Fabrication and testing of large free-form surfaces

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Introduction

- A tutorial on *Fabrication and testing of large freeform aspheres*?
- A tutorial should teach you how to do something – not really appropriate for this topic.
- Instead, I’ll give a talk that provides:
  - Summary of the problem
  - Outline the basic steps for fabrication, emphasizing commercial systems
  - Extreme aspheres at University of Arizona
- I restrict the talk to
  - Large optics > 1 m
  - Optics with surface requirements < $\lambda/10$

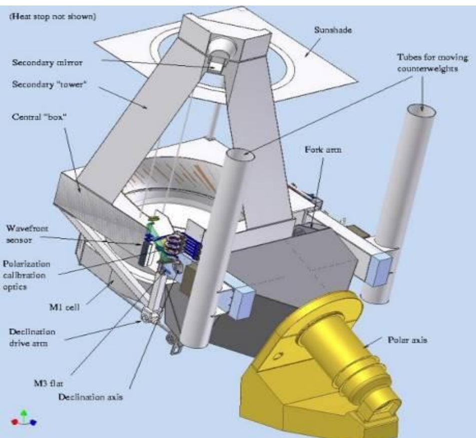
Freeform surfaces

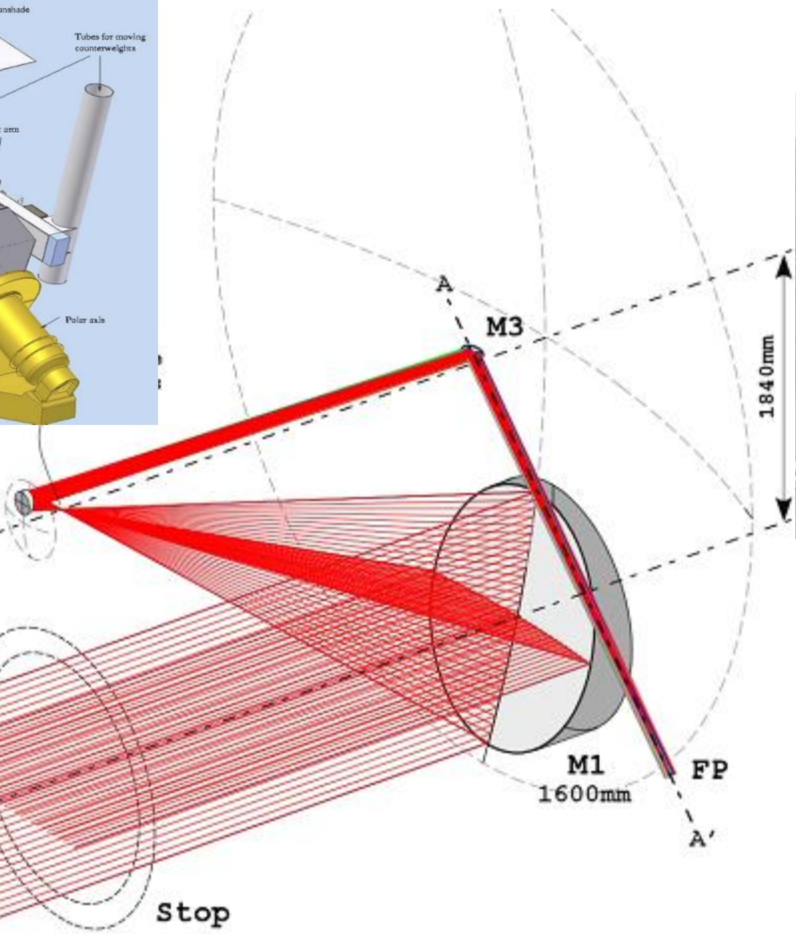
- **General aspheres**
- **Lack rotational symmetry**
  For small parts, the parent is made, then the desired off axis piece is cut out. Not interesting here.
- **When used in optical systems, these have the same tight figure requirements as other optics**
- **Difficulties come from aspheric departure**
  - Shaping (grinding and polishing)
  - Measuring
  - Aligning
- **Complexity comes from lack of symmetry**

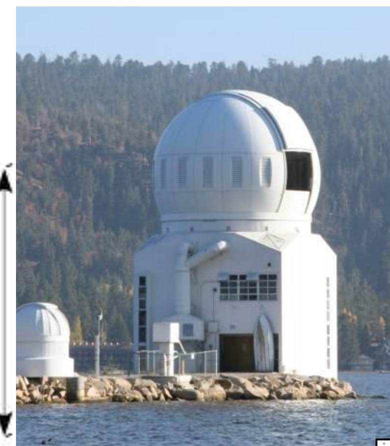
Applications for large freeform aspheres

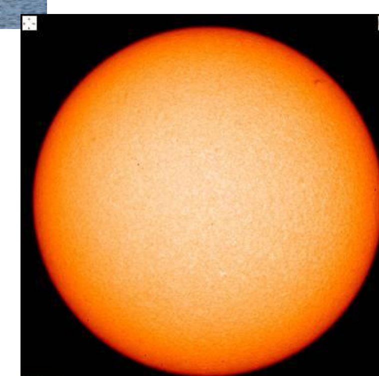
Imaging systems with unobscured pupil

- *New Solar Telescope* at Big Bear Solar Observatory
- Unobscured optical design for thermal reasons
  - 1.6-m aperture, taken from 5.3-m f/0.7 parent Gregorian design
  - Primary mirror is steep 1.7-m diameter off-axis parabola





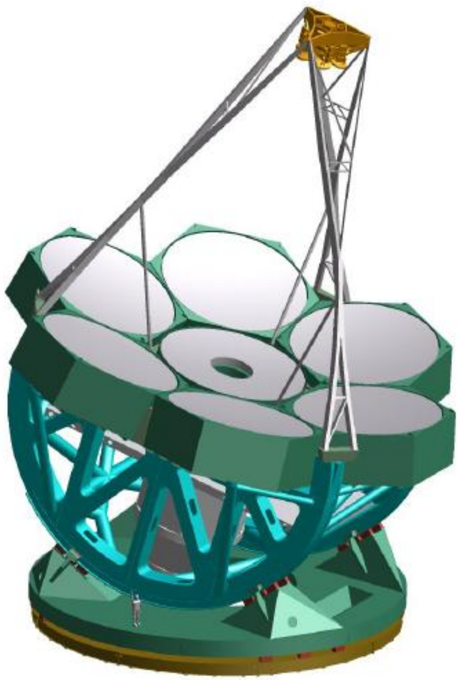




Applications for large freeform aspheres

Mirror segments for large axisymmetric systems

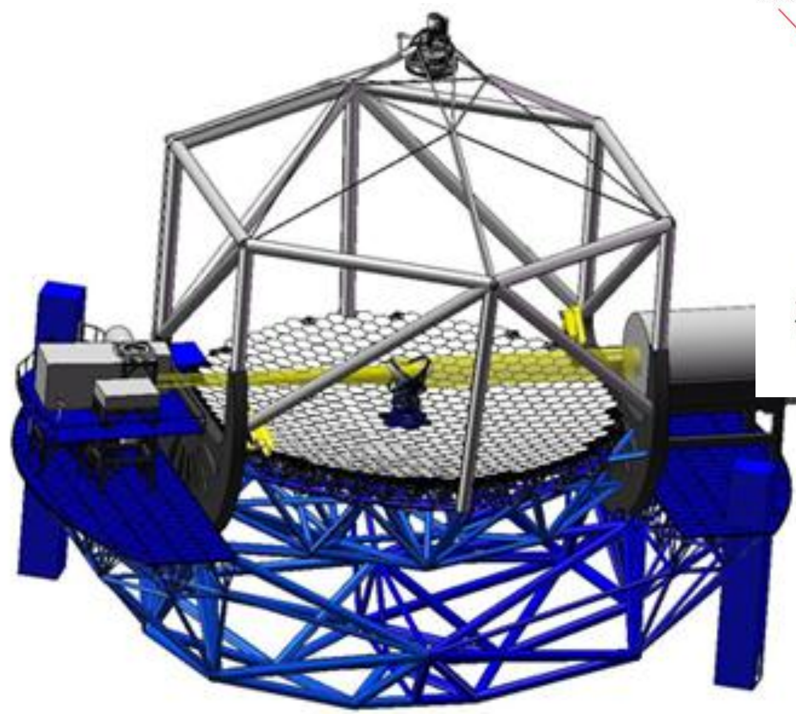
- Giant Magellan Telescope
- Thirty Meter Telescope
- James Webb Space Telescope



GMT

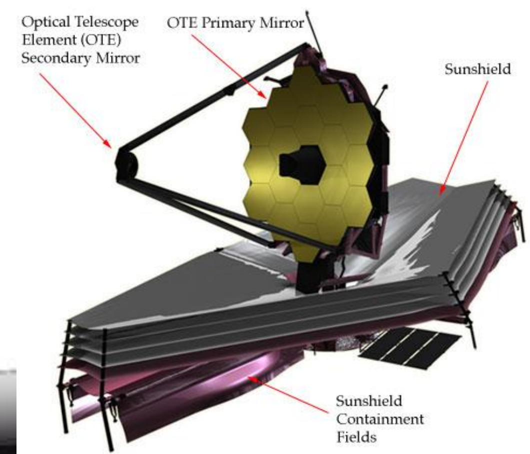
8.4-m PM segments

1.1-m SM segments



TMT

1.4-m PM segments



JWST

1.3-m PM segments

Applications for freeform aspheres

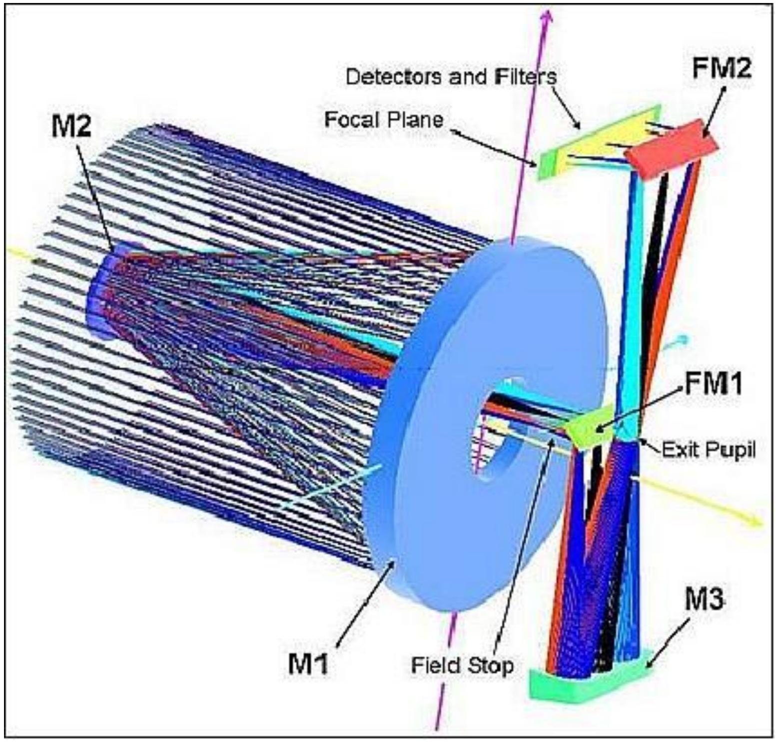
Correction optics for wide field systems

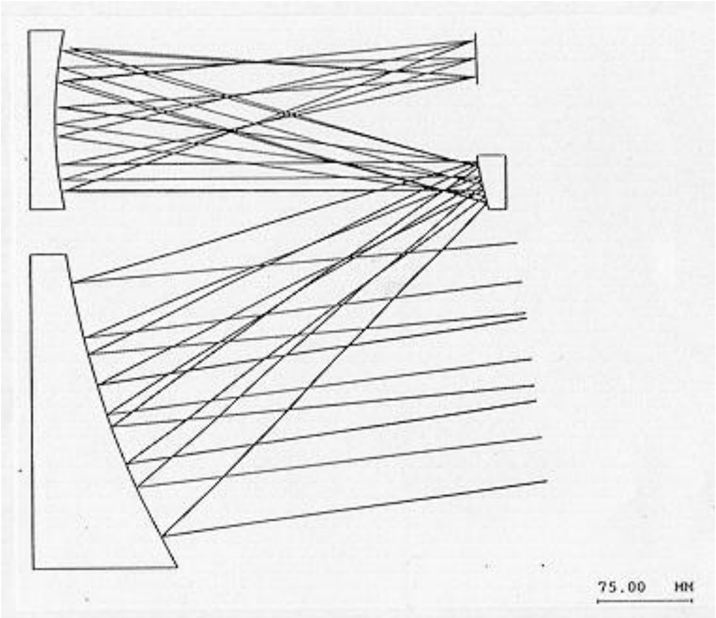
Three-mirror anastigmat uses axisymmetric Cassegrain-type primary-secondary combination, slightly off axis

Tertiary mirror is fully off axis

Other TMA designs are fully off axis

Designs often start with off axis portion of axisymmetric parent, then are allowed to depart





Initial shaping for "standard" optics

Diamond grinding to get the shape close (to within 5 – 50 μm)

Sphere

Special geometry for sphere

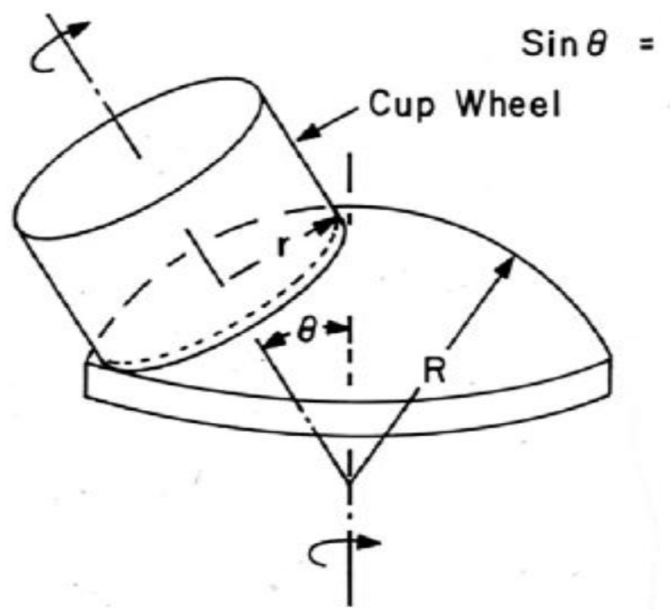
Blanchard generator allows very rapid shaping with large wheel

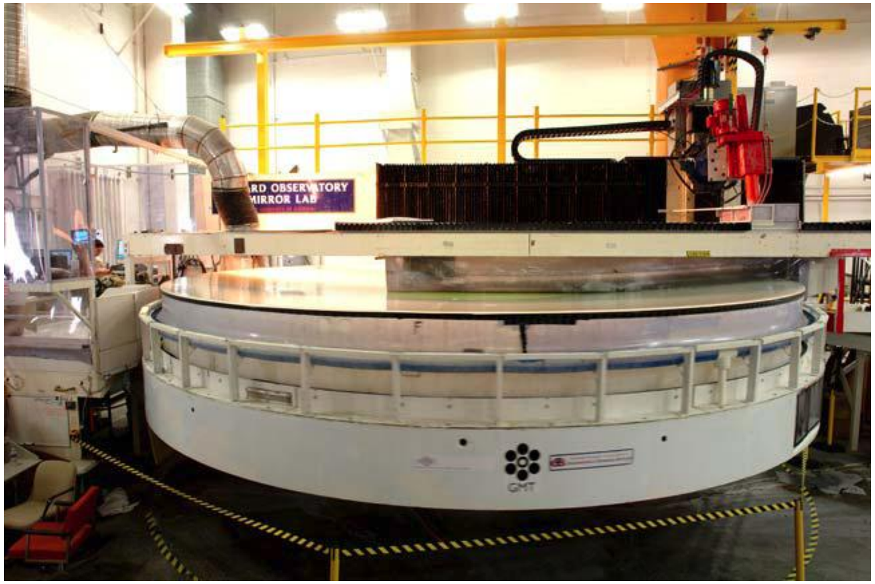
Axisymmetric asphere

Part rotates about axis.

Generator head follows a single profile

NC control of *z* vs *r*





Lapping for "standard" optics

Lapping with loose abrasives or polishing compound

Sphere

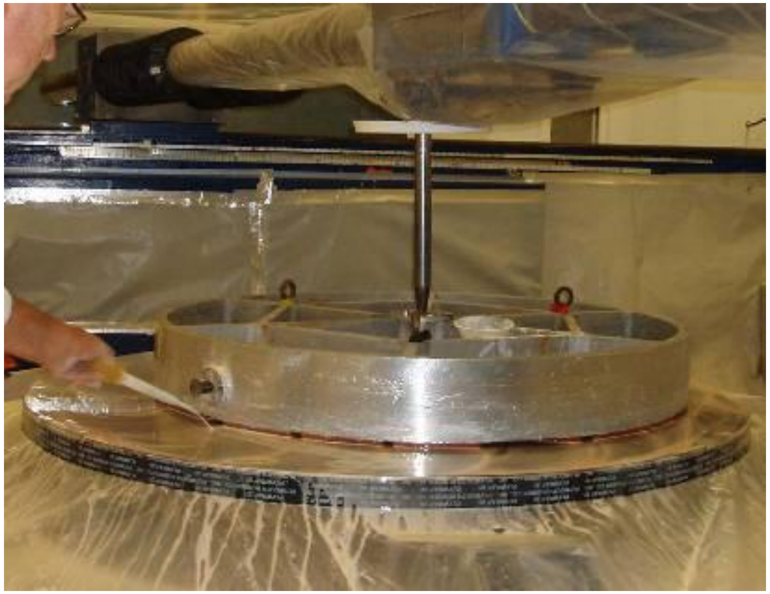
Use large rigid tools. Symmetry of sphere insures that tools fit.

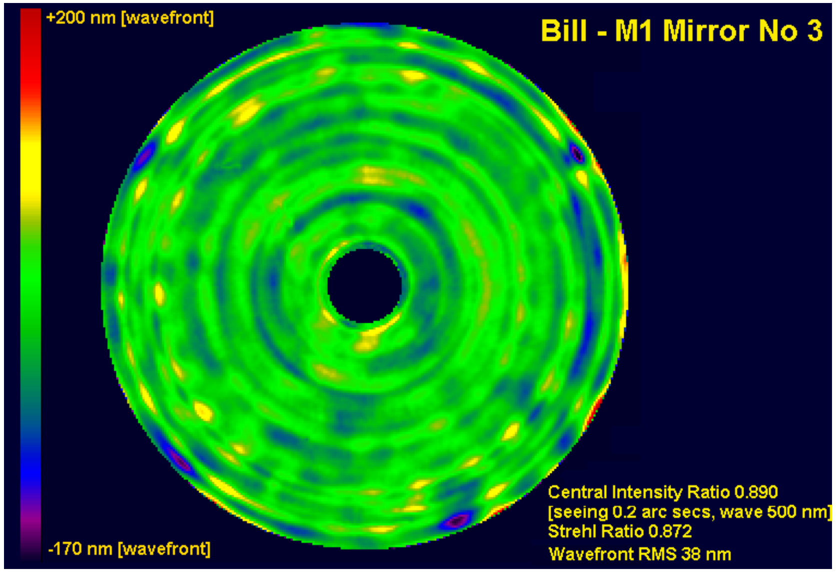
Natural smoothing does most of the work

Axisymmetric asphere

Most work is on "zones" in the surface by rotating the part under the polisher

Smaller and smaller tools are used



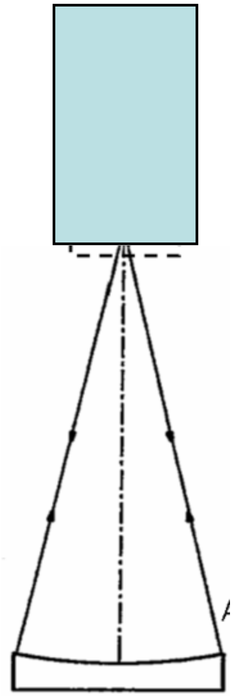


Measurement of “standard” optics

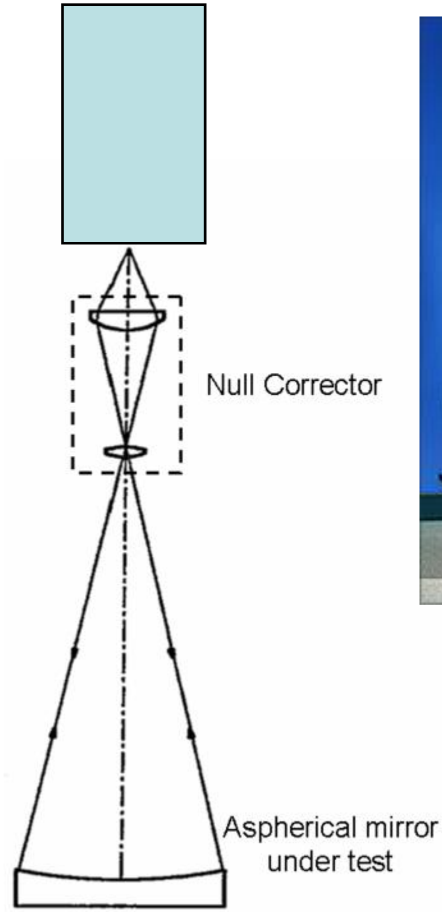
Axisymmetric aspheres

Sphere

Use interferometer



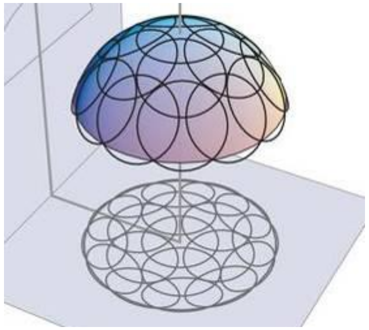
Interferometer
with axisymmetric null
corrector



Subaperture interferometry
for small optics

Annular subapertures
Zygo Verifire Asphere

Off axis
subapertures
QED SSI



The trouble with freeform aspheres

1. Initial shaping operations cannot use symmetry

   Special machines, complex operations

   Buy the right machine and take care of it – No problem.

2. Grinding and polishing tools don't fit, limiting ability to make smooth surfaces

   Special tools (Conformal polishers or laps with shape control)

   Smaller tools – these always fit.

   Rely more on directed removal, based on measurements

   Problem solved

3. Measurement is much more difficult

   Concave optics with moderate aspheric departure – no problem

   Small optics – no problem

   Large convex shapes or concave aspheres with very long radius or > 1 mm aspheric departure – Interesting problem

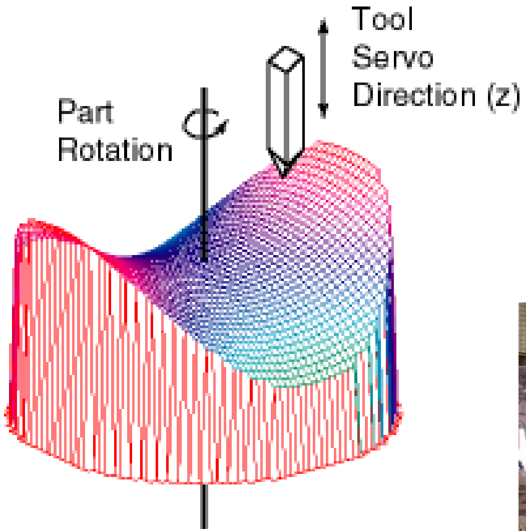
Initial shaping of freeform aspheres

Requires 3-axis coordinated motion

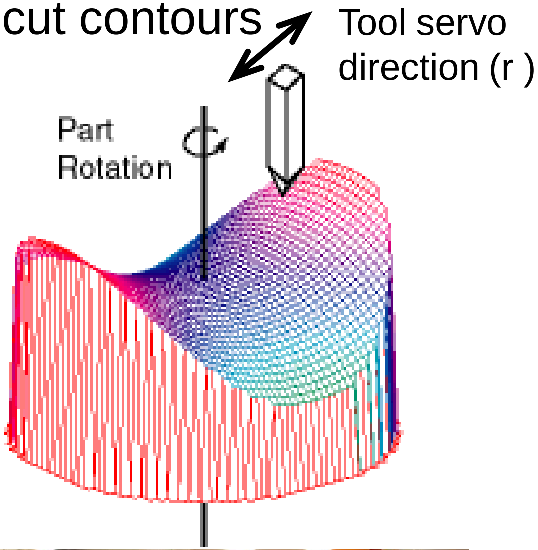
- always at a loss of accuracy
- increased complexity increases risk of mistake

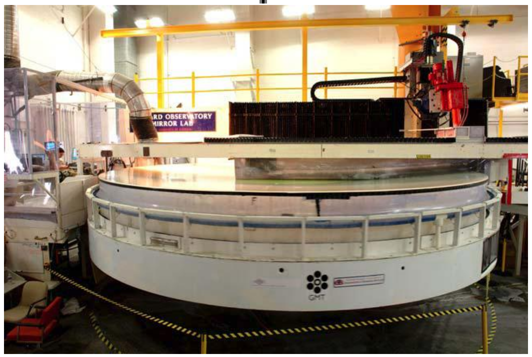
"Fast tool servo" for diamond turning

Replace diamond by grinding spindle

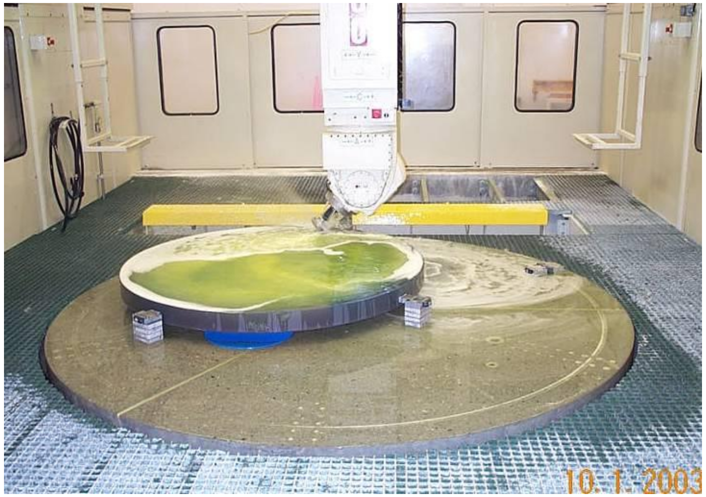


GMT used radial motion to cut contours





5-axis machining center



Multiple suppliers of machines that can achieve ~ 10 um tolerances

Accuracy depends on how much "love" the machine gets

Lapping (grinding and polishing)

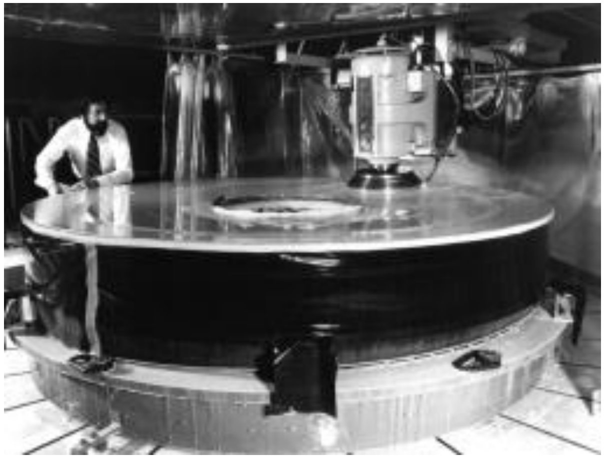
- Small-tool computer controlled surfacing using 5-axis machine, proprietary laps, polishers, algorithms
  - L3, ITT, Goodrich, UA
- Large tool for large optics
  - Stressed lap at University of Arizona
- Commercial systems capable of > 1-m
  - Zeeko: “Precessions”
  - QED Technologies: Magneto-Rheological Finishing

Small tool computer controlled polishing

Small tools always fit the aspherical surface

Well calibrated removal allows excellent results

Tends to be very slow for large optics



Small tool computer controlled polishing

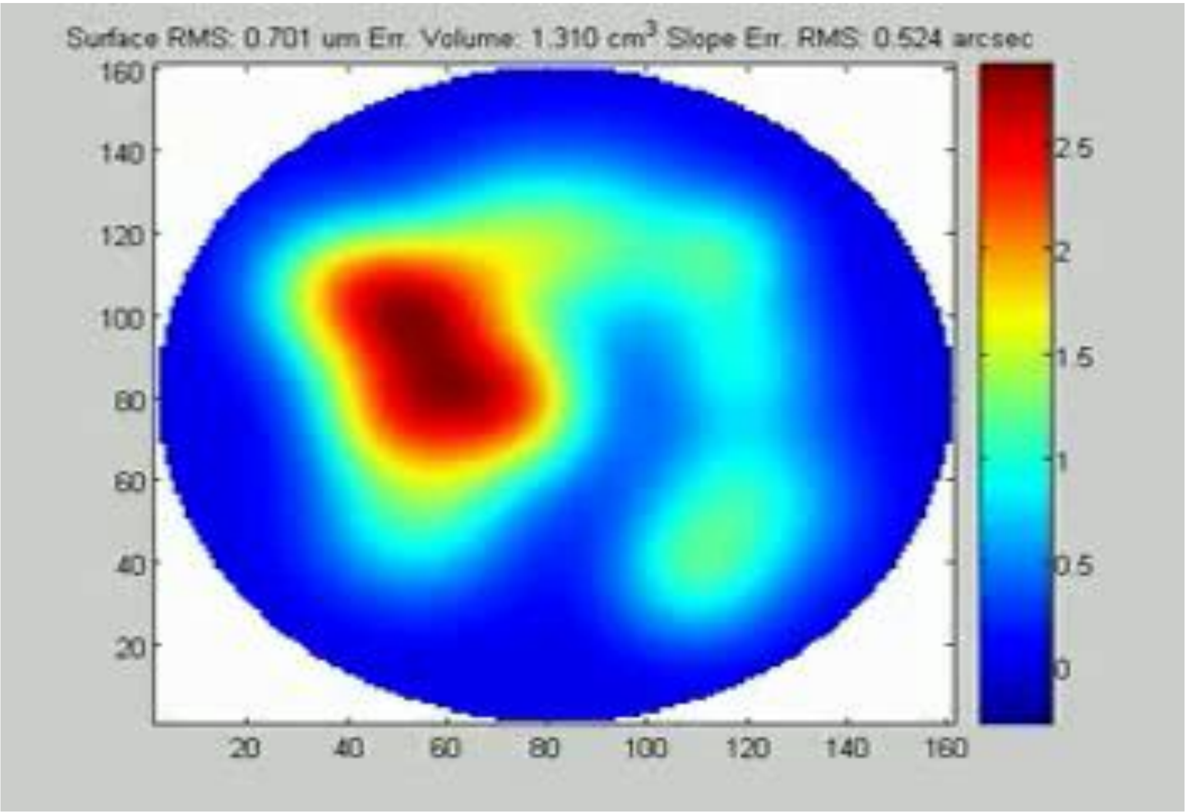
1. Measure surface error
2. Run polisher over surface, spending more time on high spots.

Limitations of small tool computer controlled polishing

- Measurement error
- Predictability of material wear
  - Material removal rate
  - Tool influence function shape
- Response of polishing tool used
  - Large tool cannot fix small scale errors
  - Small tool takes too long, imperfections introduce some small scale errors
- Edges are always challenging

CCP Video

CCP simulation



Stress lap polishing

- Large tool can be used if it fits the surface
- University of Arizona stressed lap is actively deformed so that it always fits the surface.
- Used for > 200 m^2 of axisymmetric aspheres
- Software change to allow operation on freeform aspheres

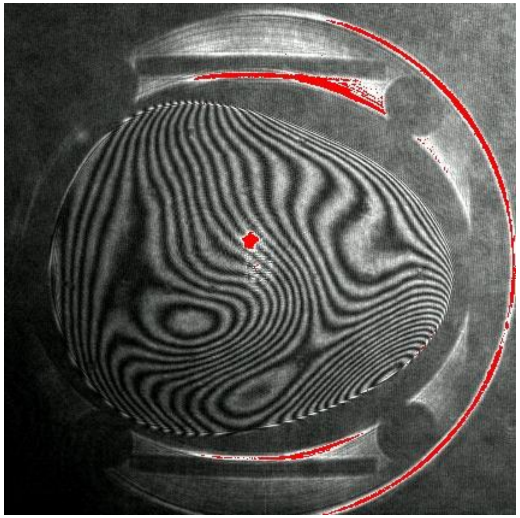
Grinding GMT

Polishing NST

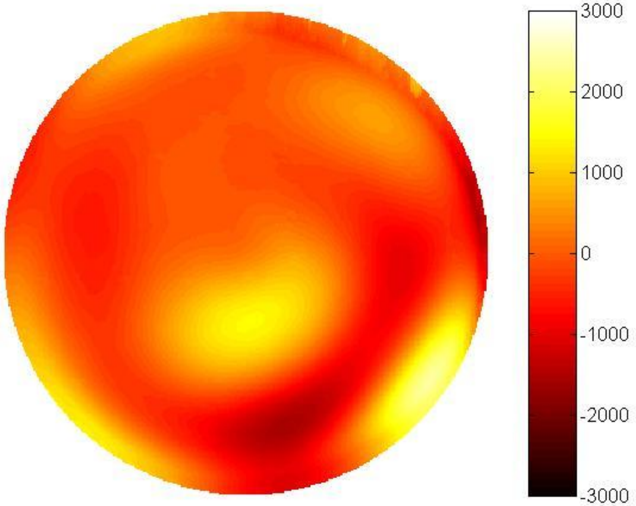
Performance of stressed lap

- NST primary was initially shaped with 5-axis NC machining
- Surface was ground polished with stressed lap, guided by only coarse metrology
- The first interferogram showed 630 nm rms irregularity, no high slopes,
- This mirror has 1400 µm aspheric departure!

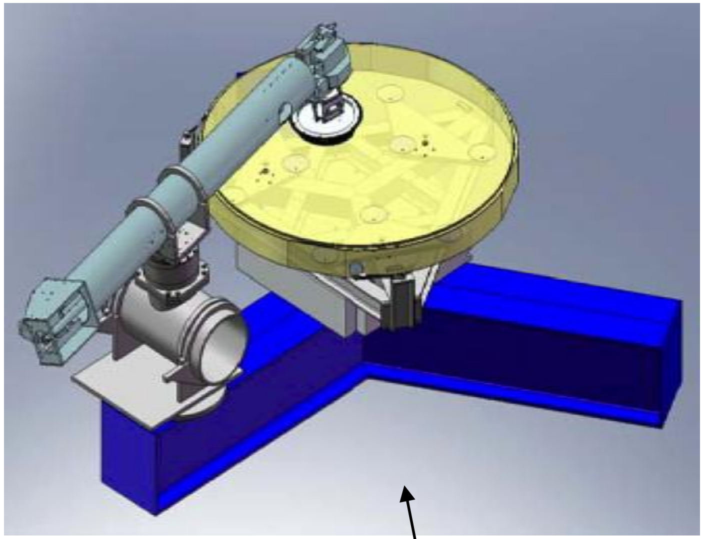
First interferogram
(Egg shaped pupil from distortion in null corrector)

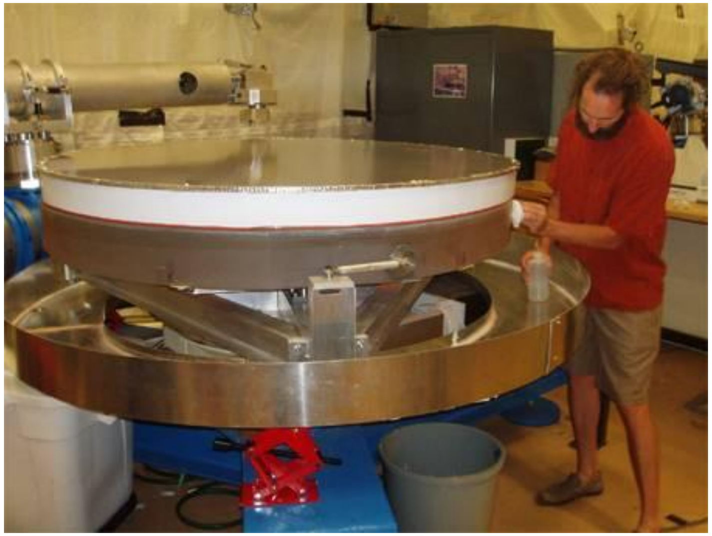


First surface map
After correction of distortion



Computer controlled polishing in Arizona

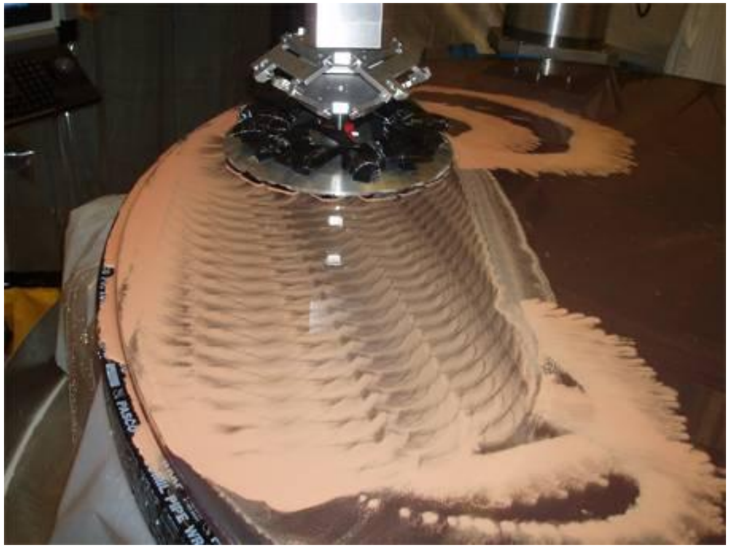




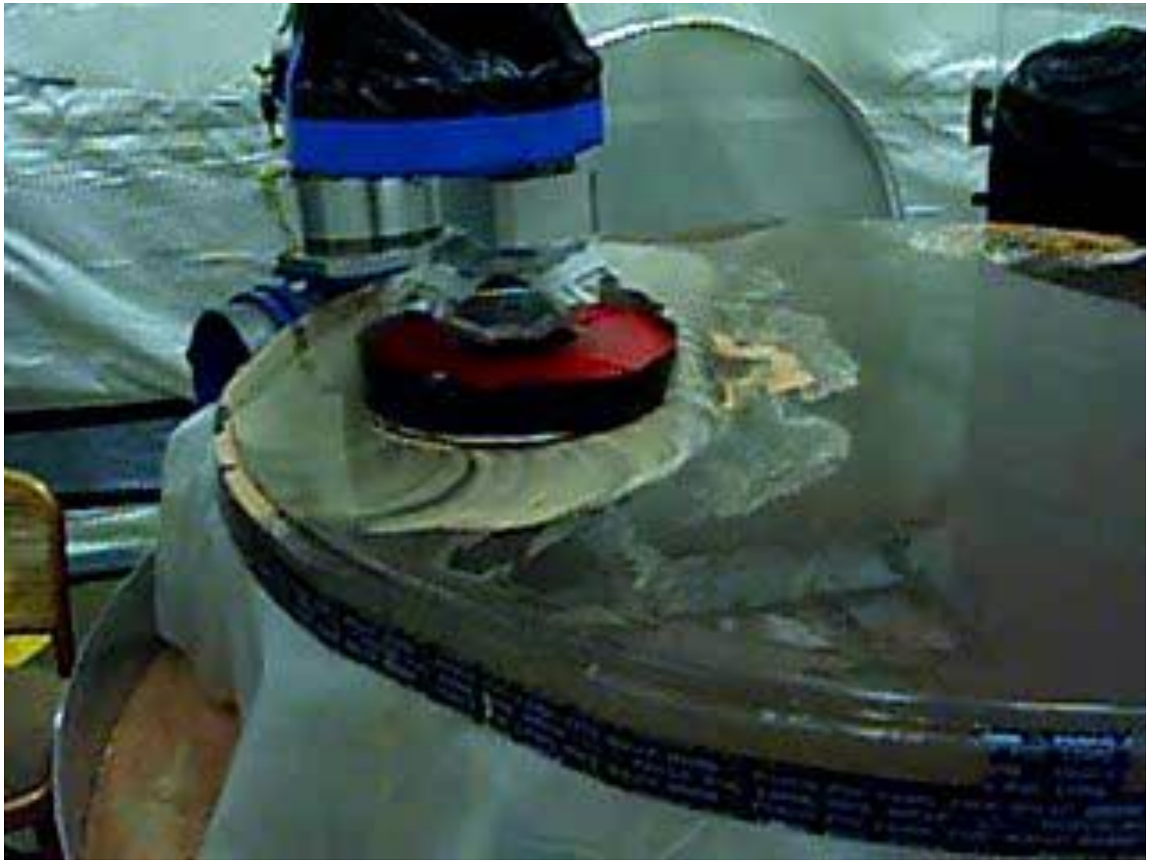
UA Swingarm computer controlled polisher

Mounting OAP onto CCP

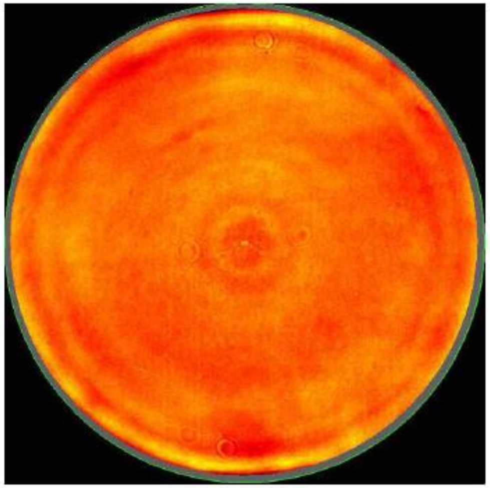
CCP in operation



UA polisher



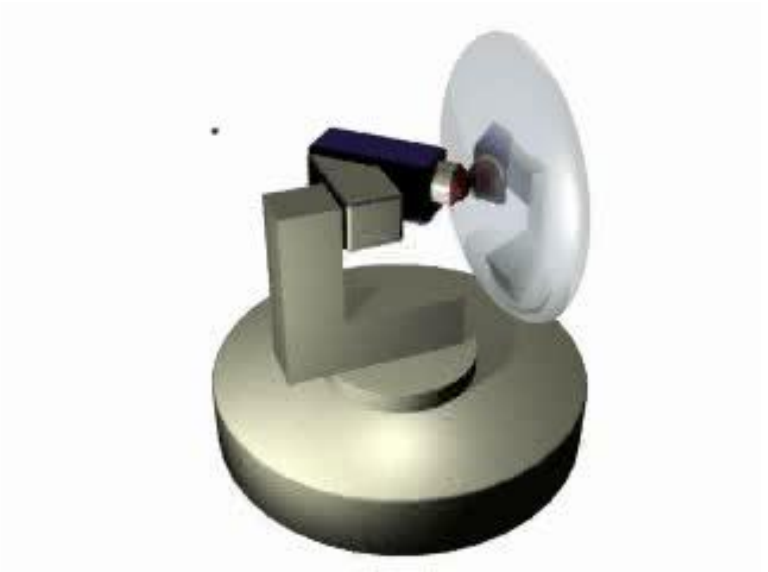
3.1 nm RMS



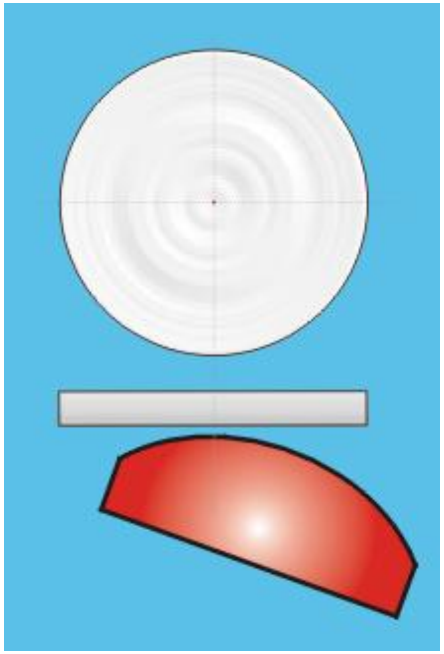
(red – low, yellow – high   on ± 25 nm scale)

Zeeko "Precessions"

- Uses inflated bonnet with polishing cloth
- 5-axis NC control



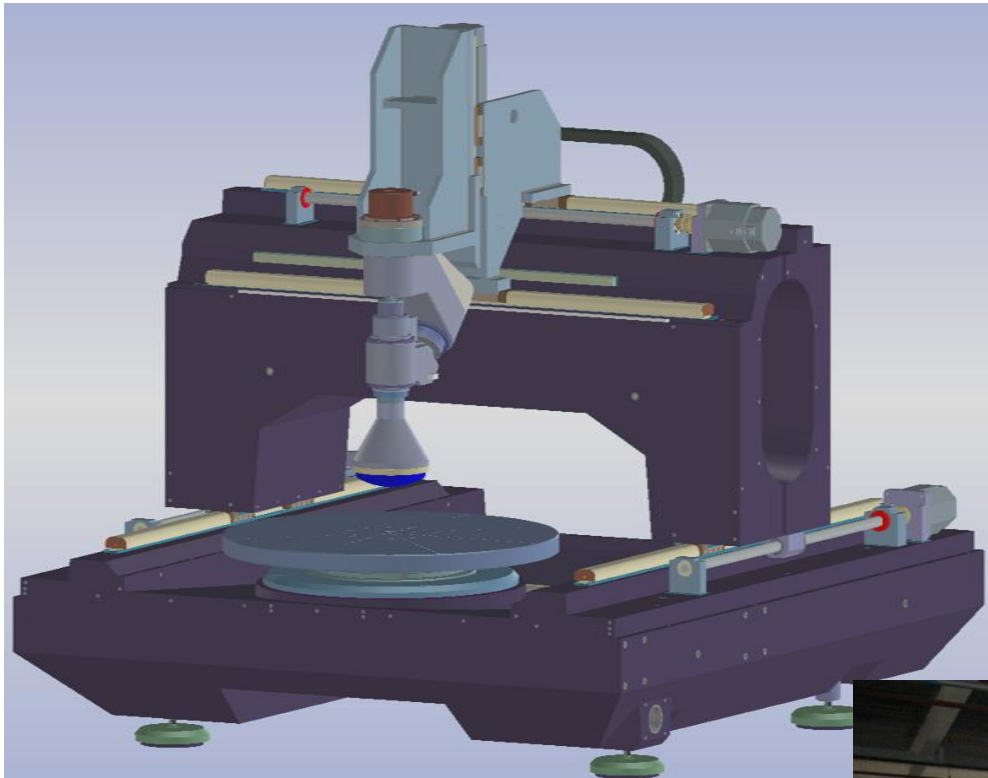
Video: Zeeko.mpg



Video: Bonnet…

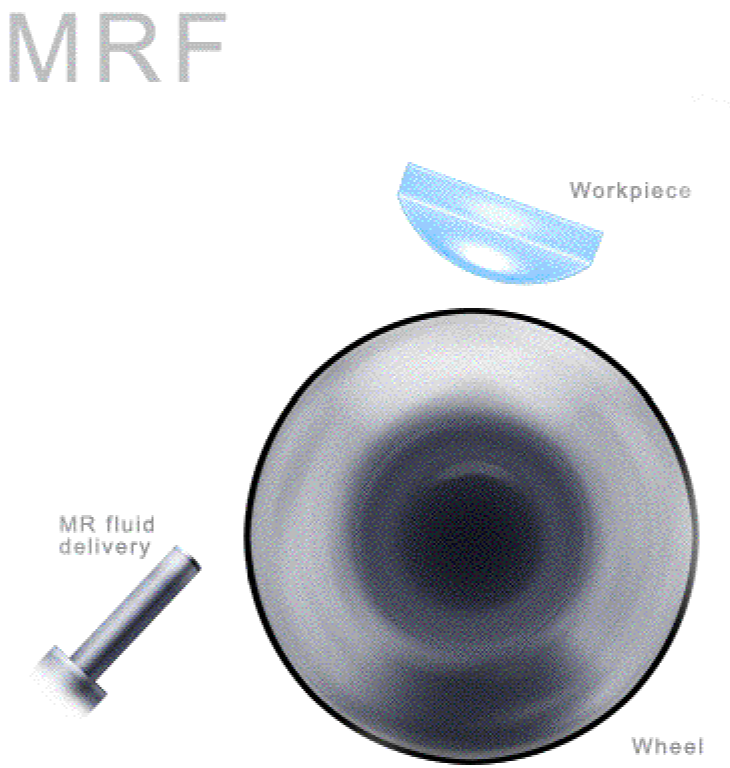
- Video : Zeeko ellipsoid polish

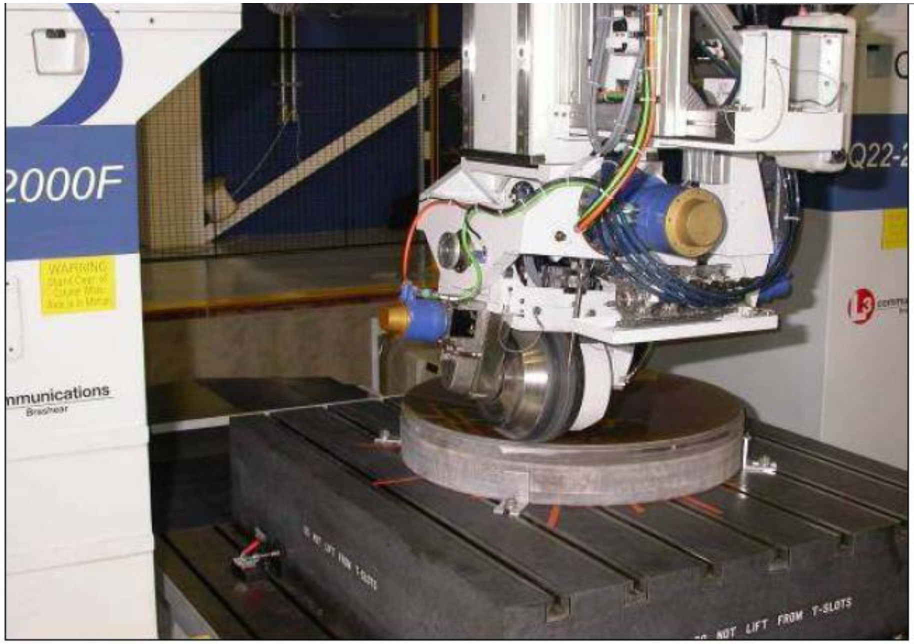
Zeeko IRP1200 (1.2-m)



Zeeko is developing IRP2400

MRF from QED Technologies

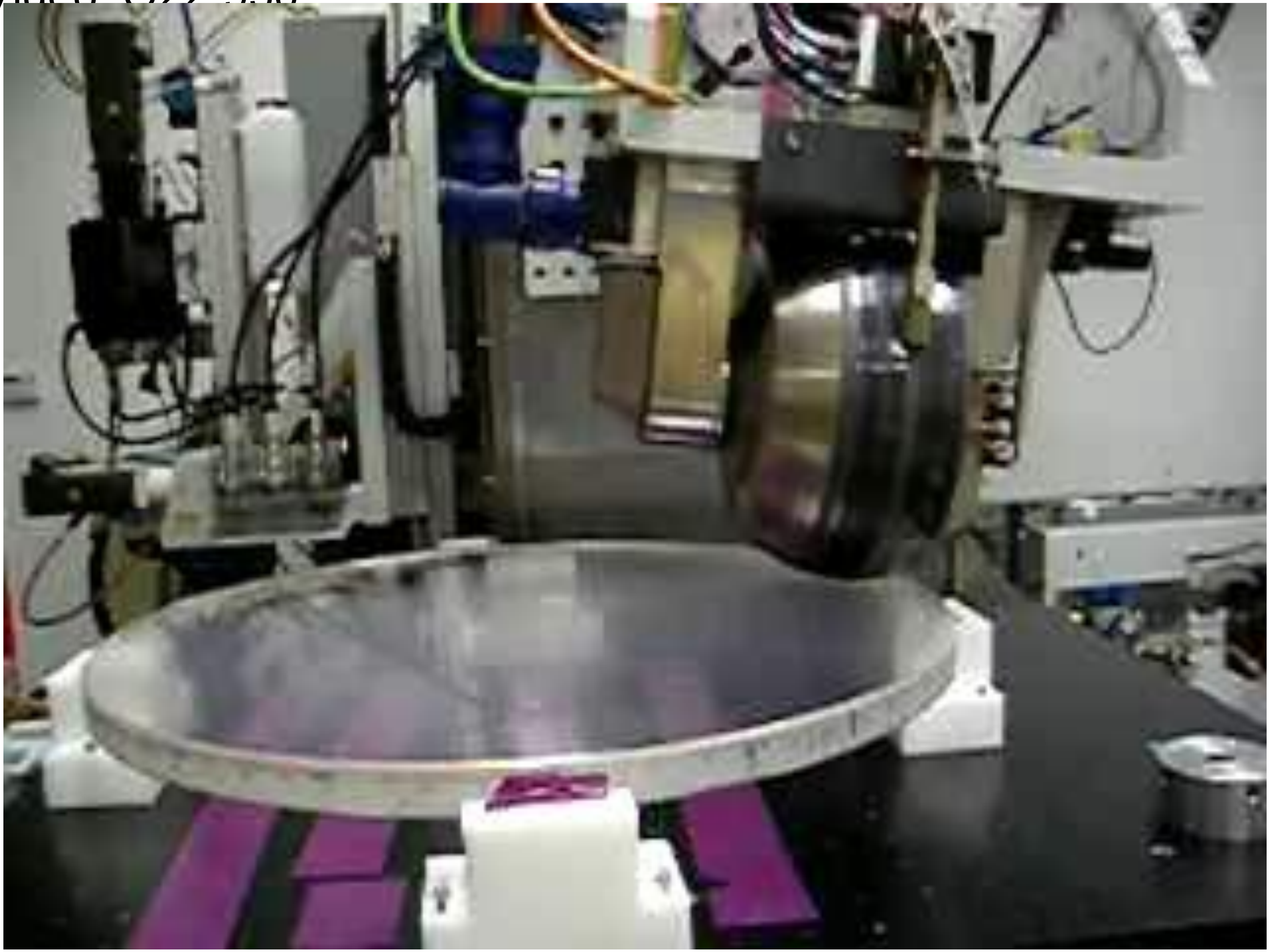




Material removal via shear motion of special fluid

5-axis CNC to control removal on optical surface

- Video: O22-950



QED Technologies

Family of QED Machines

- **Q22-XE**: <100 mm in diameter.
- **Q22-X**: Up to 200 mm in diameter.
- **Q22-Y**: Raster tool path, up to 200 mm in size.
- **Q22-400X**: Up to 400 mm in diameter.
- **Q22-750P2:** Plano optics up to 750 mm x 1,000 mm in size.
- **Q22-950F-Polishing Center:** Freeform optics up to 950 x 1,250mm with pre-polishing capabilities
- **Q22-2000F:** Freeform optics up to 2+ meters
- **SSI-A®:** mild aspheres metrology without null lenses
- **ASI™:** high-departure aspheres metrology

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QED Technologies

Q22-2000F MRF® Polishing Center

- Optics up to 2.4 m in diameter
- Round, Rectangular, Hexagonal apertures
- Plano, sphere, asphere, freeform
- Precise figuring
- Fast convergence

Q22-2000F MRF Polishing Center at Brashear

Integrated Optical Systems – Brashear

Polishing Technologies

- Multiple solutions exist
- All have demonstrated excellent performance
- Efficiency depends on
  - Volume removal rates
  - Reliability of polishing influence function
  - Use of natural smoothing
- Accuracy depends mostly on the measurements

Measurements of freeform aspheres

- Coordinate measuring machines: can measure *anything*
- Interferometry
  - No commercial solutions for general 1-m class parts
  - Concave parts with modest aspheric departure can be measured with null correctors (computer generated holograms)
- Developments at University of Arizona
  - Metrology for GMT segments
    - The challenge of a lifetime
  - Metrology developed for large convex off axis aspheres
    - Applicable for wide class of aspheres

Coordinate measuring machines

Measures any shape

Accuracy of ~ 1 µm is typical

Limited by data point density, measurement time

Leitz *Infinity*

measuring volume of 1200 x 1000 x 700mm

Accuracy 0.3 µm + 1 µm/m

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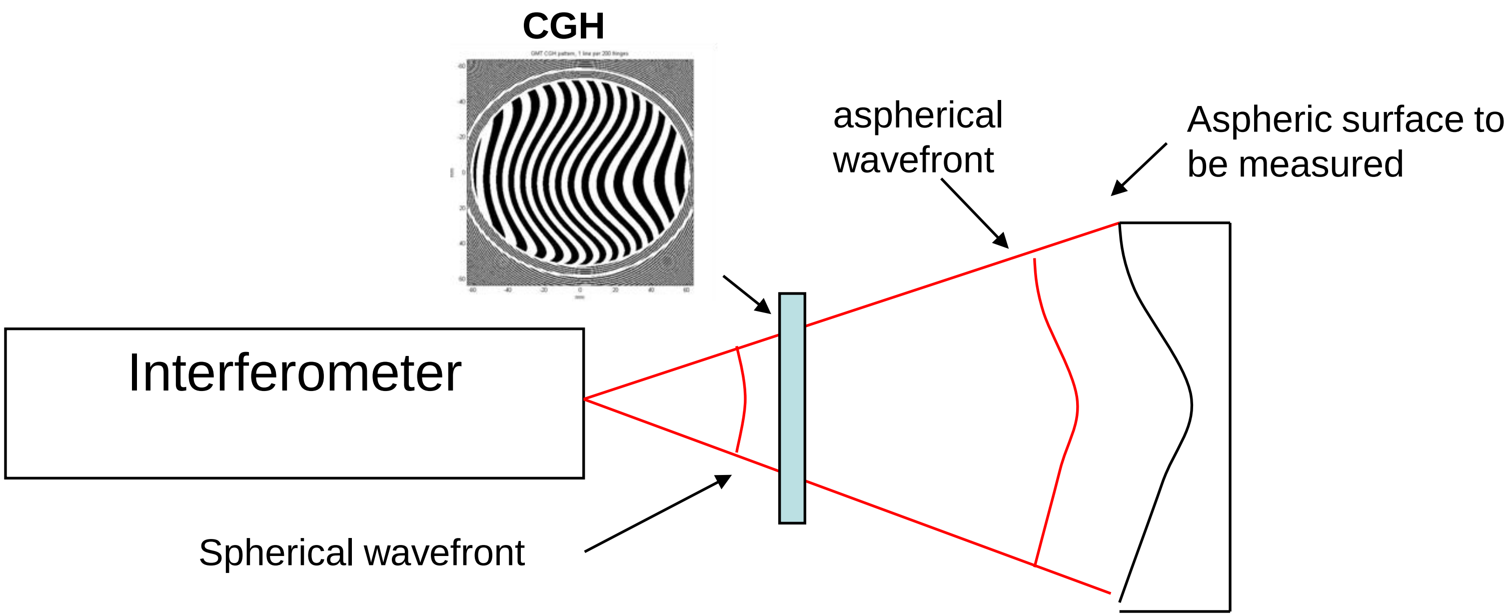
Interferometry + CGH null correctors

- Computer generated holograms use diffraction to modify spherical wavefront from interferometer into a shape that matches the asphere – no symmetry required
- CGHs fabricated using writing technology for IC reticles
- Alignment features are incorporated into the CGH
- Limitations:
  - Center of curvature must be accessible
    - Concave surfaces with < 30 m ROC
  - Amount of aspheric correction limited to ~2000 waves.

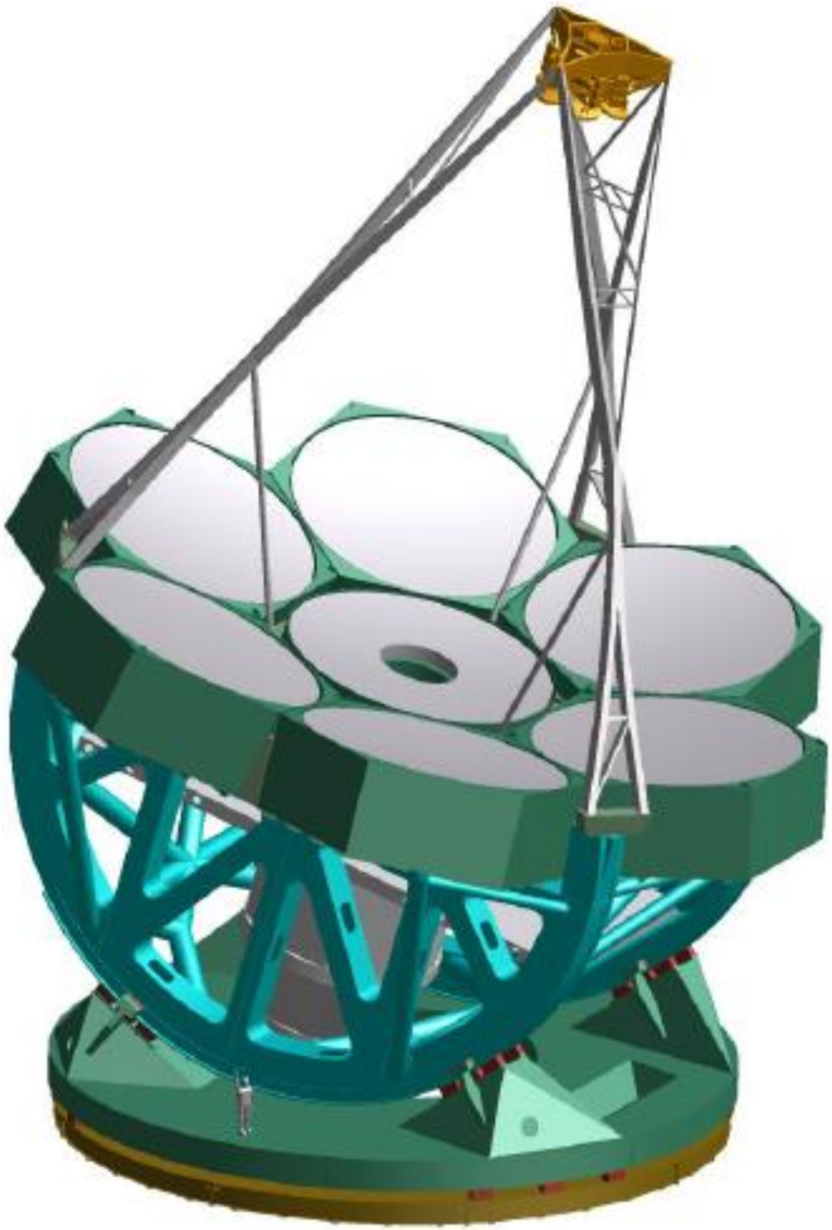


Extreme freeform aspheres at UA

Testing challenges and solutions for two extreme aspheres

- Giant Magellan Telescope primary mirror segment
  - 8.4-m diameter
  - 14.5 mm aspheric departure
  - 36 m radius of curvature
- Off axis convex aspheres
  - Off axis parabolic surfaces
  - Convex, 1.4-m in diameter
  - 300 um aspheric departure

The Giant Magellan Telescope



25-m aplanatic Gregorian

Primary mirror

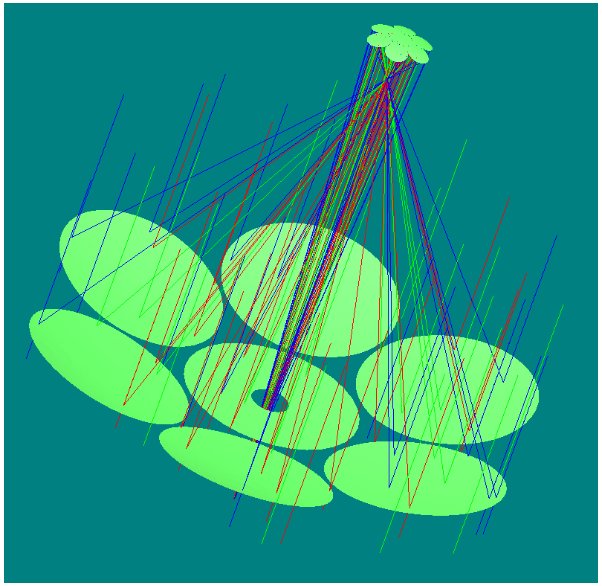
f/0.7 near-paraboloid

Made from 8.4-m segments

Secondary mirror

Ellipsoid

segmented like primary

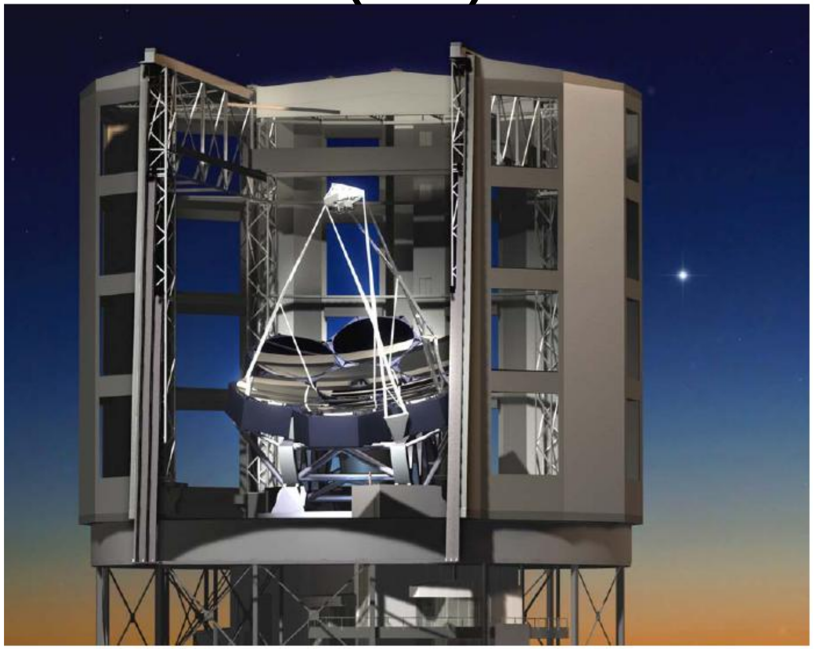


The University of Arizona
Tucson Arizona

Large Binocular Telescope

LBT 2 x 8.4m (2005)

GMT 7 x 8.4m (2018)



1997

Optical testing of GMT segments

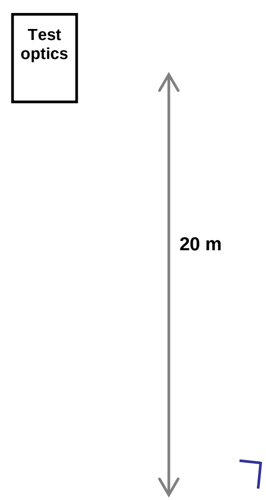
Heritage (LBT)

~1.4 mm aspheric departure

GMT

~14 mm aspheric departure

Test wavefront defined to match aspheric shape of mirror



Axisymmetric

Test optics at ~20 meters

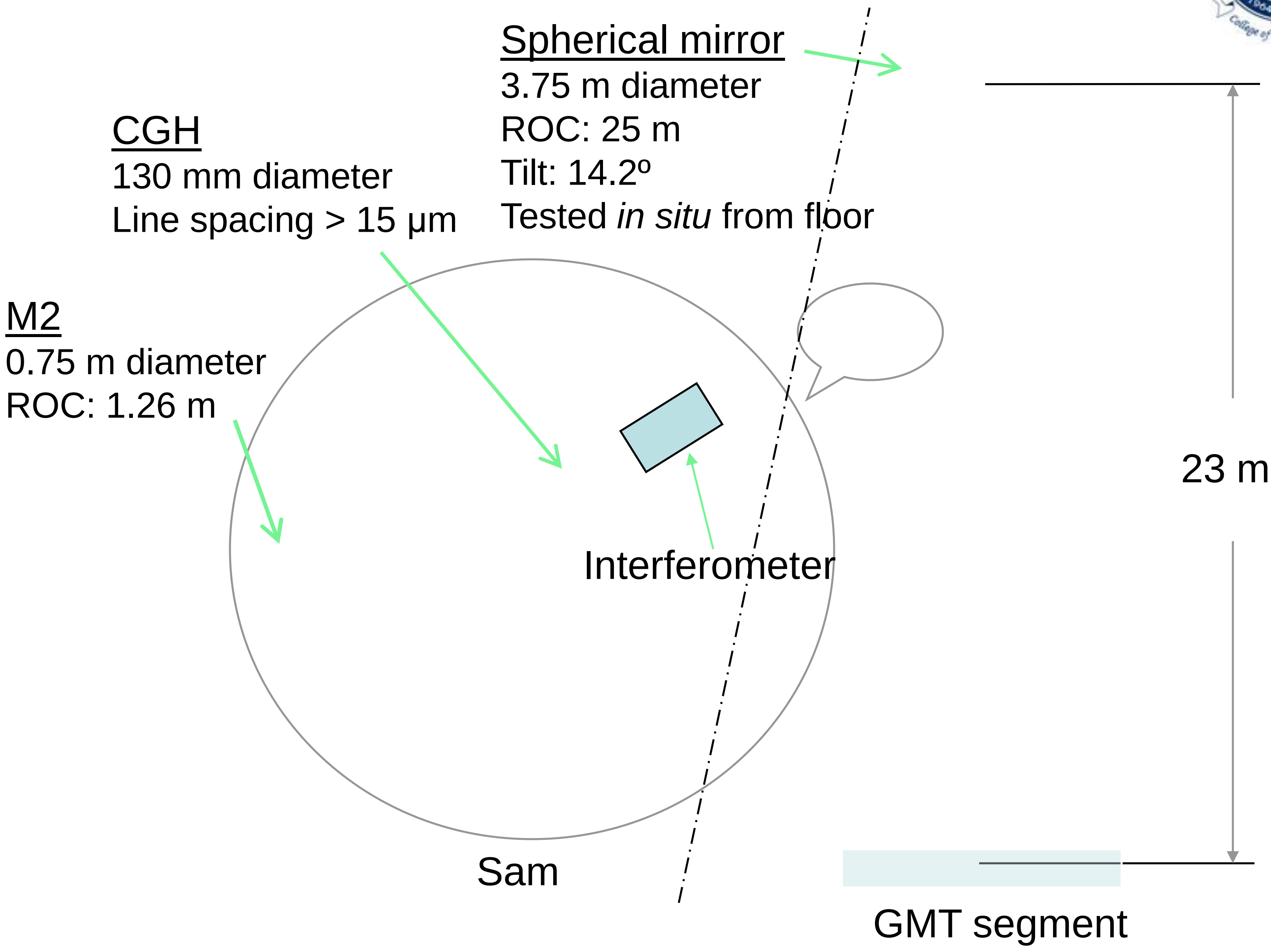
Light from optical test is only 200 mm diameter near the test optics – allows direct measurement of test system

No Axisymmetry

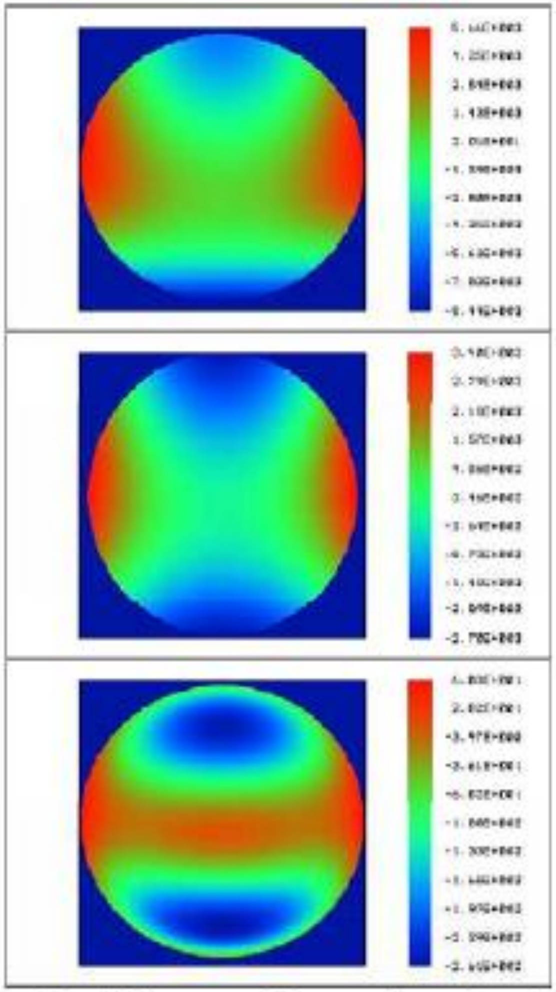
Light path defined by GMT is much larger

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

Interferometric testing for GMT



GMT testing : wavefront correction

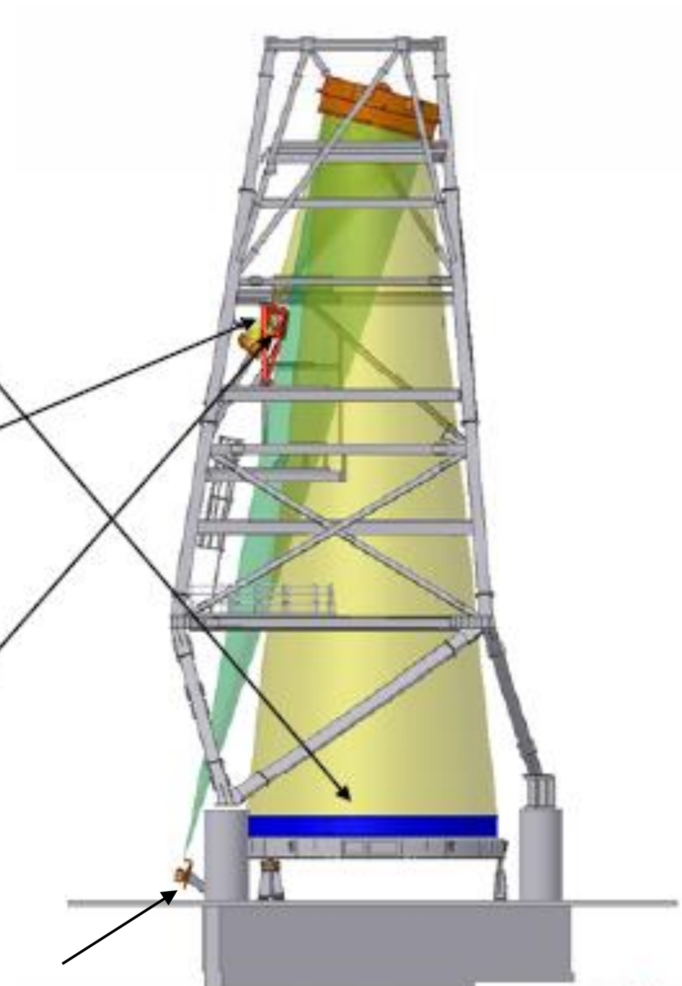


Difference from sphere (µm)

14 mm p-v at GMT surface

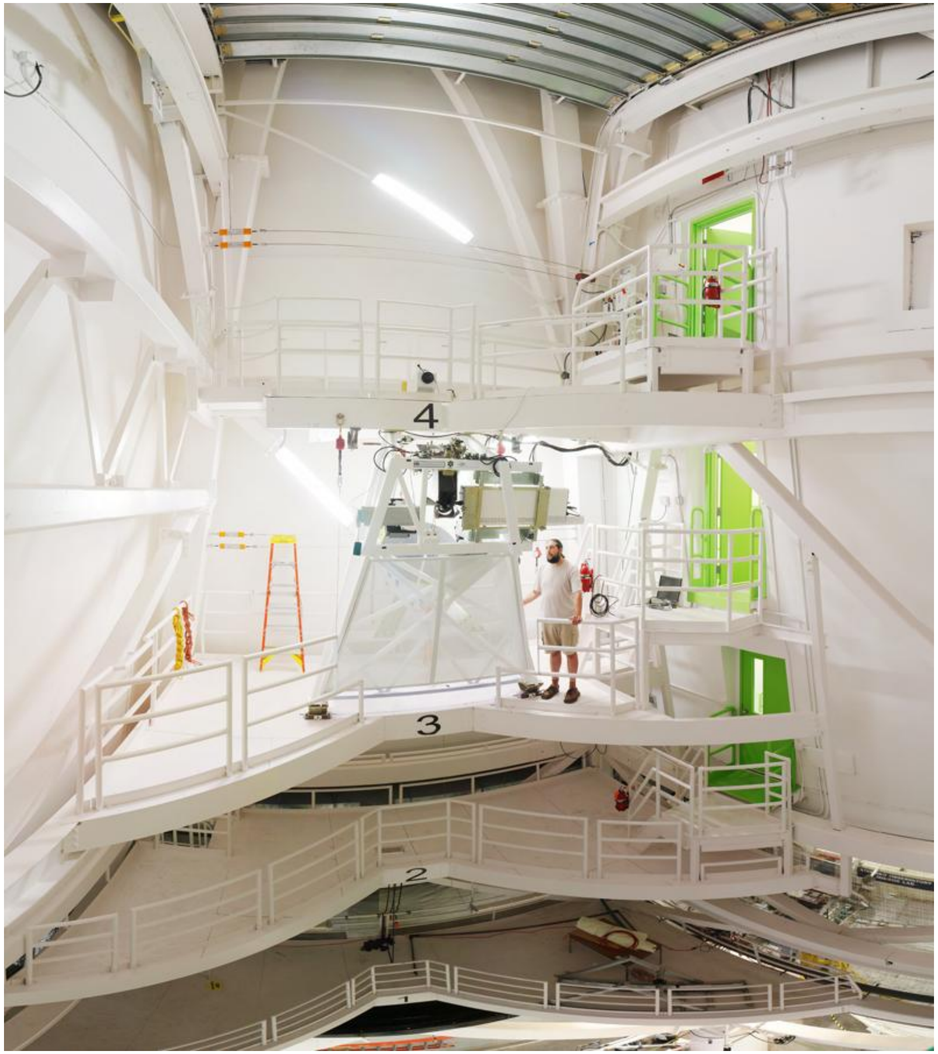
6.1 mm p-v at intermediate focus between fold spheres

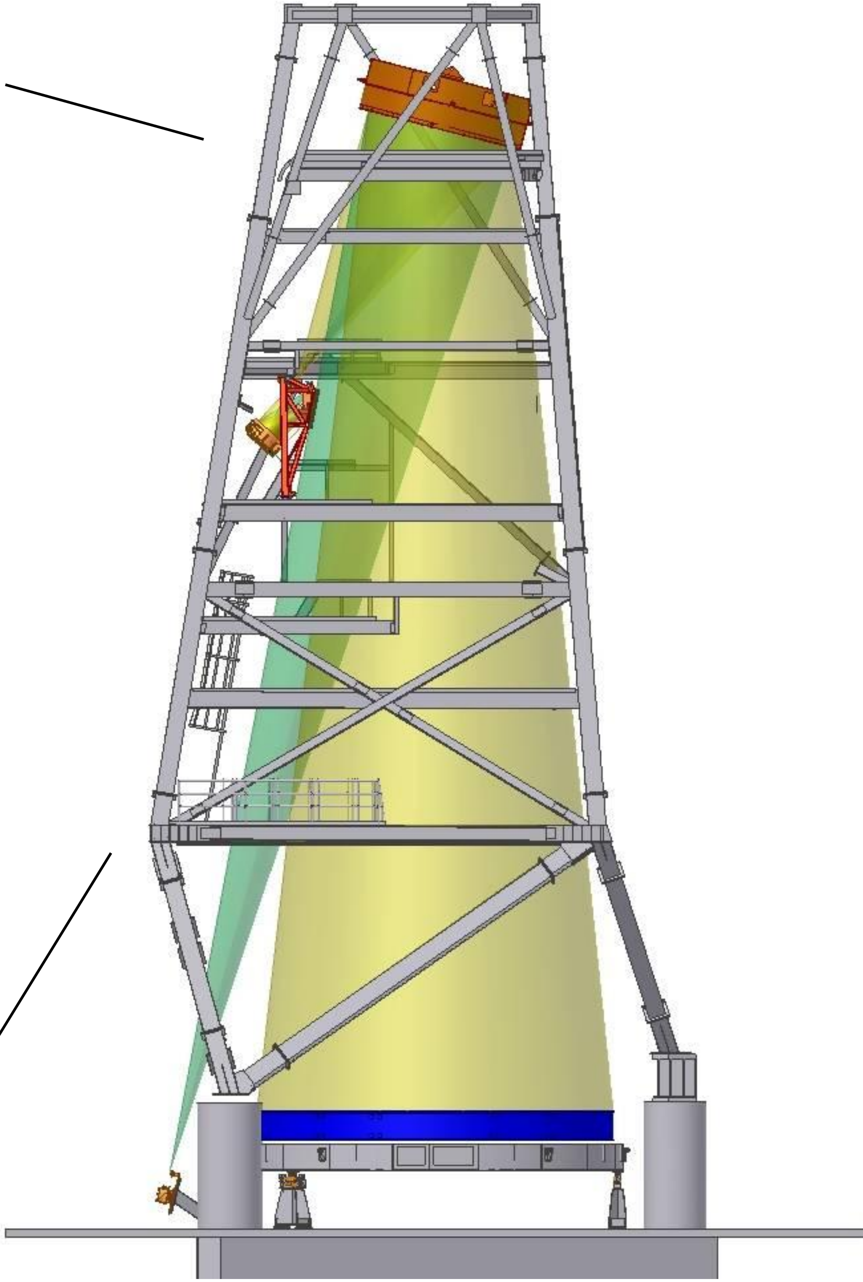
320 µm p-v between 76 cm sphere and CGH



Interferometer provides *in situ* measurement of 3.8-m mirror 26 meters away

GMT optical test





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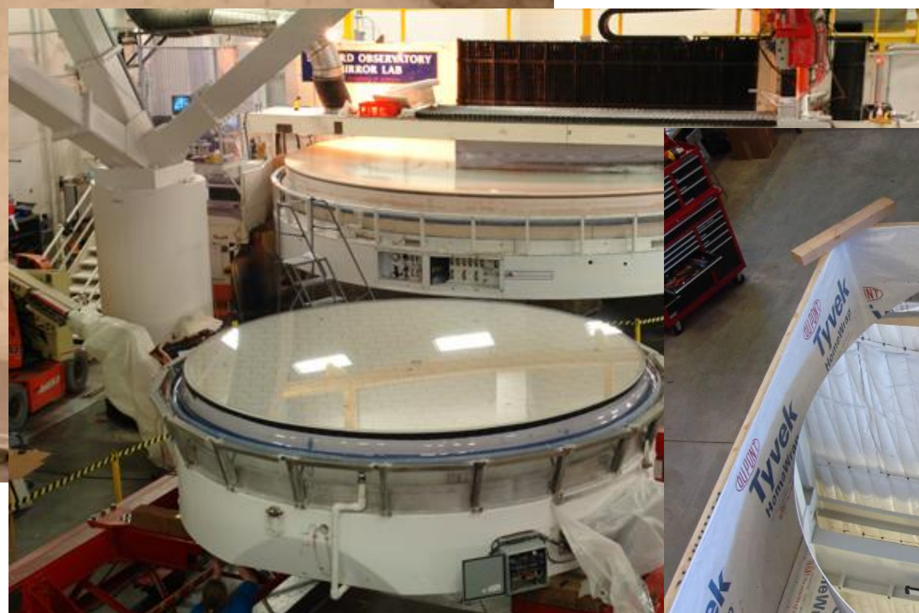
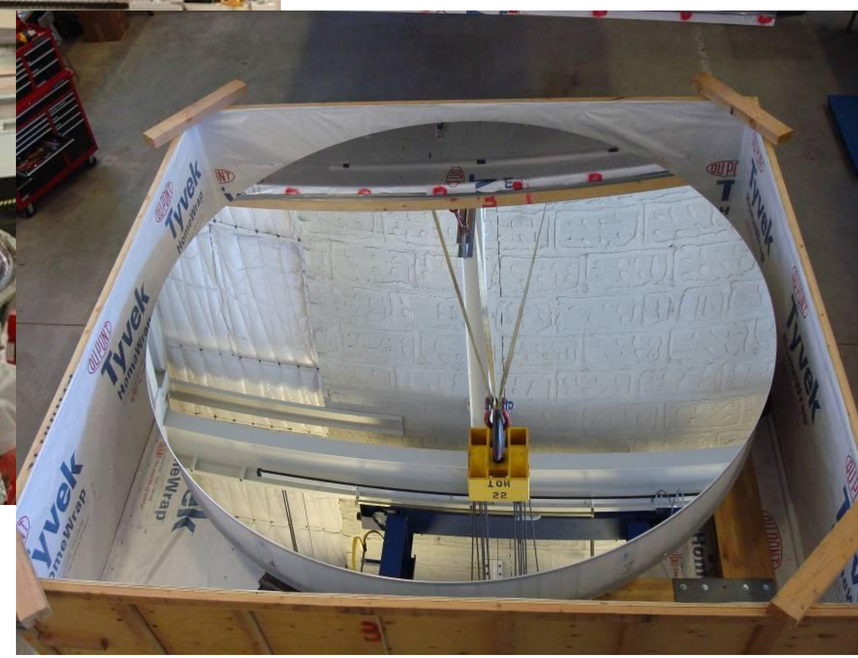
Making the 3.75 m fold sphere

Cast in the Mirror Lab
spinning oven

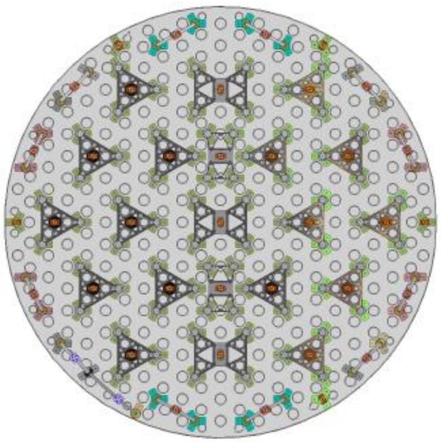


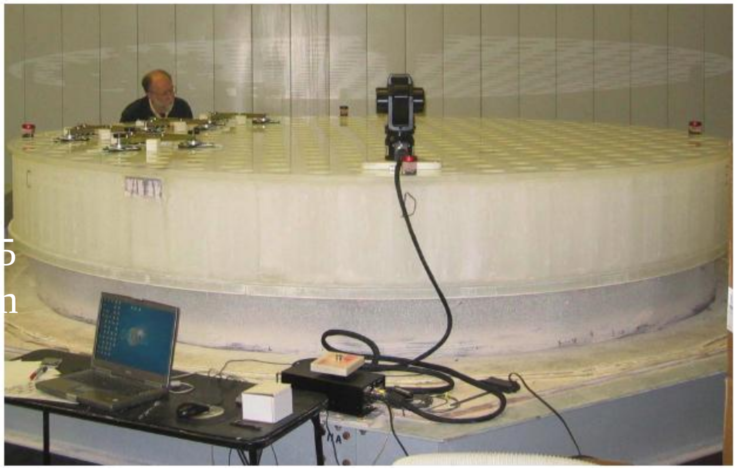
Polished at the Mirror Lab



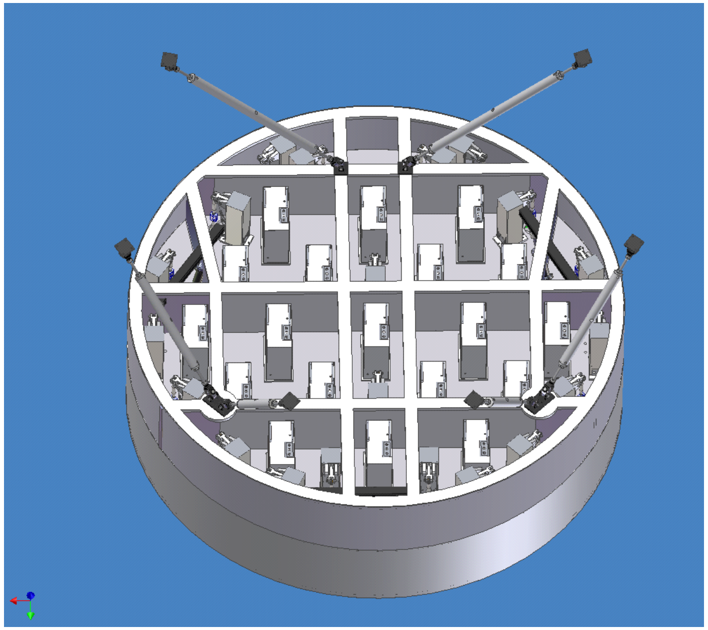
Coated at Kitt Peak

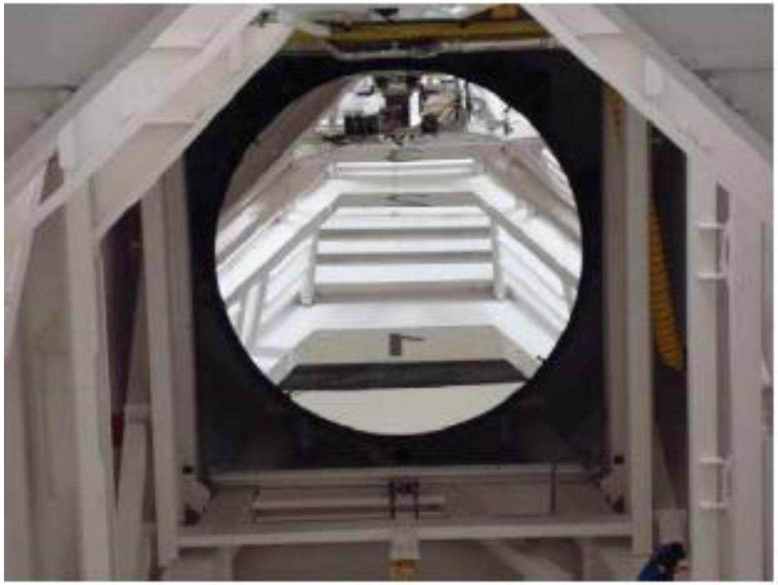
Support of 3.75-m fold sphere



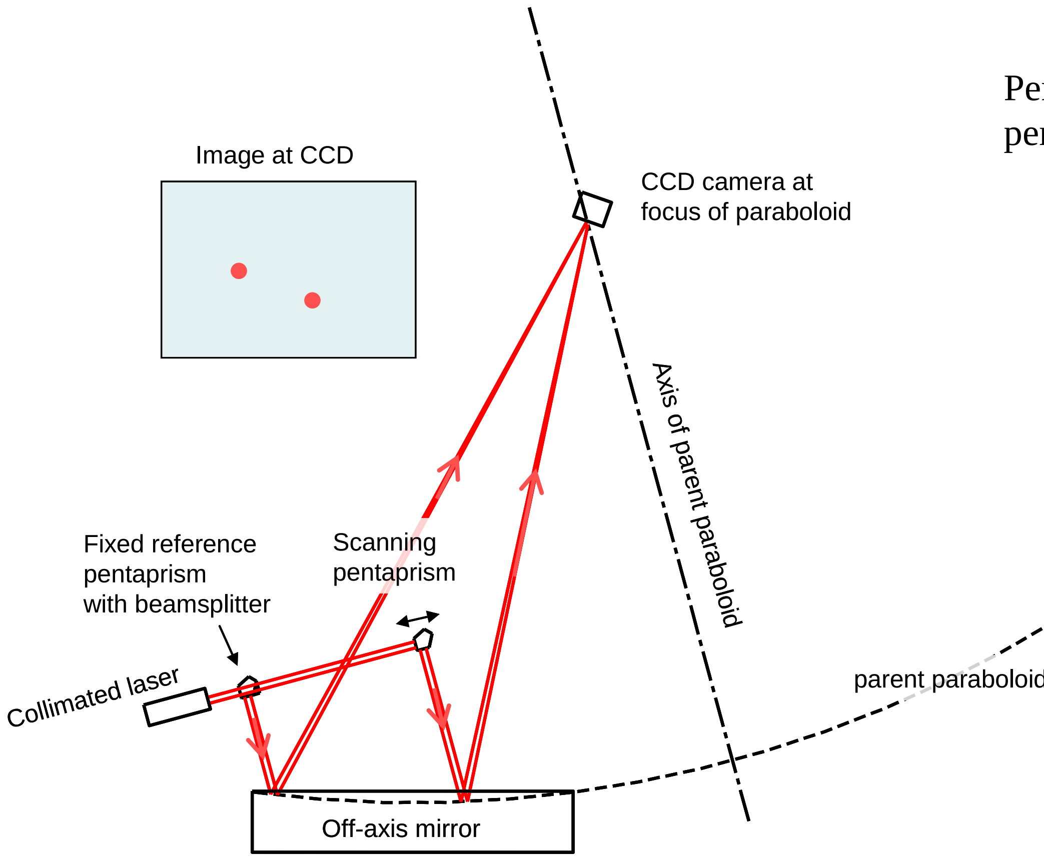


Hangs from “Active” support, allowing quasi-static force adjustment based on *in situ* measurement



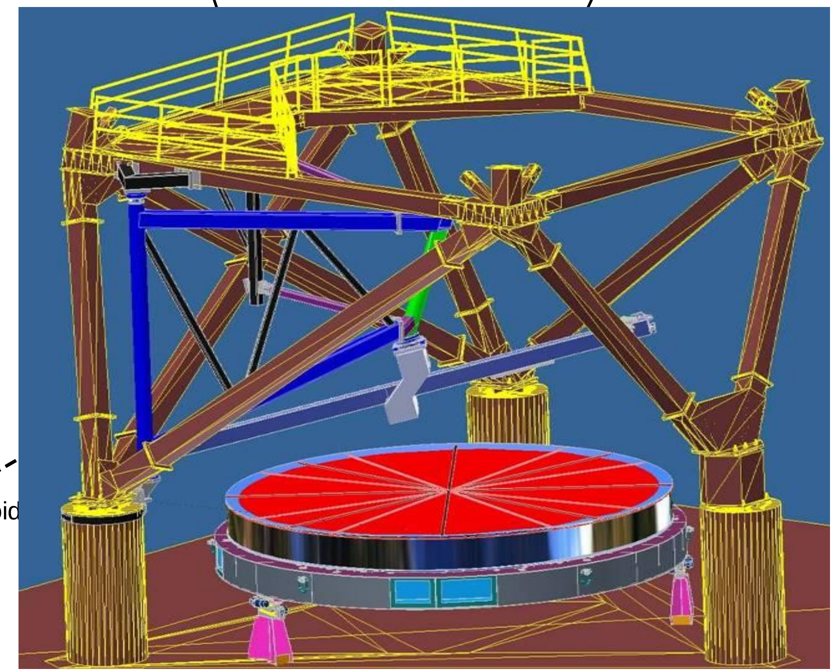


Scanning pentaprism test



Pentaprism rail lies in plane perpendicular to parent axis.

Hub rotates rail to scan different diameters.

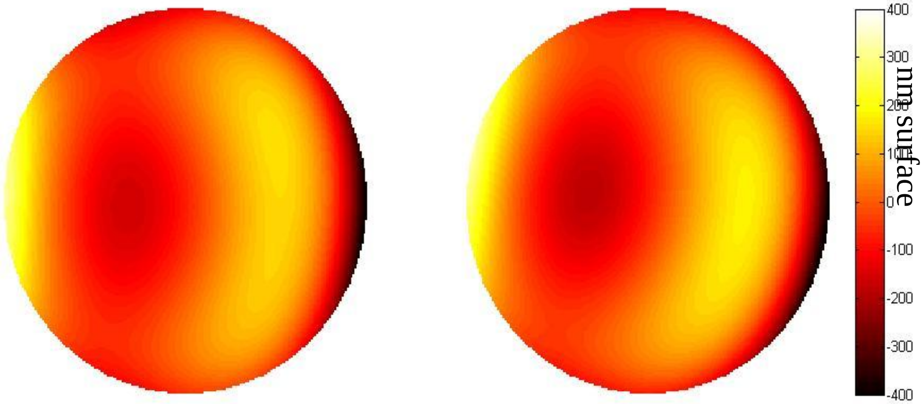


Scanning pentaprism measures slope errors by producing collimated beams parallel to parent axis. Displacement of focused spot is measured with camera in focal plane.

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

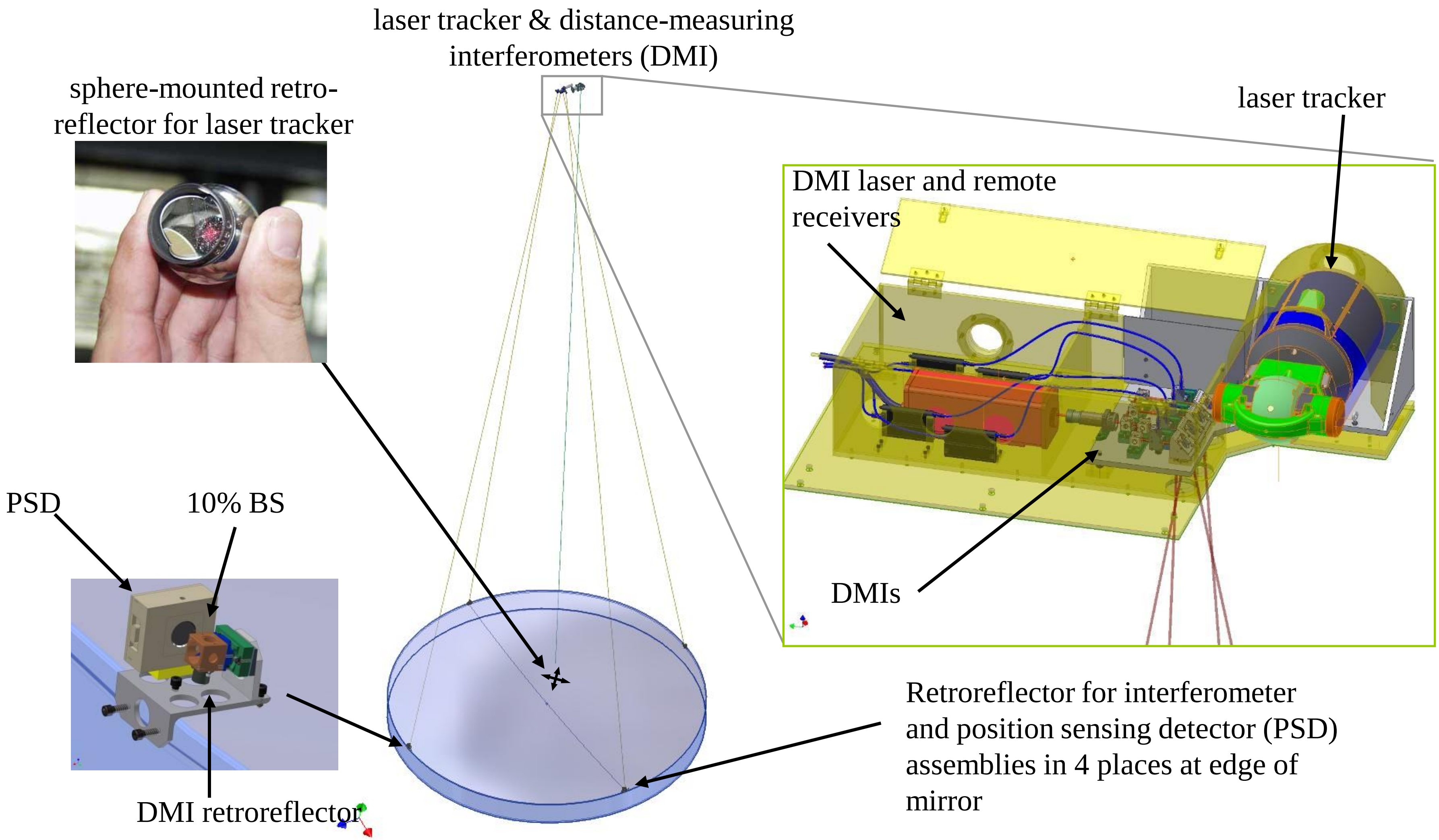
- 1/5 scale GMT pentaprism test
- This was done in late 2007 before the mirror was finished.
- The pentaprism test only samples lowest order aberrations
- The PP results agree with results from interferometry to a few nm



interferometric test

pentaprism measurement

Laser Tracker Plus



Accuracy of < 0.5 um demonstrated

The University of Arizona
Tucson Arizona

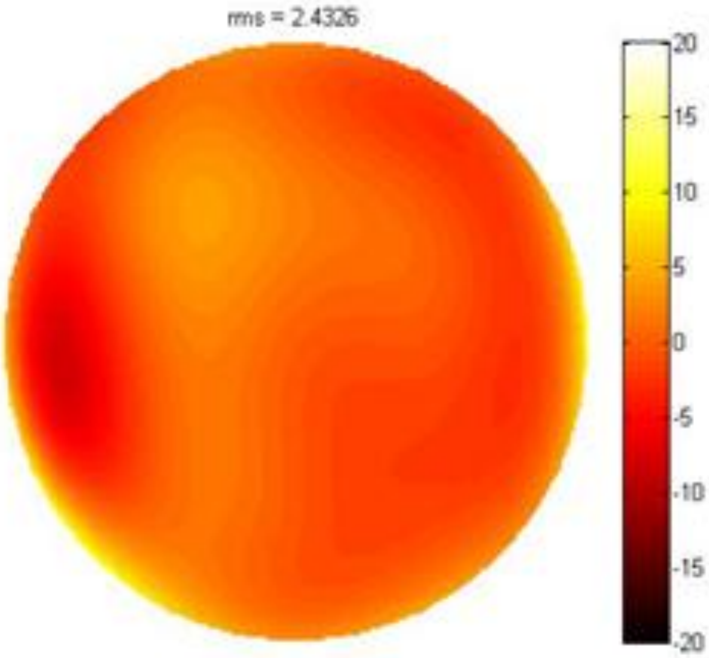
GMT status, early October 2009

Surface is polished specular

~2.4 um rms irregularity

Optical test system works, but is not yet calibrated

Expect 6 months of polishing, fussing with the test



Extreme freeform aspheres II

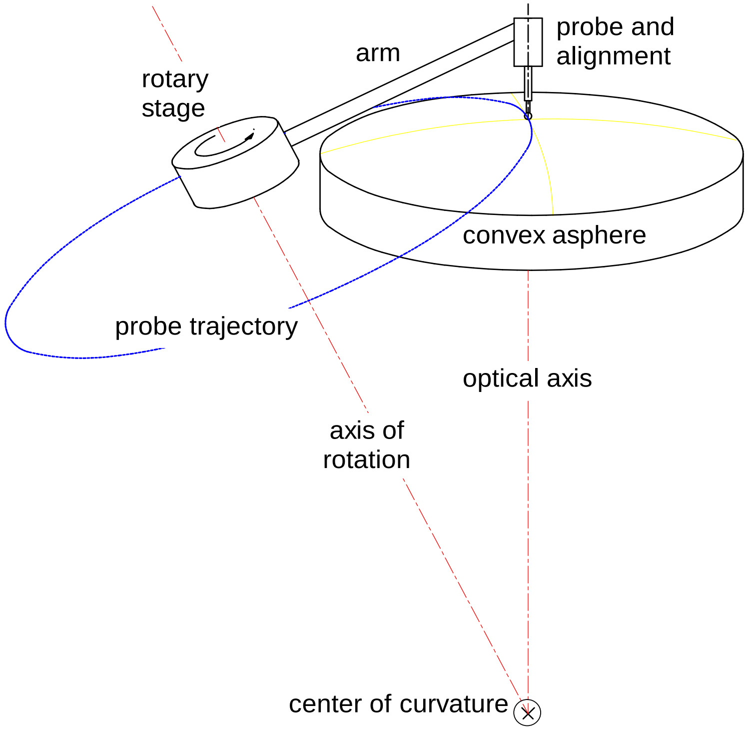
1.4-m convex off-axis aspheres

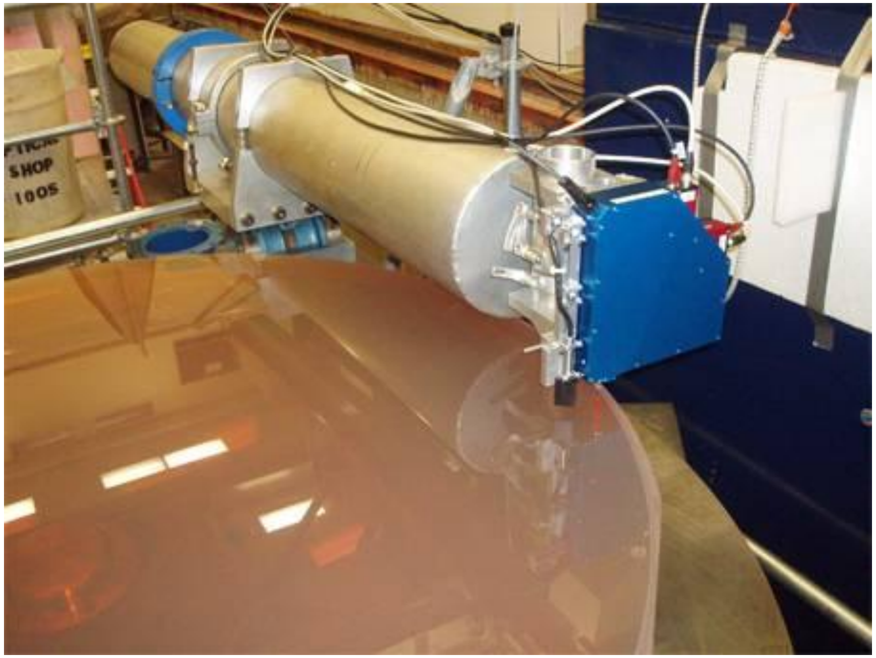
~300 µm aspheric departure

- Solid Zerodur substrates
- Surface measurements
  - In situ measurements with Swingarm Optical CMM
  - Mechanical measurement of curvature
  - Measurements with Fizeau interferometry

Swingarm Optical CMM

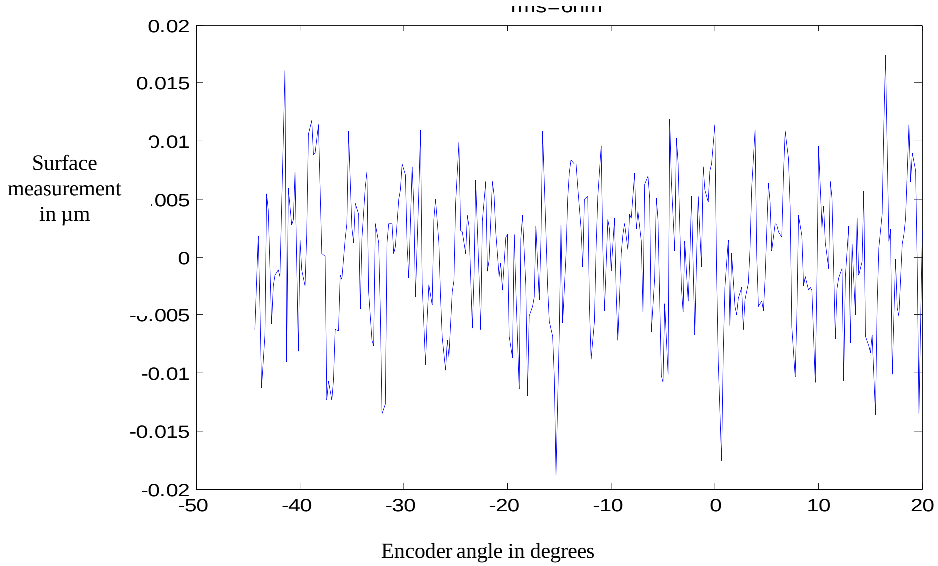
- Uses optical displacement probe
- Continuous arc scans create profiles
- Profiles stitched together to give surface maps
- *In situ* measurements on polishing machine



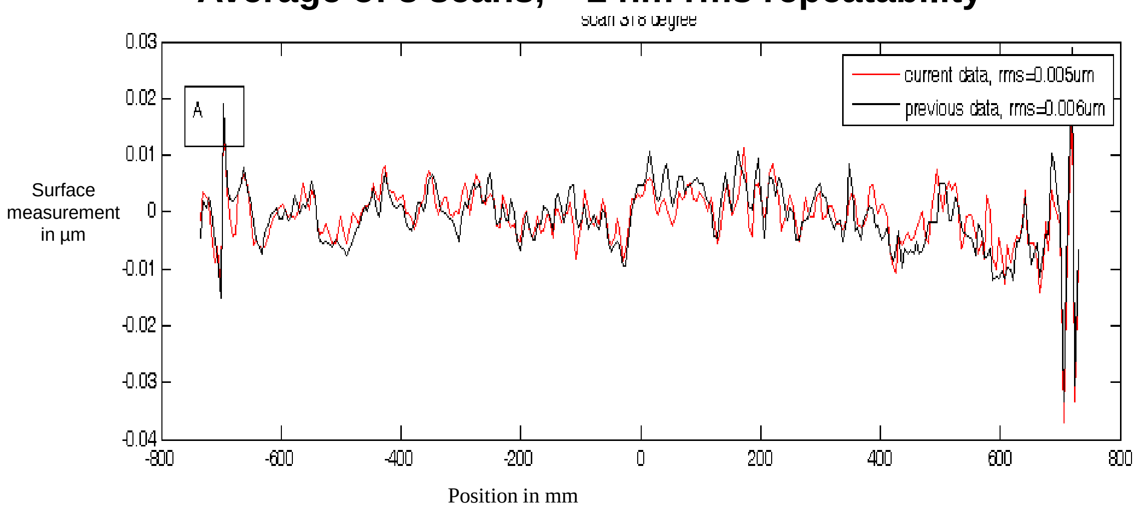


SOC performance

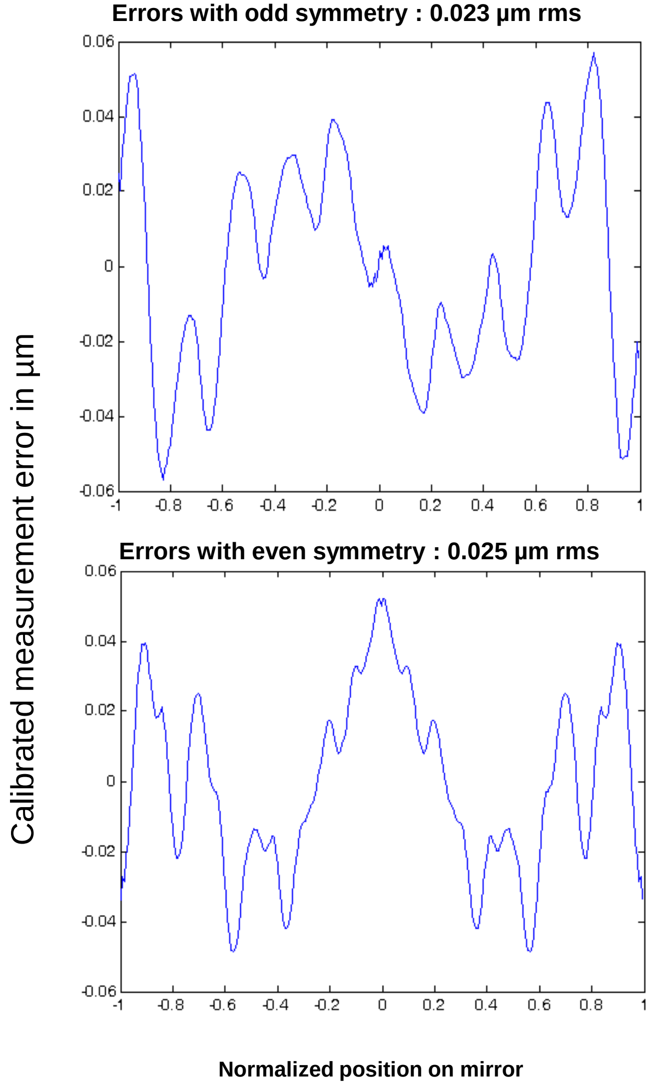
Repeatability ~ 6 nm rms/scan



Average of 8 scans, < 2 nm rms repeatability

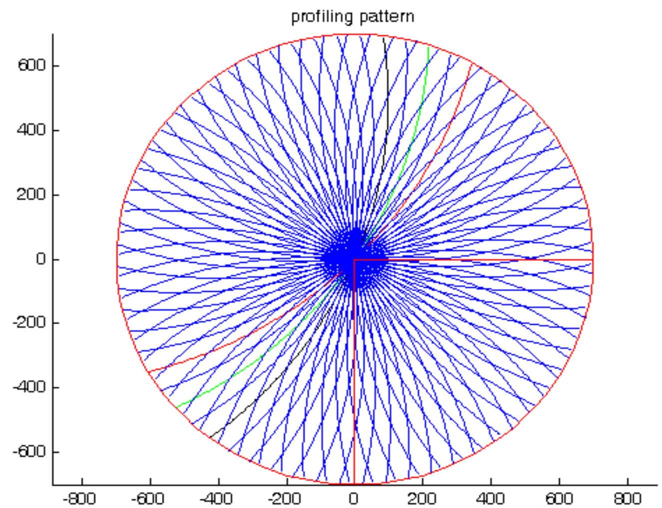


Repeatable errors calibrated to ~5 nm rms/scan

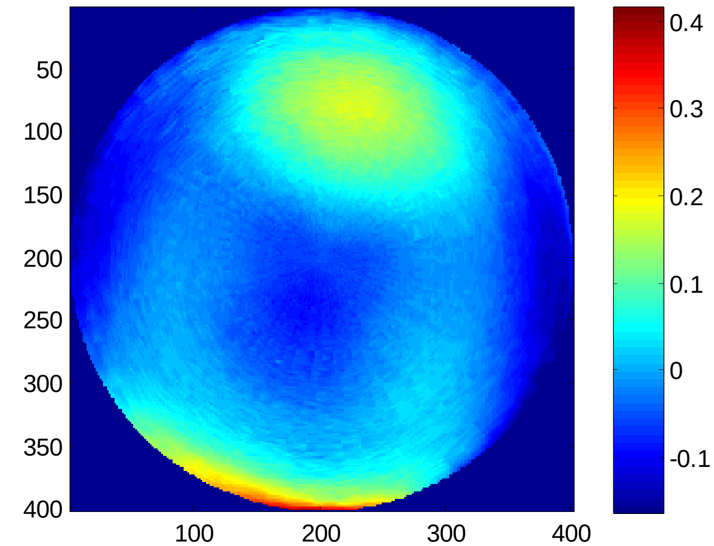


Surface maps from SOC data

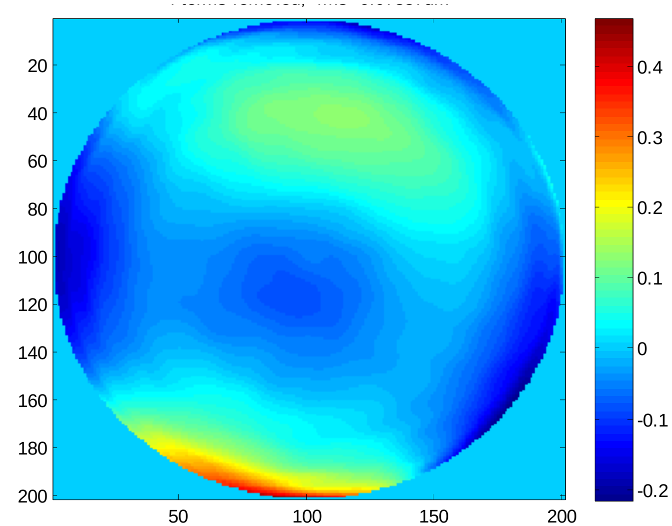
Pattern of 64 scans



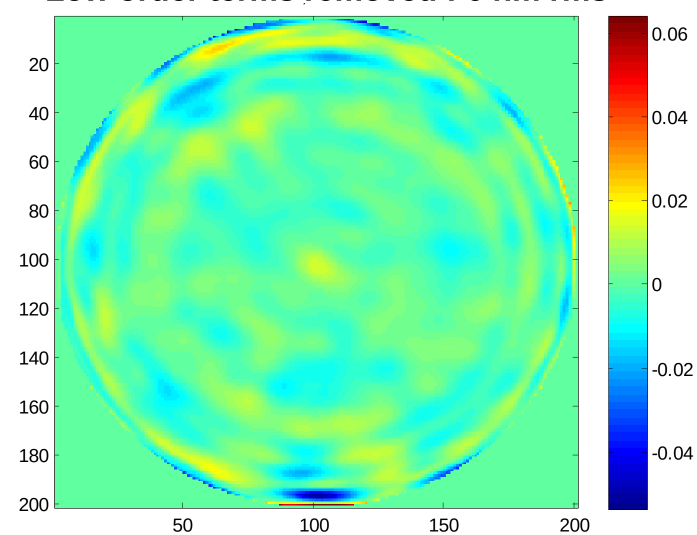
Interpolated data : 75 nm rms



896 term reconstruction : 78 nm rms

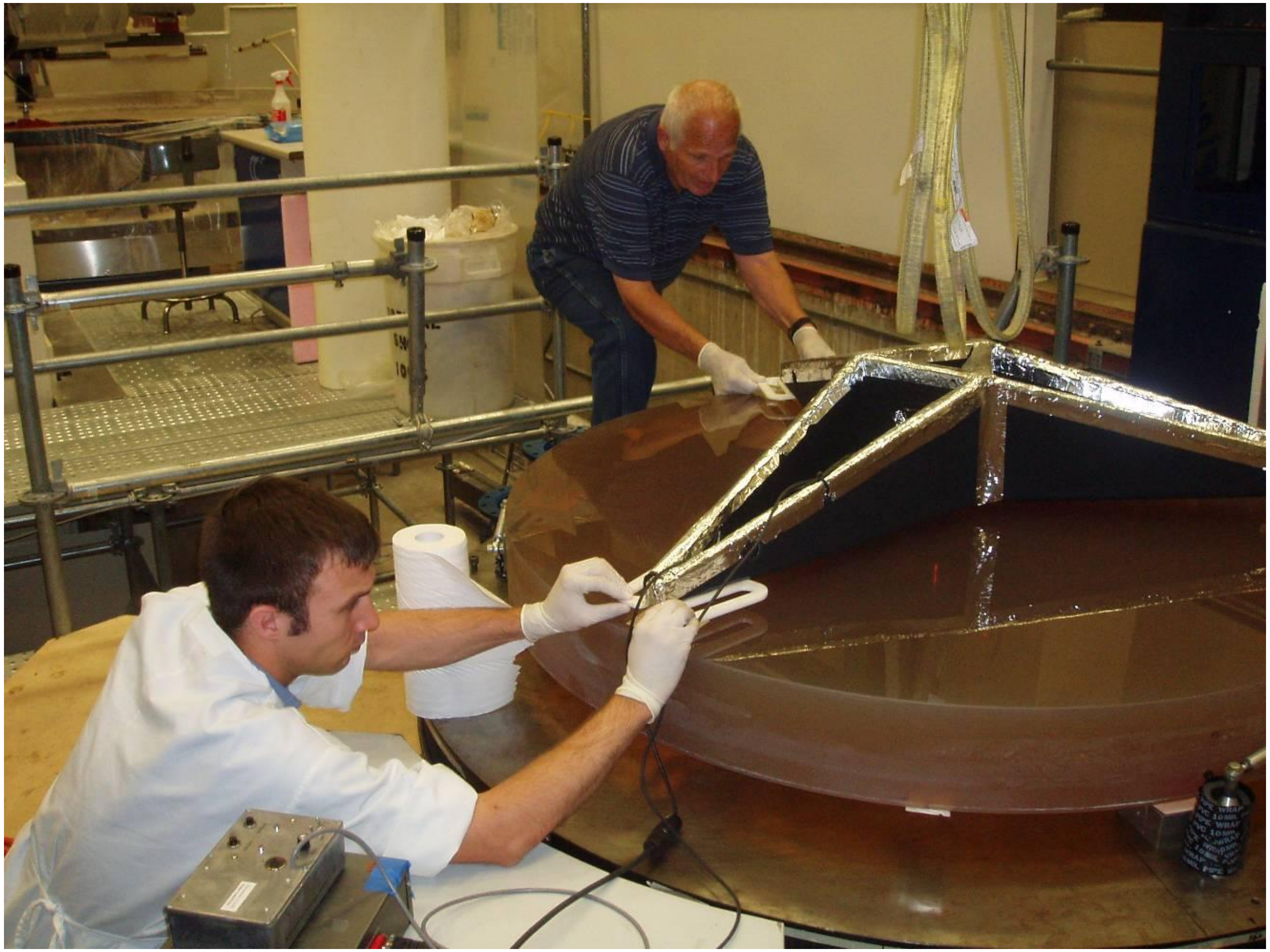


Low order terms removed : 6 nm rms

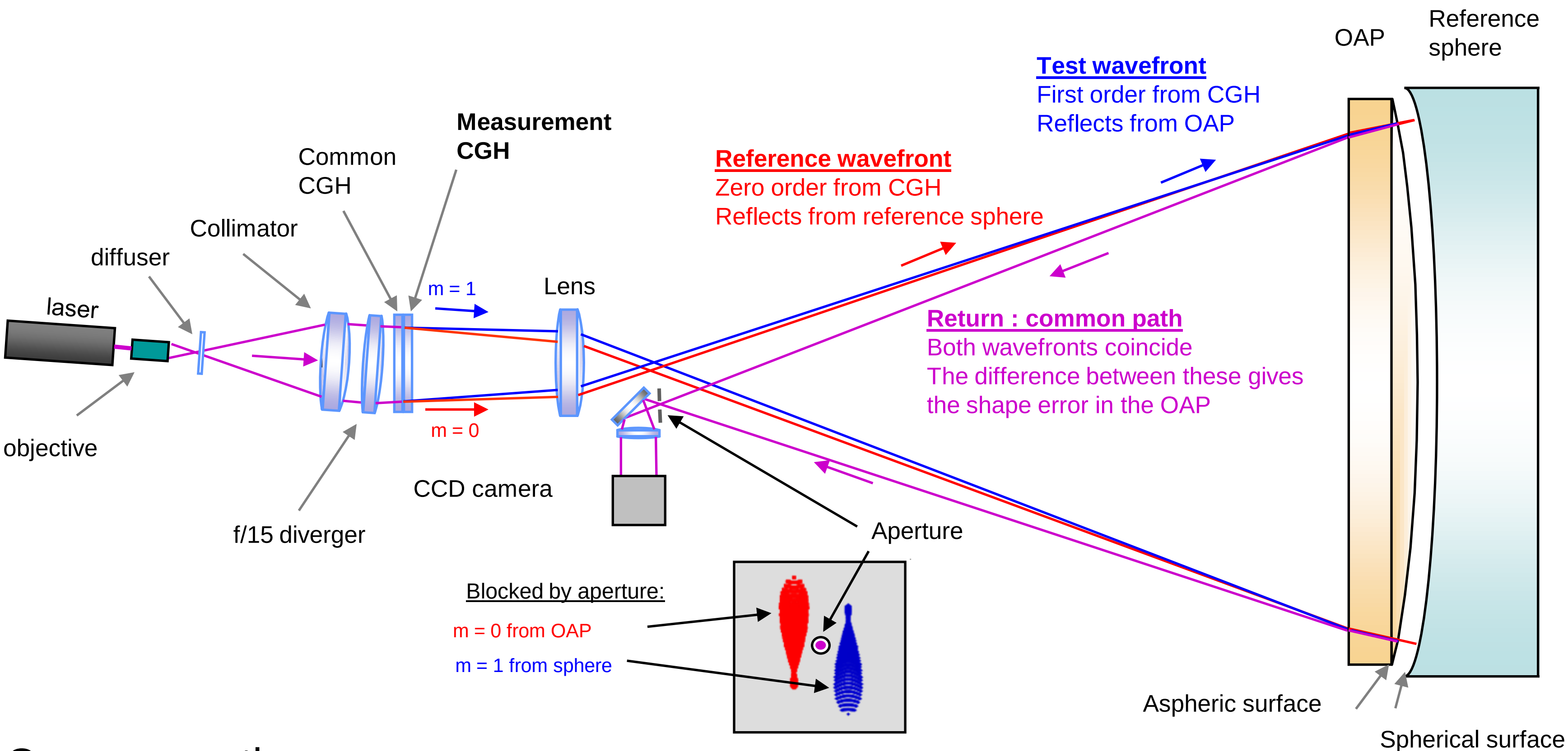


Power (ROC measurement) using spherometer

- 3-ball spherometer ~0.1 micron resolution
- Geometry carefully controlled, measure sag to < 0.3 µm



Fizeau test using a spherical reference, corrected by imaging a CGH



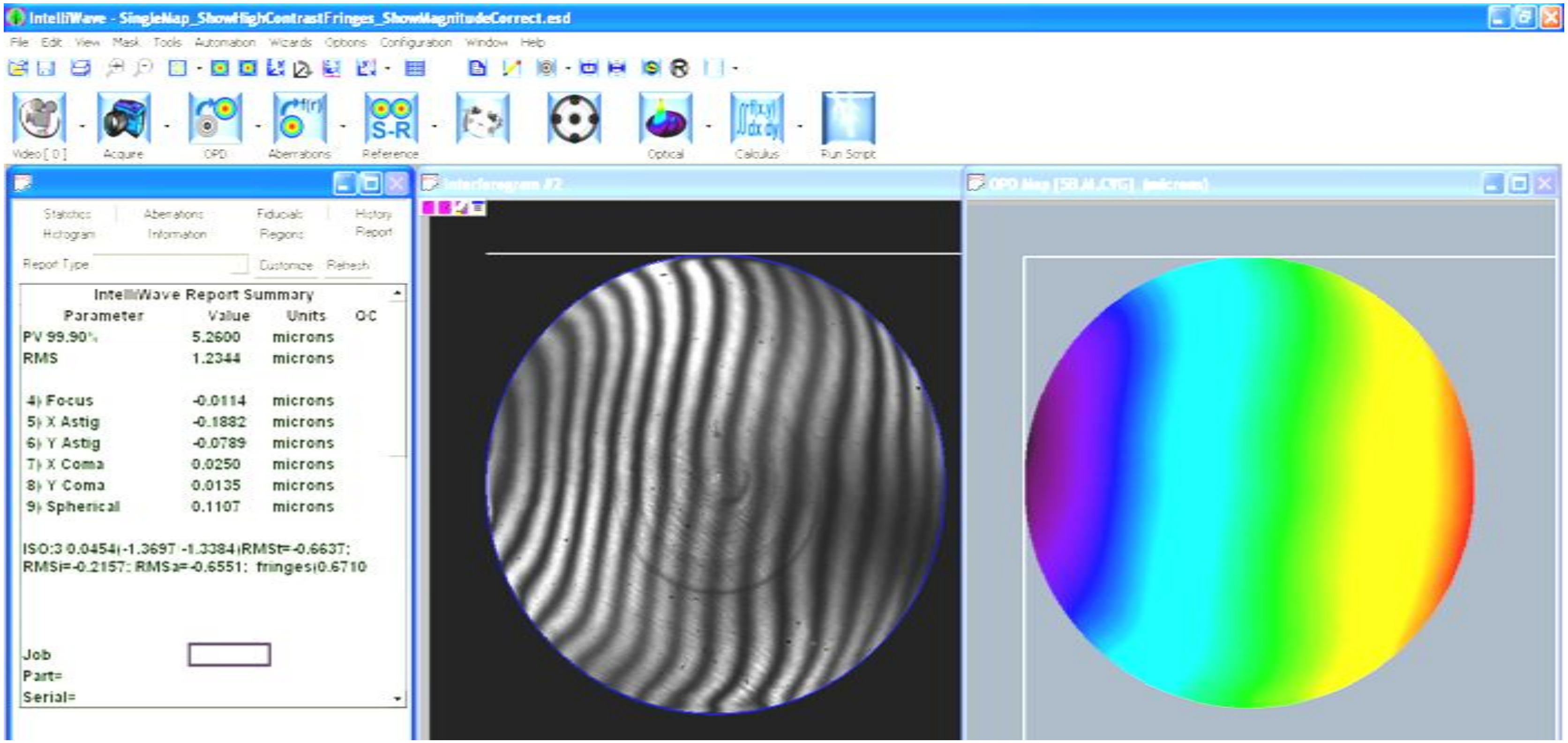
Common path
Phase shift interferometry

3 nm rms accuracy

Reference and test wavefronts come to focus and pass through aperture

All other orders and reflections are blocked

UA achieved very low noise measurements with CGH Fizeau system



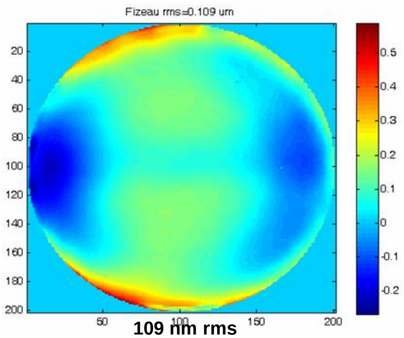
Excellent fringe visibility
Excellent spatial resolution
Low measurement noise

Comparison of Fizeau, SOC

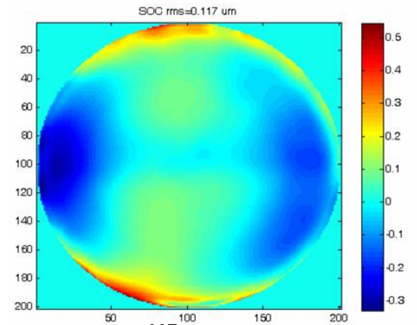
- The Fizeau test was budgeted as < 3.3 nm rms uncertainty, after correction for low order terms.
- SOC measurements of the OAPs are consistent with this.

Fizeau | **SOC**

Raw data



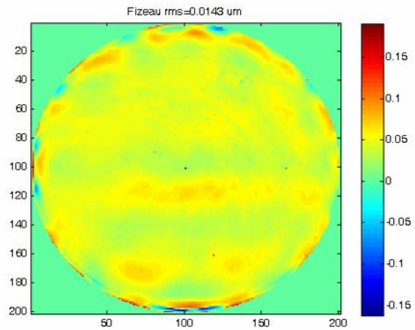
109 nm rms



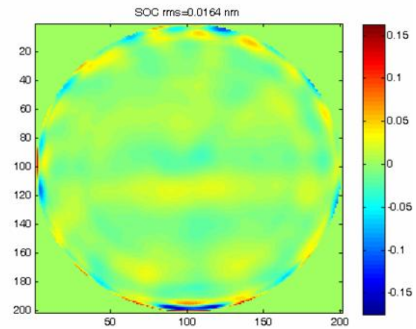
117 nm rms

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

After removing low order terms

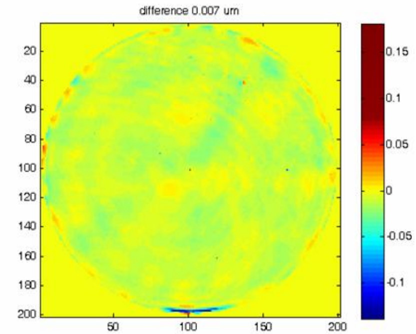


14 nm rms



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

Conclusion

- Free-form aspheres are here to stay
- Mature methods and equipment are available for shaping and finishing large free-form optics.
- The interferometric measurement can be the most difficult (and costly) aspect of manufacturing
- The UA Swingarm Optical CMM has demonstrated excellent performance. This shows real promise of providing a general metrology solution.

- I thank Zeeko, QED, UA for help with this talk