Fabrication challenges and solutions
a. k. a.
Design and manufacture of mirrors Part 2

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Outline

- final slide on active optics and model fitting
- fabrication
  - machining
  - polishing
- measurement
  - interferometry
  - null correctors
  - GMT measurements

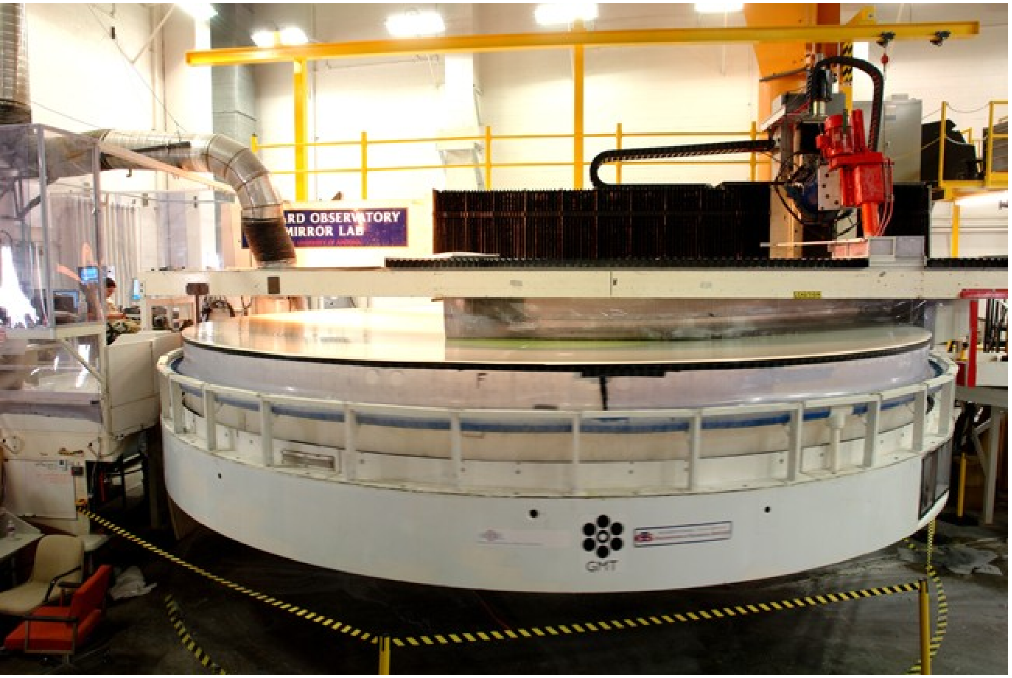
Comments on model fitting

- You can solve any model fitting problem in the same way.
  - Measure or calculate the influence of each parameter on the data.
  - Think of it as an influence function, or a sensitivity, or a derivative.
  - E. g. fitting functions to data
    - Influence functions are your functions evaluated at the data points.
    - Solution is the coefficients of the functions.
    - Easy with, e. g., Matlab “\” operator.
- Be aware of redundancies in model.
  - Use SVD if there are any.
- For SVD, units can matter.
  - SVD minimizes the “length” of the solution vector.
  - If model parameters are of different kinds (e. g., primary mirror support forces and secondary mirror displacements), scale them so a unit change in each is equally “painful”.
- Avoid huge range of numbers by normalizing data.
- Think of the problem in physical terms, not just as a system of equations.

Optical fabrication (what happens after the casting)

1. Machine (generate) surface to accuracy ~10 μm rms.
   - Measure with mechanical profiler or laser tracker.
1. Lap with loose abrasives to ~1 μm accuracy.
   - Measure with laser tracker or IR interferometer.
1. Polish and figure to required accuracy.
   - Measure with visible interferometer.
   - Redundant measurements of anything you might get wrong.

Generating



- Spinning tool has diamond particles embedded in a metal or resin substrate.
- Shape of surface is determined mostly by motion of tool.
  - Surface accuracy is limited by accuracy of machine.
- Grinding leaves microscopic roughness ~ ¼ particle size, and sub-surface damage (micro-fractures) to depth of ~1 particle size.
  - Particle size is typically 200-400 μm.

Loose-abrasive grinding and polishing

- Loose-abrasive grinding and polishing are *lapping* operations, and provide much better control of surface shape.
- Disk (lap) rests on mirror surface with defined force, not defined position, normal to surface.
- Removal rate depends on relative speed, pressure, and abrasive material.
- Typical sequence is loose-abrasive with 100, 40, 20, 9 μm particles, then polish with ~1 μm metal oxide particles.
  - Polishing introduces chemical removal of material, leaves a specular surface with no sub-surface damage.
  - Removal rate ~ 1 nm per meter of relative motion, gives very good resolution.

Figuring and smoothing

- Lapping operations remove surface errors by figuring and smoothing.
- Figuring is directed removal, generally based on Preston's (1927) relation $\Delta z = k\ p\ v\ \Delta t$.
  - Vary dwell time, pressure, and/or speed as a function of position on mirror.
  - Requires a map of surface error.
  - Calculate removal vs position using an integral over time, incorporating motion of lap across surface.
- Smoothing is removal of glass from high spots because lap exerts more pressure there.
  - Does not require knowledge of where the highs are.
  - Depends on stiffness of tool: bending stiffness and compressibility.
  - Most effective for small-scale shape errors.

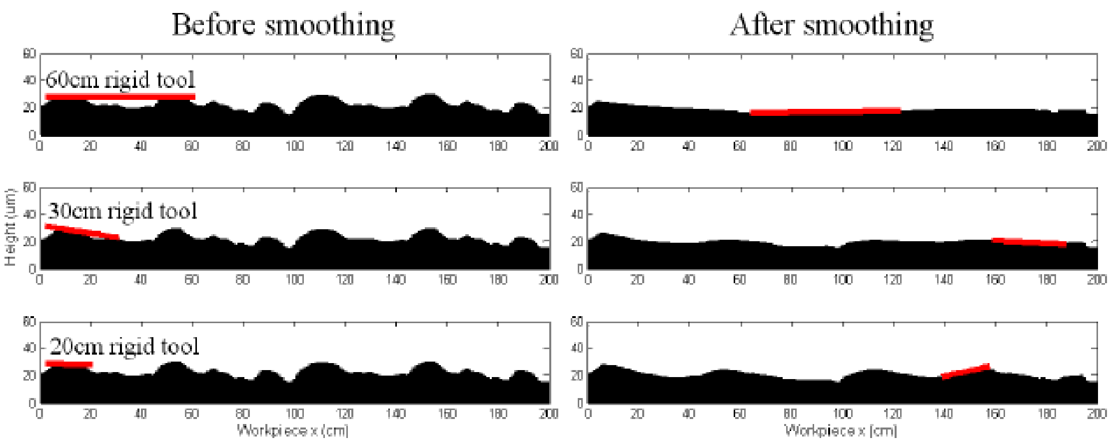


Fig. 3. Smoothing effect simulation using an infinitely rigid tool (Media 1).

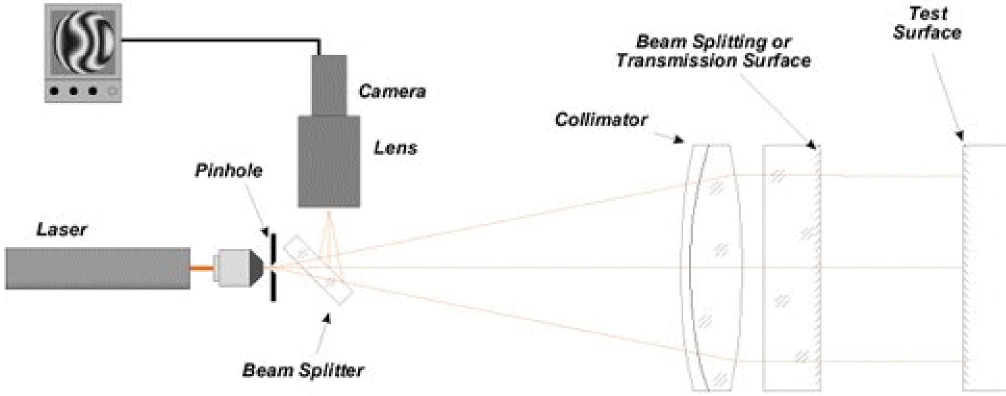
Pitch and polishing surfaces

- Traditional polishing surface is pitch, used by Isaac Newton to polish first telescope mirrors.
- Extremely viscous fluid, like tar. Behaves like a solid for short periods, like a viscous fluid on longer timescales.
- Serves 2 roles:
  - Abrasive particles embed in pitch surface and are dragged across mirror surface.
  - Flows to match the shape of the mirror when pressed against mirror.
- Lap surface must match mirror surface to microns in order to achieve smoothing, and to maintain uniform pressure for figuring.
- Synthetic polishing pads are often used on top of pitch.
  - A layer of pitch or other viscous material is generally required, so lap surface can match mirror surface.

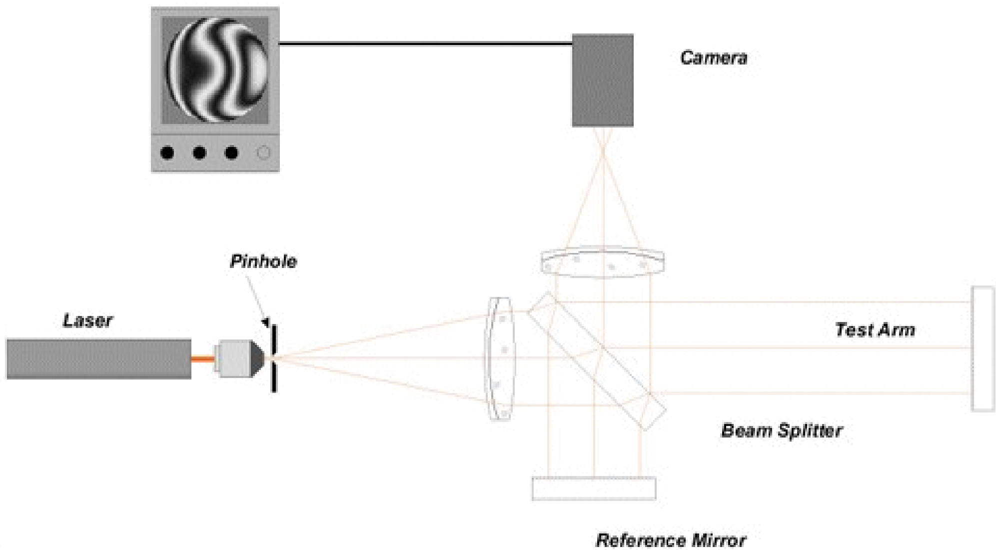
Polishing aspheres

- Smoothing with a stiff lap makes excellent spherical surfaces with relatively little effort.
  - The lap and the mirror come to a common surface with equal curvature everywhere: a sphere.
- Departure from a spherical surface makes it difficult to achieve smoothing and complicates figuring.
  - Difficult to make lap have right shape everywhere on mirror.
  - Pitch can press to fit surface at one location, but it will have wrong shape when lap moves across surface.
- Options include:
  - small lap so misfit is limited to a few microns
  - flexible lap so it will droop to match surface
  - methods of localized removal that do not use a lap
    - ion beam figuring
    - magneto-rheological finishing
  - All of these sacrifice or compromise smoothing.
- Options that preserve smoothing:
  - stressed-mirror polishing (Nelson and co.)
  - stressed-lap polishing (Angel and co.)

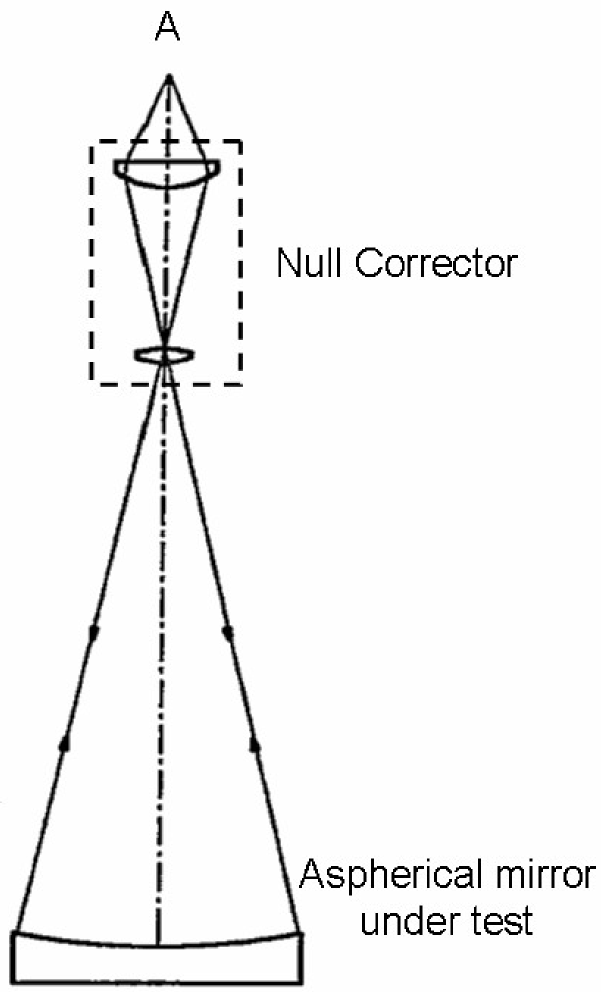
Measurement



Laser Fizeau Interferometer

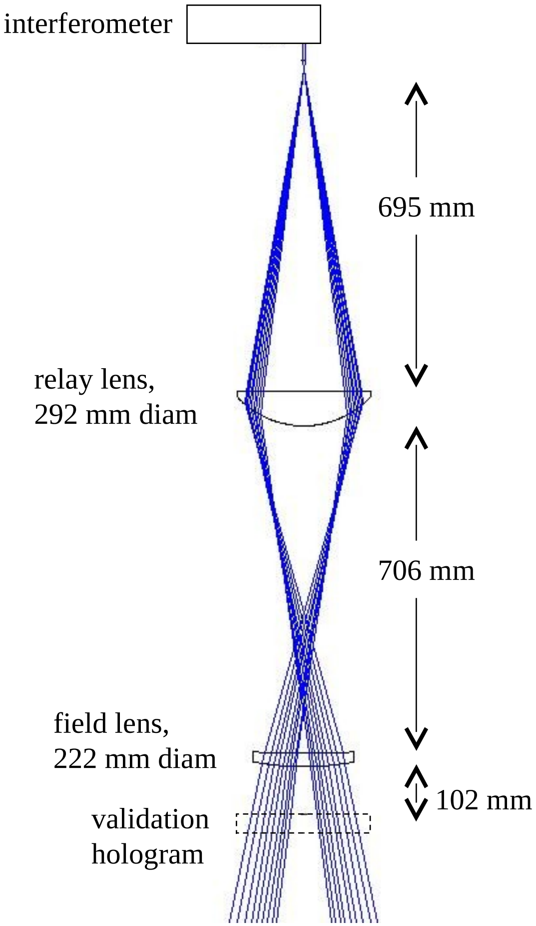


Twyman Green Interferometer

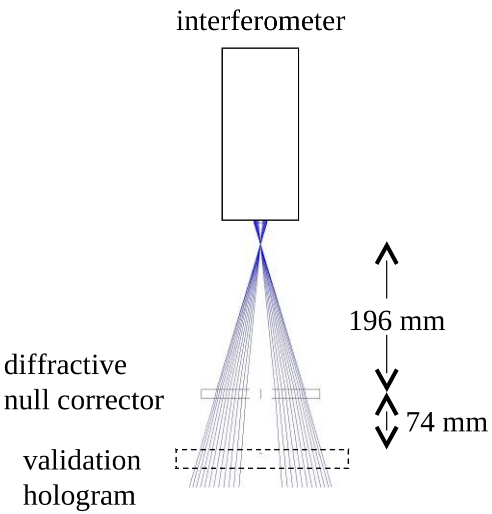


- Interferometer and null corrector form a template wavefront.
- Mirror is figured until it matches that wavefront, producing a null interference fringe (or, with tilt, straight fringes).

Null correctors and validation holograms for LSST



M1 test uses 2-element refractive null corrector. Validation hologram, designed to mimic perfect mirror, can be inserted at paraxial CoC.



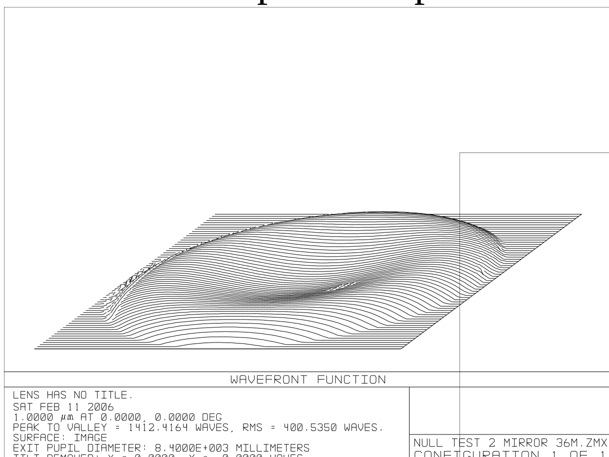
M3 test uses single-element diffractive null corrector, and similar validation hologram.

Validation holograms provide independent validation of wavefront accuracy, including conic constants, and serve as mechanical references for centers of curvature and optical axes.

Optical tests for LBT and GMT

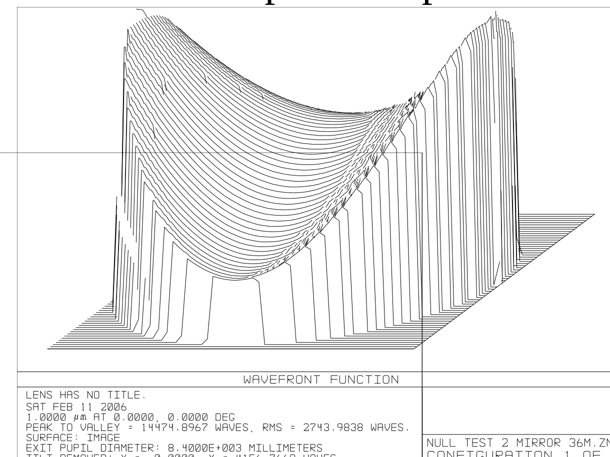
LBT (8.4 m f/1.1)

1.4 mm aspheric departure



GMT segment

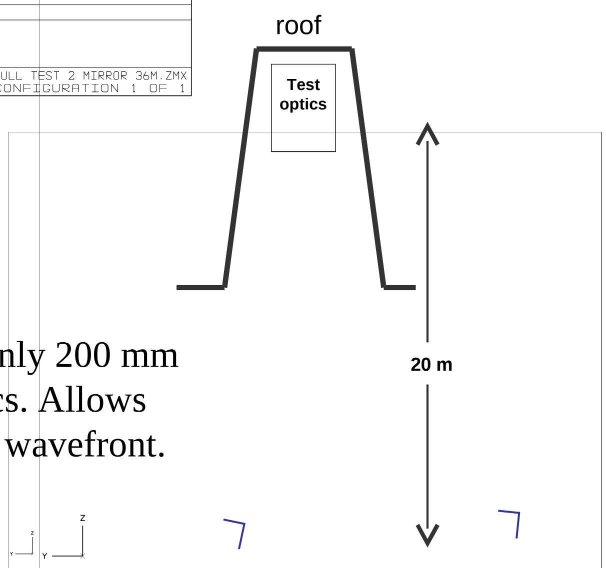
14 mm aspheric departure



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.

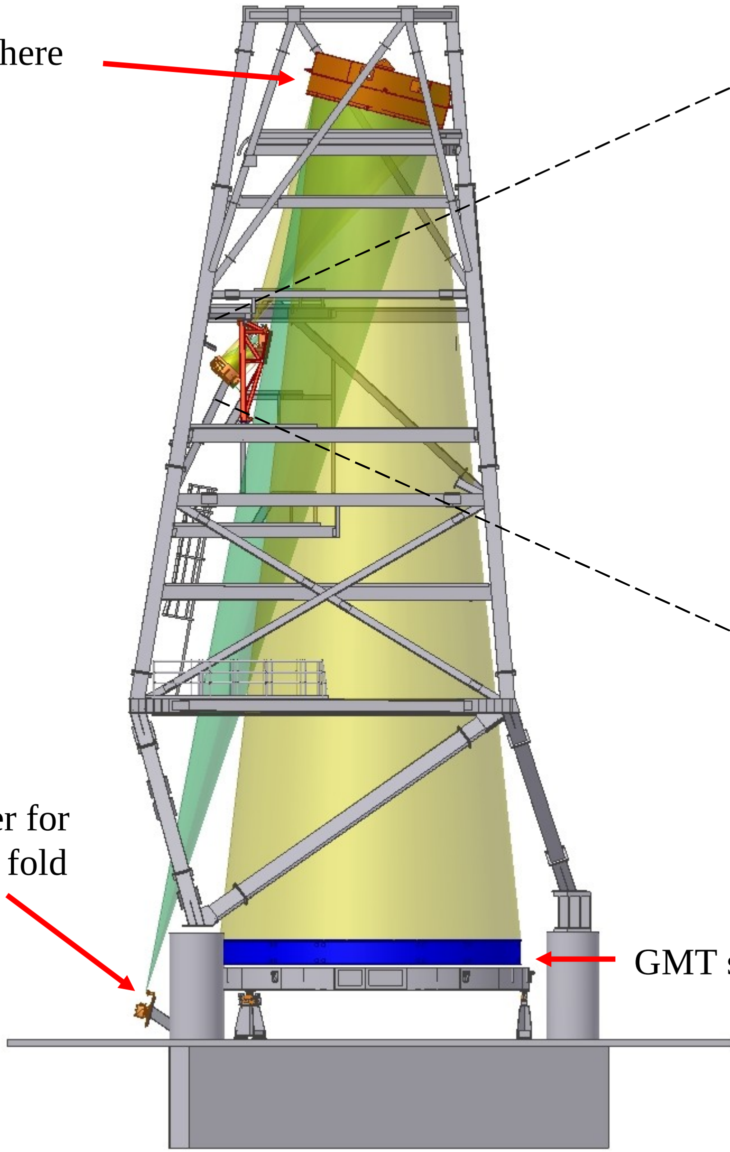


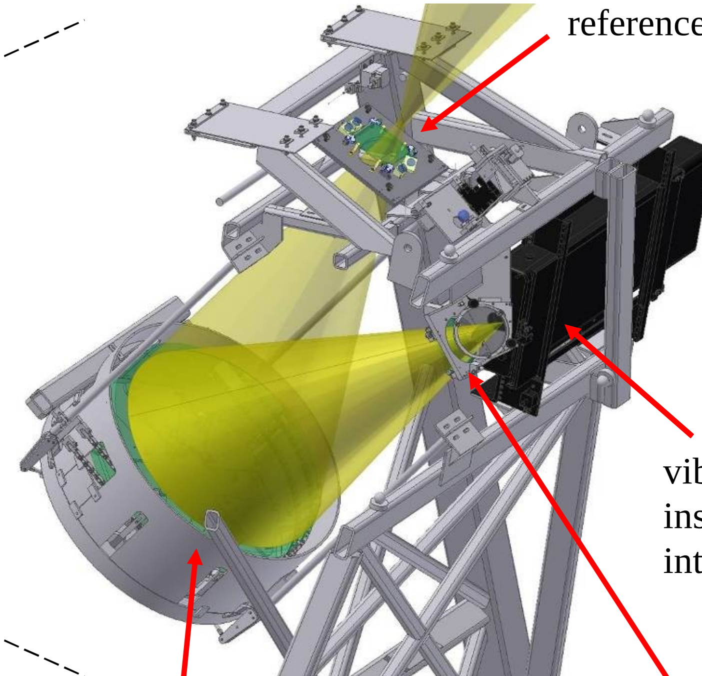
No axisymmetry

Light path defined by GMT is much larger: 3.5 m diameter at top of tower. Direct measurement of wavefront is impossible.

Use independent tests instead.

GMT optical test

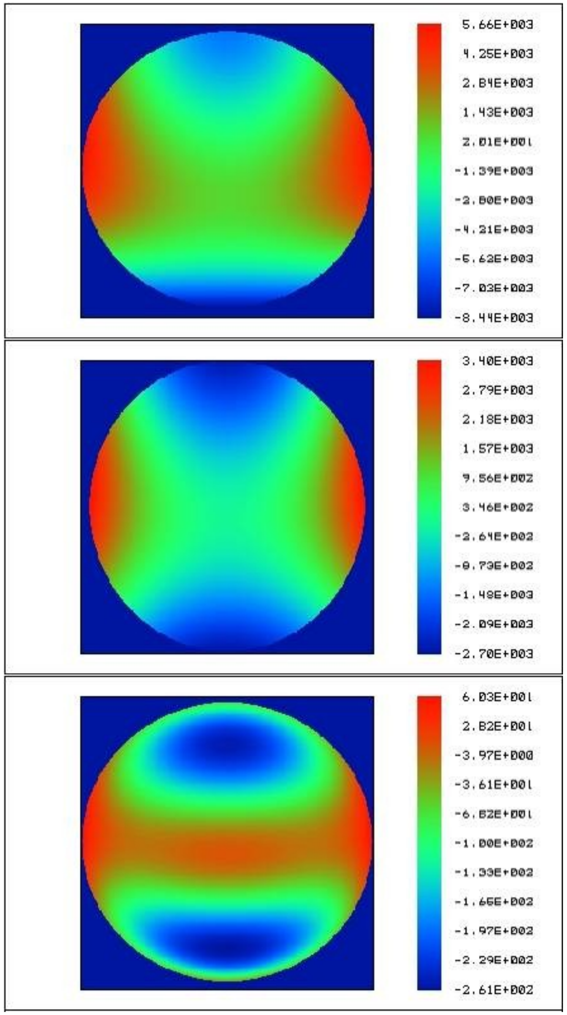




Reference CGH validates WF from first 2 elements of null corrector, and is used to align large fold sphere and GMT segment to that WF. But no hologram can validate WF from full null corrector.

Shaping of test wavefront by null corrector

Follow wavefront from segment back to interferometer:

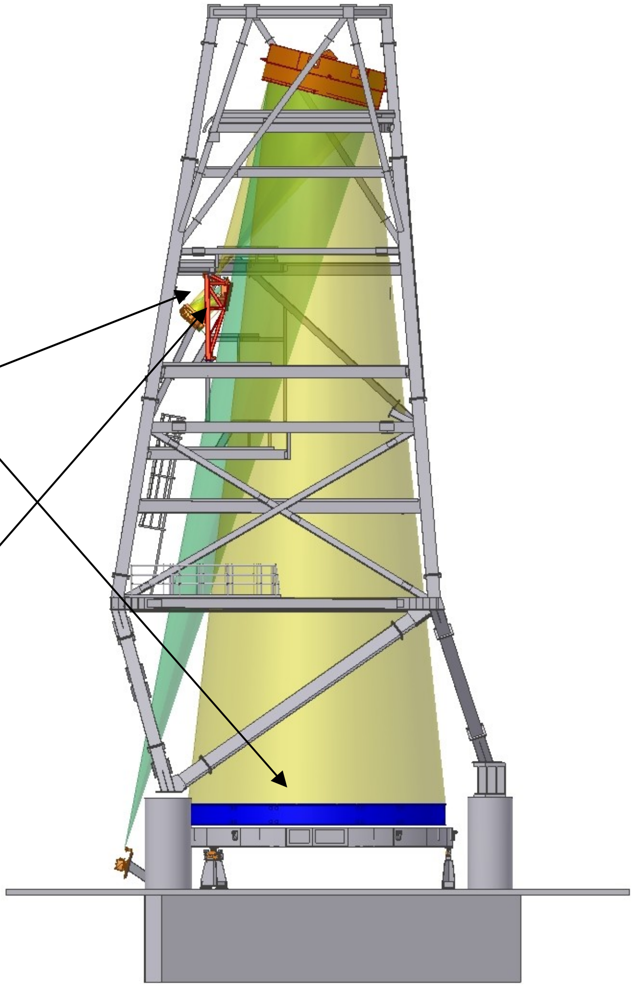


difference from sphere (µm)

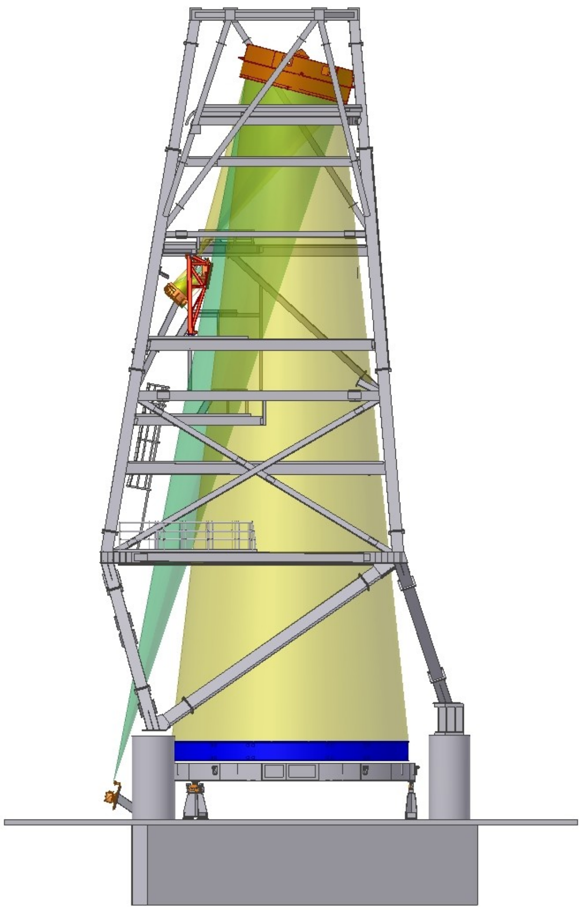
14 mm p-v at GMT surface

6.1 mm p-v at intermediate focus between fold spheres

320 µm p-v between 76 cm sphere and CGH

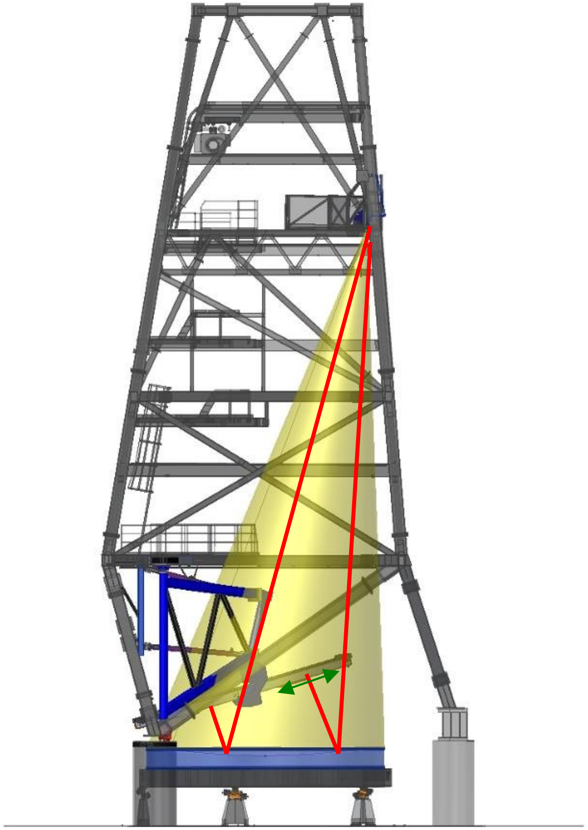


4 independent measurements



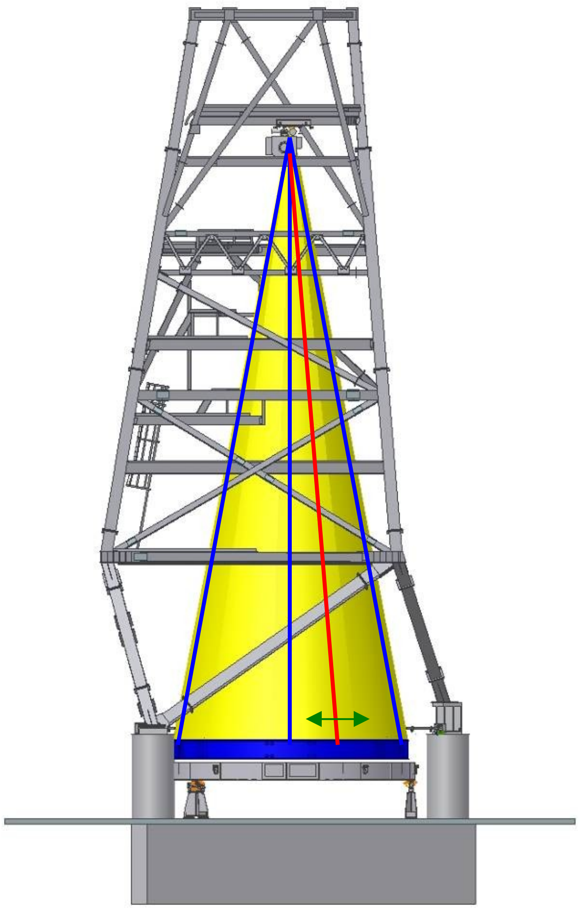
Principal optical test

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