (LBT, LSST)
- lowest resonance of 4.8 Hz with 9 ton 3.75-m fold sphere + cell

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

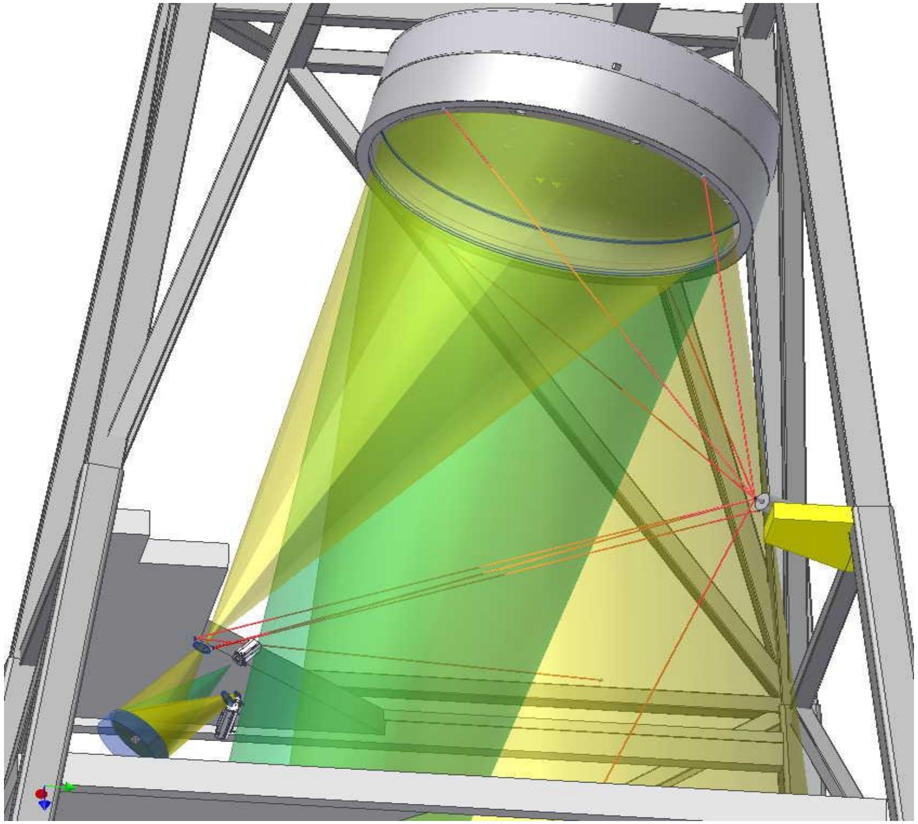






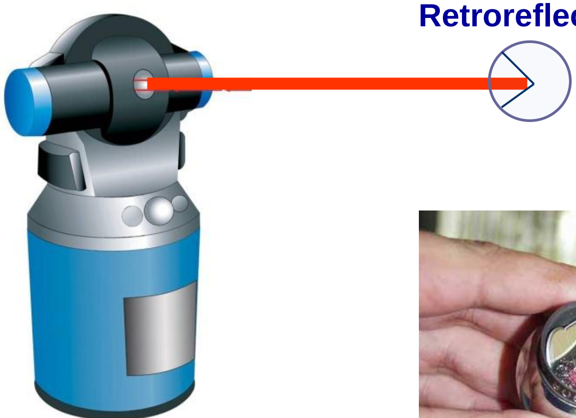
Active system alignment relies on laser tracker

- 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



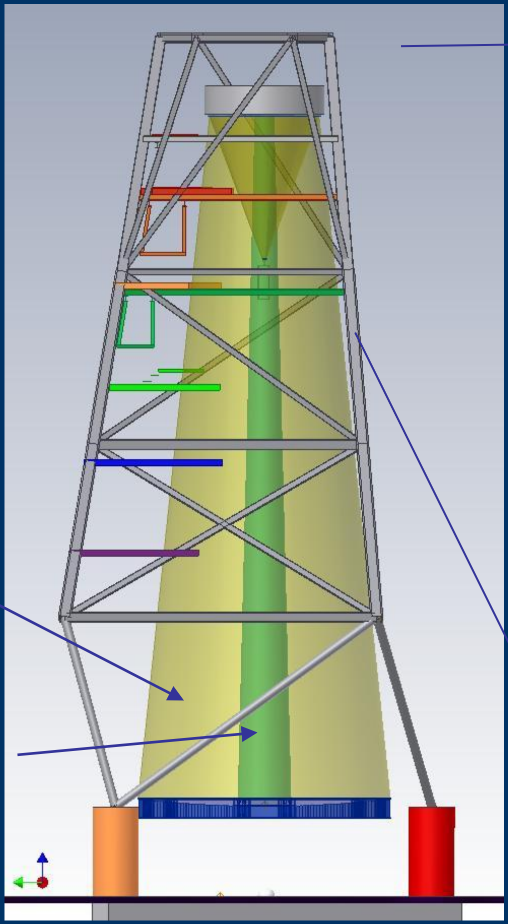
Measures ρ, θ, ϕ to determine position to ~25 µm

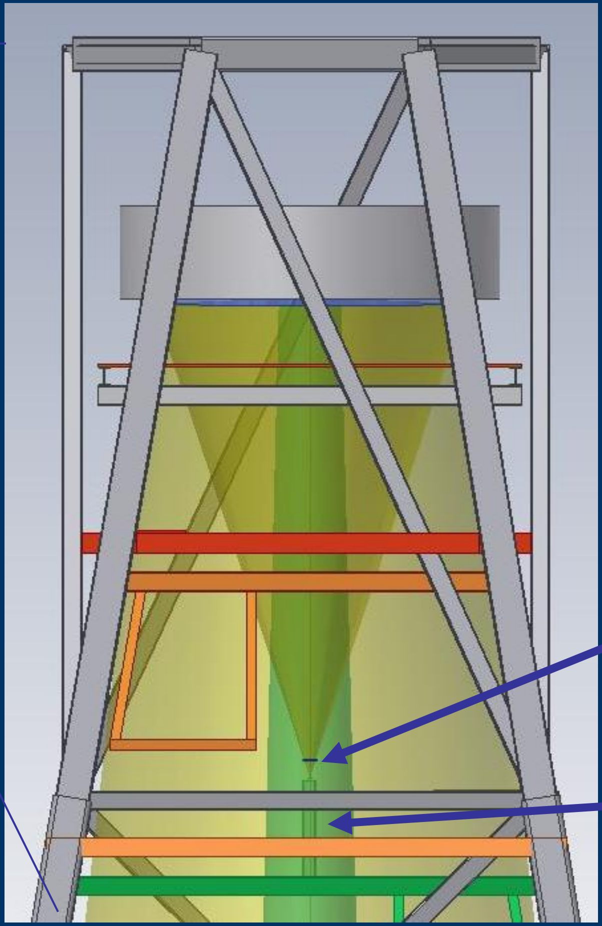
Measurement of center segment

Tilt the fold sphere to nadir

Cone defined by light from outer edge of mirror

Cone defined by light from edge of central hole





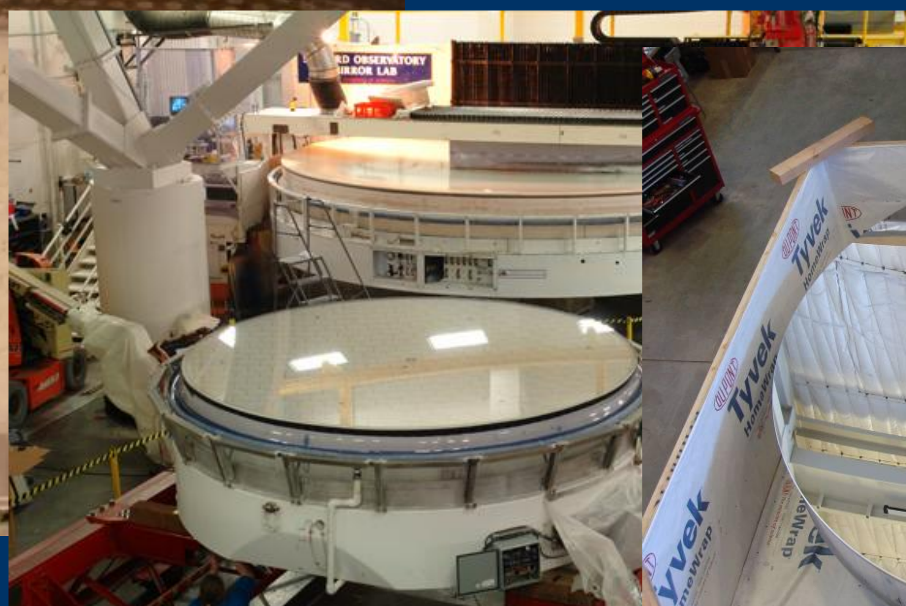
<u>50 mm CGH</u> compensates 20µm aspheric departure

Vibration insensitive interferometer

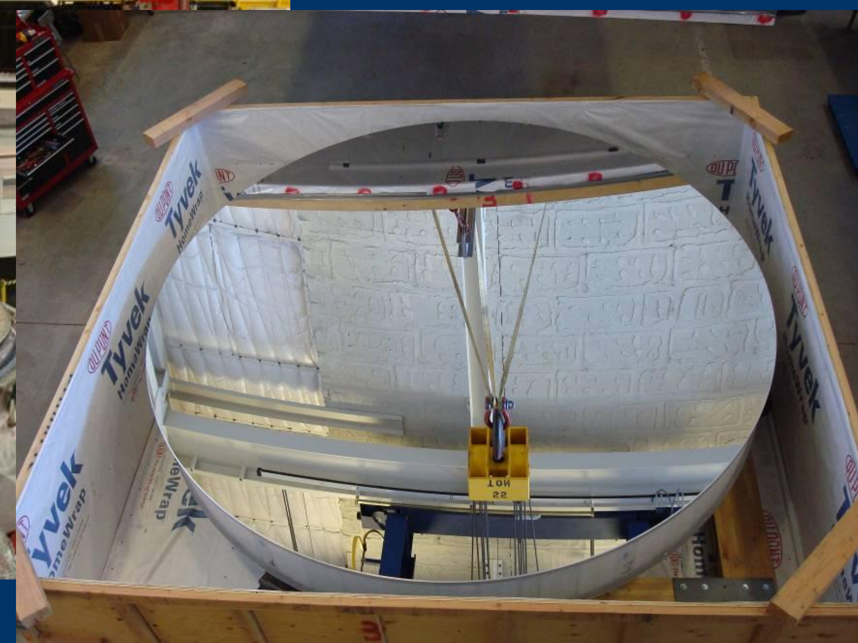
3.75 m fold sphere

- 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

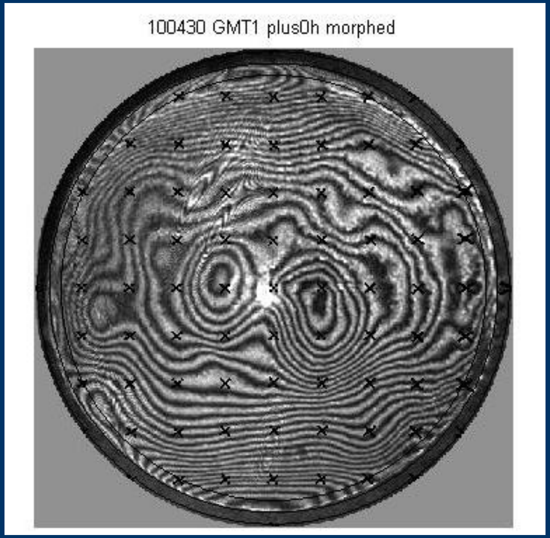


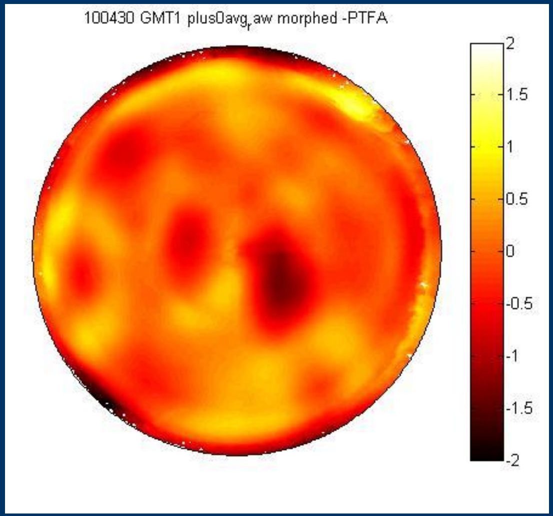
Polished, measured at the Mirror Lab



Coated at Kitt Peak

Operational test system





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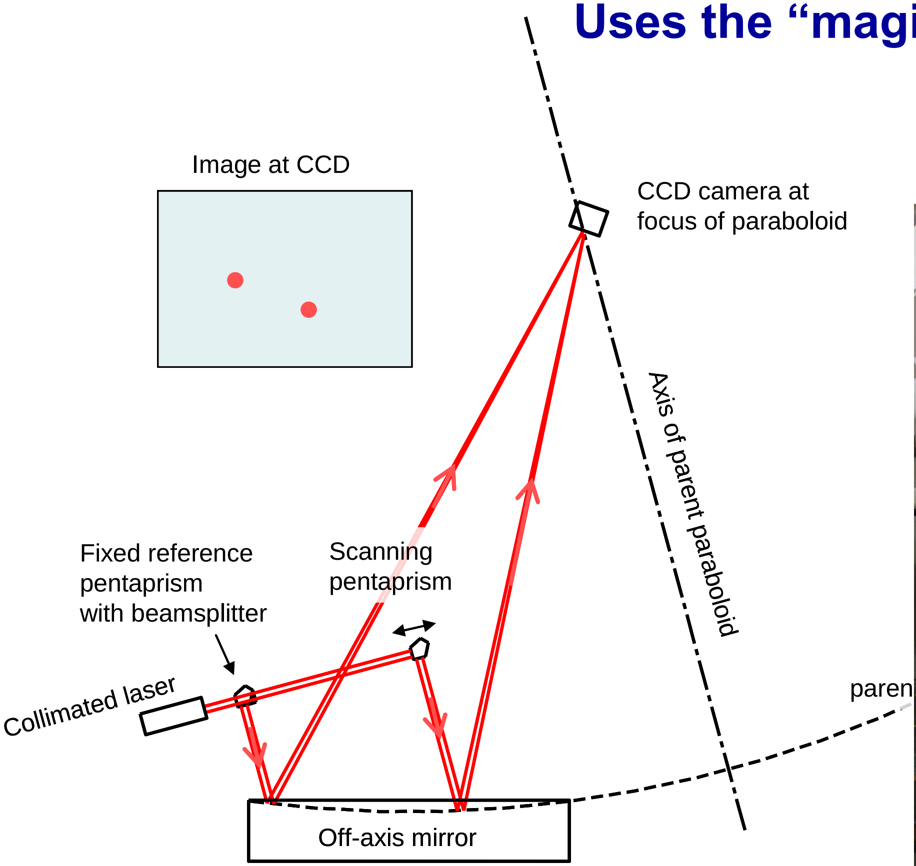
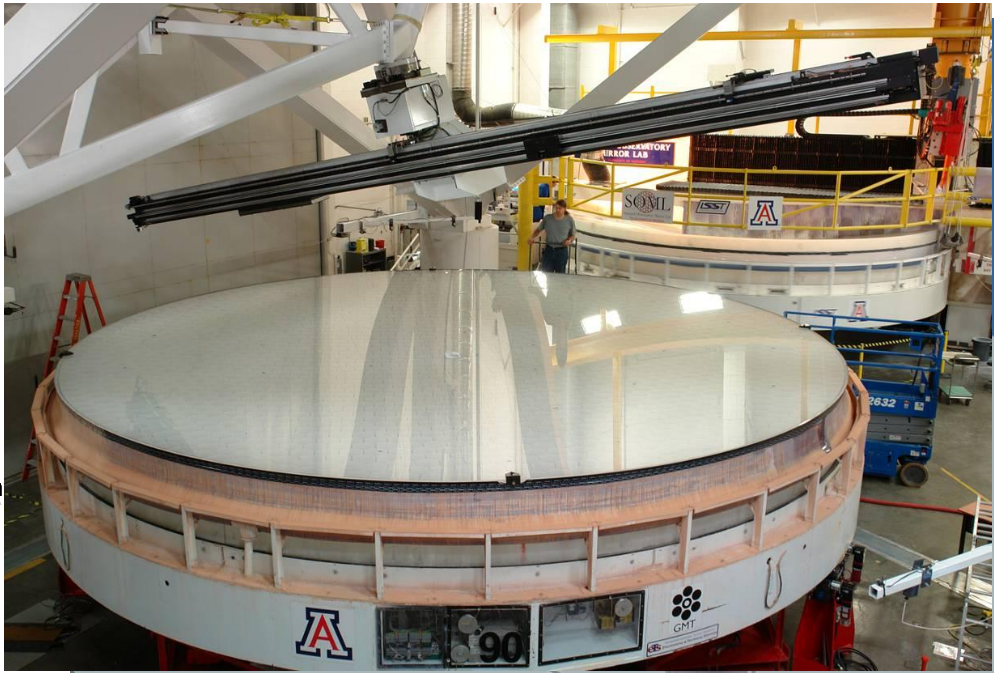
LOFT Large Optics Fabrication & Testing

Scanning pentaprism test

Uses the "magic" of the pentaprism



Pentaprism rail lies in plane perpendicular to parent axis.

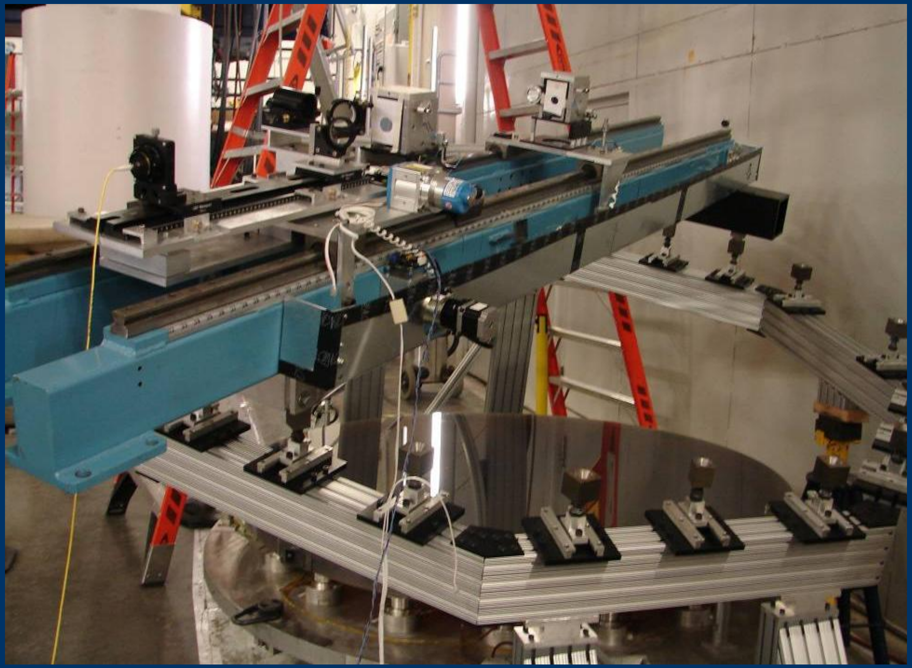


Scanning pentaprism measures slope errors by producing collimated beams parallel to parent axis. Displacement of focused spot is measured with camera in focal plane.

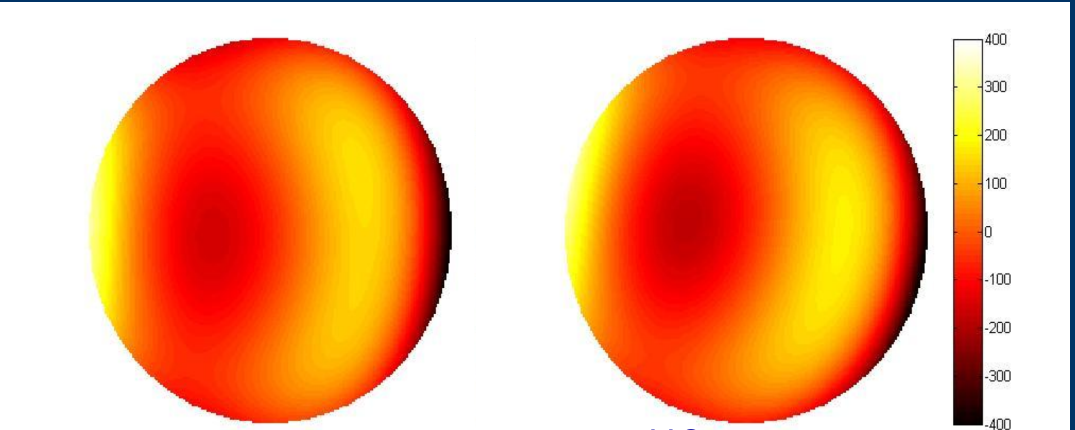
Scanning pentaprism test as implemented for GMT off-axis segments. Pentaprism rail is suspended from tower.

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!



interferometric test   pentaprism measurement



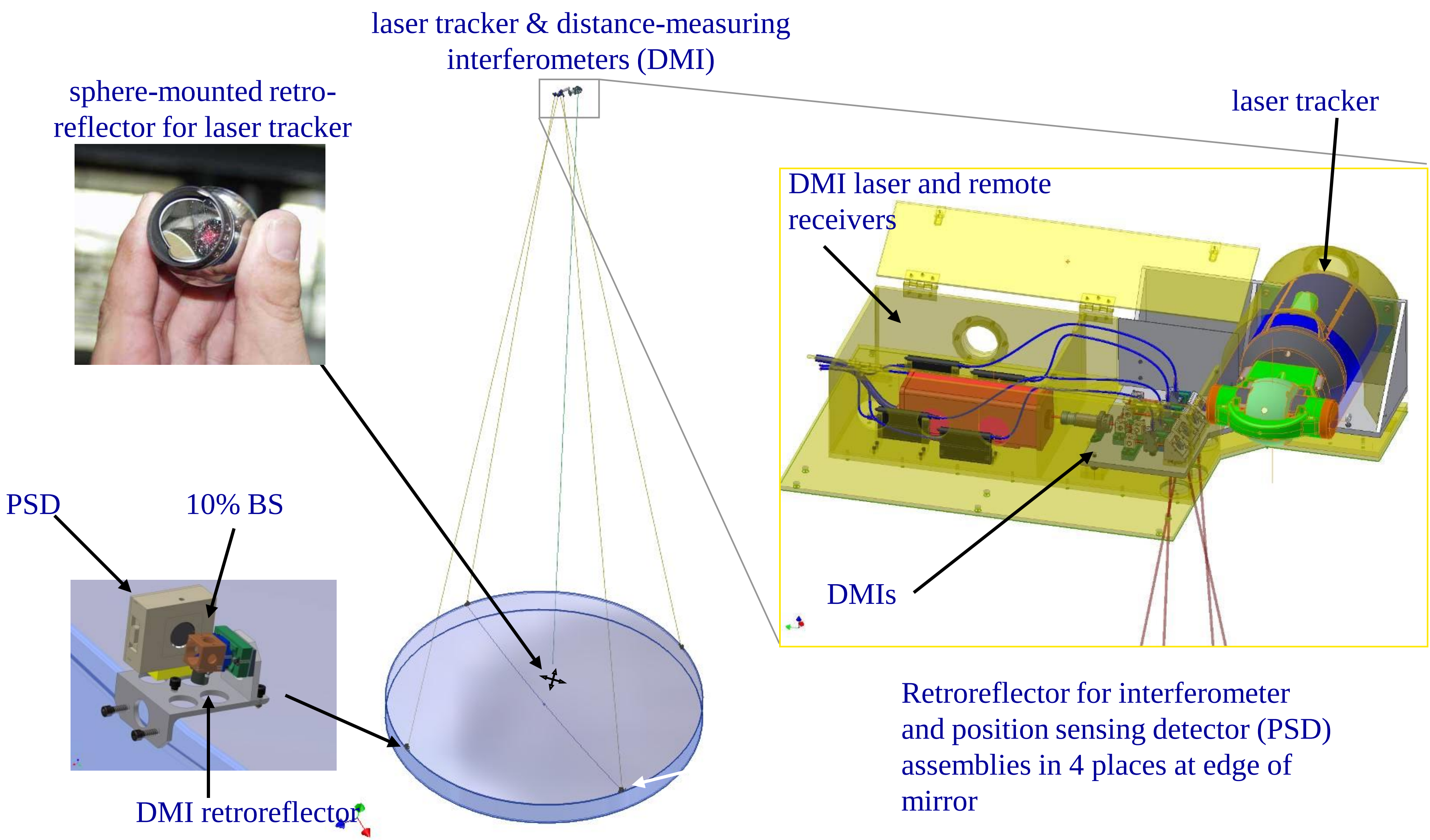
102 nm rms   113 nm rms

(Peng Su)

The University of Arizona
Tucson Arizona

Laser Tracker Plus

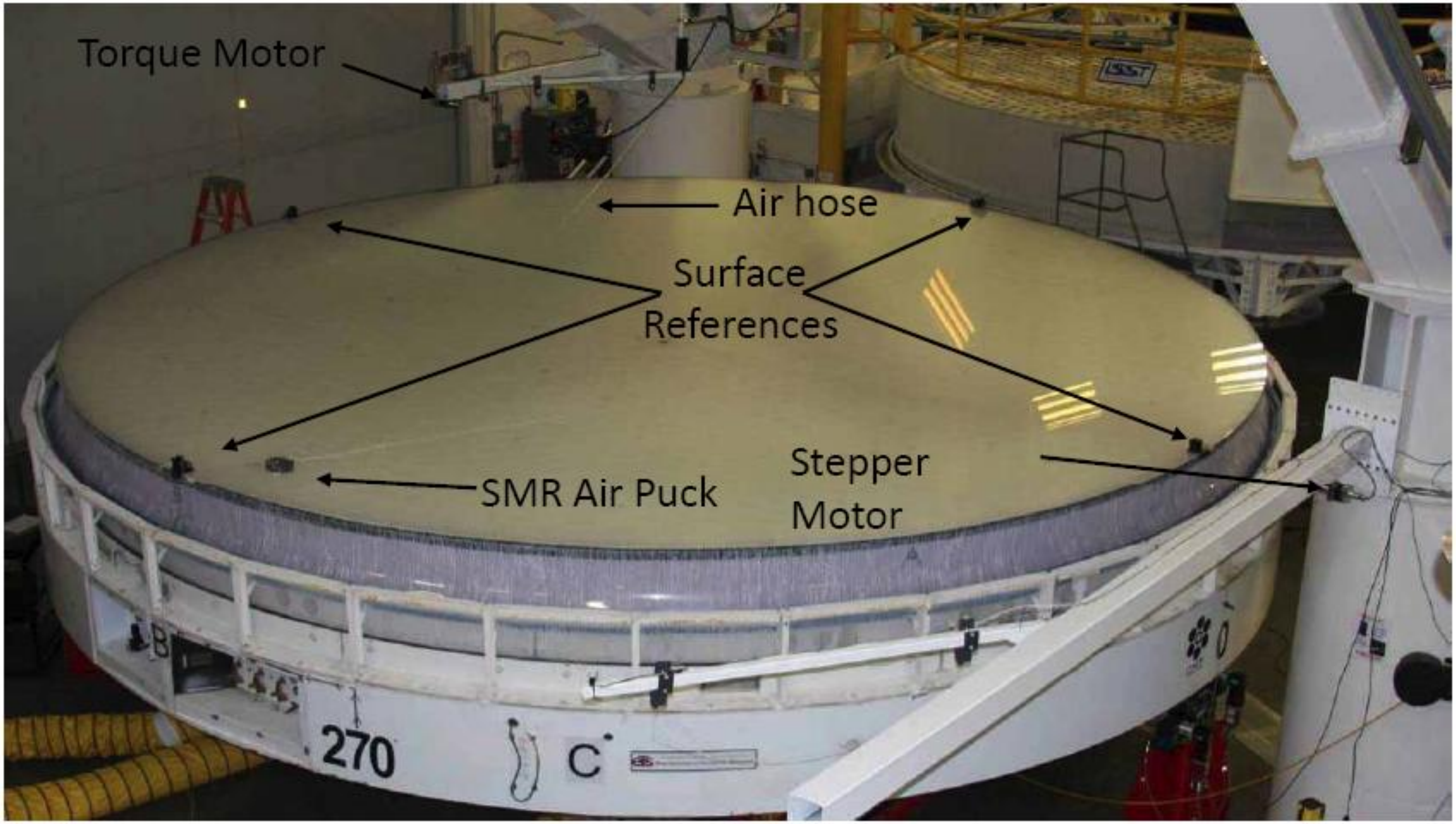
Guide initial figuring



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

T. Zobrist

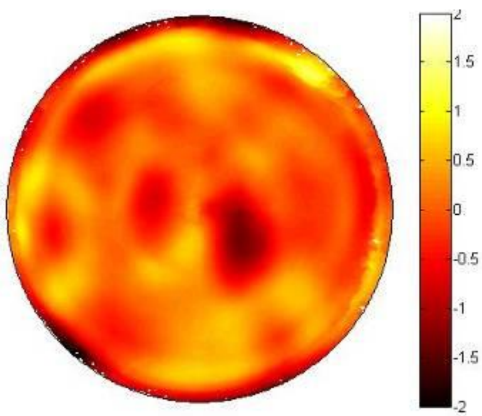
Ball positioning system



GMT segment during a measurement with Laser Tracker Plus system

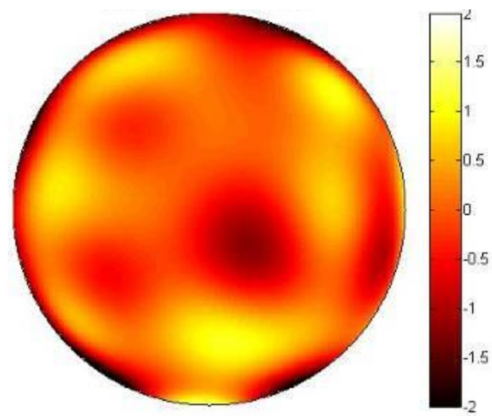
Comparison of Laser Tracker with Interferometer

Interferometry



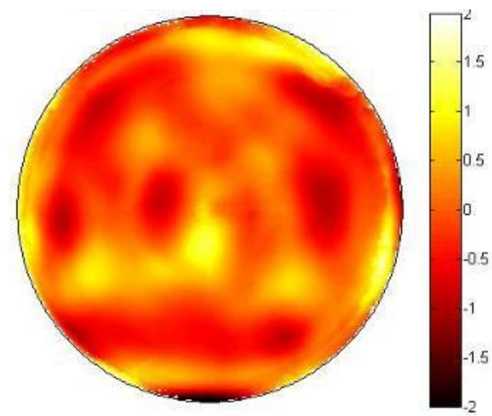
0.44 um rms

Laser Tracker
(200 point sample)



0.53 um rms

Difference



0.48 um rms

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SCOTS : Software Configurable Optical Test System

LOFT
Large Optics Fabrication & Testing

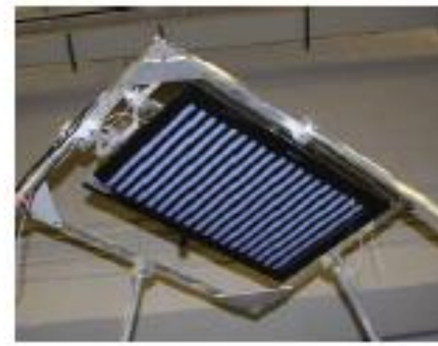
Concept from Roger Angel for measuring solar reflectors

Applied to GMT measurements (Peng Su, Bob Parks, Tom Zobrist)

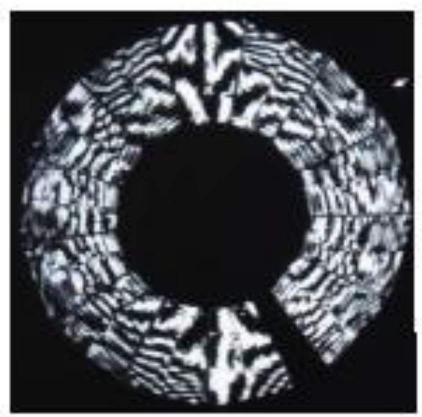
Uses simple technology –

LCD screen and CCD camera

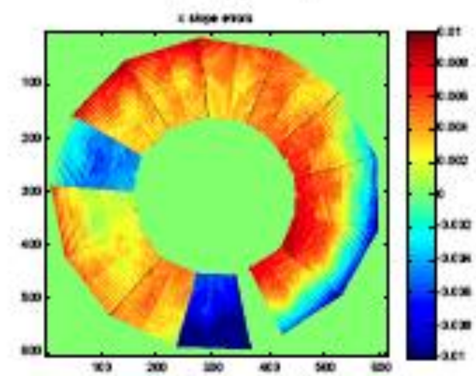
UA President Shelton, Congresswoman Giffords and Prof. Angel beside collector



Display grid pattern



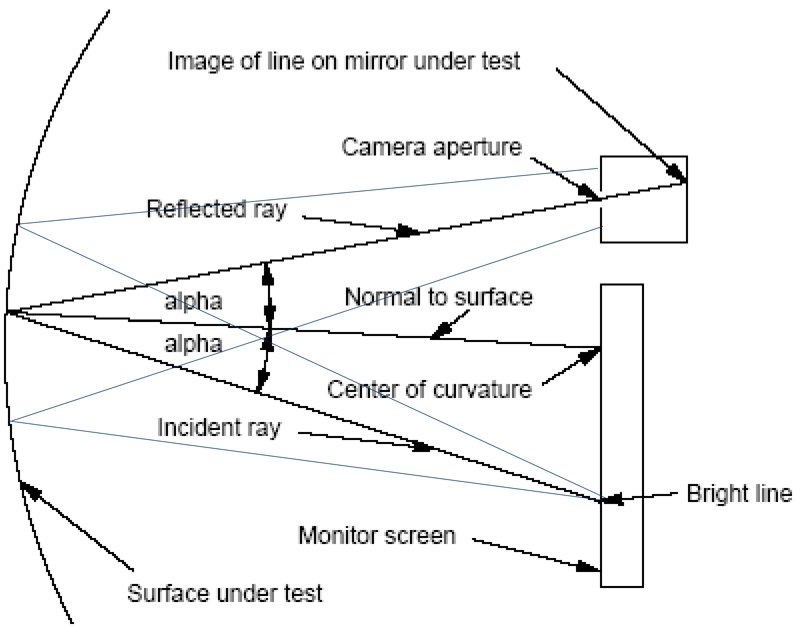
Camera view of grid pattern



Collector slope data

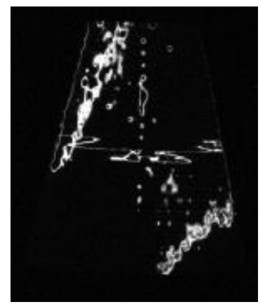
Measurement Principle

- 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

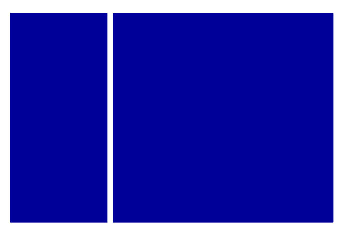


Line scanning

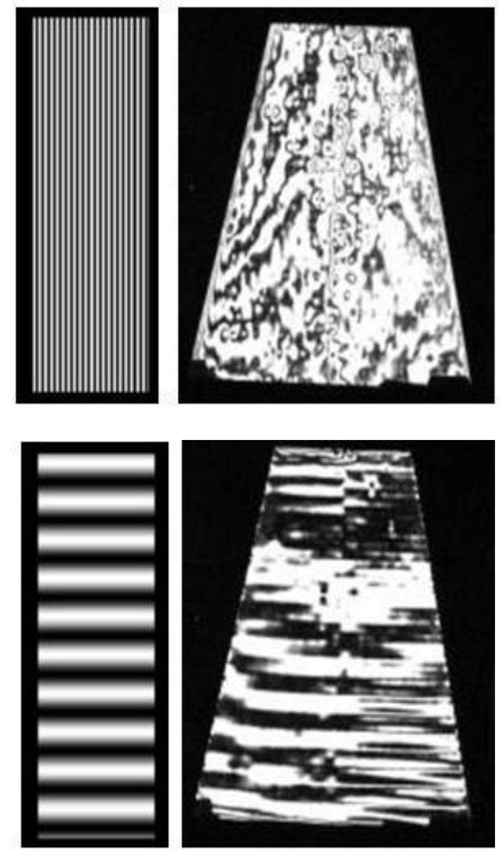
Image at CCD



Monitor image



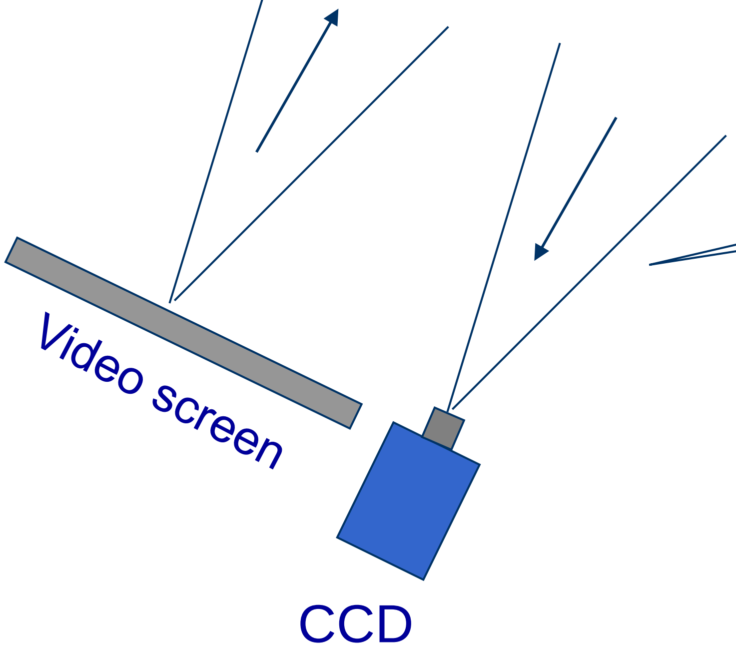
Fringe projection

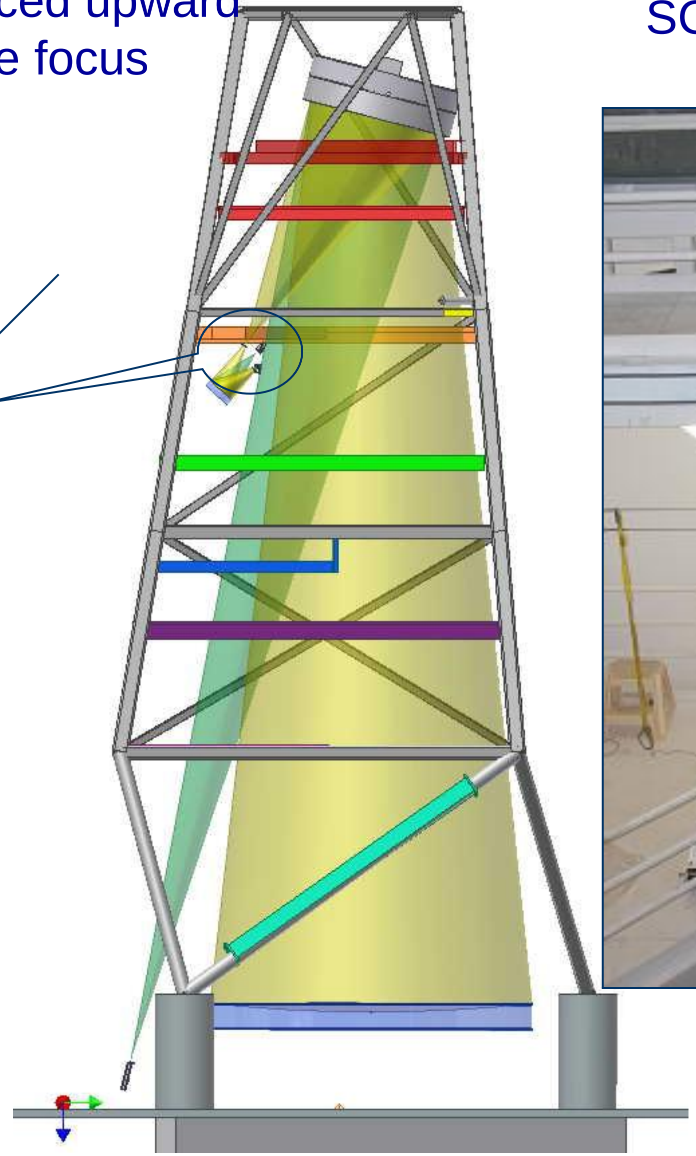


Implementation for GMT

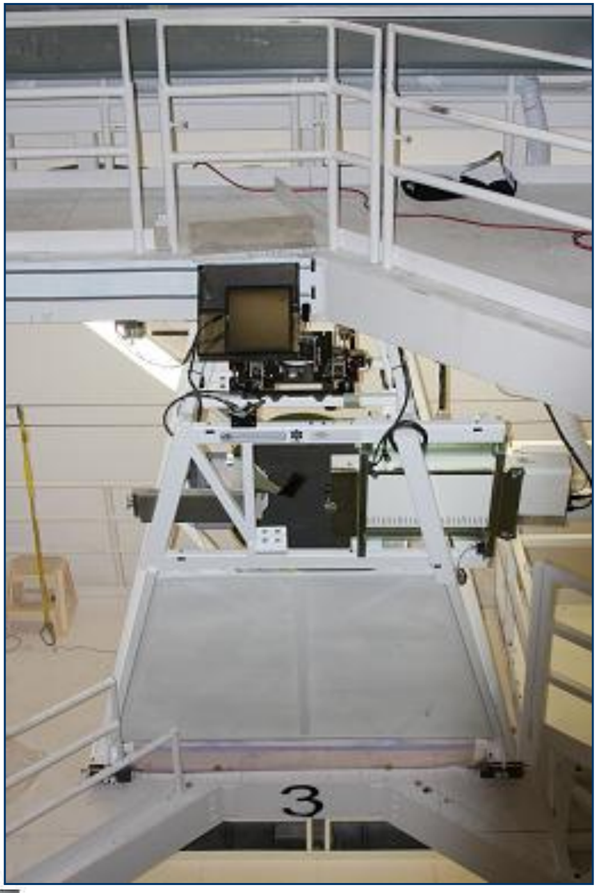
Uses reflection from large fold sphere

Video monitor and CCD placed upward looking near intermediate focus



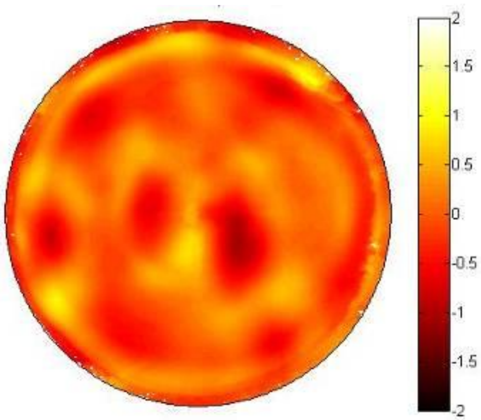


Looking down at Sam and SCOTS

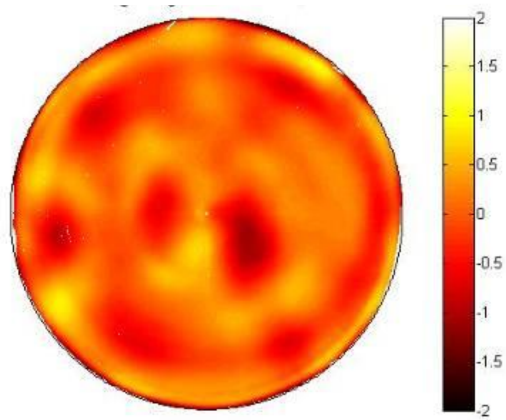


SCOTS Comparison with Interferometry

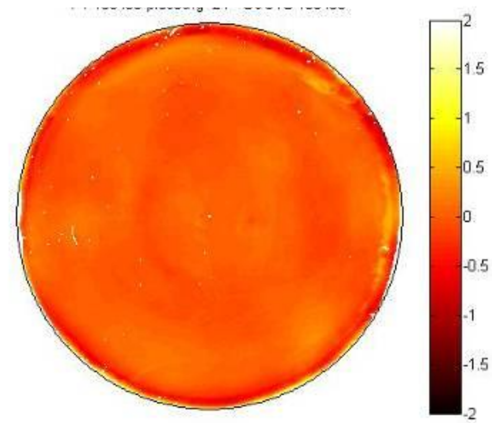
Wow!



Principal test
21 polynomials subtracted
0.32 µm rms



SCOTS
21 polynomials subtracted
0.35 µm rms



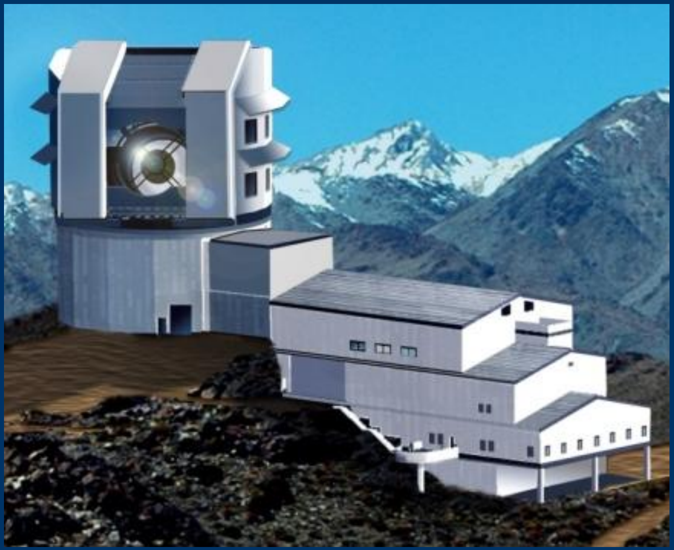
difference
0.16 µm rms

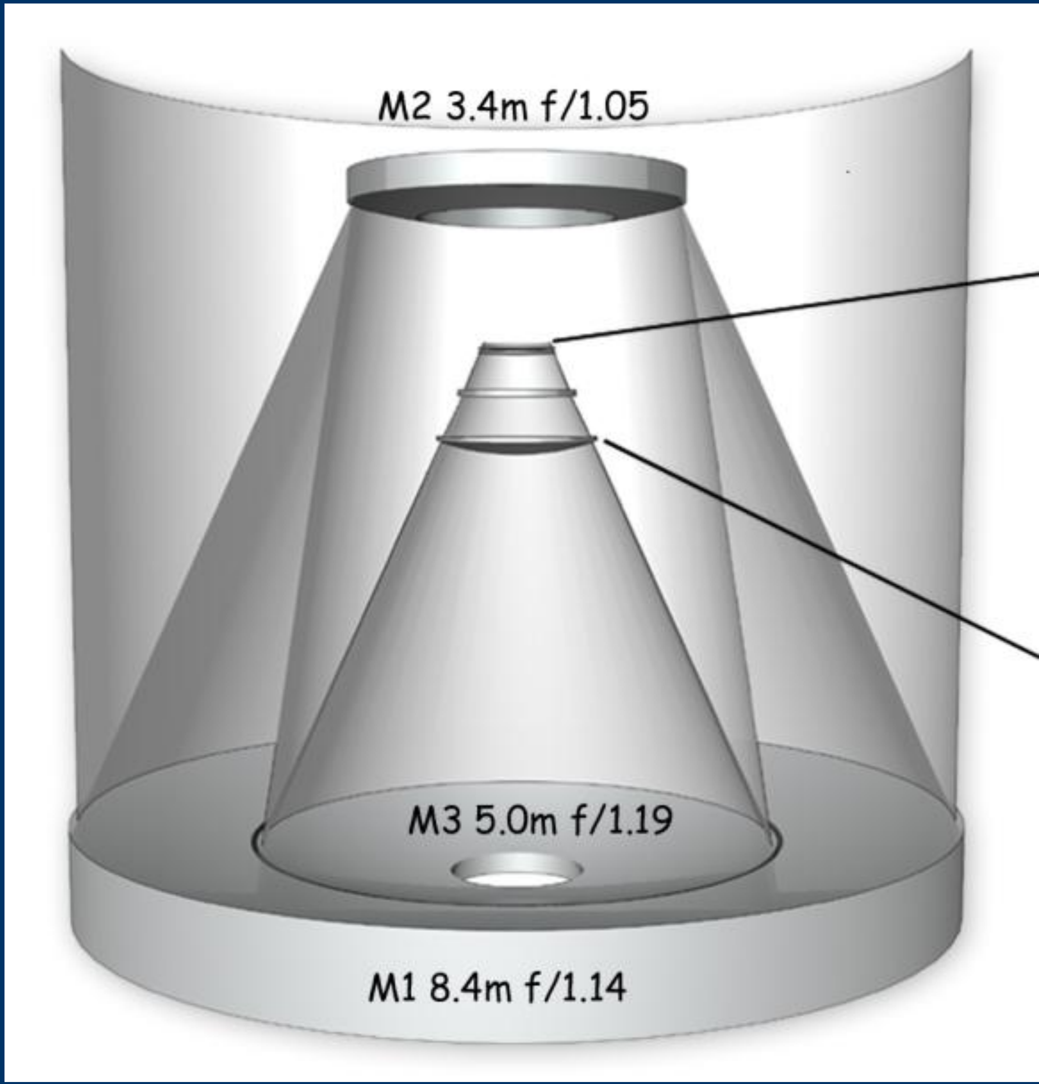
All maps show surface error in microns. Circle indicates 8.4 m diameter.

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

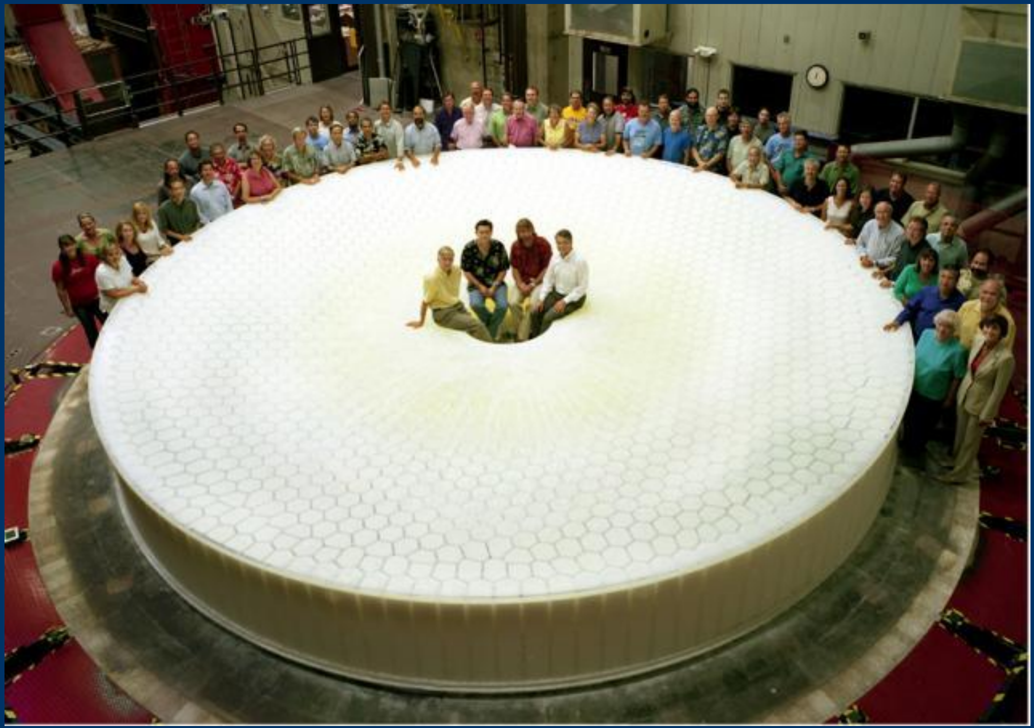
15-sec exposures to survey the sky

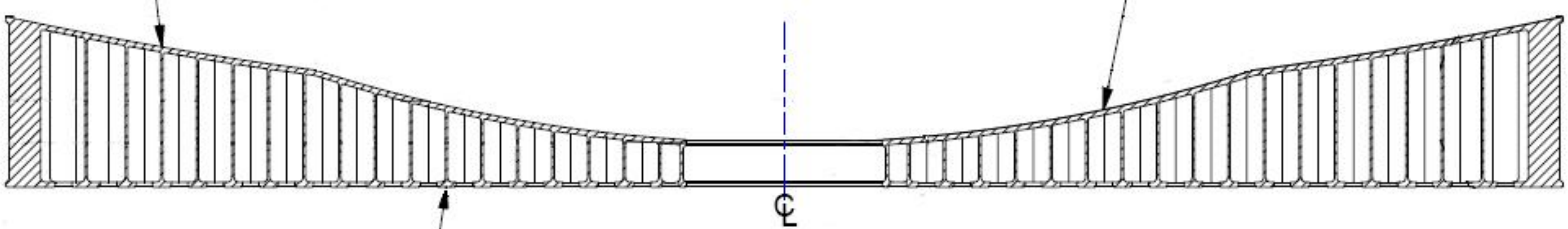
30TB of data per night!

Plan for 2016 operation in Chile

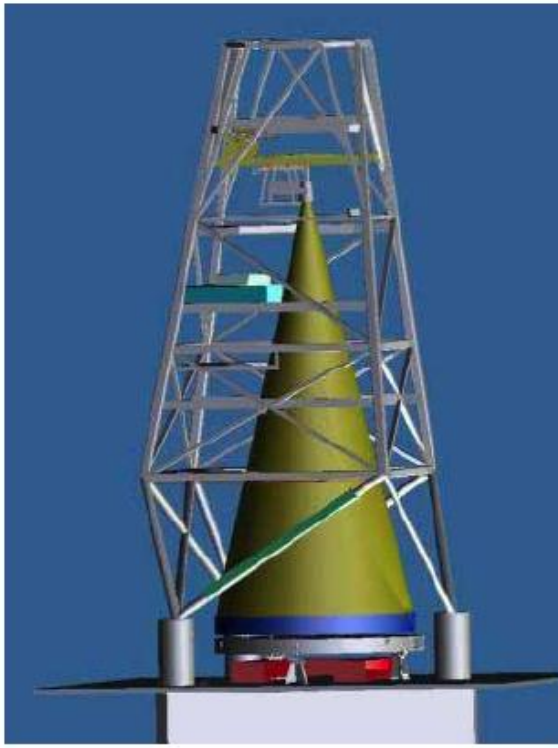
LSST PM-TM

- Spin cast blank at UA
- PM curvature from spinning, TM shape cut in with diamond generated

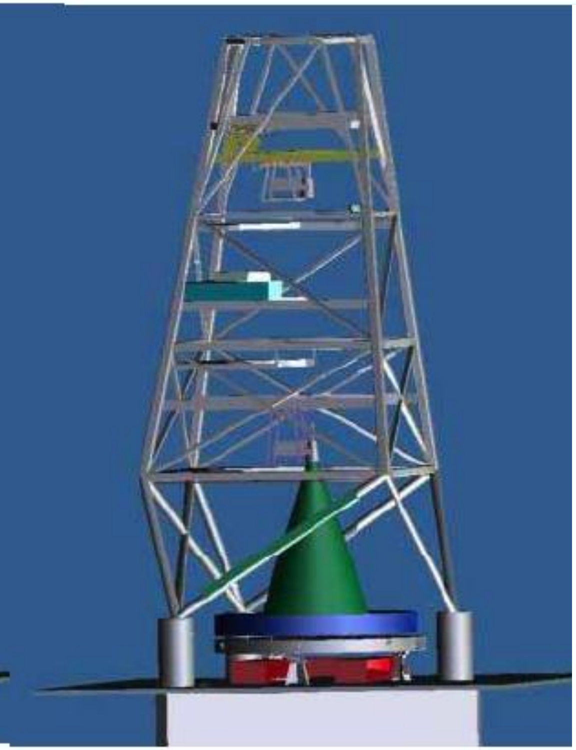




Null test of M1, M3



Configuration for test of M1
R = 19.8 m



Configuration for test of M3
R = 8.3 m

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

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

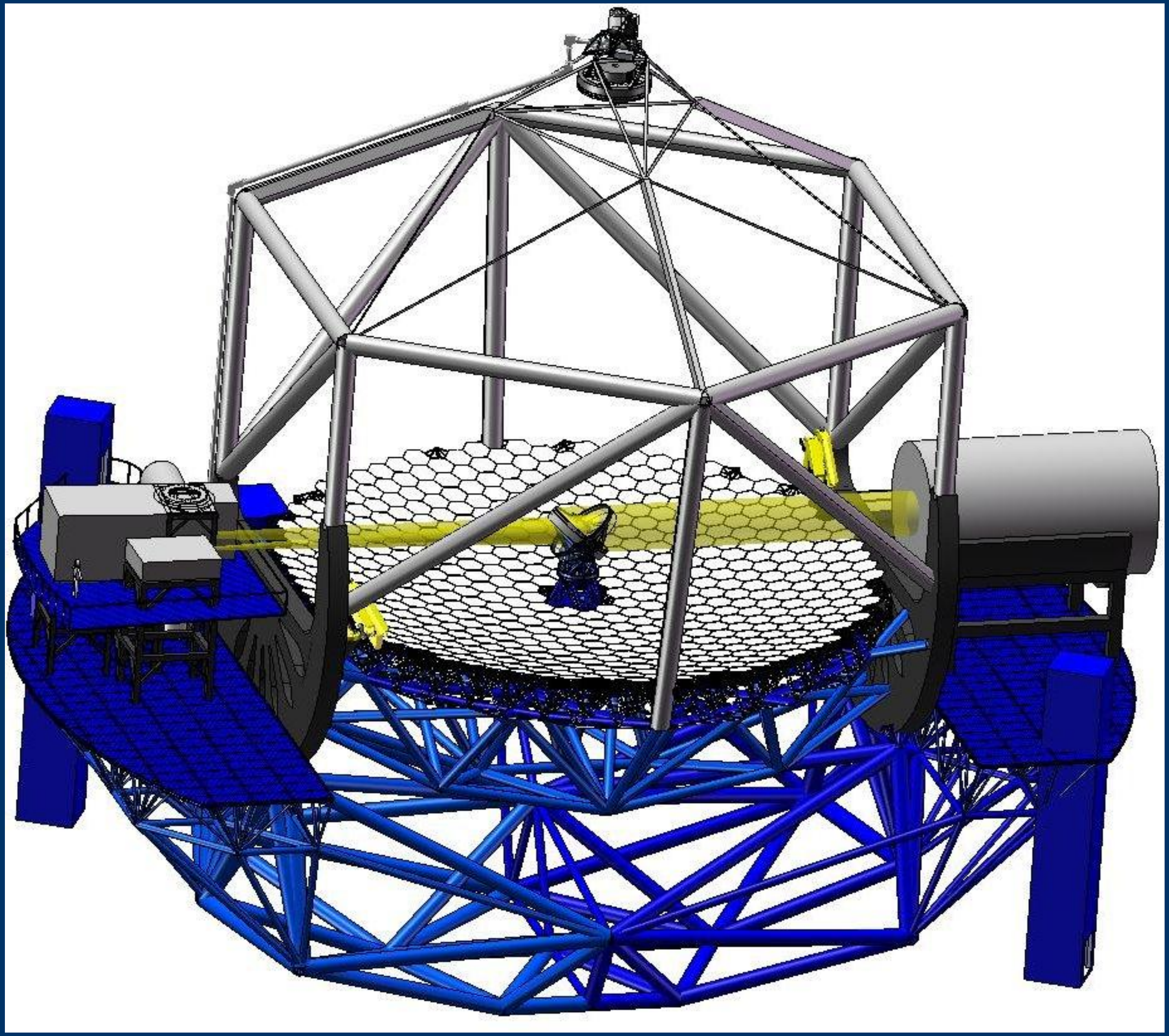
2018 first light

TMT optical challenges

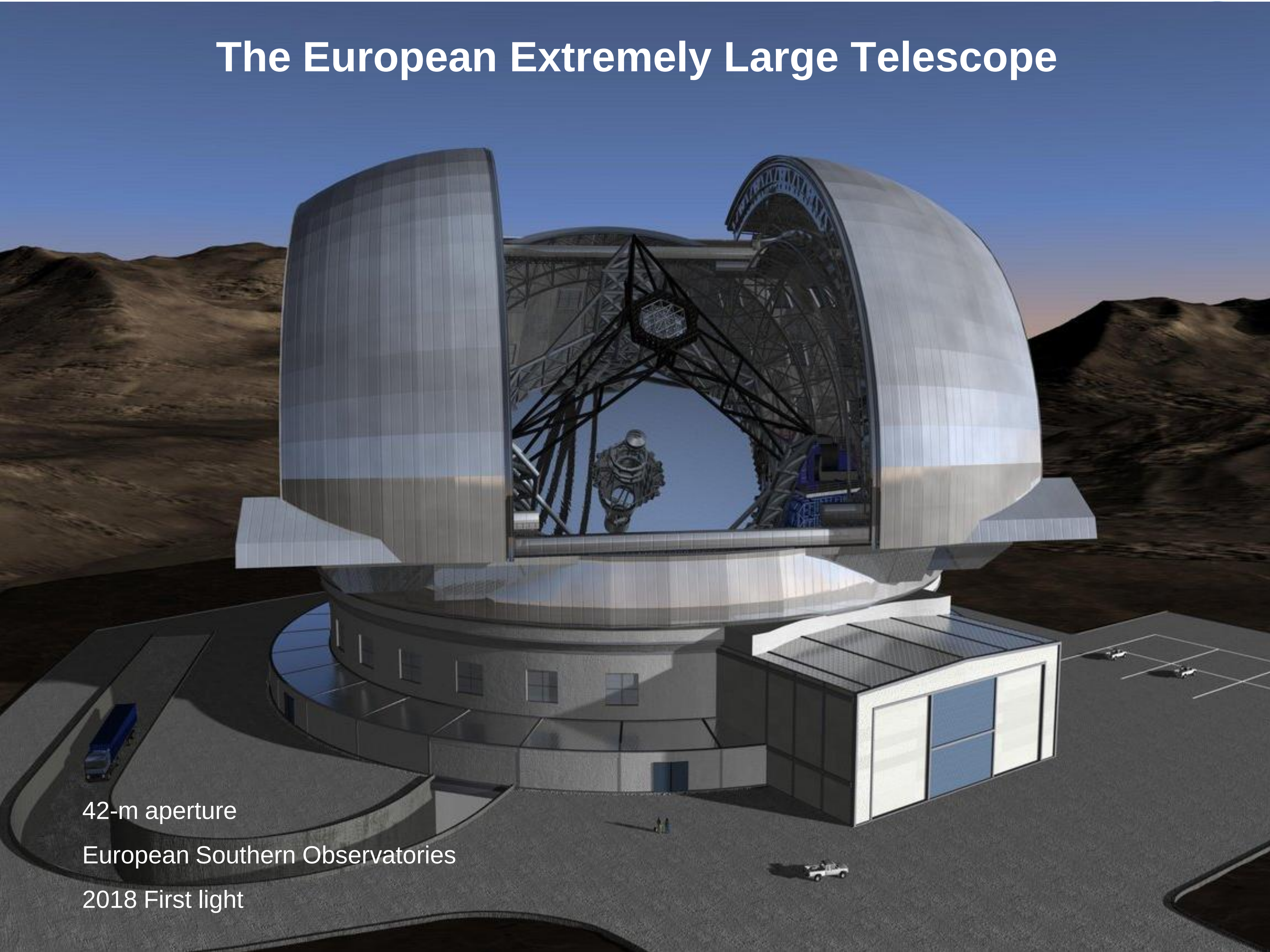
3.1-m convex secondary mirror

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

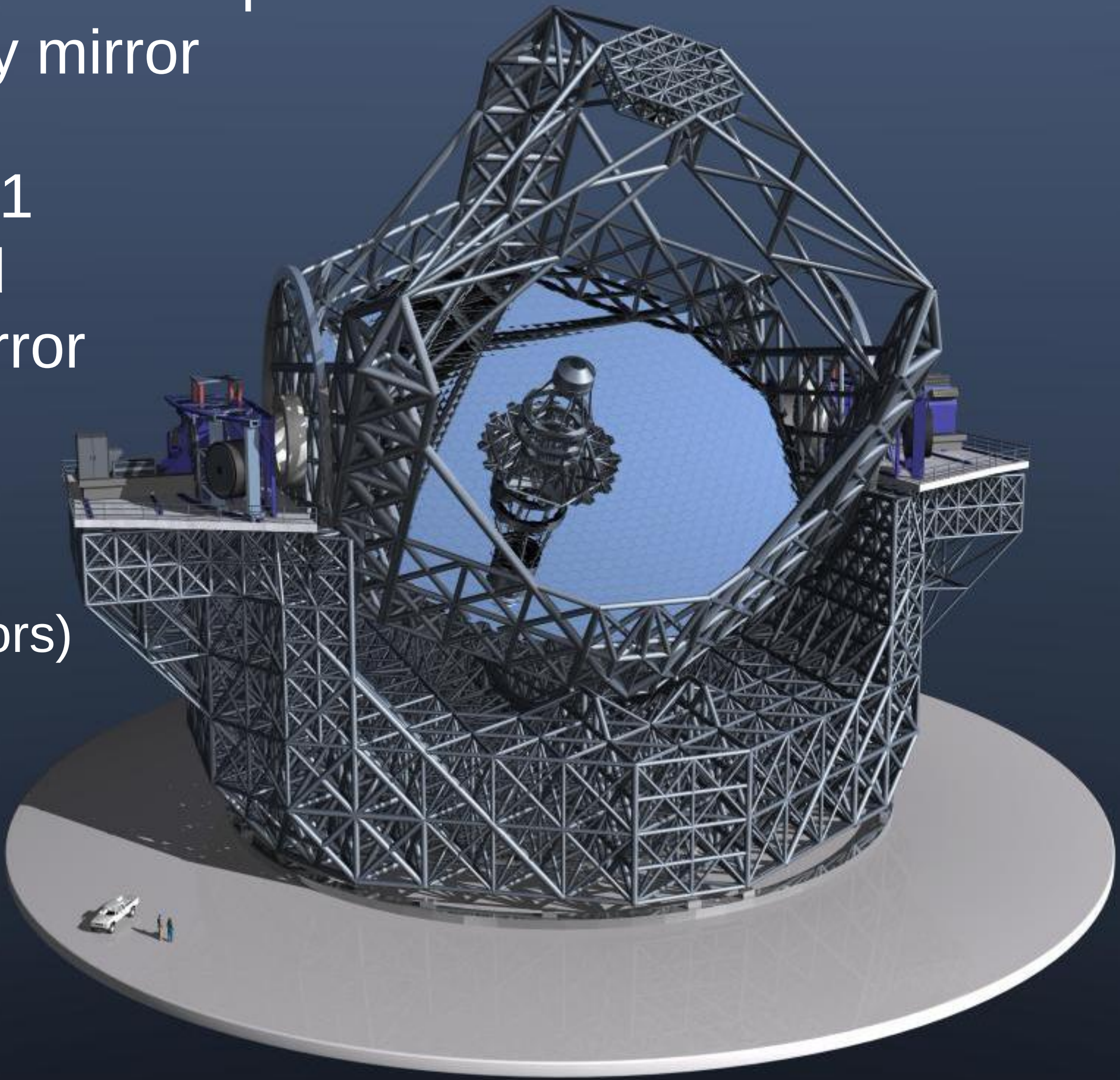
2018 First light

E-ELT telescope

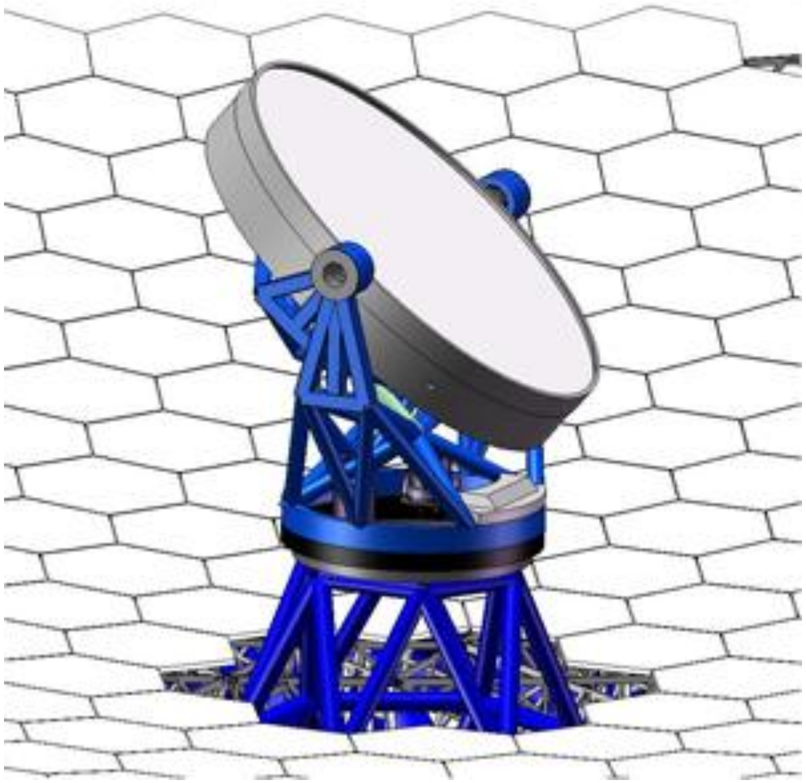
6 meter convex aspheric secondary mirror

42-meter f/1 segmented primary mirror

(plus other mirrors)

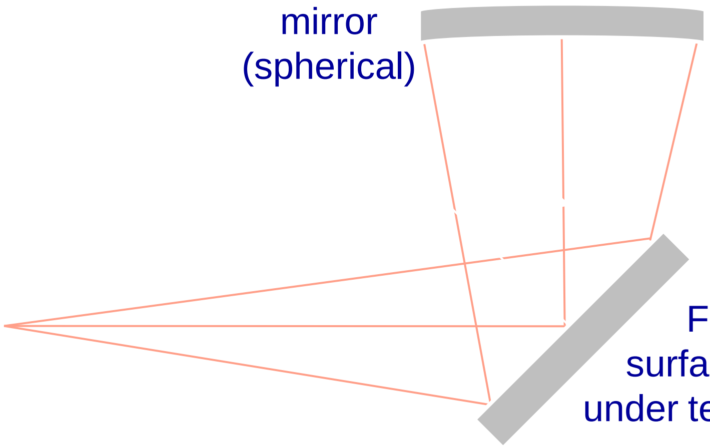


Measurement of large flat mirrors



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

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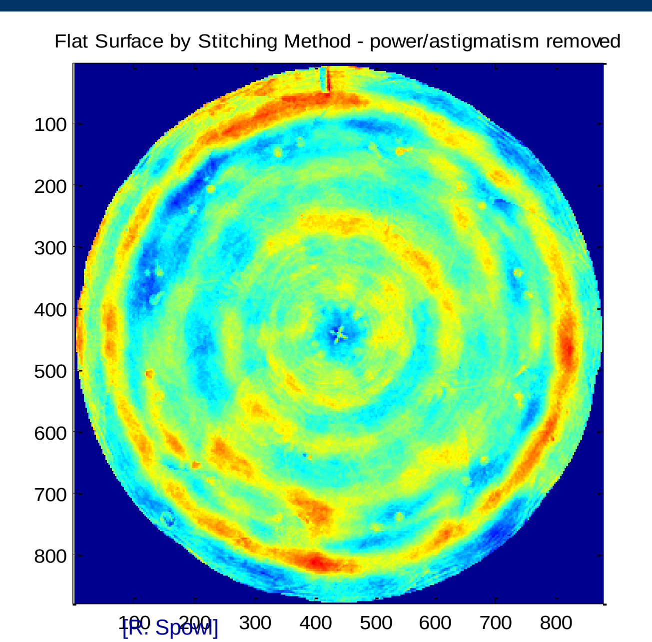
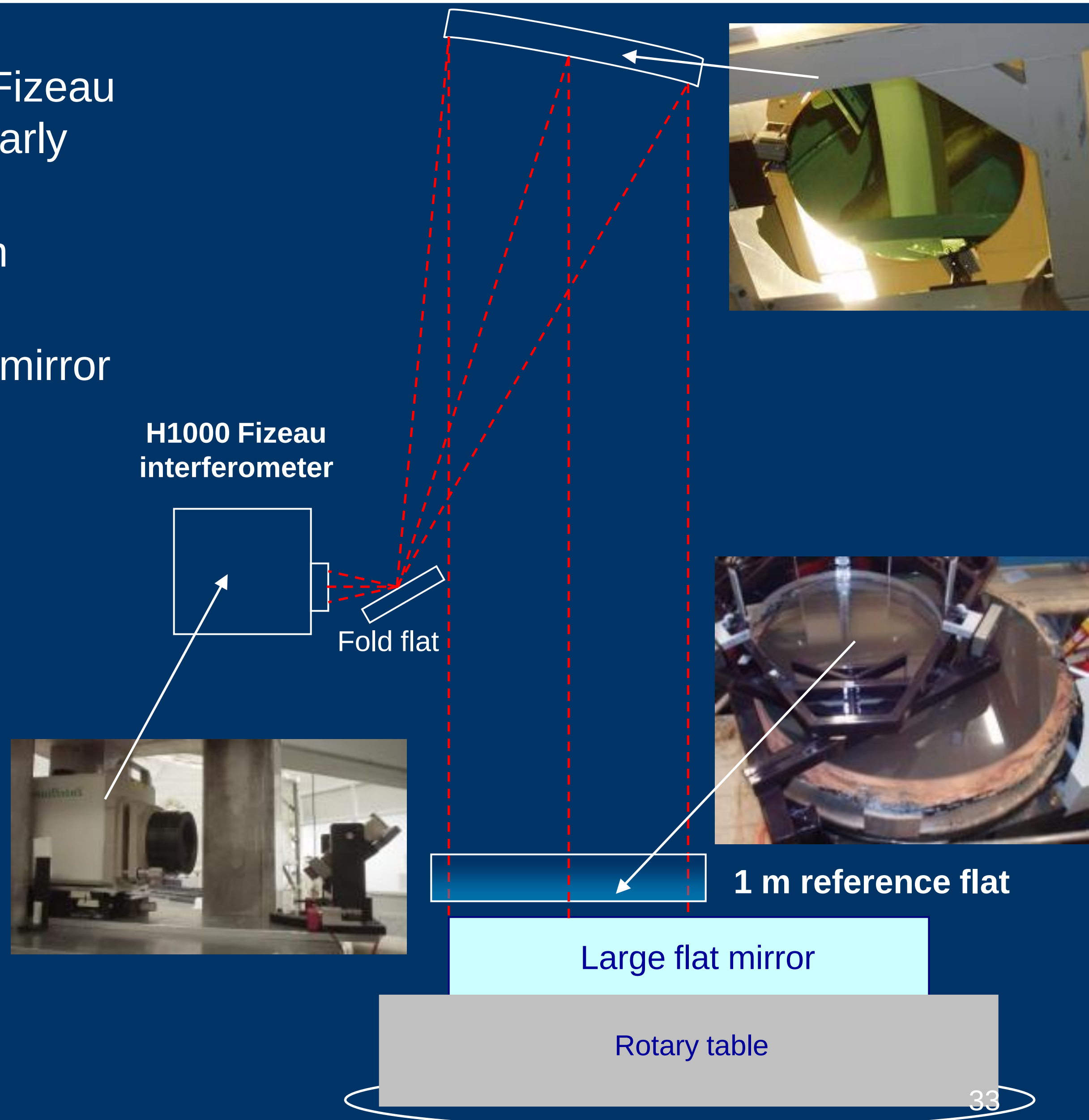
1-m vibration insensitive interferometer

LOFT Large Optics Fabrication & Testing

- 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!



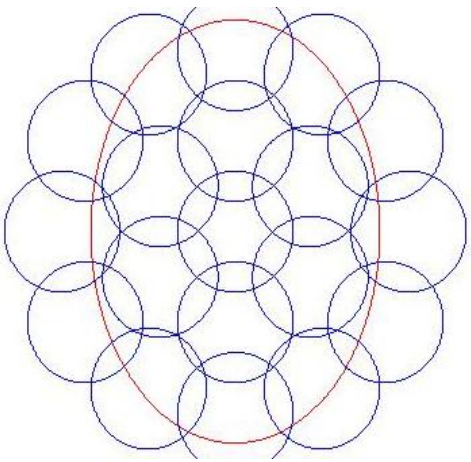
7 nm rms



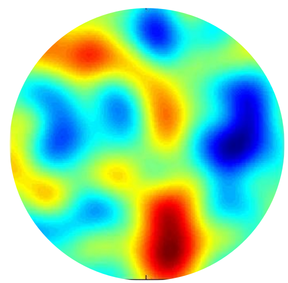
(J. Yellowhair, R. Su)

UA Fizeau test for TMT tertiary

Layout of subapertures

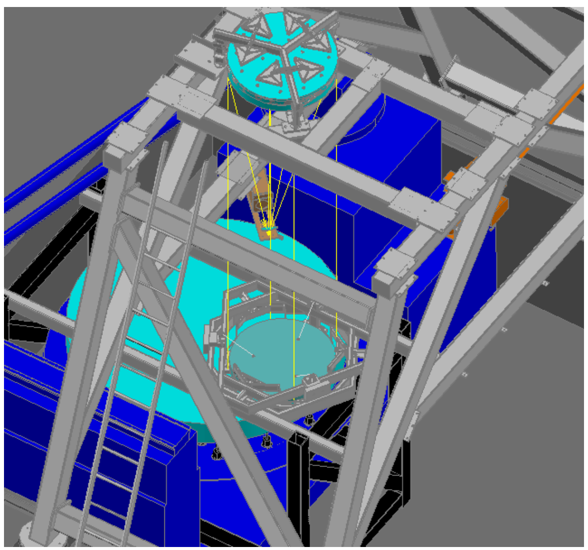


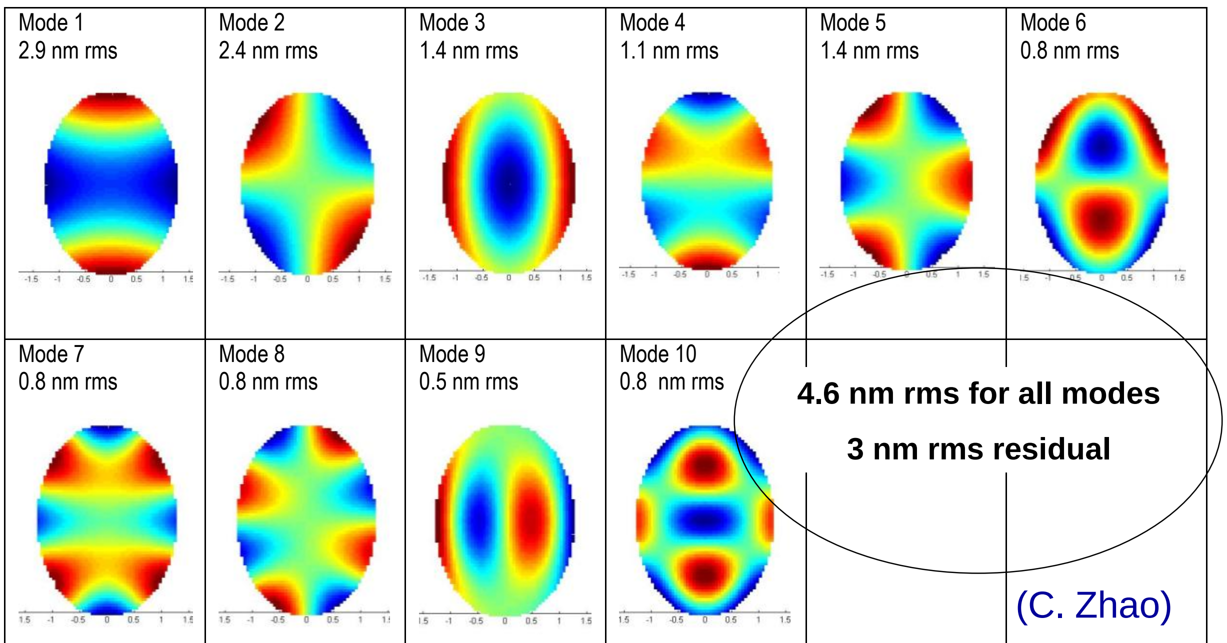
3 nm rms typical measurement noise



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

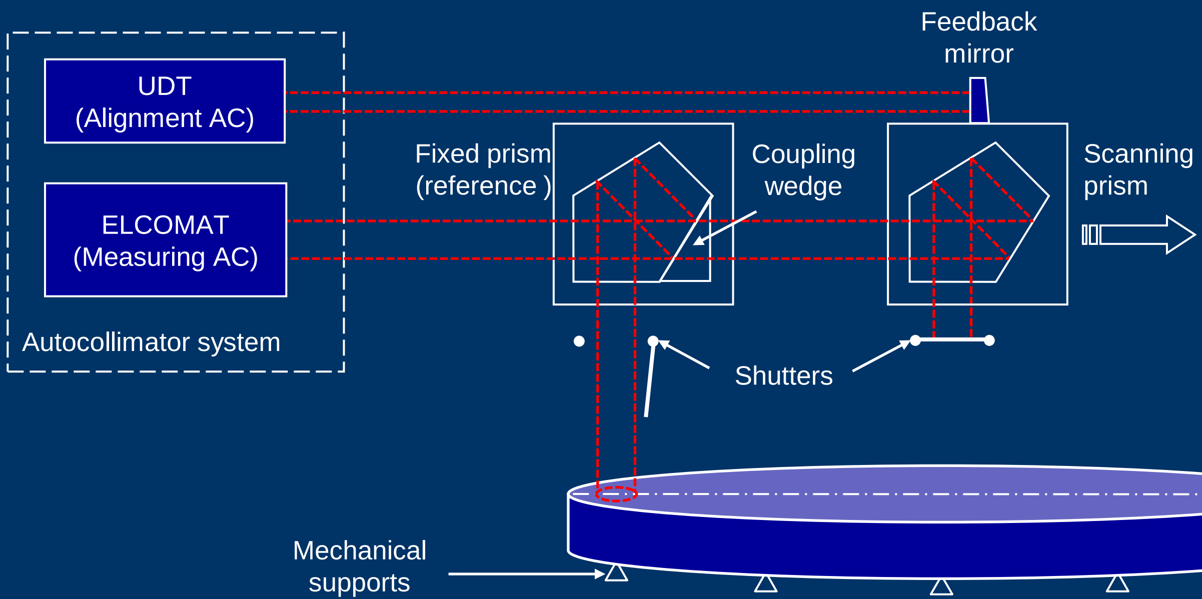
5.5 nm rms measurement accuracy with proven UA hardware!



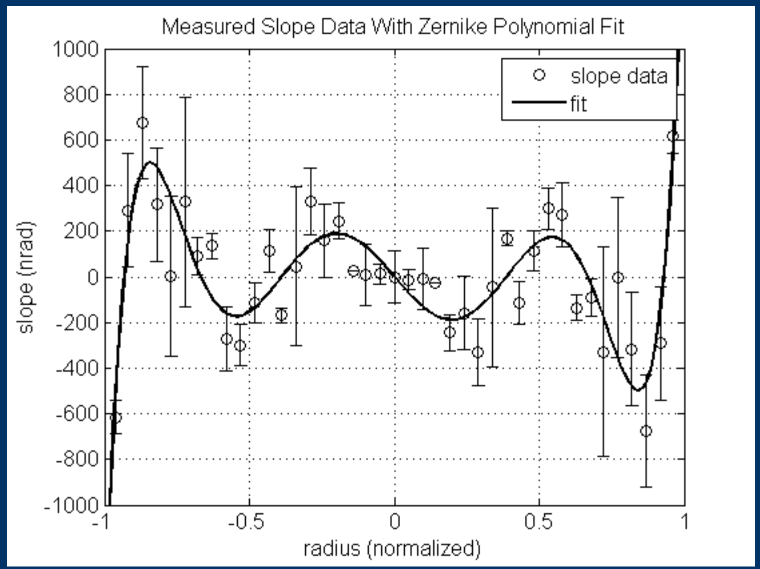


(C. Zhao)

Scanning pentaprism test for flat mirrors



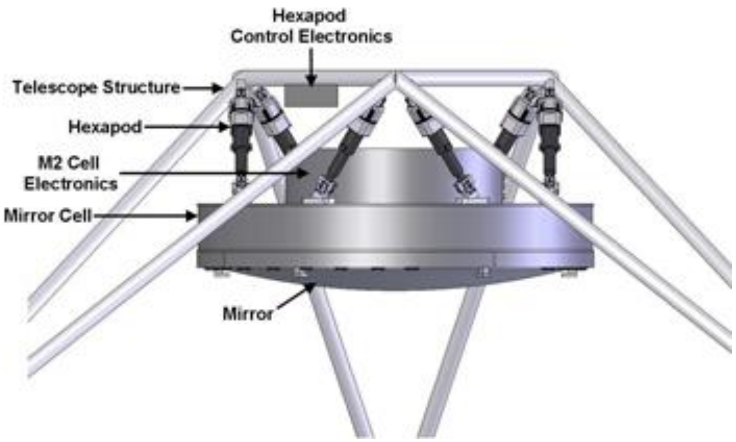
- Demonstrated performance is 0.2 µrad rms
- Power measurement for 1.6-m flat was 11 nm rms



(J. Yellowhair)

Measurement of large convex aspheres

TMT secondary mirror in telescope



LSST SM blank : ULE

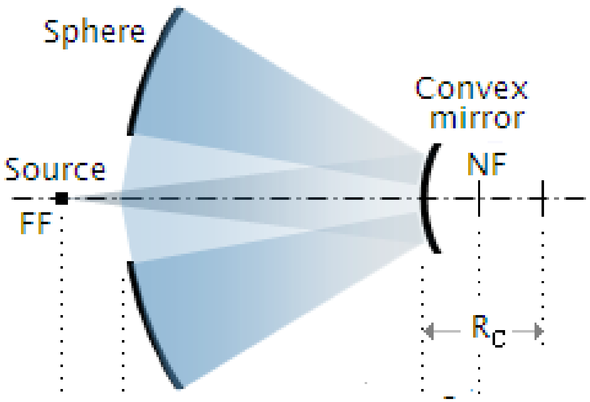
<u>Convex secondary mirrors</u>

TMT secondary: 3.1-m

LSST secondary: 3.4-m

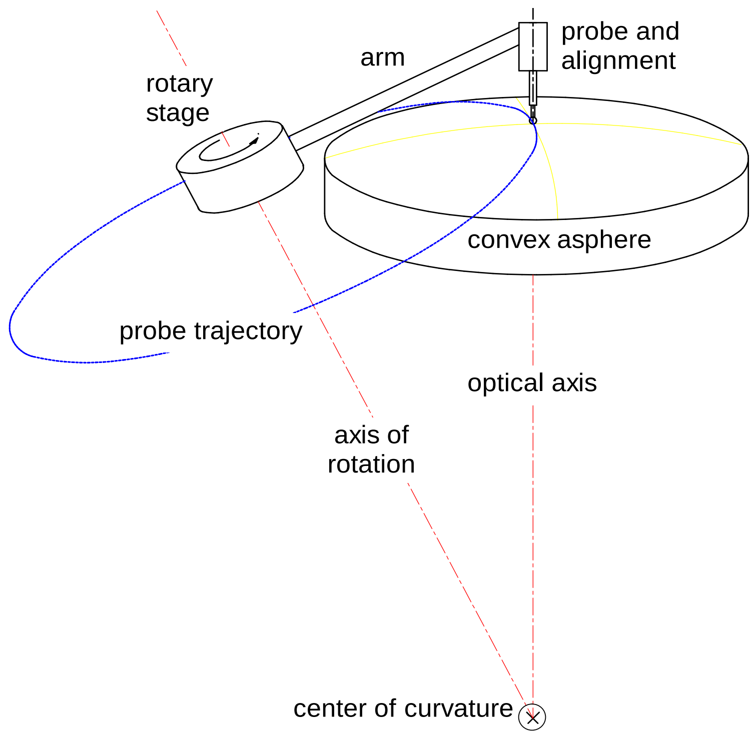
E-ELT secondary: 6-m

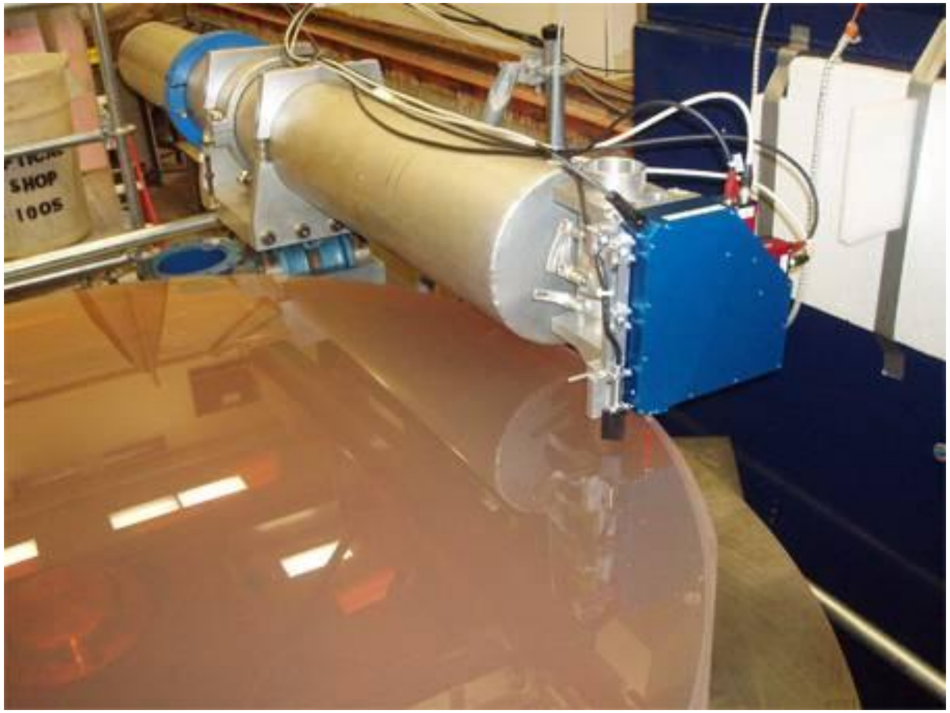
Conventional test of such mirrors uses the Hindle test, not practical at these sizes



Swingarm Optical CMM

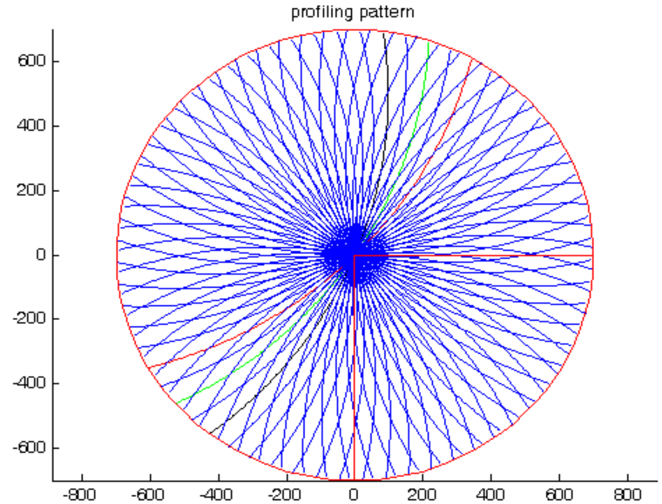
- Scans surface with optical displacement probe
- Continuous arc scans create profiles
- Profiles stitched together to give surface maps
- Works for convex or concave surface



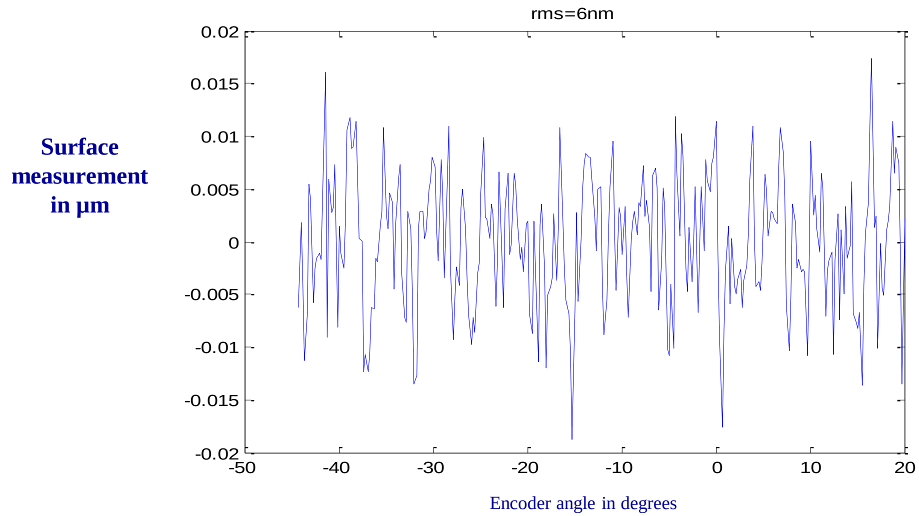


Surface maps from SOC data for 1.4-m off axis asphere

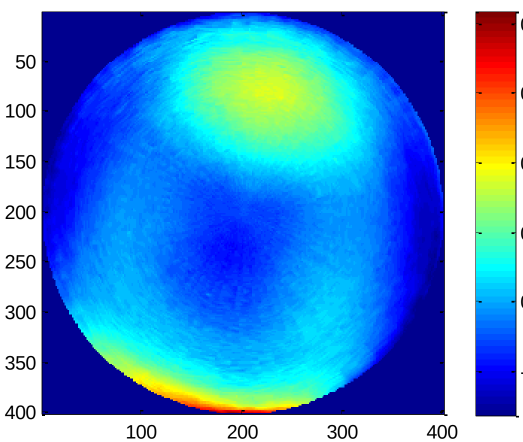
Pattern of 64 scans



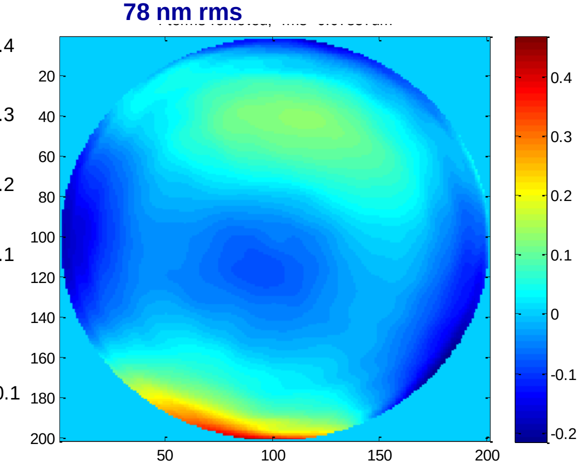
Repeatability ~ 6 nm rms/scan



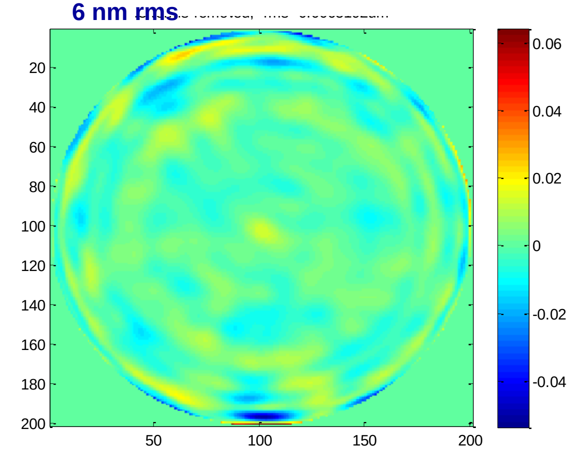
Interpolated data
75 nm rms



896 term reconstruction
78 nm rms



Low order terms removed
6 nm rms

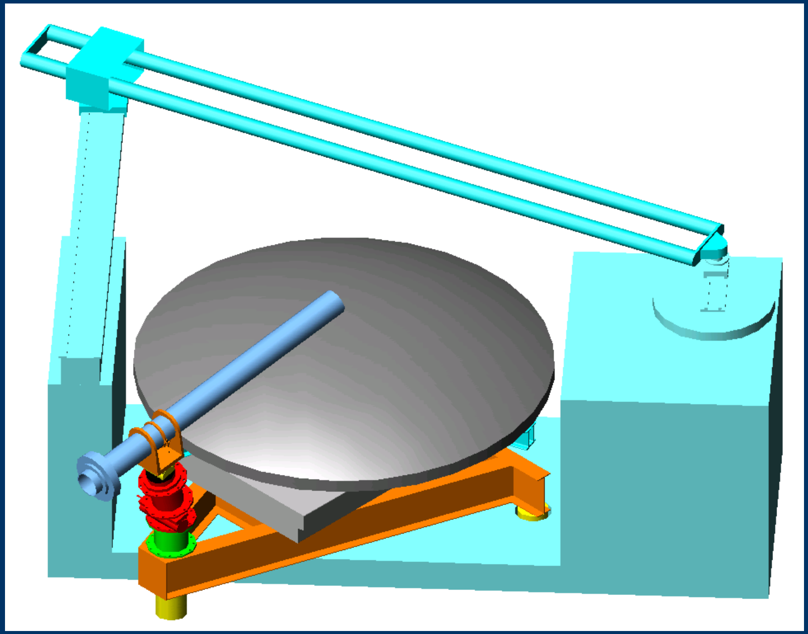


Repeatable errors of 34 nm rms are calibrated out

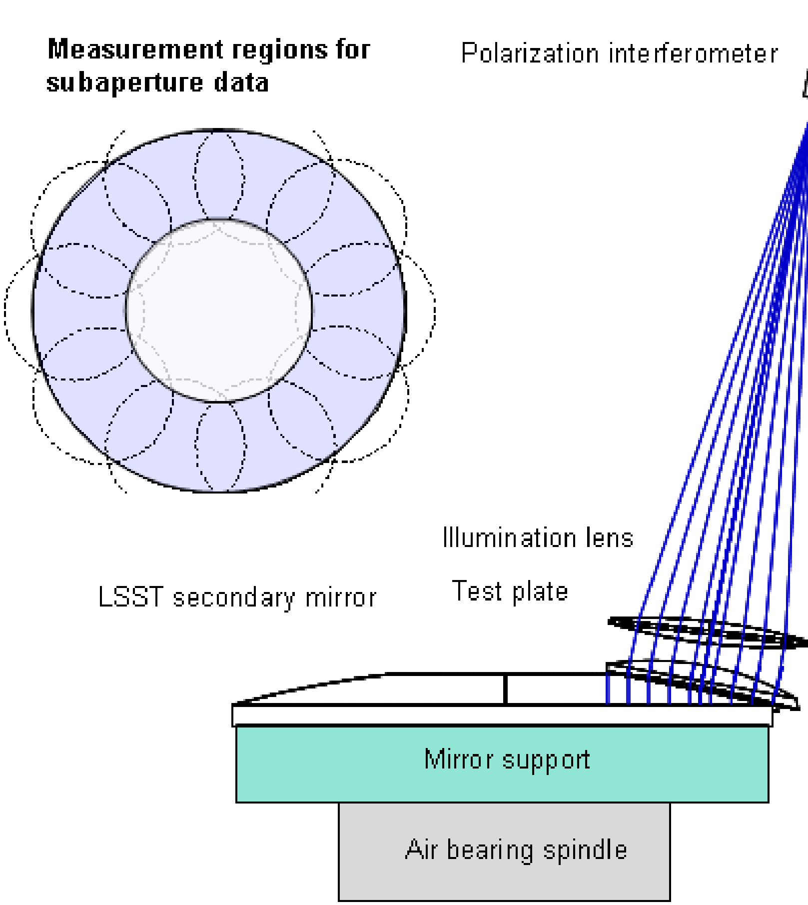
(P. Su)

Measurement with Swingarm Optical CMM

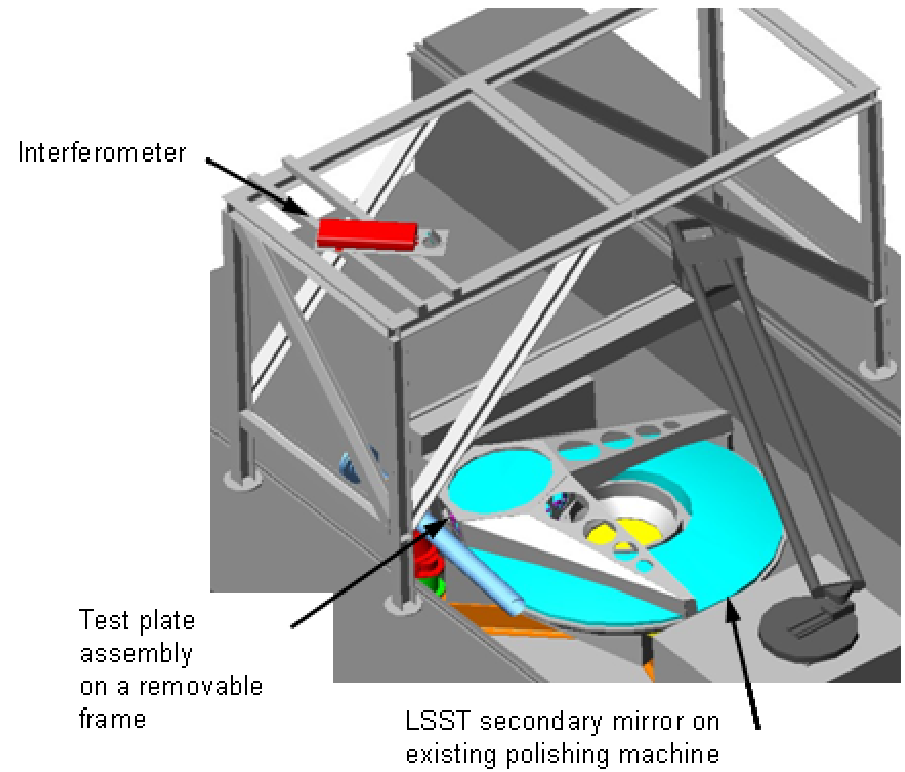
- Original system built at Optical Sciences was made with 3.8-m capacity.
- This was designed to be integrated with 4-m polishing machine
- Performance is expected to be < 20 nm rms at this size



Fizeau interferometry for large secondary mirrors



Preliminary layout in the existing UA facility



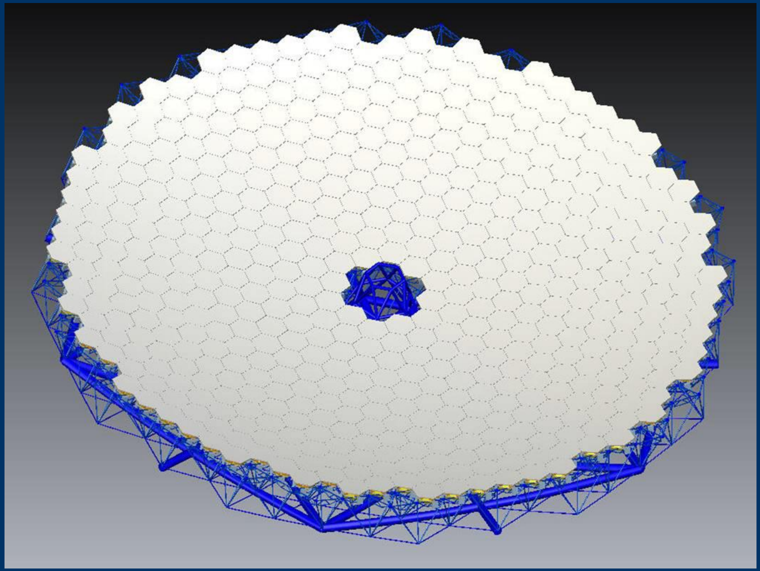
Reference surface on test plate has concave matching asphere for off axis portion of the secondary mirror

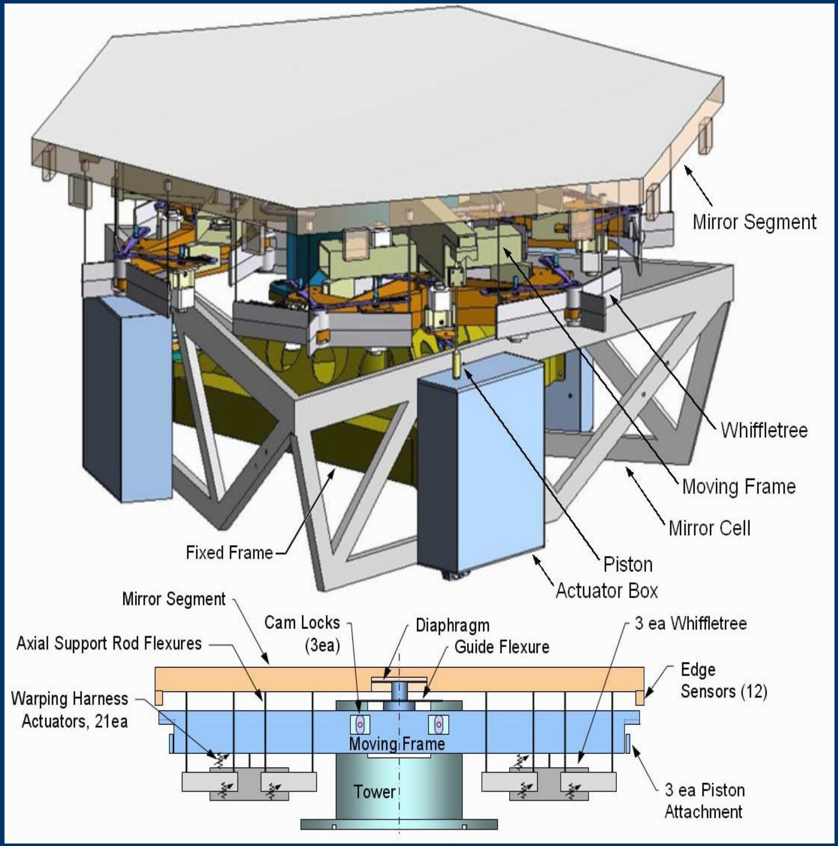
We have also developed concept for using a spherical reference, corrected with CGH

TMT primary mirror

30–m f/1 near paraboloid

492 segments





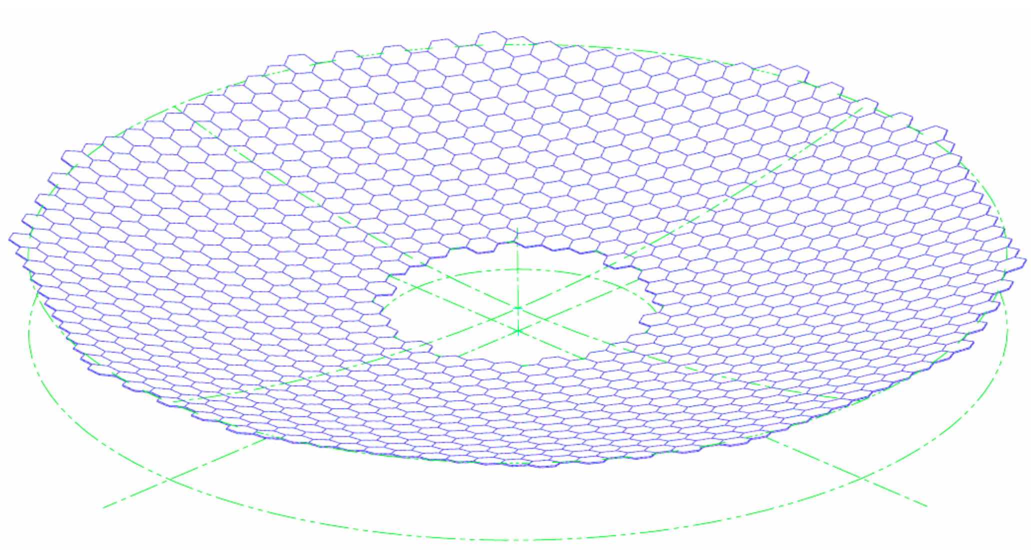
1.44-m segments, 45 mm thick

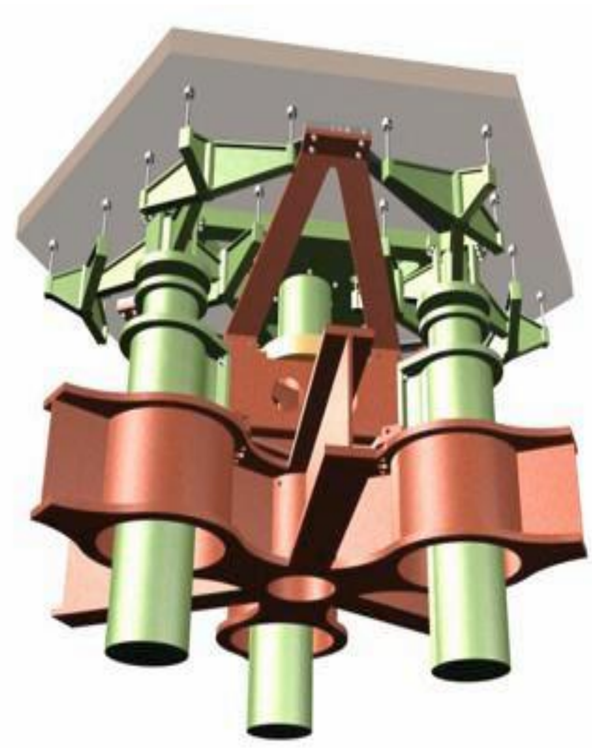
Each is supported by 27-point whiffle tree, warped with 21 actuators

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

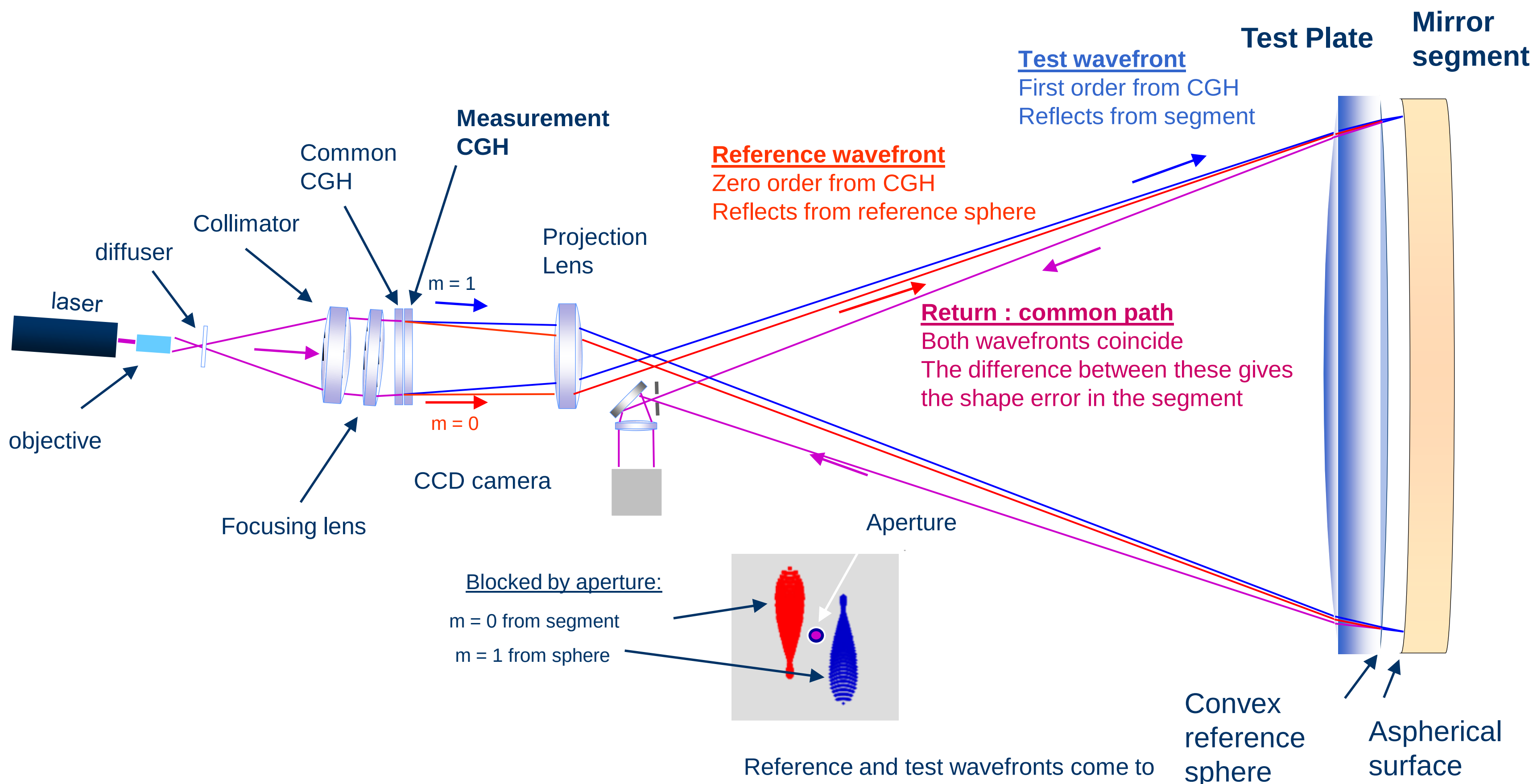
The challenges of measuring the TMT, E-ELT PM mirror segments

- 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



Reference and test wavefronts come to focus and pass through aperture

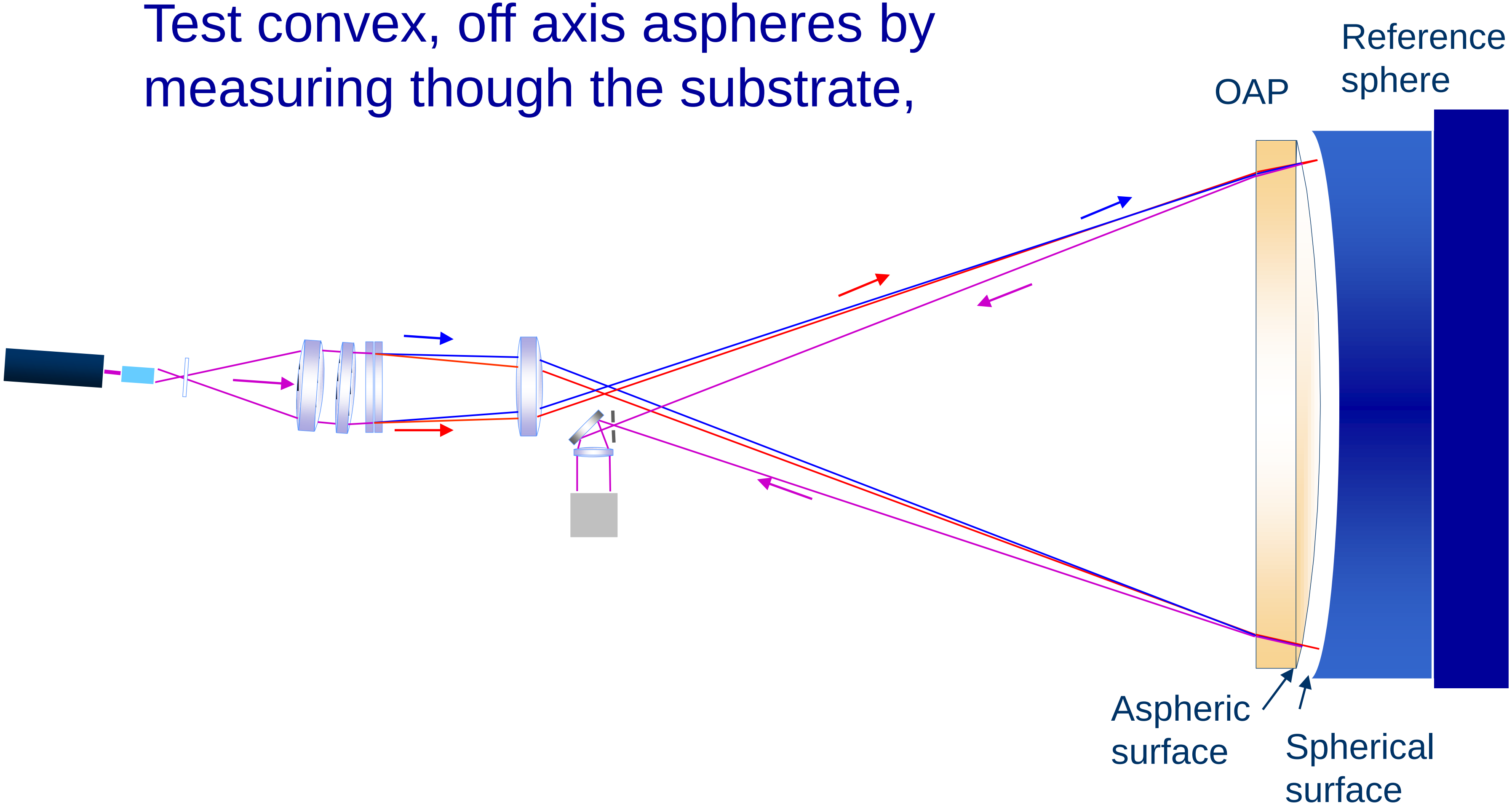
All other orders and reflections are blocked

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

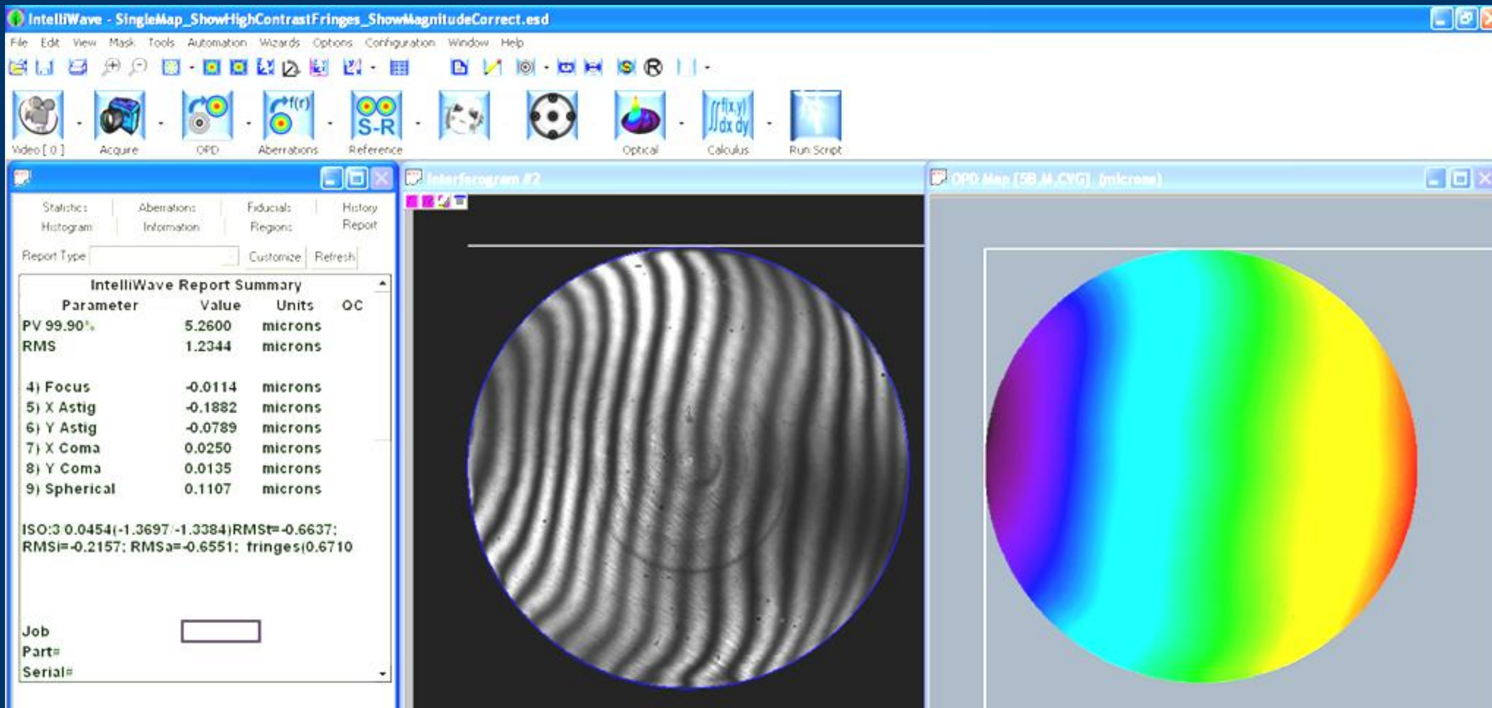
Test convex, off axis aspheres by measuring though the substrate,



THE UNIVERSITY OF ARIZONA
TUCSON ARIZONA

UA achieved very low noise measurements with CGH Fizeau system

LOFT
Large Optics Fabrication & Testing



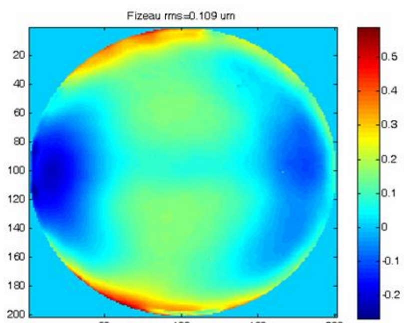
Excellent fringe visibility
Excellent spatial resolution
Overall accuracy of < 4 nm rms
< 1 nm rms noise per measurement (average of 50 maps)
Verified effects of straie in glass to cause < 1 nm rms
Largest sources of error: ghost reflection in CGH, coating irregularity on fold flat

Comparison of Fizeau, SOC for off-axis aspheres

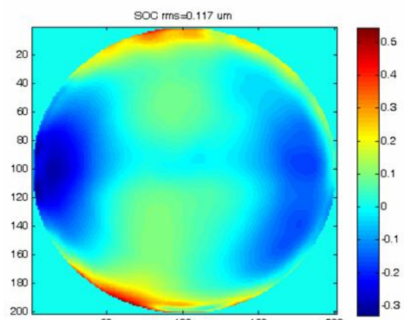
- **The Fizeau test was budgeted as < 3.3 nm rms uncertainty, after correction for low order terms.**
- **SOC measurements of the OAPs are consistent with this.**

Fizeau **SOC**

Raw data



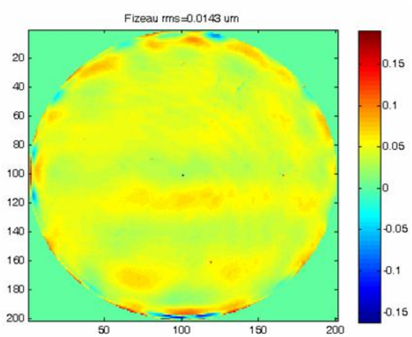
109 nm rms



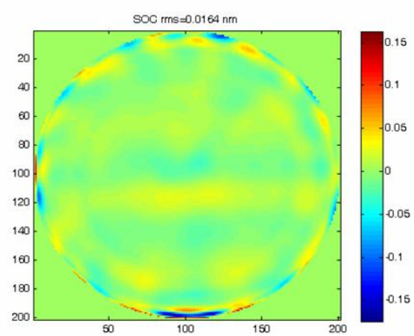
117 nm rms

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

After removing low order terms

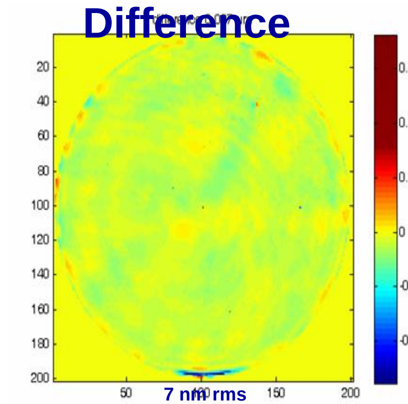


14 nm rms



16 nm rms

Difference



7 nm rms

Largest errors in Fizeau came from
coating defect on large fold flat 1 nm rms
ghost fringes 1 nm rms

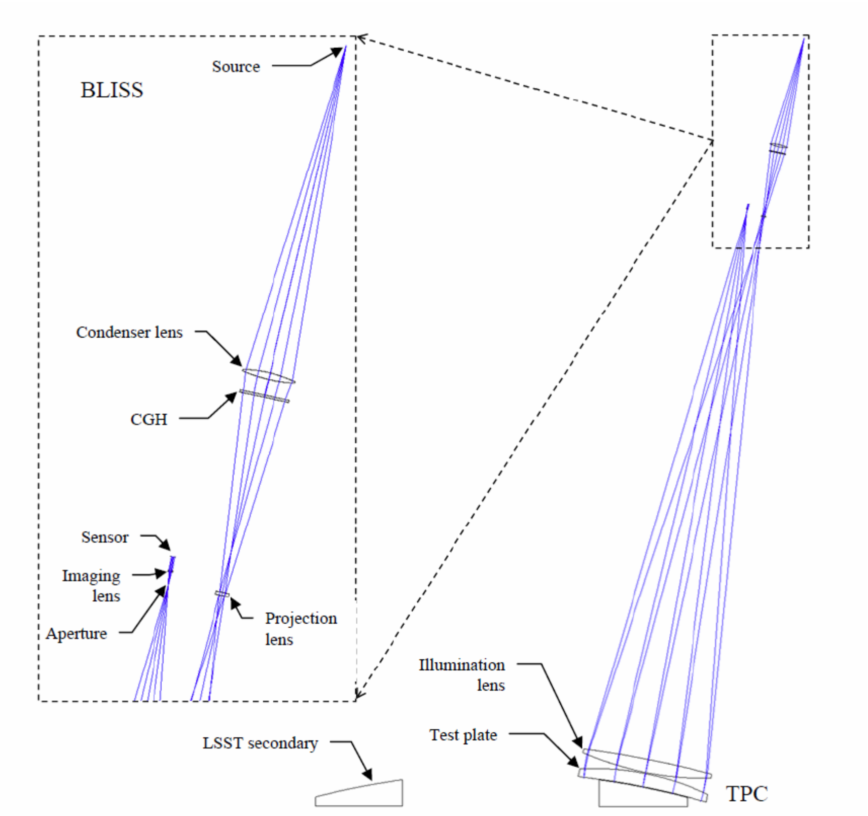
What next?

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.