Design and manufacture of mirrors, and active optics

Buddy Martin

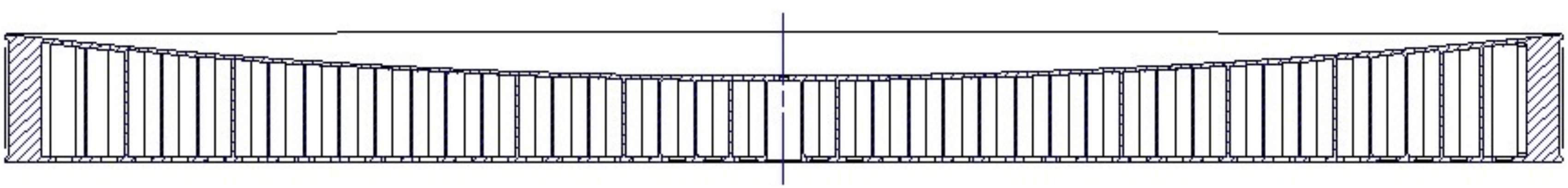
Steward Observatory Mirror Lab

Outline

- What makes a good mirror?
- Modern mirror concepts
  - thin solid mirrors
  - segmented mirrors
  - lightweight mirrors
- Honeycomb mirrors
  - design
  - casting
- Optical manufacture
  - requirements
  - aside on active optics and model fitting
  - fabrication
    - machining
    - polishing
  - measurement
    - interferometry
    - null correctors
    - GMT measurements

What makes a good mirror? (mechanical)

- Fundamental requirement is to deliver a *good* wavefront to focal plane in almost all conditions.
  - Hold its shape to a fraction of a wavelength on large scales
  - Be smooth to a *small* fraction of a wavelength on small scales
  - Contribute little to local seeing (temperature gradients in air)
- Stiffness against wind: bending stiffness $\propto Et^3$
  - E = Young's modulus, t = thickness
- Stiffness against gravity: bending stiffness $\propto Et^2 / \rho$
  - This puts a premium on low mass.

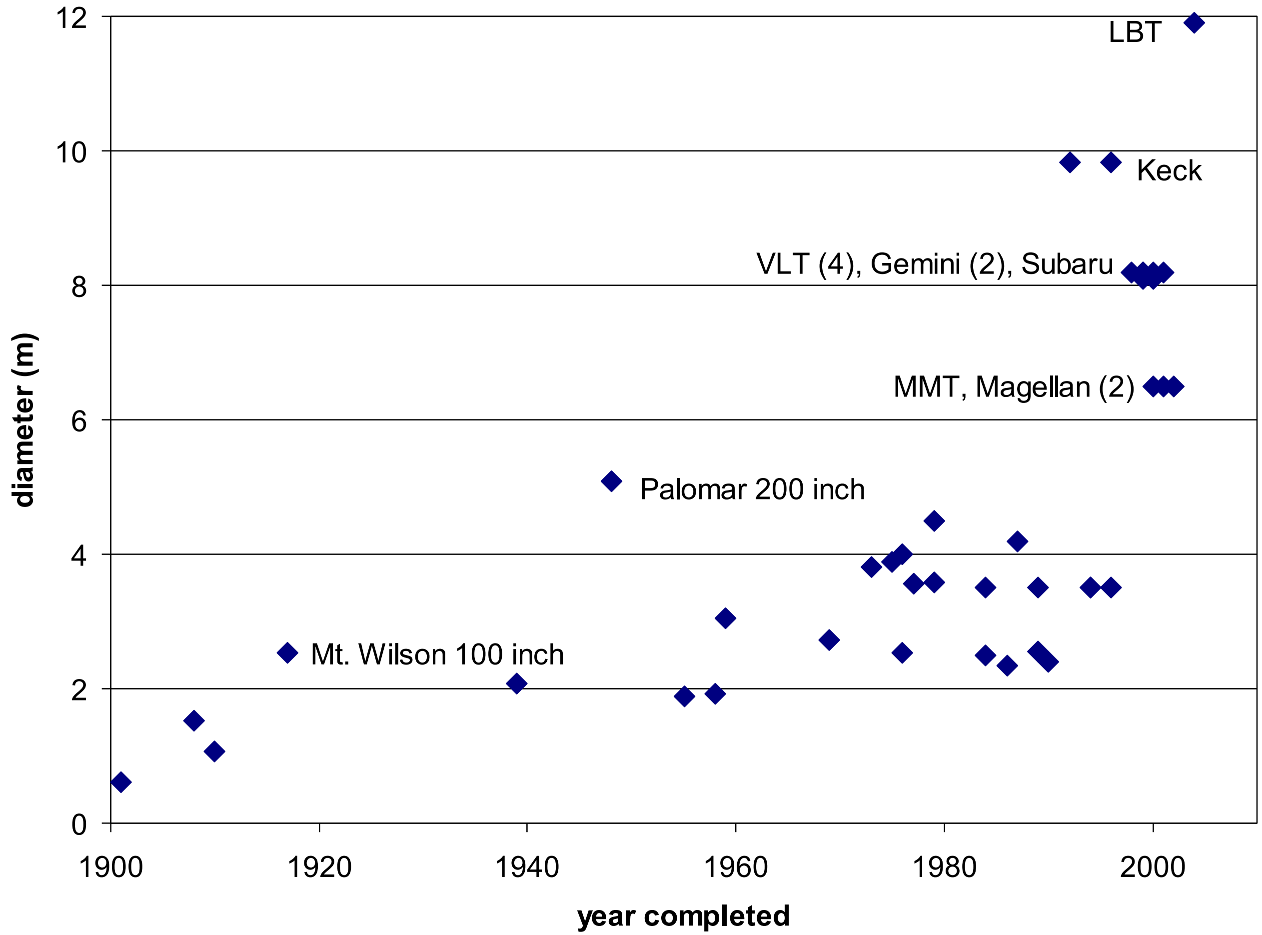


cross-section of an 8.4 m honeycomb mirror for the Giant Magellan Telescope

What makes a good mirror? (thermal)

- Thermal distortion: displacement = $\alpha\,\Delta T\,t$ for "swelling"
  curvature = $\alpha\,\Delta T / t$ for bending
  - α = thermal expansion coefficient, ΔT = temperature variation within mirror
- "Mirror seeing" $\propto T - T_{air} \approx dT_{air}/dt \cdot \tau$
  - dT_{air}/dt = rate of change of air temperature
  - τ = mirror's thermal time constant $\propto c\rho t^2 / k$
    - c = specific heat, k = thermal conductivity, t = thickness
  - Becomes a problem for T - T_{air} > ~0.3 K, τ > ~1 hr
  - For glass or glass-ceramics, want t < 5 cm
- Bottom line: Mirror should be stiff & light, have low thermal expansion & short thermal time constant.

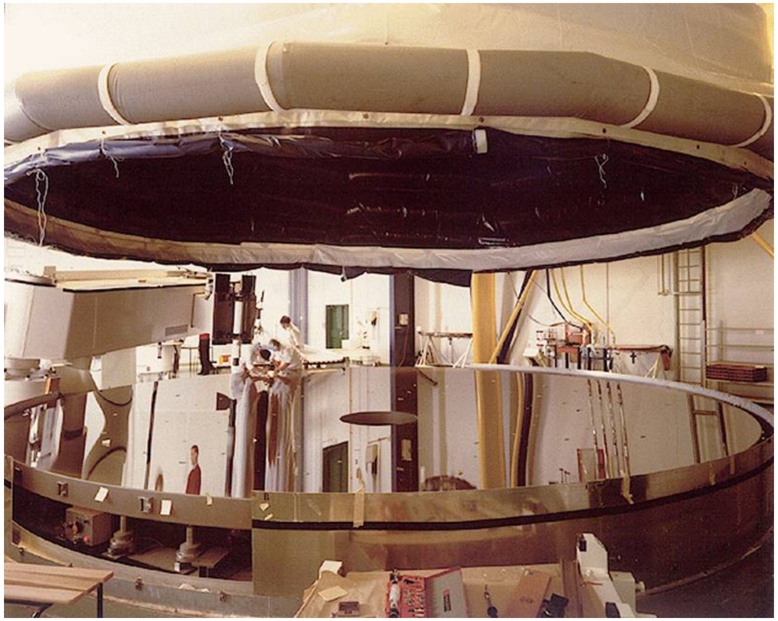
Optical telescopes

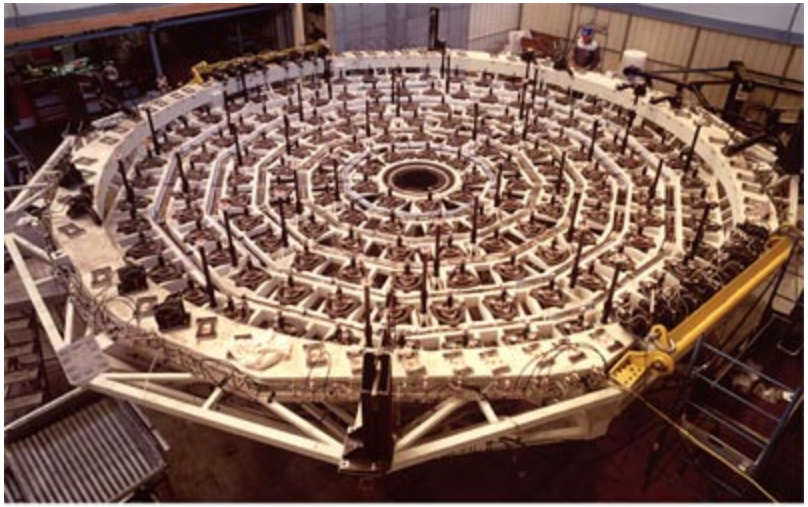


- Hale Telescope at Palomar used first large lightweighted mirror.
- Most powerful telescope for 45 years because of difficulty making a larger mirror that would not distort due to its weight and thermal inertia.

New mirror concepts after 1980: 1. Thin, solid mirrors

- 3 solutions emerged ~1980:
- Thin, solid mirrors whose shape is controlled by active optics
  - Active optics concept by Ray Wilson and colleagues in Europe
  - Concept:
    - Replace stiffness by active control of shape
    - Reduces mass and thermal inertia (somewhat) with 175 mm thick mirror
  - Technology:
    - Zerodur glass ceramic and ULE glass, both with near zero thermal expansion
    - Precise active mirror supports
    - Wavefront sensors similar to those used for adaptive optics
  - ESO VLT (4 x 8.2 m), 2 Gemini telescopes, Subaru telescope



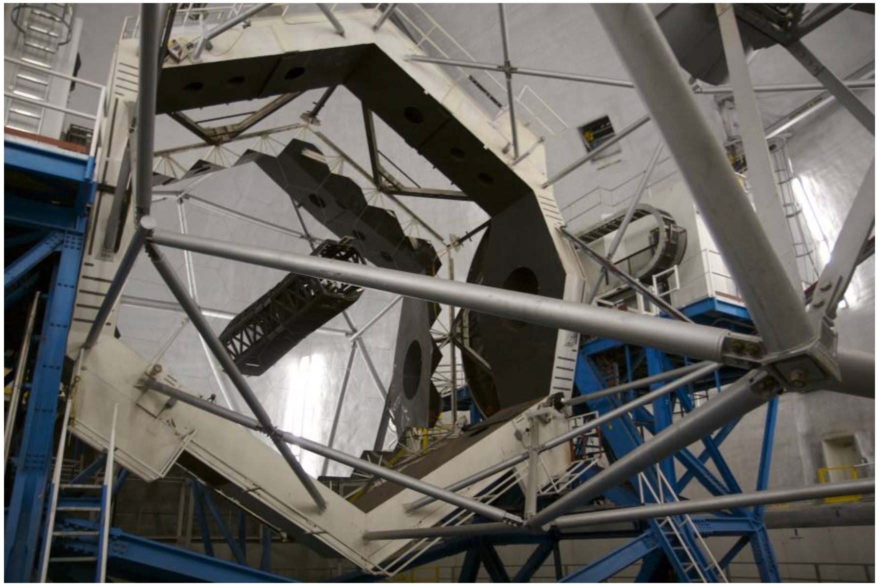


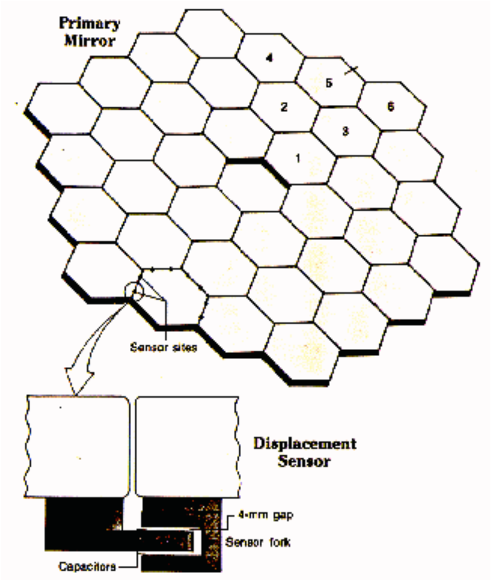
Active Mirror Supports in VLT M1 Cell

ESO PR Photo 34a/99 (13 August 1999)

2. Segmented mirrors

- Developed by Jerry Nelson and colleagues at UC
- Concept:
  - Achieve continuous optical surface by active control of position of small segments.
  - Reduces mass and thermal inertia even more than thin solid mirror (75 mm vs 175 mm)
- Technology
  - Precise segment positioning actuators (~10 nm resolution)
  - Precise segment-segment displacement sensors
  - Occasional wavefront measurement of segment phasing
- Used for Keck, Hobby-Eberly, Grantecan, SALT
- To be used for TMT (30 m), ESO ELT (42 m)

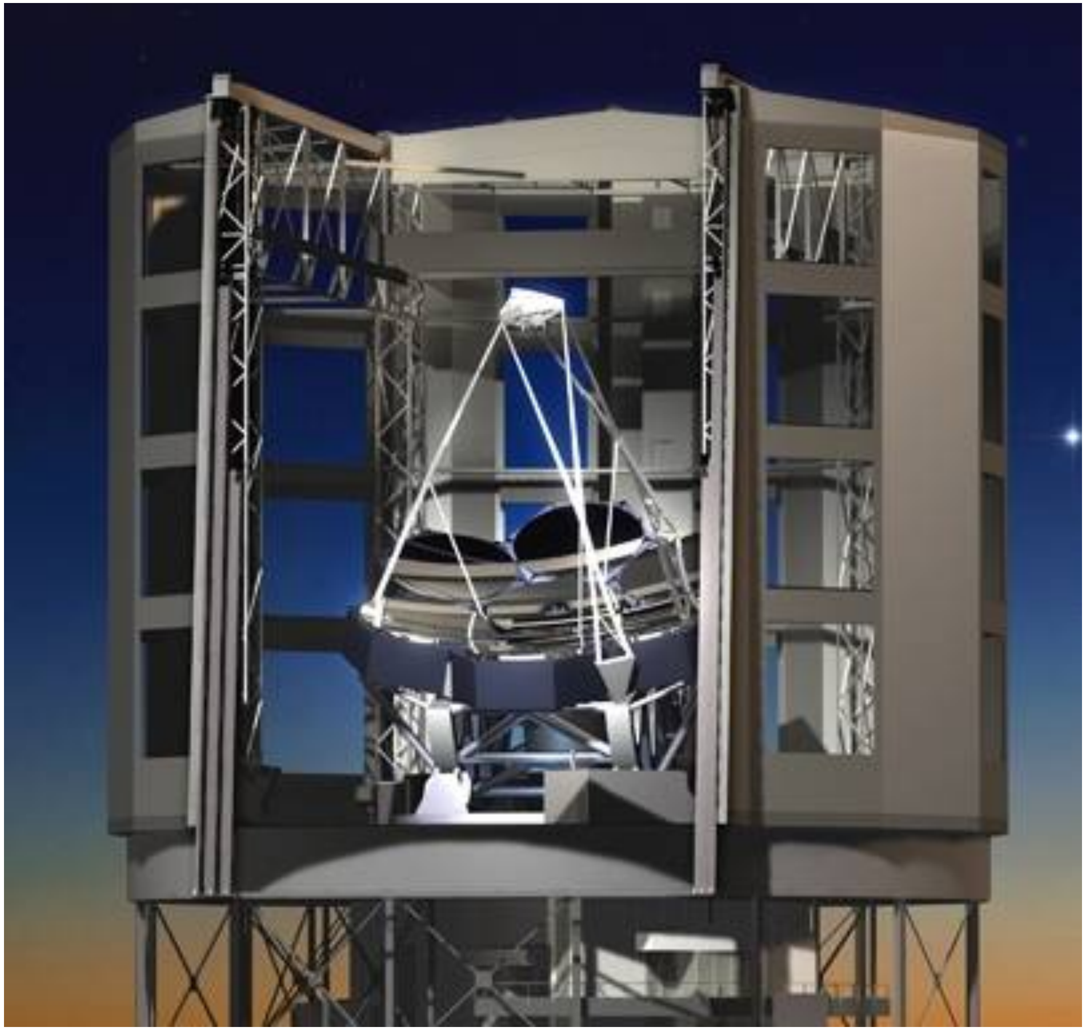




3. Honeycomb mirrors

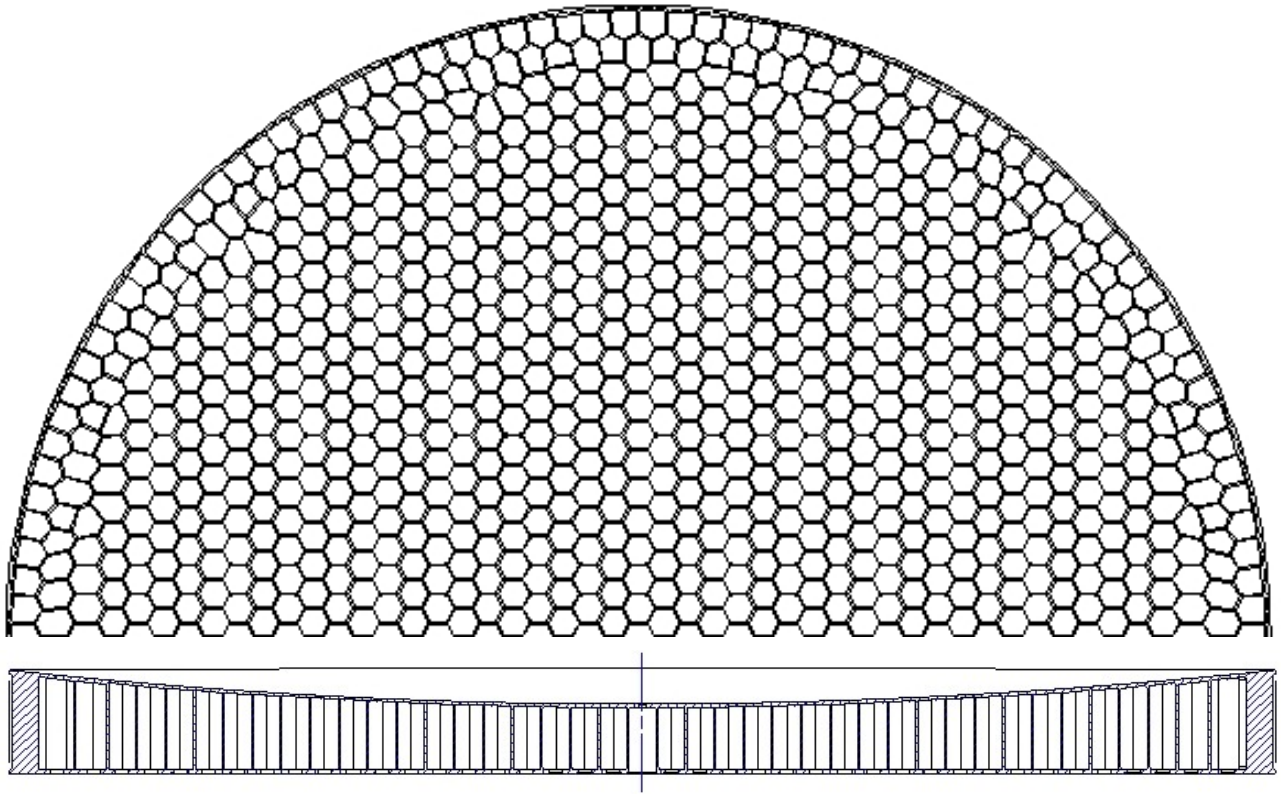
- Developed by Roger Angel and colleagues at UA
- Concept:
  - Extend Palomar technology to 8 m with more extreme lightweighting
  - Maintain stiffness of traditional mirrors, reducing dependence on active control
  - Achieve very short thermal time constant with thin glass sections, active ventilation
- Technology
  - One-piece spin-casting of honeycomb structure with 80% lightweighting
  - Polishing and measuring very fast mirrors (short focal length, f/1 - f/1.25)
- Used for MMT, 2 Magellan telescopes, LBT
- To be used for LSST, GMT 25 m

Giant Magellan Telescope



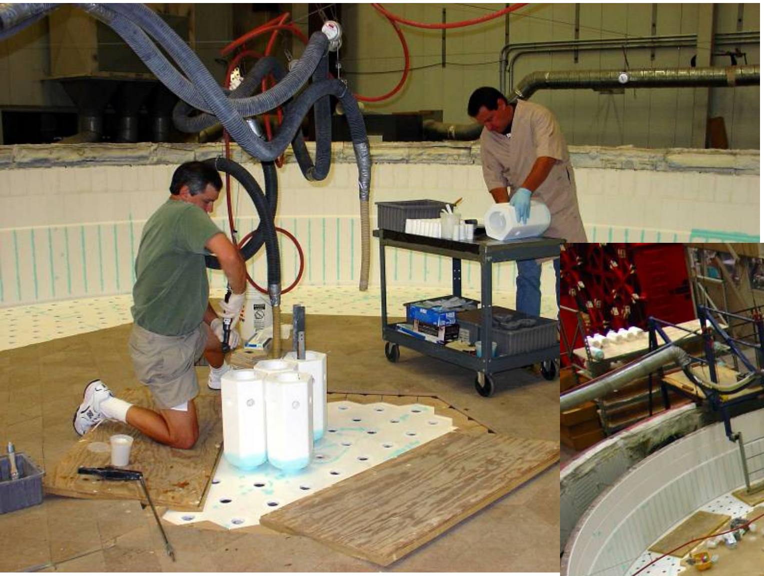
- 25 m optical telescope being built in Chile
- Primary mirror has 7 segments, each a honeycomb mirror 8.4 m in diameter.
- Secondary mirror is segmented to match primary, with 1.1 m segments.
- Fine alignment, adaptive correction, and phasing are done with small, agile secondary segments.

Structure of a GMT mirror segment

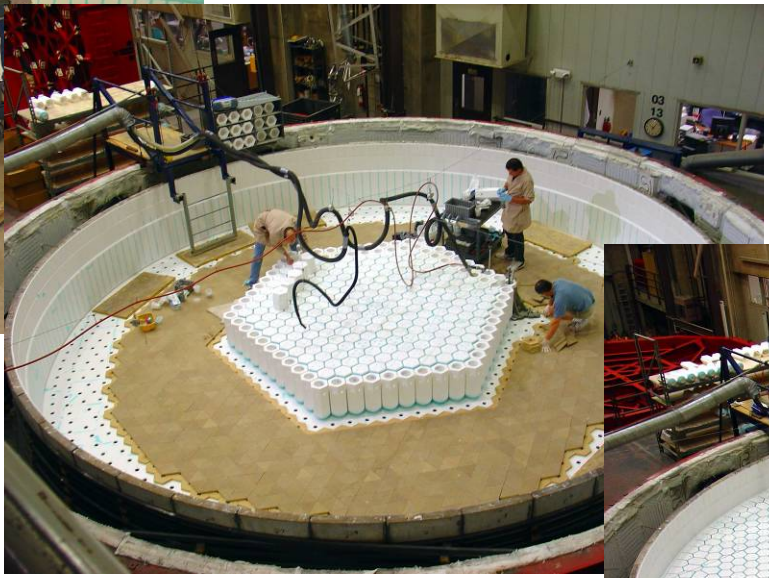


1. Honeycomb structure puts most of mass at top and bottom, where they provide the most stiffness.
2. Borosilicate glass has lowest thermal expansion ($\alpha = 3$ ppm/K) among materials that can be cast into complex form.
3. Facesheet thickness = 28 mm to make $\tau < 1$ hr.
4. Hex cavity size = 192 mm to limit gravity sag of unsupported facesheet to 7 nm.
5. Rib thickness = 12 mm contributes little mass while maintaining safety.
6. Overall thickness 700 mm to give desired stiffness against wind.

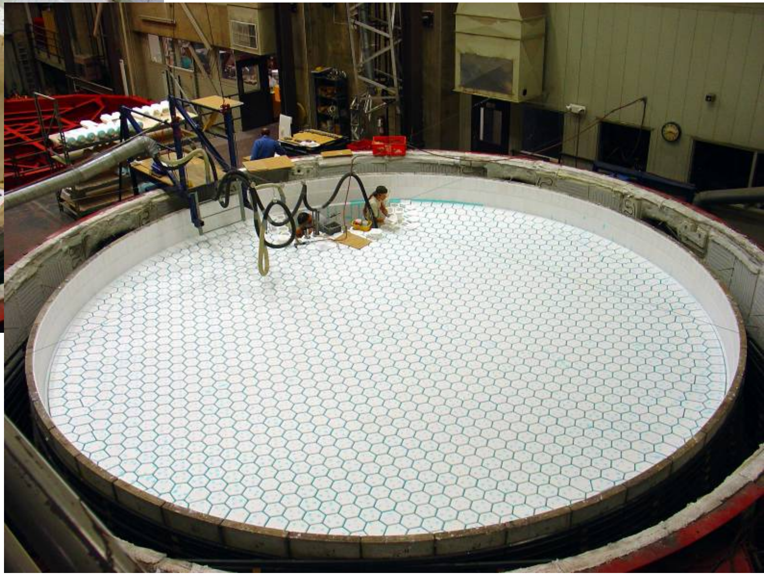
Casting process for GMT mirror: mold assembly



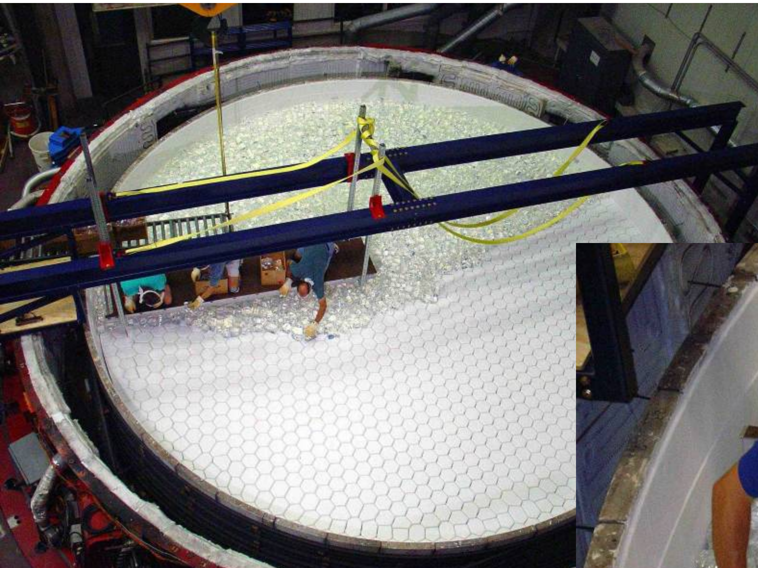
Machine and install 1681 ceramic fiber boxes in silicon carbide tub.

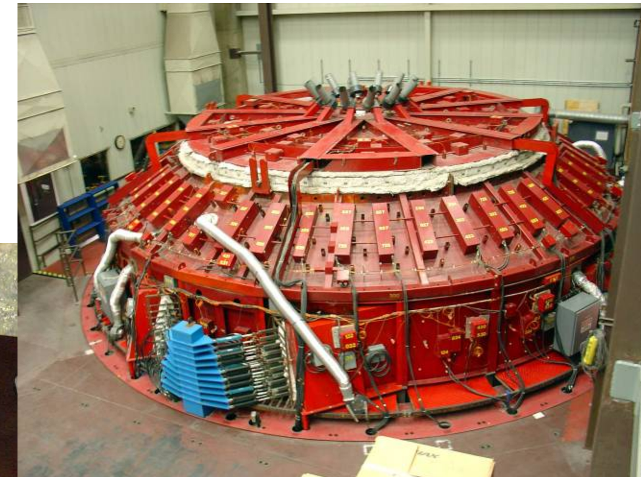


Tops of boxes follow shape of mirror surface; no two are identical.



Loading of glass

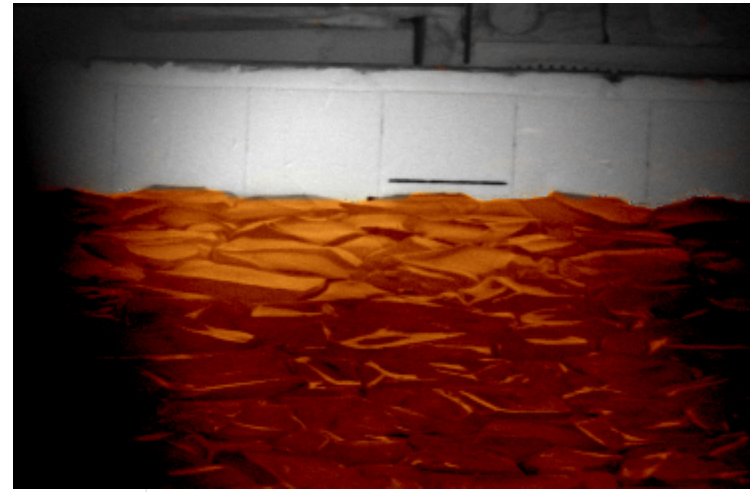


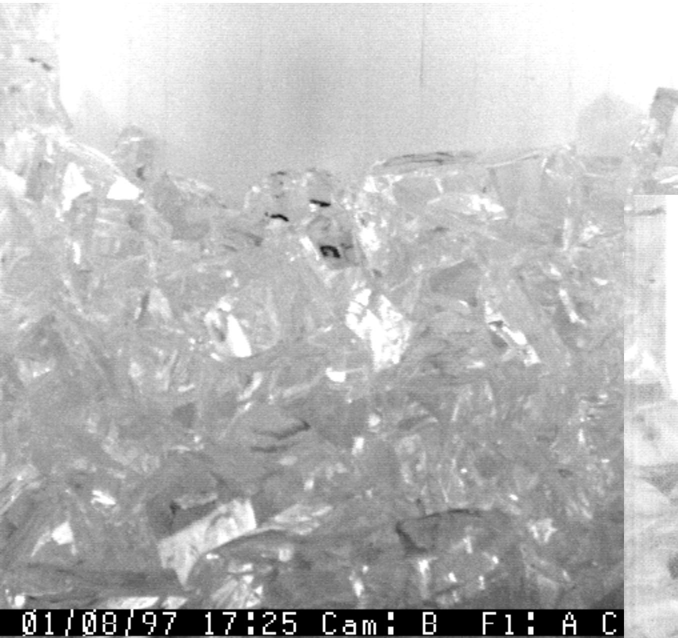


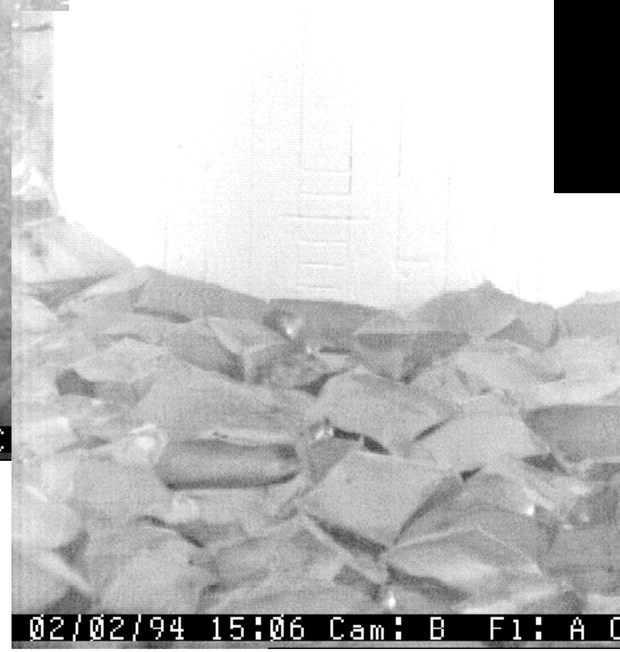
Inspect, weigh, and load 18 tons of Ohara E6 borosilicate glass in 2-5 kg blocks.

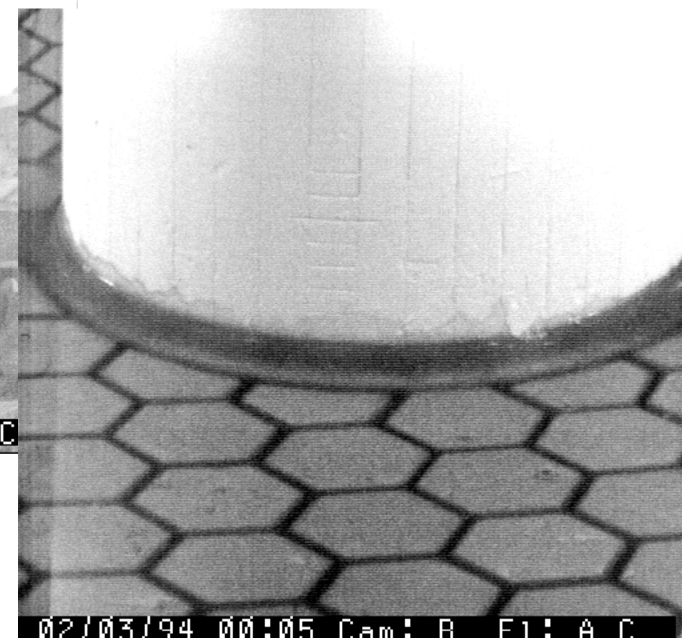
Spin-casting gives parabolic shape to ~1 mm accuracy. Eliminates need to grind out ~20 tons of solid glass for an LBT mirror.

Glass melting









UV cameras mounted in the furnace lid monitor the casting.

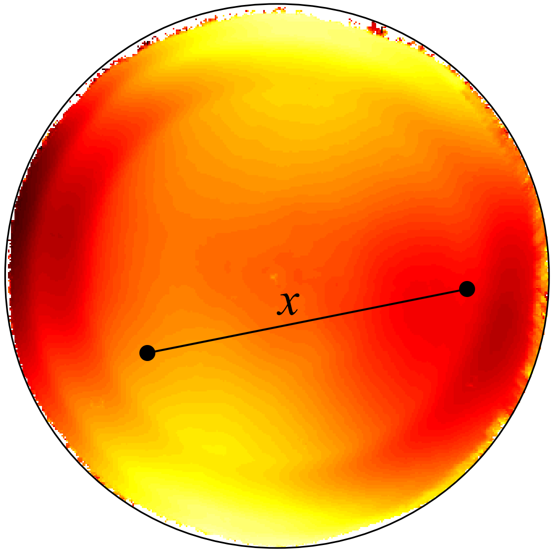
Heat to 1160˚C, spin at 4.9 rpm, hold 4 hours to allow glass to fill mold. Cool rapidly to 900˚C then slowly for 3 months, 2.4˚C/day through annealing.

First GMT mirror blank

Accuracy requirements

- “Seeing” is degradation of images due to index variations and turbulence in atmosphere.
  - Typically 0.5 - 1.0 arcsecond at an excellent site, exceptionally 0.3 arcsecond.
- Telescope optics must be more accurate than best wavefront the atmosphere will deliver, at all spatial scales.
  - Without adaptive optics, telescope optics must not significantly degrade images delivered by the atmosphere.
  - With AO, most of DM stroke should be reserved to correct the atmosphere, not the telescope optics.

- Atmosphere induces large WF errors on large spatial scales, small errors on small scales.
- Spectrum of WF errors is described by *structure function* = mean square difference in WF between points in pupil, as a function of their separation *x*.

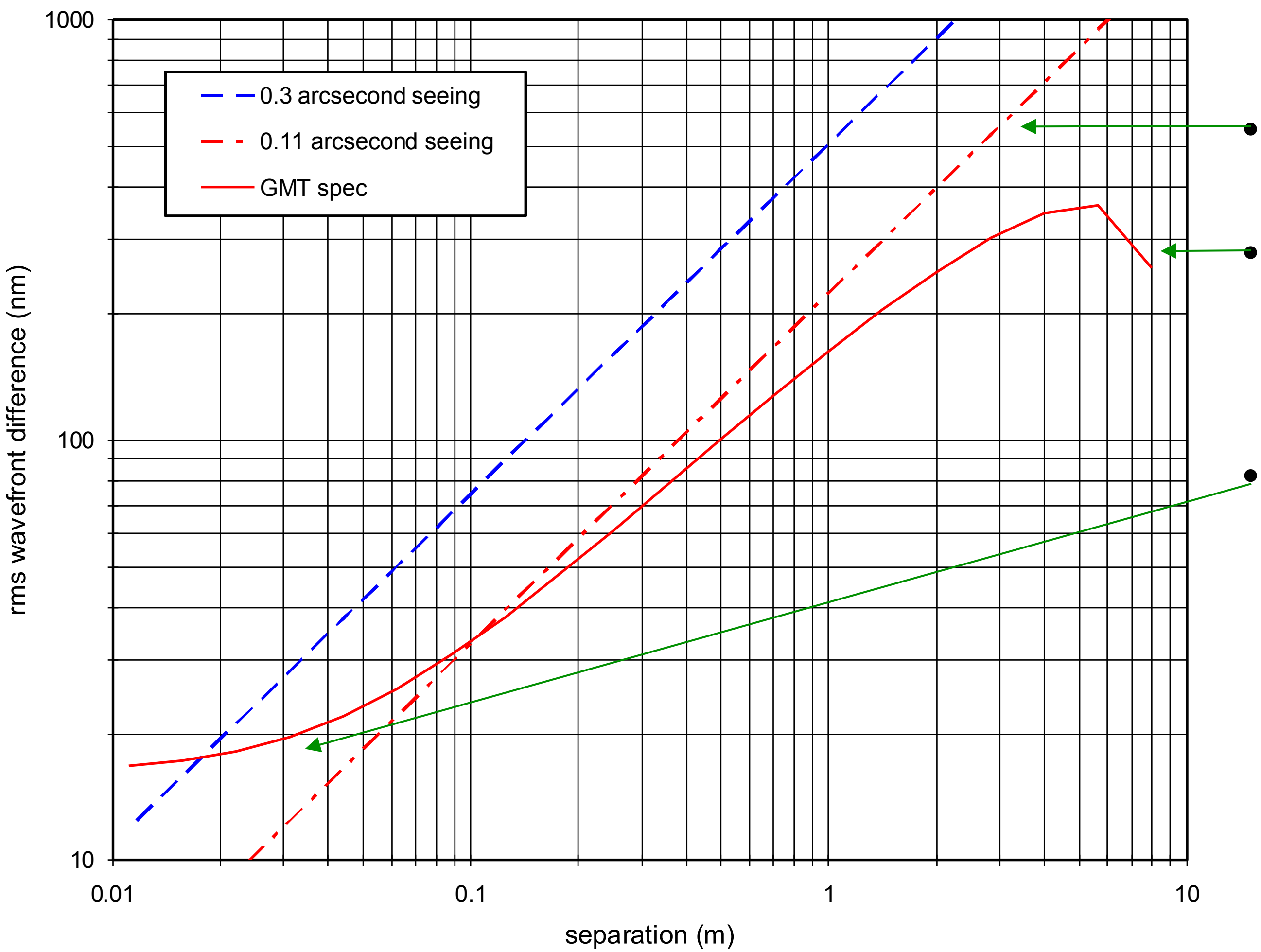


Structure function specification

Structure function due to atmosphere: $\delta^2(x) = \left(\frac{\lambda}{2\pi}\right)^2 6.88\left(\frac{x}{r_0}\right)^{\frac{5}{3}}$

Image FWHM: $\theta = 0.98\frac{\lambda}{r_0}$

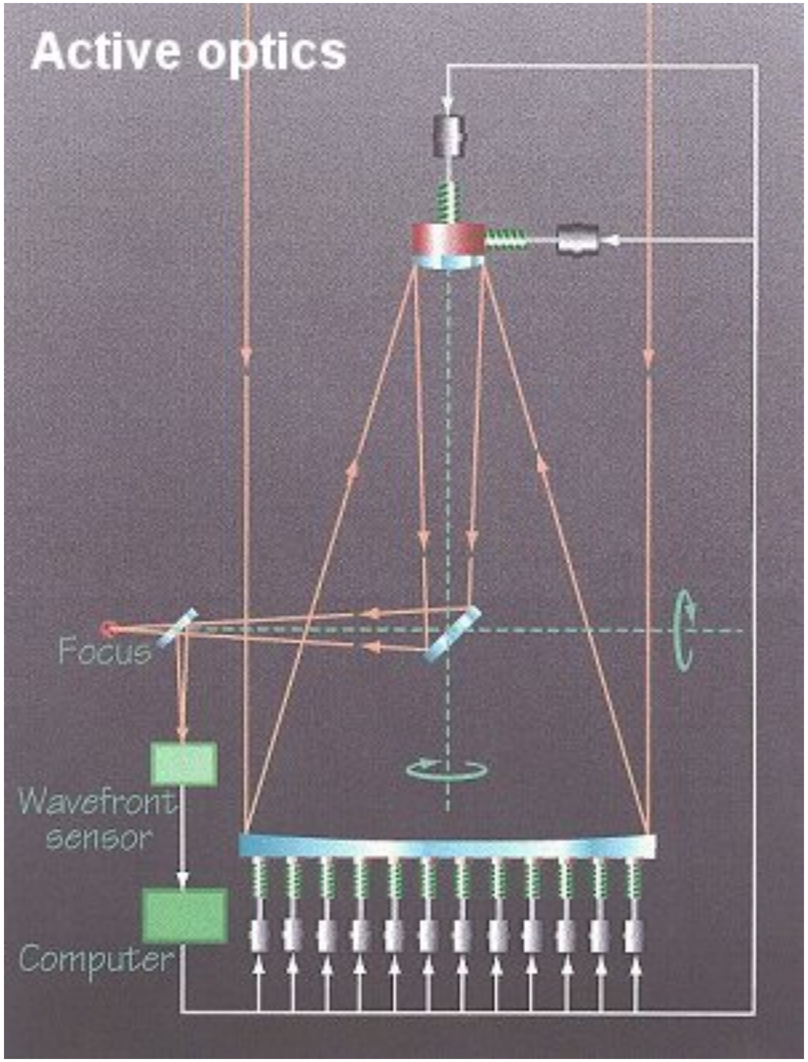
r_0 = coherence length, or Fried parameter



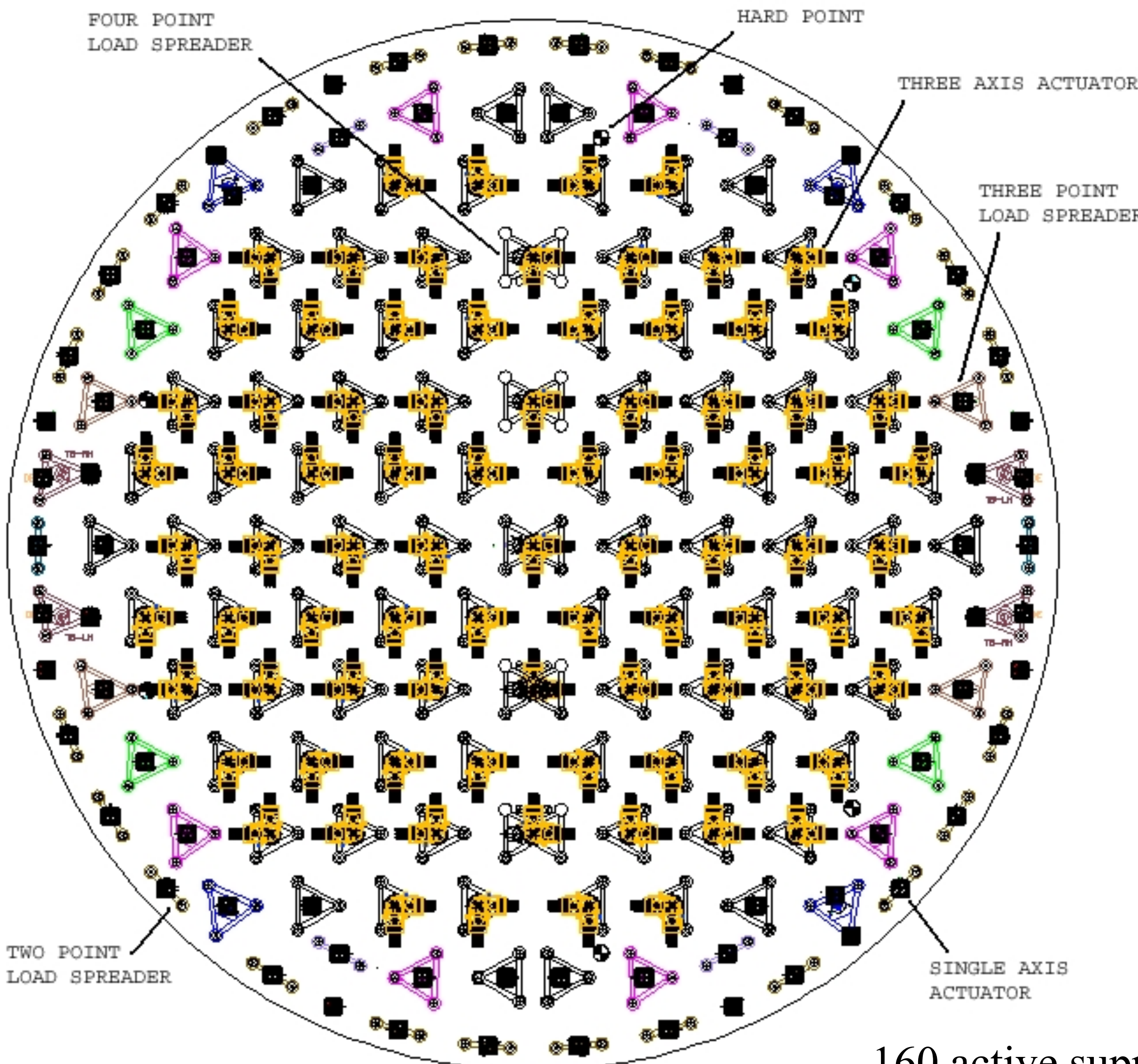
- Start with 0.11 arcsecond seeing.
- Eliminate tilt across full pupil: tighten on large scales.
- Add allowance for 2% scattering loss due to 16 nm rms WFE on small scales.

Impact of active optics on requirements

- Active optics is active control of alignment (primary and secondary) and shape of primary, based on WF measurements in telescope.
  - Necessary because no 8 m mirror is rigid
  - Built into all modern telescopes
- Active optics is slow (> 1 minute) and corrects only large-scale errors.
- Implication for manufacturing:
  - No need to completely eliminate all low-order shape errors, because they will be controlled with active optics at telescope.
- Manufacturing requirement is to control large-scale shape within easy range of active-optics correction in telescope.
- When mirror surface error is measured in lab, simulate active-optics correction of low-order components.
  - Tells how much large-scale error you can easily correct.



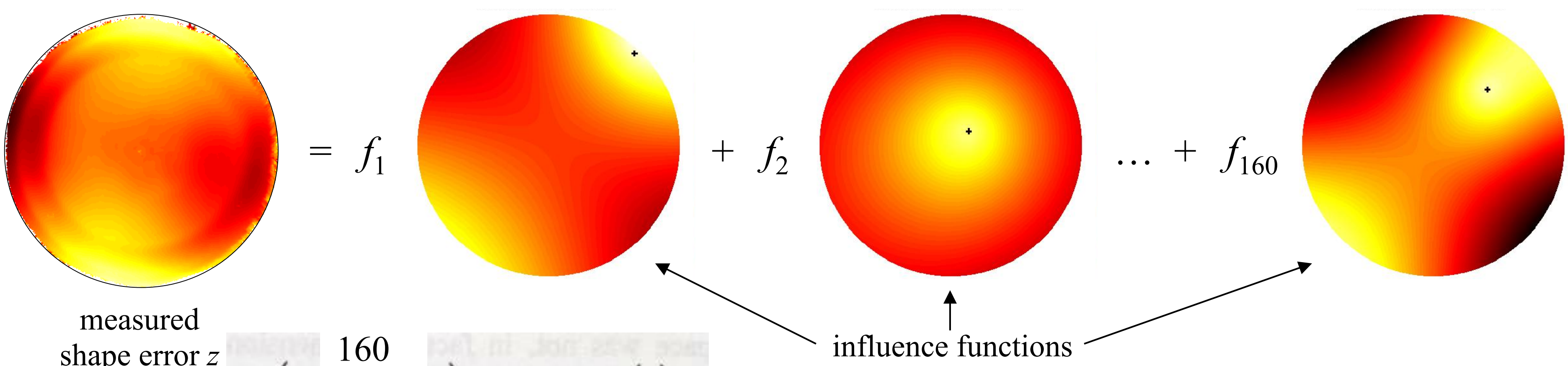
GMT mirror support layout



160 active support actuators

Active optics as a model-fitting problem

- Problem is to calculate the support forces that will best correct the measured wavefront error.
- Calculate or measure the effect on the mirror shape of a unit force on each actuator.
  → 160 influence functions
- Find linear combination of influence functions that would match current shape error.
- *Data* are measured surface displacements z_i. *Model* is sum of influence functions. Model *parameters* (to be determined) are forces f_j.



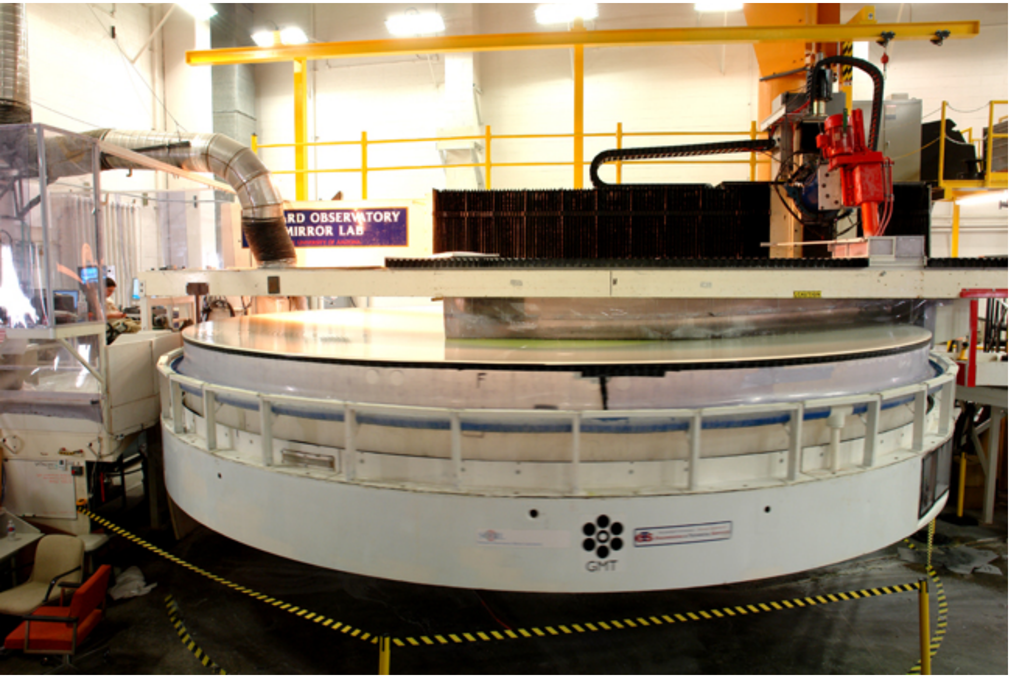
$$\begin{array}{cc} & 160 \\ \sim 300 & \begin{pmatrix} \quad \mathbf{A} \quad \end{pmatrix} \end{array} \cdot \begin{pmatrix} f \end{pmatrix} = \begin{pmatrix} z \end{pmatrix}$$

- Influence functions are not localized because of compensation for net force and moment.
- Each 2-D shape becomes a ~300 x 1 column vector.
- ***A*** has units of nm/N. Each column of ***A*** is one influence function.

Optical fabrication (what happens after the casting)

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

Generating (machining)



- 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, 50, 25, 12 μm particles, then polish with ~1 μm metal oxide particles.
- Loose-abrasive grinding uses a hard lap surface and loose (not bound) abrasive particles.
  – It works by mechanical abrasion, e. g. by breaking away microscopic pieces of glass.
- Polishing uses both mechanical and chemical removal of material, leaves a specular (shiny, transparent) surface with no sub-surface damage.
  – Removal rate ~ 1 nm per meter of relative motion, gives very good resolution of removal.

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 simply 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.

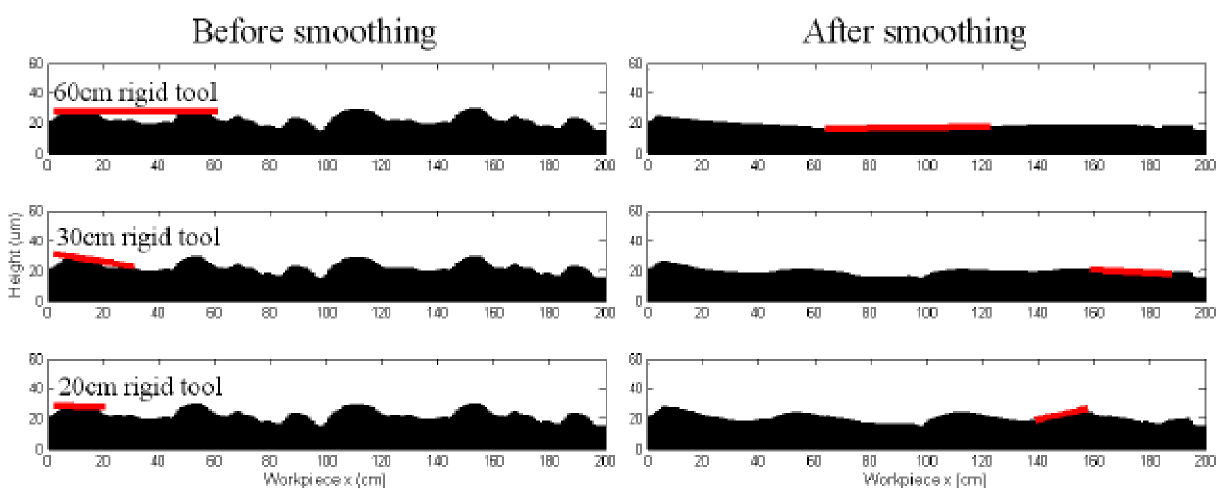
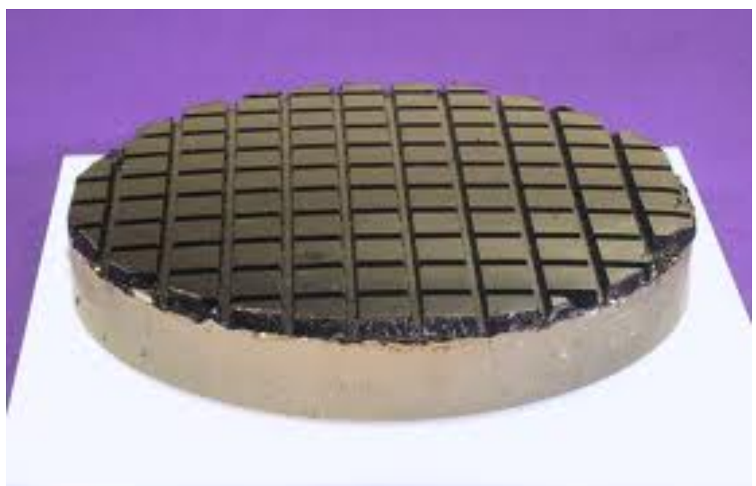


Fig. 3. Smoothing effect simulation using an infinitely rigid tool (Media 1).

Pitch and polishing surfaces

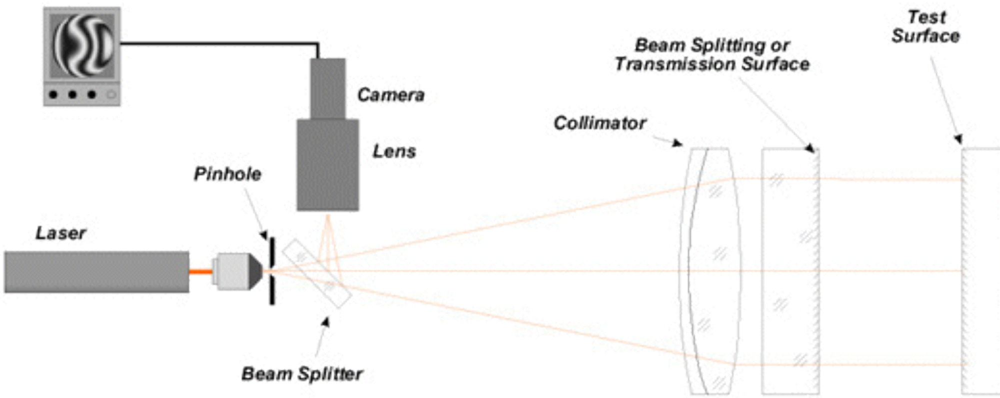
- Traditional polishing surface is pitch, used by Newton to polish first telescope mirrors.
- Extremely viscous fluid, like tar. Behaves like a solid for short periods, like a viscous fluid on longer timescales.
- Serves 2 roles:
  - Abrasive particles embed in pitch surface and are dragged across mirror surface.
  - Flows to match the shape of the mirror when pressed against mirror.
- Lap surface must match mirror surface to ~1 micron in order to achieve smoothing, and to maintain uniform pressure for figuring.
- Synthetic polishing pads are often used on top of pitch.



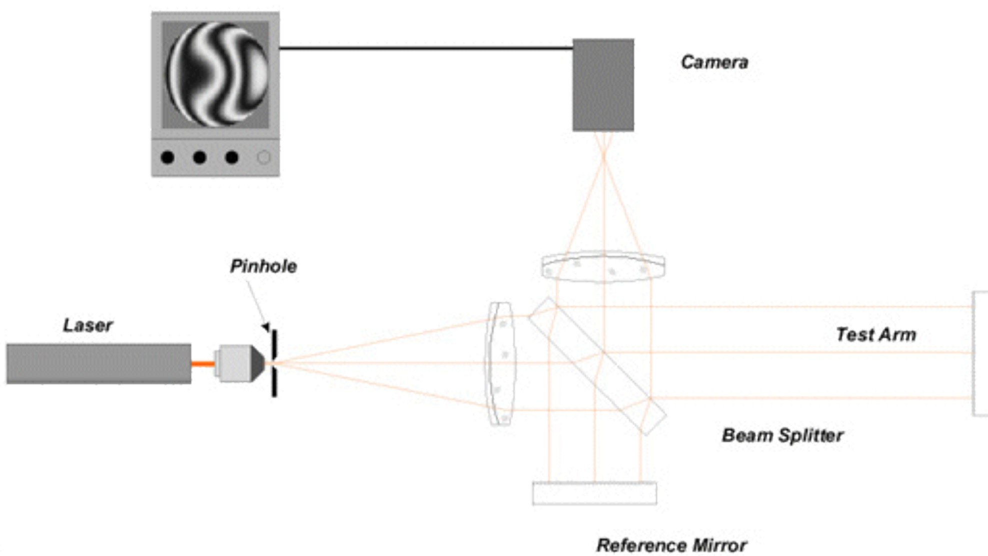
Polishing aspheres

- 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.)
  - rigid-conformal lap (Kim and Burge)

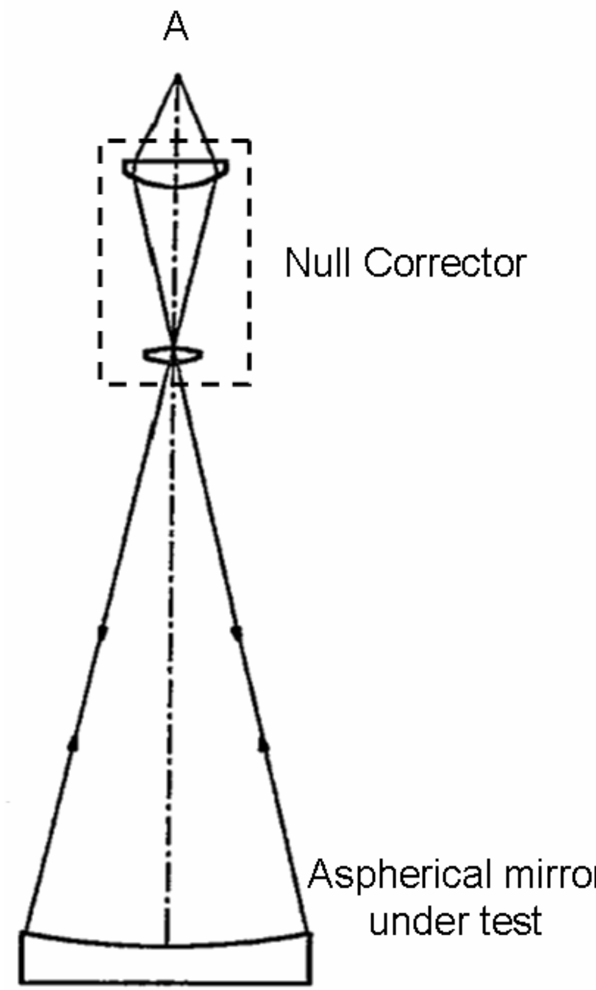
Measurement



Laser Fizeau Interferometer

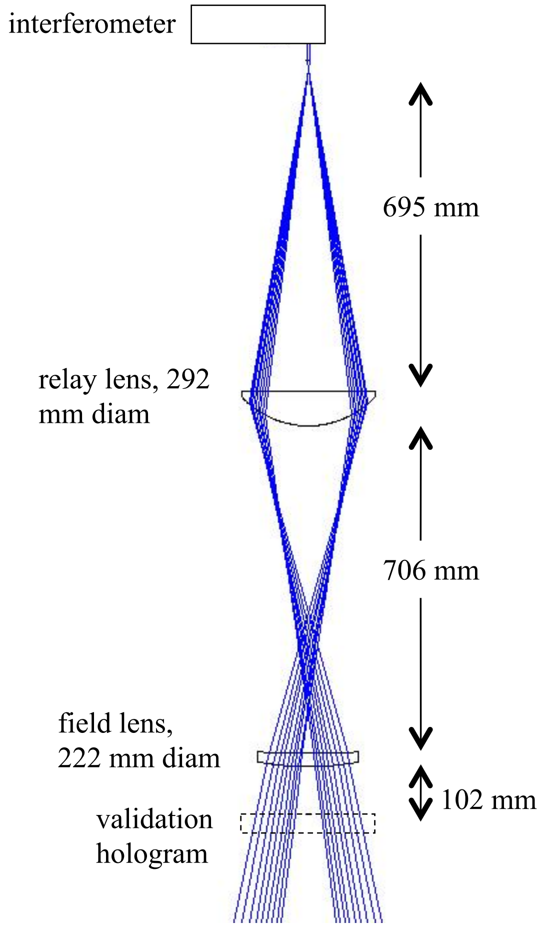


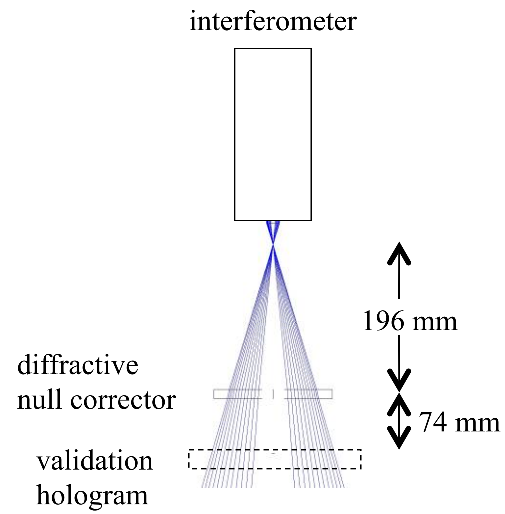
Twyman Green Interferometer



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

Measuring aspheres: null correctors and validation holograms for LSST





Test of tertiary mirror uses single-element diffractive null corrector, and similar validation hologram.

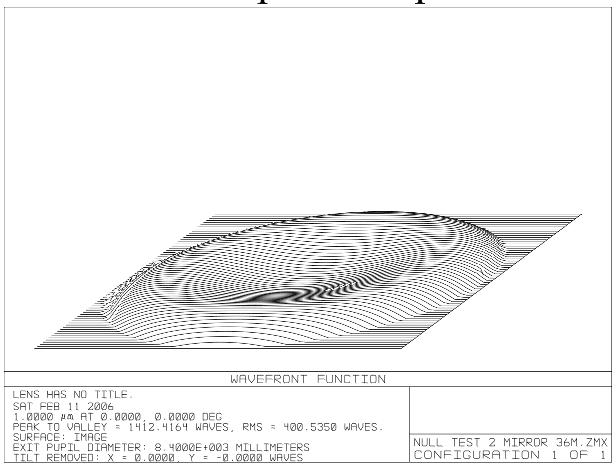
Validation holograms provide independent validation of accuracy of test wavefront.

Test of primary mirror uses 2-element refractive null corrector. To validate its accuracy, a computer-generated hologram (CGH) designed to mimic perfect mirror can be inserted below null corrector.

Optical tests for LBT and GMT

LBT (8.4 m f/1.1)

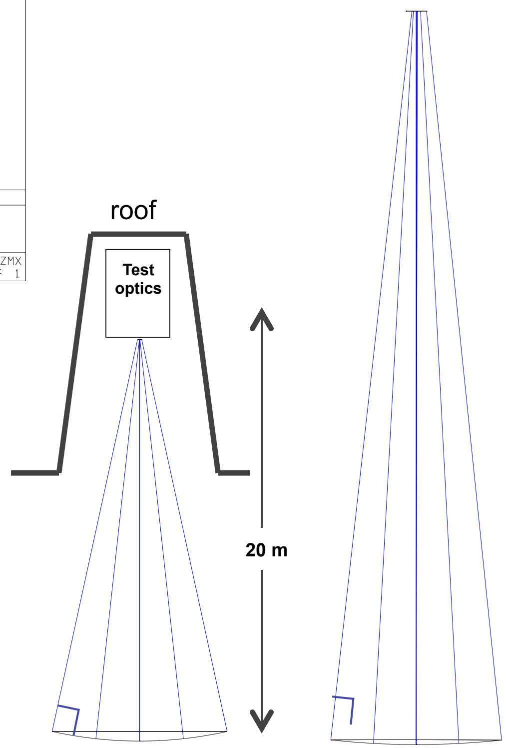
1.4 mm aspheric departure



Axisymmetric

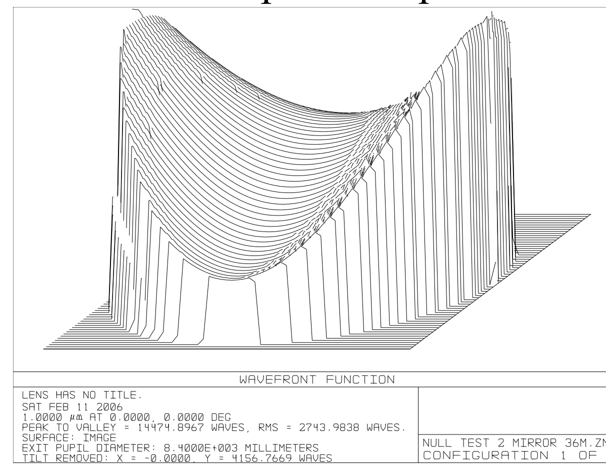
Test optics at ~20 m

Light beam from optical test is only 200 mm diameter near the test optics. Allows direct measurement of test wavefront with hologram.



GMT segment

14 mm aspheric departure

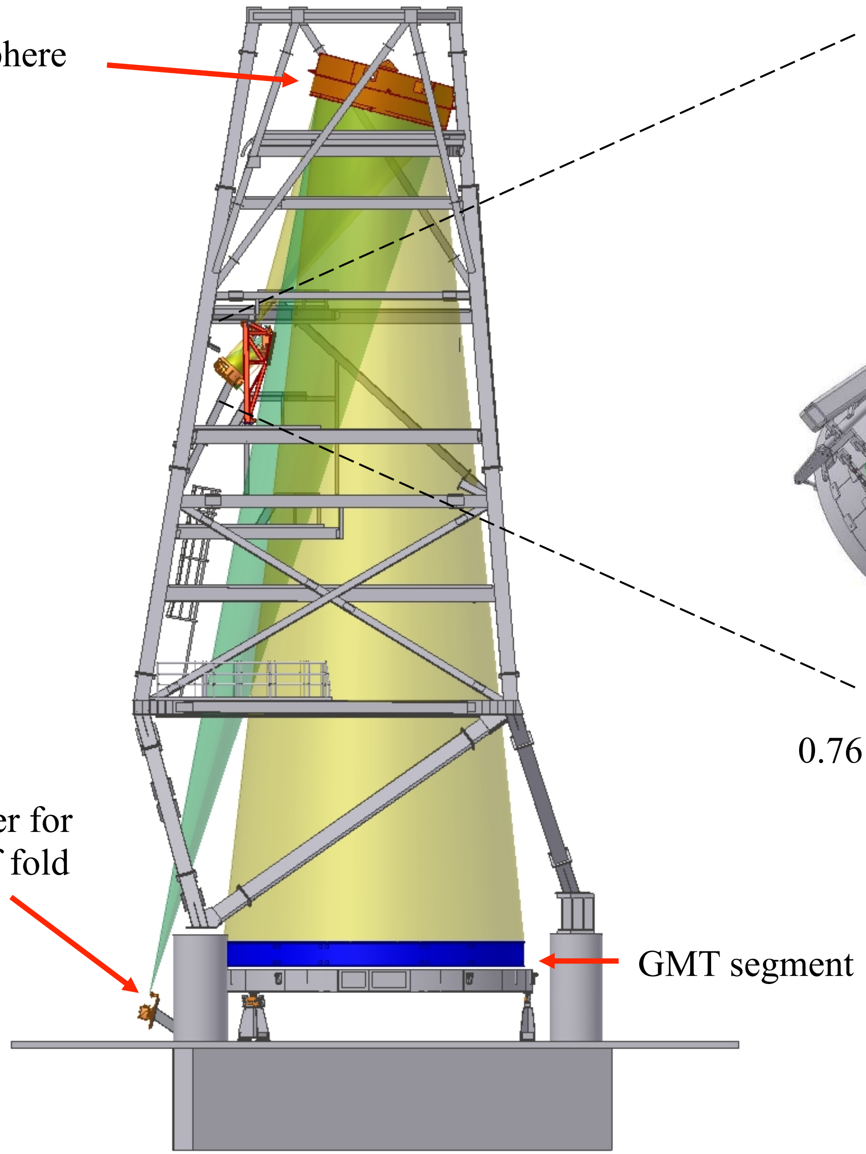


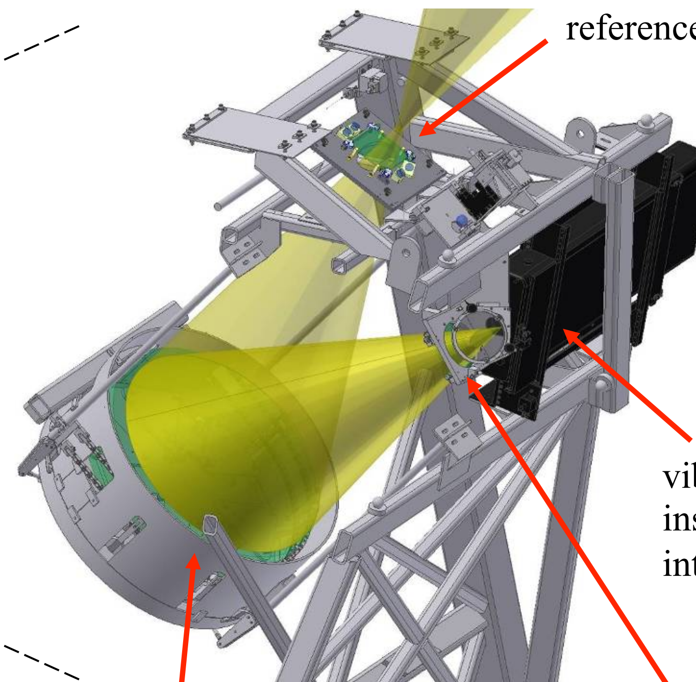
No axisymmetry

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

Use independent tests instead.

GMT optical test

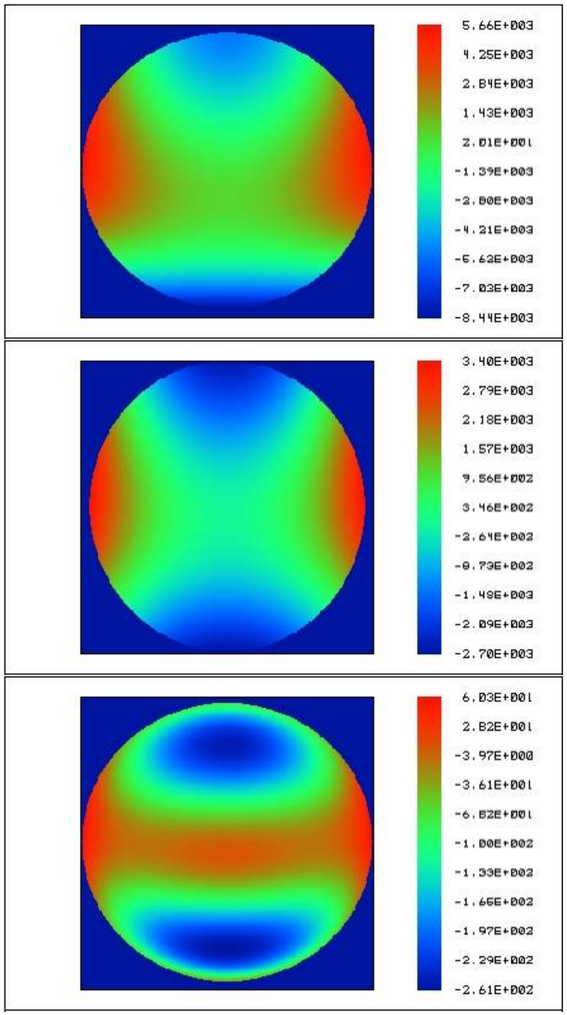




Reference CGH validates WF from first 2 elements of null corrector, and is used to align large fold sphere and GMT segment to that WF. But no hologram can validate WF from full null corrector.

Shaping of test wavefront by null corrector

Follow wavefront from segment back to interferometer:

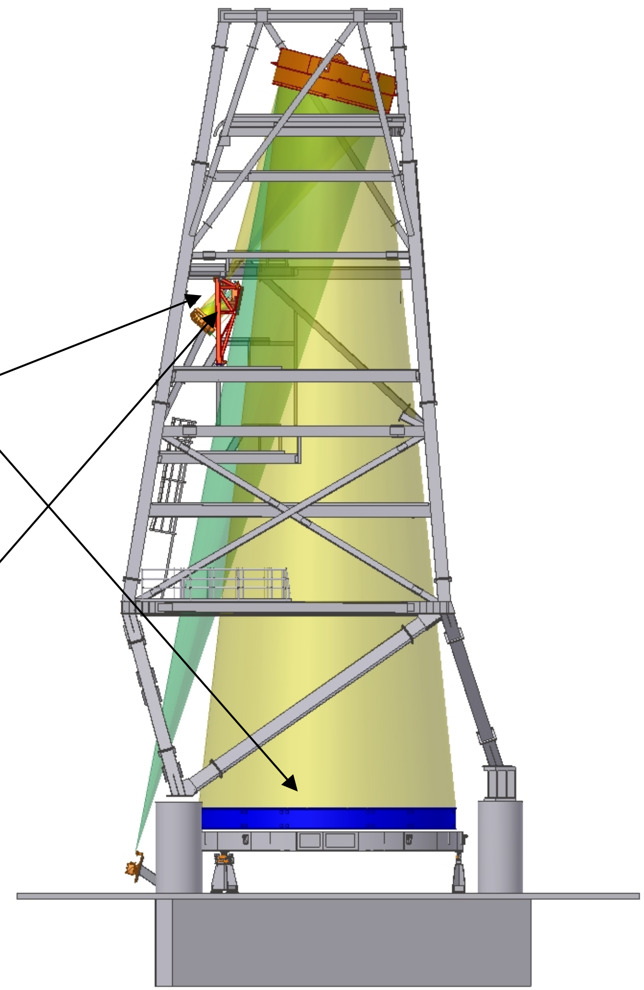


difference from sphere (µm)

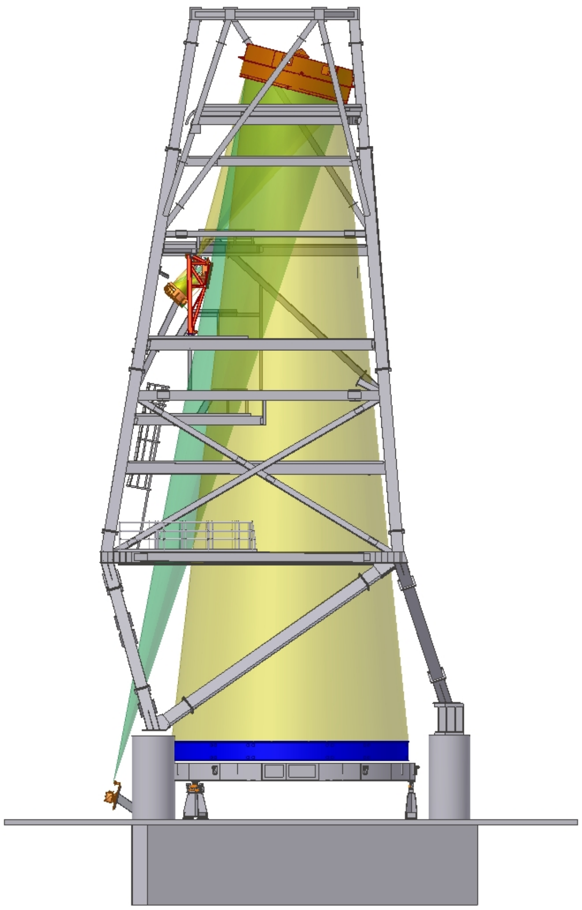
14 mm p-v at GMT surface

6.1 mm p-v at intermediate focus between fold spheres

320 µm p-v between 76 cm sphere and CGH

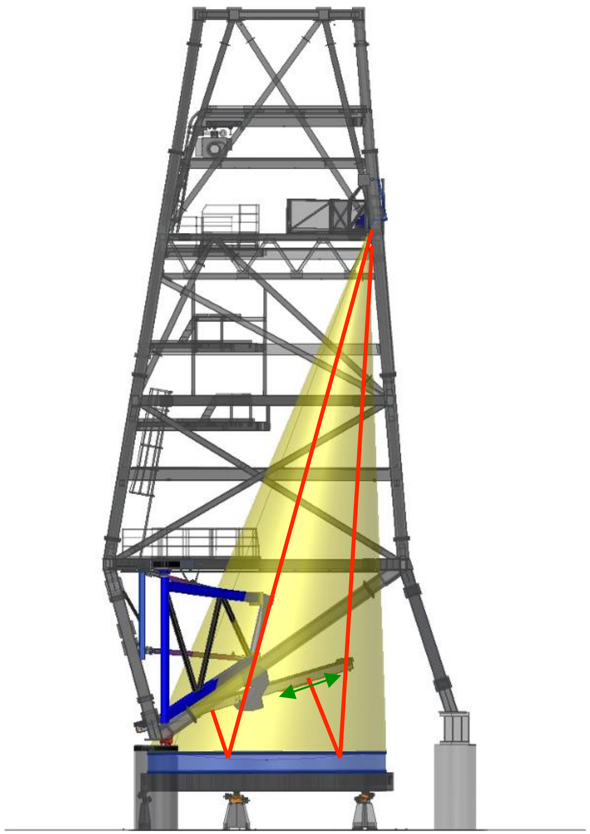


4 independent measurements



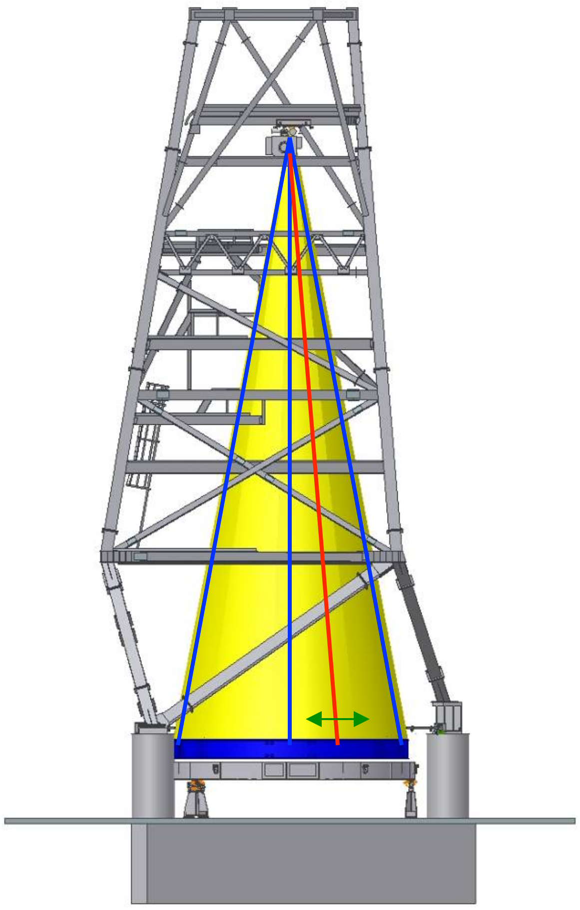
Principal optical test

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

More on active optics and model fitting

- Calculate or measure the effect on the mirror shape of a unit force on each actuator.
  → 160 influence functions
- Measure current shape error.
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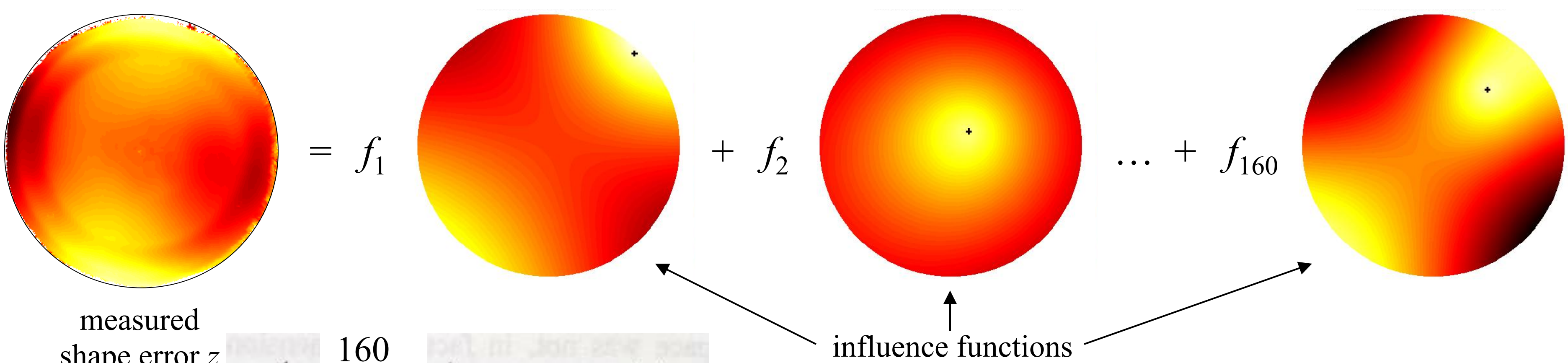

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- Influence functions are not localized because of compensation for net force and moment.
- Each 2-D shape becomes a ~300 x 1 column vector.
- $\boldsymbol{A}$ has units of nm/N. Each column of $\boldsymbol{A}$ is one influence function.

Solving $\boldsymbol{A}f = z$

- See *Numerical Recipes* for insightful (but not easy) description of options.
- Generally have more displacements than forces (more data than unknown model parameters).
- No exact solution: want the approximate solution that minimizes sum of squares of residual errors.
- Find it any of a number of ways, e. g. Matlab "\" operator, *if you know there are no redundant equations*.
  - 2 or more influence functions that are very similar counts as redundancy.
- If there are, solution will blow up because similar influence functions will be combined with large forces so as to nearly cancel.
- In our case there is redundancy because forces are not independent. They satisfy
  - sum of forces = weight of mirror
  - net moment about $x = 0$
  - net moment about $y = 0$
- Could fix that by removing 3 influence functions.
- But generally you also want to limit the forces: remove patterns of forces that contribute little to reducing residual error but use lots of force.
- Take care of both issues, and be much better aware of what's going on physically, by solving with singular-value decomposition….

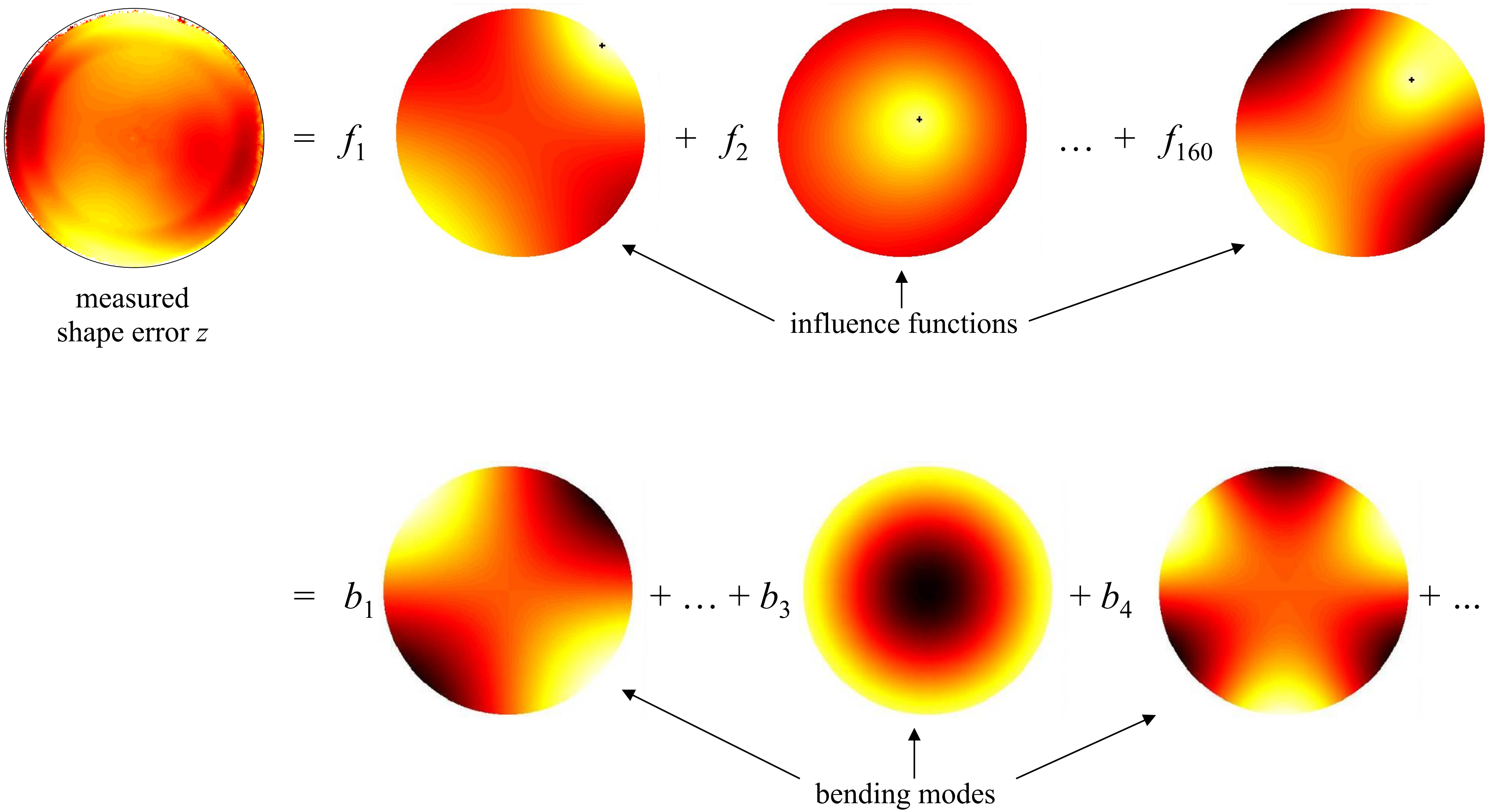
Singular-value decomposition

- From *Recipes*:

$$\begin{pmatrix} \\ \\ \mathbf{A} \\ \\ \\ \end{pmatrix} = \begin{pmatrix} \\ \\ \mathbf{U} \\ \\ \\ \end{pmatrix} \cdot \begin{pmatrix} w_1 & & & \\ & w_2 & & \\ & & \cdots & \\ & & \cdots & \\ & & & w_N \end{pmatrix} \cdot \begin{pmatrix} & & \\ & \mathbf{V}^T & \\ & & \end{pmatrix} \tag{2.6.1}$$

- Interpret these factors in physical terms:
- ***U*** has same dimensions as ***A*** apart from normalization. Columns of ***U*** are displacement vectors that form an orthonormal basis for all displacements that can be achieved with your 160 actuators.
  - Each column is called a *bending mode*.
- ***V*** is 160 x 160. Columns of ***V*** are force sets that form an orthonormal basis and match up with columns of ***U***: column j of ***V*** produces column j of ***U***.
- ***W*** is a 160 x 160 diagonal matrix whose elements w_j give magnitudes of displacement.
  - If $f = c_j\, V_j$ then $z = c_j\, w_j\, U_j$
  - Think of w_j as the flexibility of bending mode j; it contains all the scaling information.
- SVD is unique apart from re-ordering of columns of ***U*** and ***V***, and corresponding w_j.
- Standard order has w_j decreasing from most flexible to stiffest.

Resolve measured shape error into bending modes



(What does mode 2 look like?)

Solution by SVD

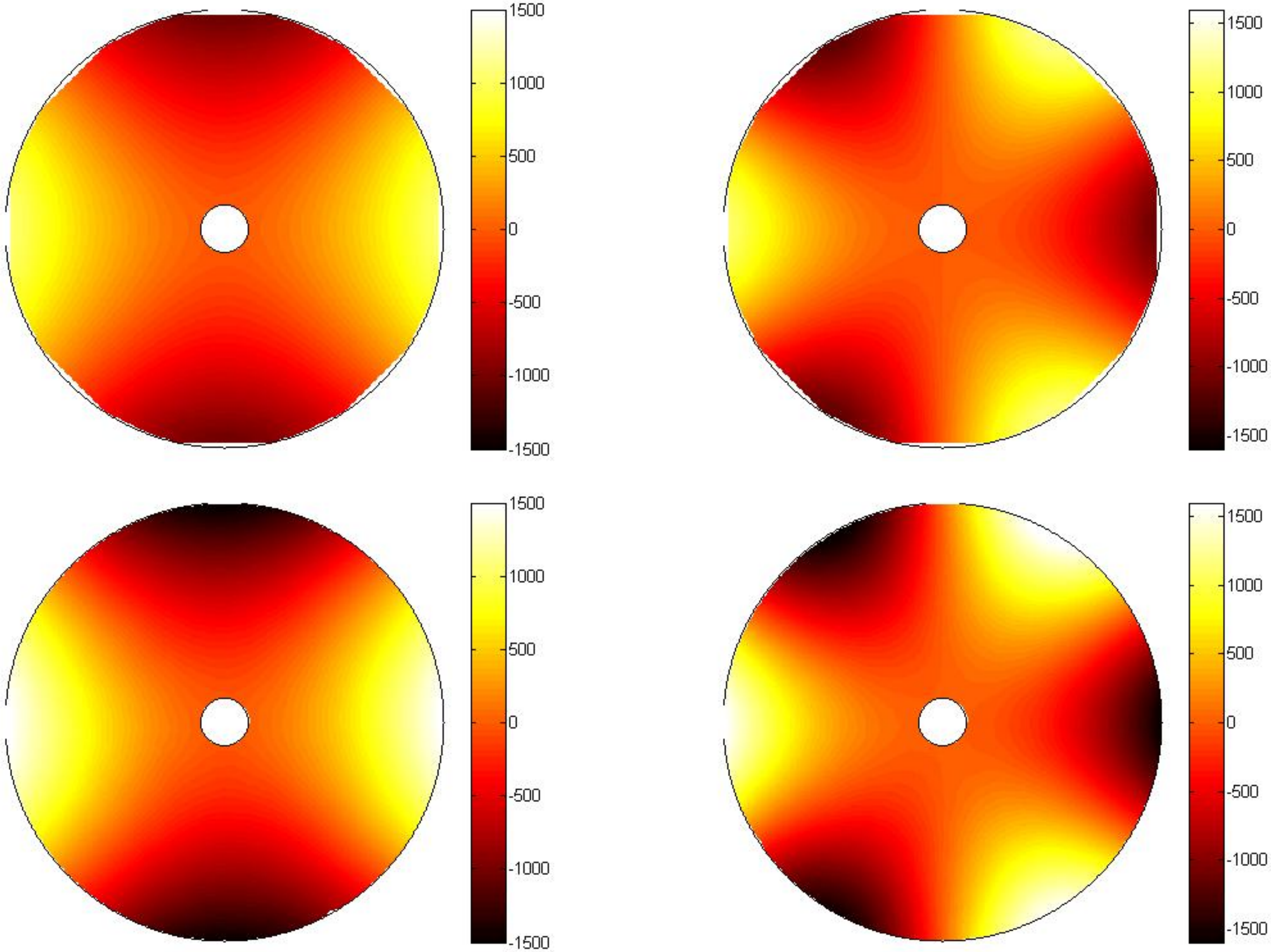
$$\begin{pmatrix} f \end{pmatrix} = \begin{pmatrix} \mathbf{V} \end{pmatrix} \cdot \begin{pmatrix} \mathrm{diag}(1/w_j) \end{pmatrix} \cdot \begin{pmatrix} \mathbf{U}^T \end{pmatrix} \cdot \begin{pmatrix} z \end{pmatrix}$$

- From right to left:
  1. Take scalar product of measured surface error and each bending mode:
     - Resulting vector tells how much of each bending mode there is (mode coefs b_j from prev slide).
  2. Multiply each mode coefficient by stiffness $1/w_j$.
     - Resulting vector tells how much of each force mode.
  3. Convert from force modes to actuator forces.
- If there is redundancy, some $w_j = 0$.
  - Corresponding columns of $\boldsymbol{V}$ are the force vectors that cause no displacement: the *nullspace* of $\boldsymbol{A}$.
  - Can add an infinite amount without changing mirror shape.
  - Eliminate them by setting those $(1/w_j)$ to zero.
- Do same for any w_j small enough to give unreasonable forces.
- Go further: Eliminate all the modes that don't affect the shape enough to justify their large forces.

Measured bending modes for LBT primary mirror

calculated by FEA

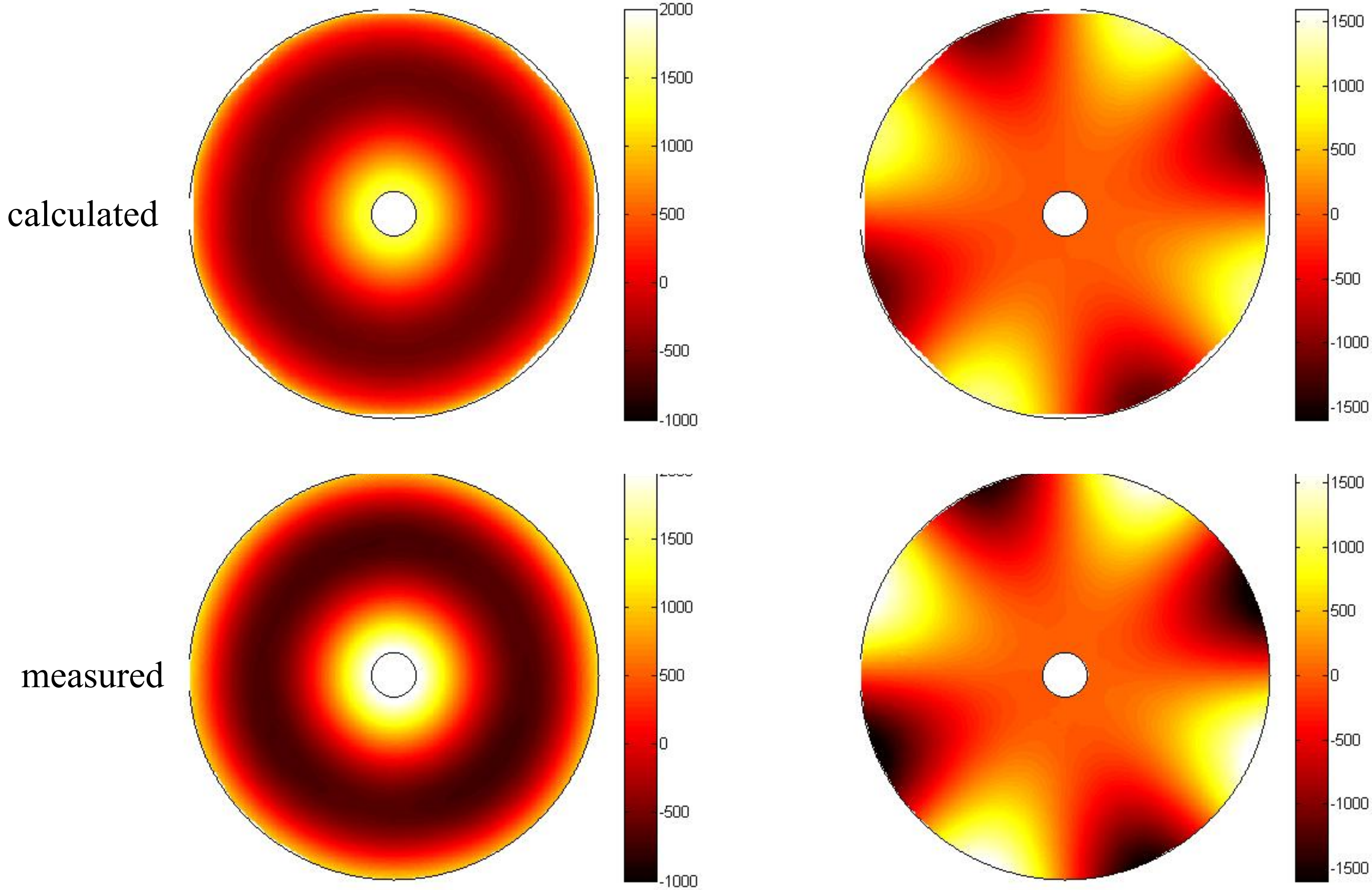
measured in lab



mode 1
5 N rms force

mode 3
30 N rms force

Measured bending modes for LBT primary mirror



mode 5
60 N rms force

mode 6
85 N rms force

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.
    - Trivial 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.