Fabrication challenges and solutions
a. k. a.
Design and manufacture of mirrors, and active optics

Buddy Martin

Steward Observatory Mirror Lab

Outline

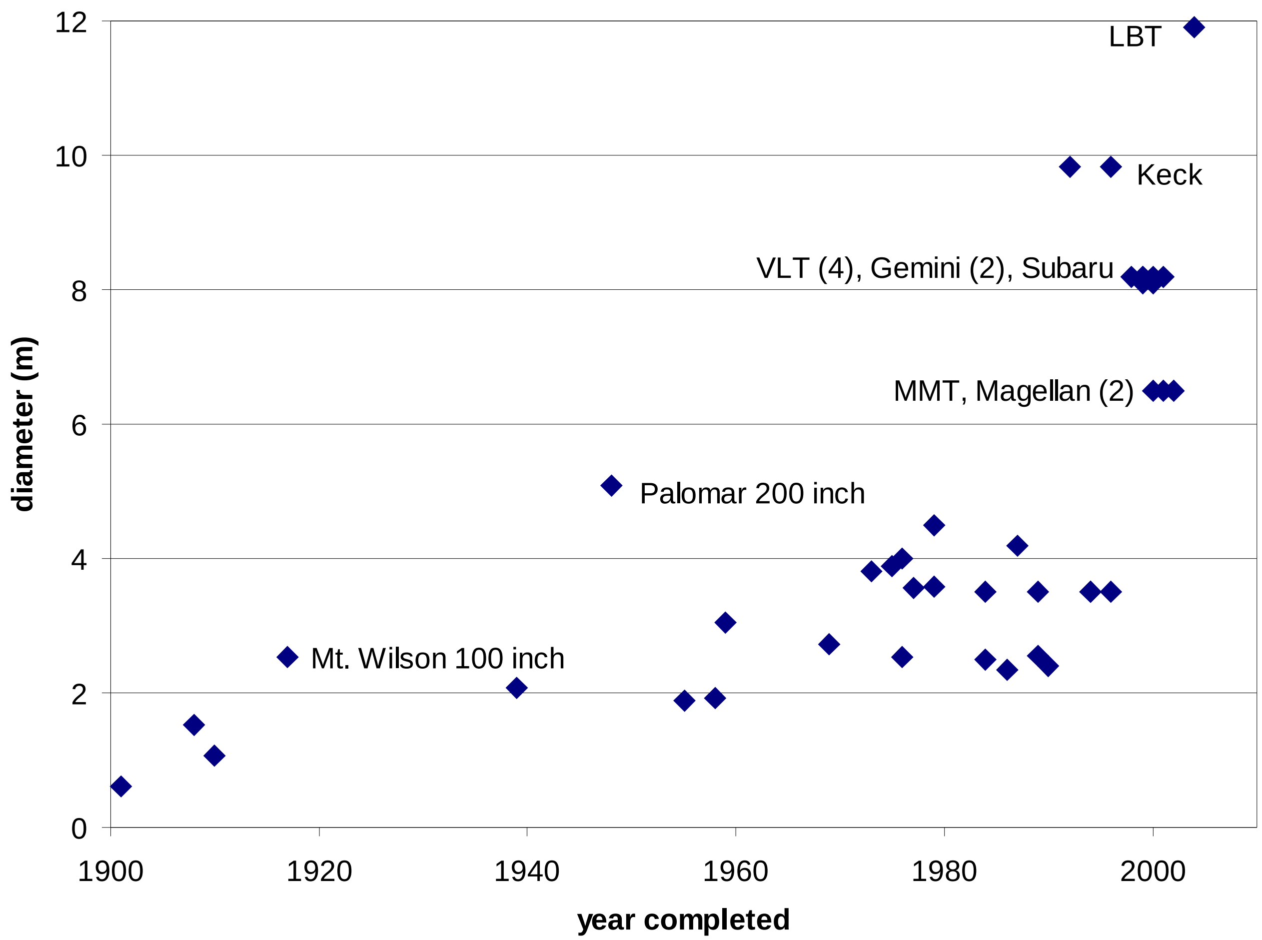
- What makes a good mirror?
- Modern mirror concepts
  - thin solid mirrors
  - segmented mirrors
  - lightweight mirrors
- Honeycomb mirrors
  - design
  - casting
- Optical manufacture
  - requirements
  - aside on active optics and model fitting
  - fabrication (2/17/11 lecture at Mirror Lab)
    - machining
    - polishing
  - measurement (2/17/11 lecture at Mirror Lab)
    - interferometry
    - null correctors
    - GMT measurements

What makes a good mirror?

- Fundamental requirement is to deliver a “good” wavefront to focal plane in almost all conditions.
  - Hold its shape to a fraction of a wavelength
  - 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 prop. to $E\ t^3$
  - E = Young’s modulus, t = thickness
  - more complicated for lightweight mirror
  - Stiffness of honeycomb mirrors is about right; use this as baseline for comparisons.
- Stiffness against gravity: bending stiffness prop. to $E\ t^2 / \rho$
  - Again, use honeycomb mirrors as baseline.
- 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” prop. to $T - T_{air} \sim dT_{air}/dt \cdot \tau$
  - dT_{air}/dt = rate of change of air temperature
  - τ = mirror’s thermal time constant $\sim c\ \rho\ t^2 / k$
    - c = specific heat, k = thermal conductivity, t = thickness
  - Becomes a problem for $T - T_{air} > \sim 0.3$ K, $\tau > \sim 1$ 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.

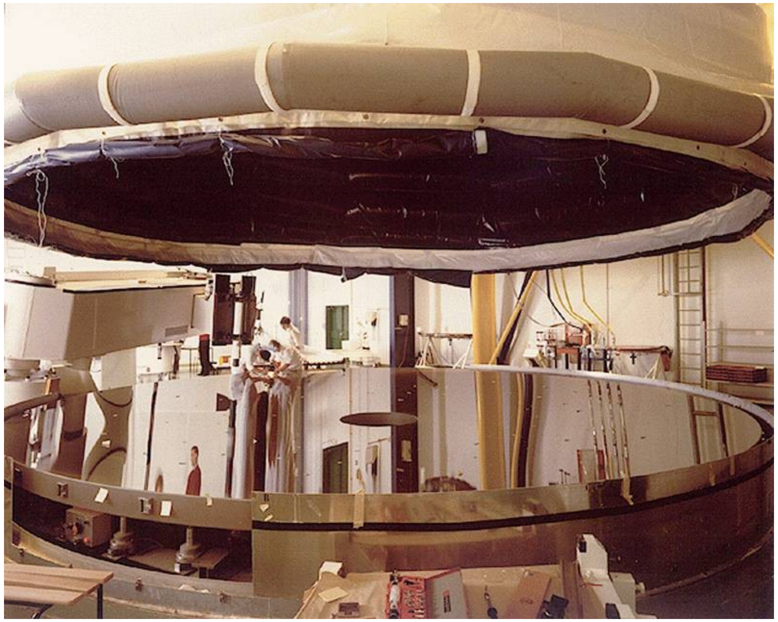
Optical telescopes

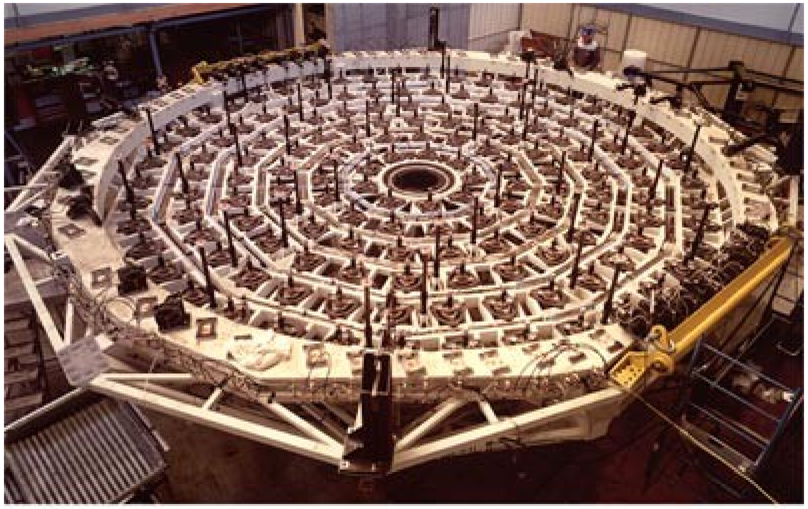


- Hale Telescope at Palomar used first large lightweighted mirror.
- Most powerful telescope for 45 years because of difficulty making a larger mirror that would not distort due to its weight and thermal inertia.

New mirror concepts after 1980

- 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 expansion coefficient
    - 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



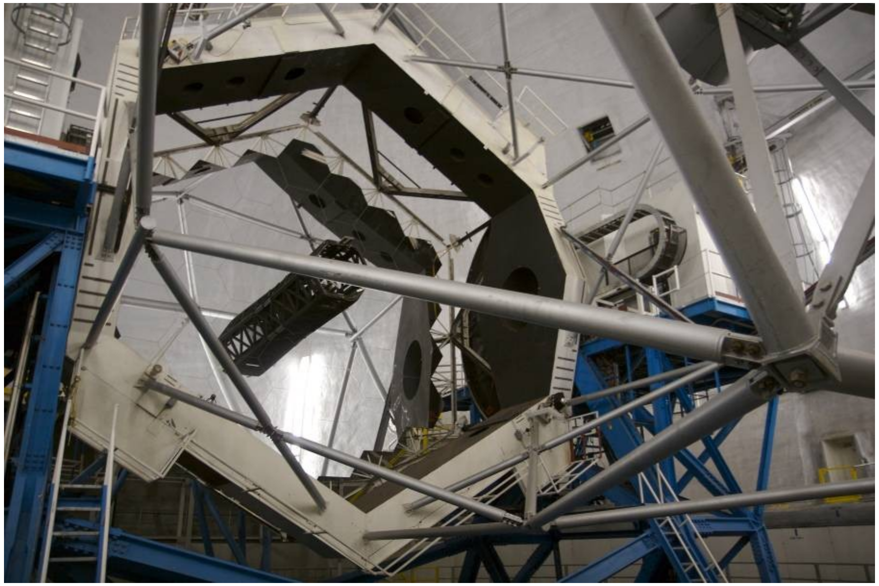


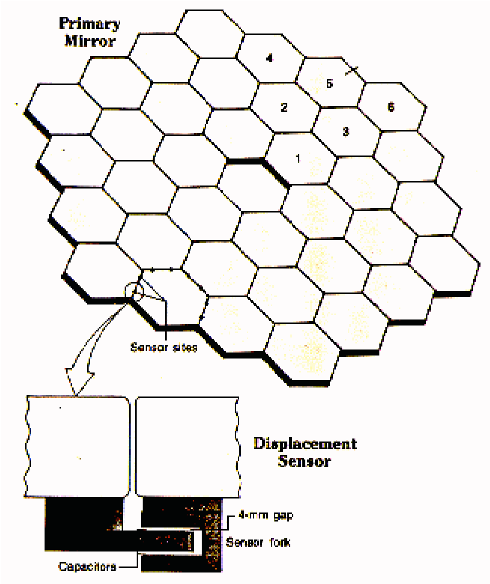
Active Mirror Supports in VLT M1 Cell

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

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
  - Precise segment-segment displacement sensors (capacitive)
  - Occasional wavefront measurement of segment phasing
- Used for Keck, Hobby-Eberly, Grantecan, SALT
- To be used for TMT (30 m), ESO ELT (42 m)

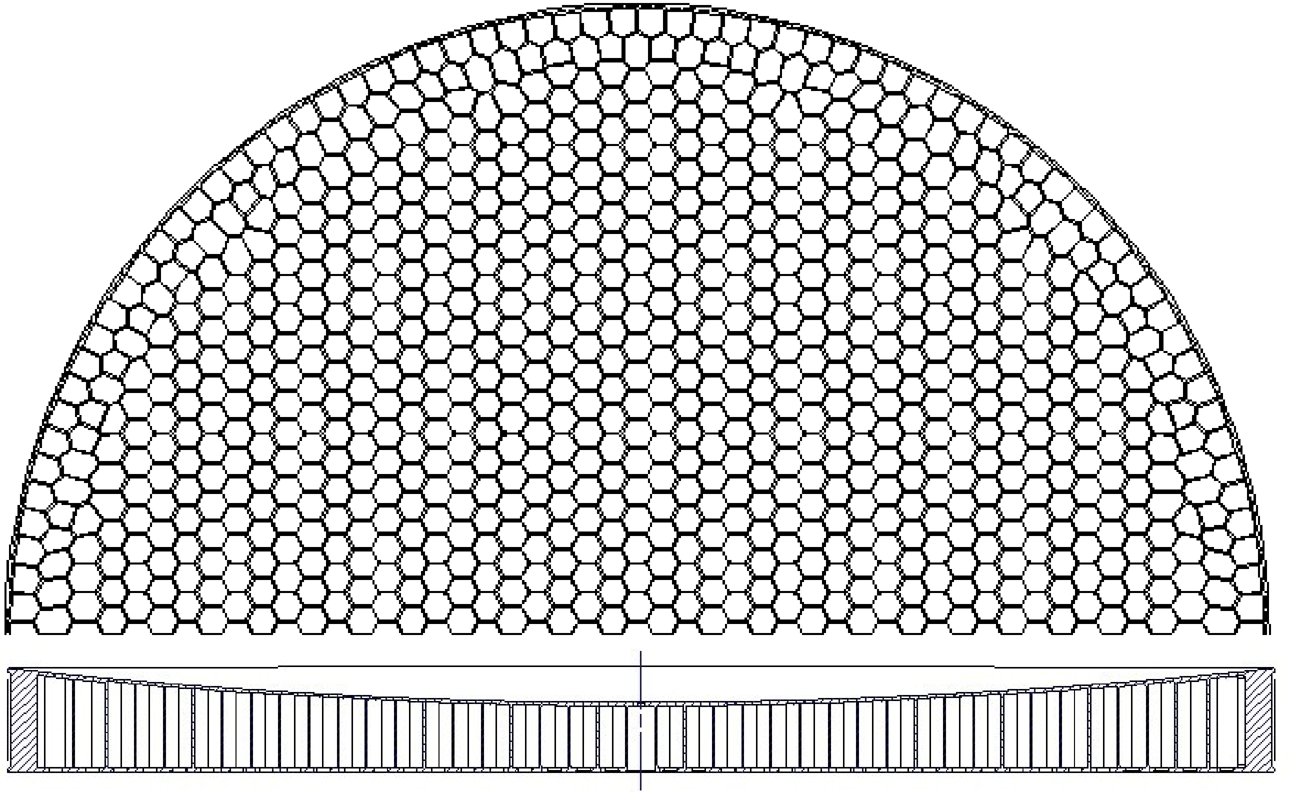




Honeycomb mirrors

- 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

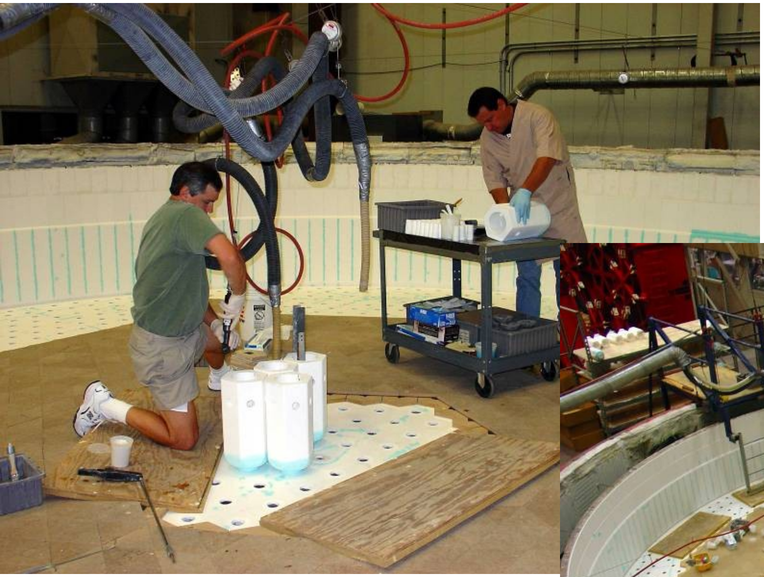
LBT mirror design



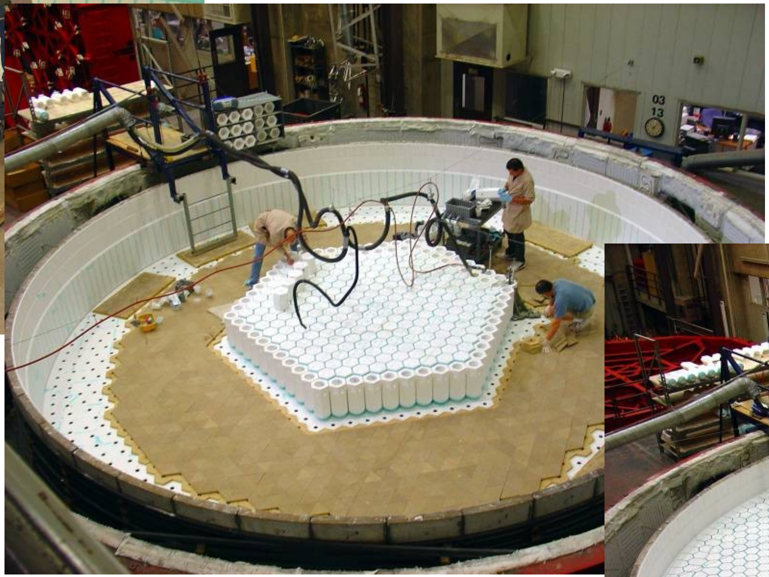
1. Borosilicate glass has the lowest expansion coef (3 ppm/K) among materials that can be cast into complex form.
2. Facesheet thickness = 28 mm to make $\tau < 1$ hr
3. Hex cavity size = 192 mm to limit gravity sag of unsupported facesheet to 7 nm
4. Rib thickness = 12 mm contributes little mass while maintaining safety.
5. Overall thickness 890 mm to give desired stiffness against wind.

- (1) - (4) are common to all SOML mirrors; (5) is typical.

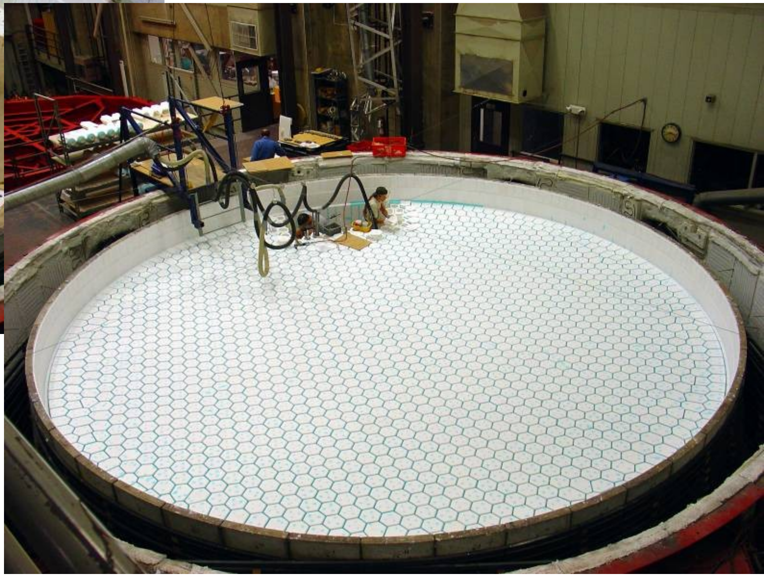
Casting process for GMT mirror: mold assembly



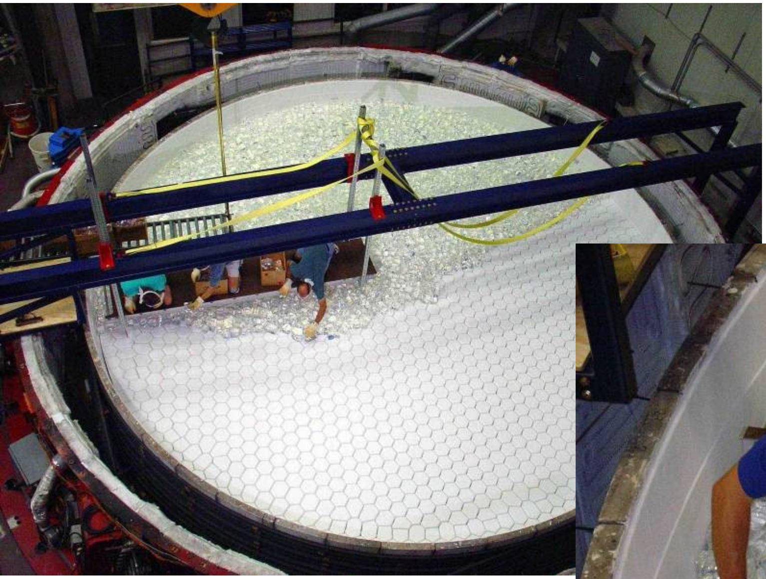
Machine and install 1681 ceramic fiber boxes in silicon carbide tub.

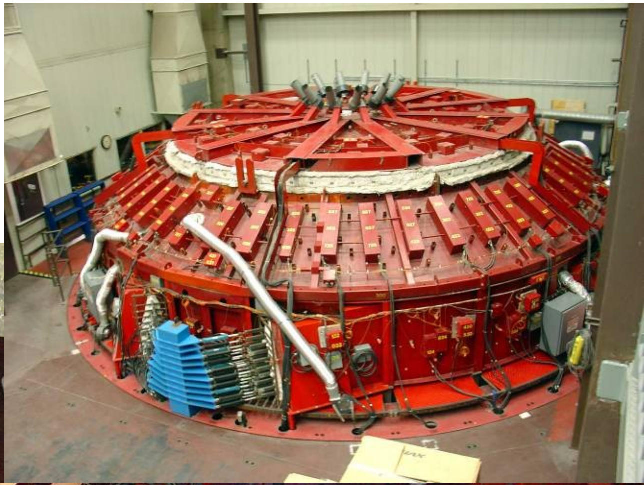


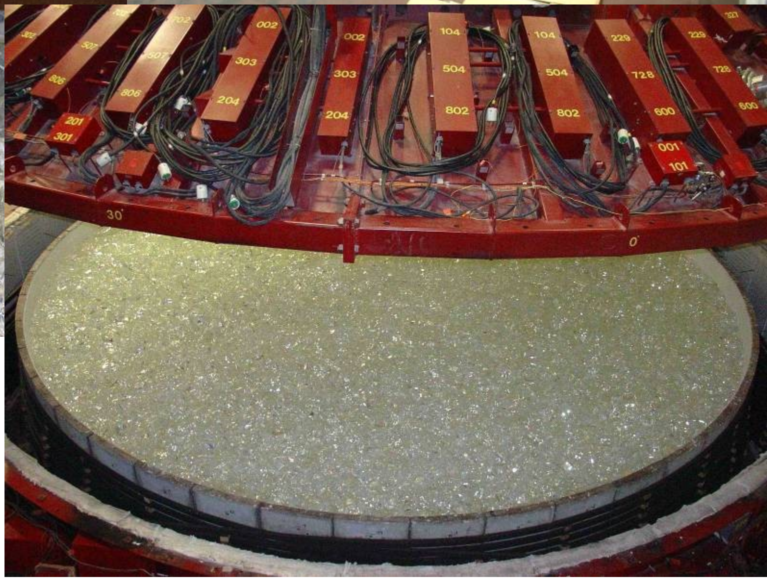
Tops of boxes follow shape of mirror surface; no two are identical.



Loading of glass



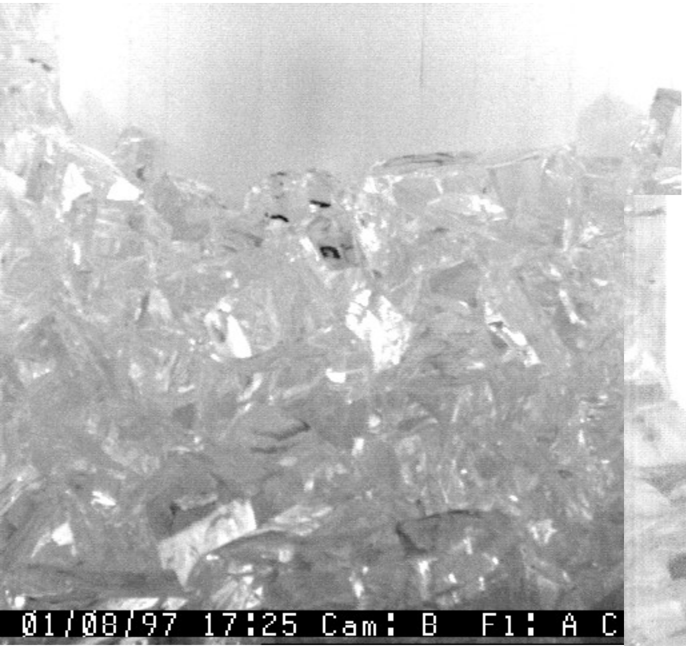


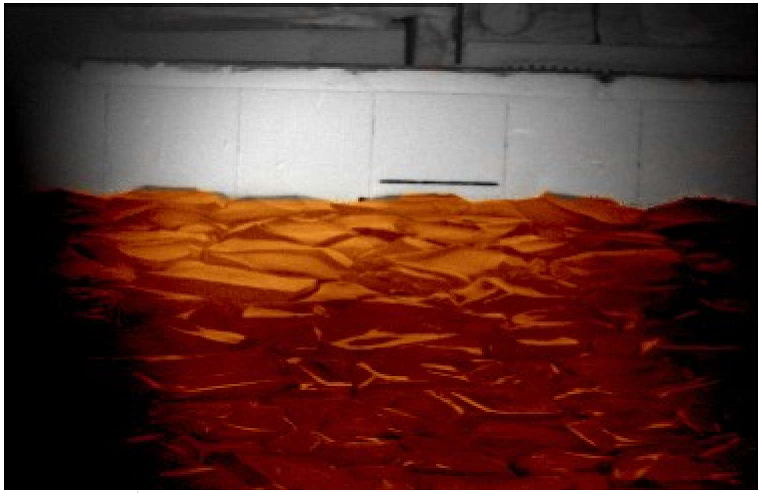


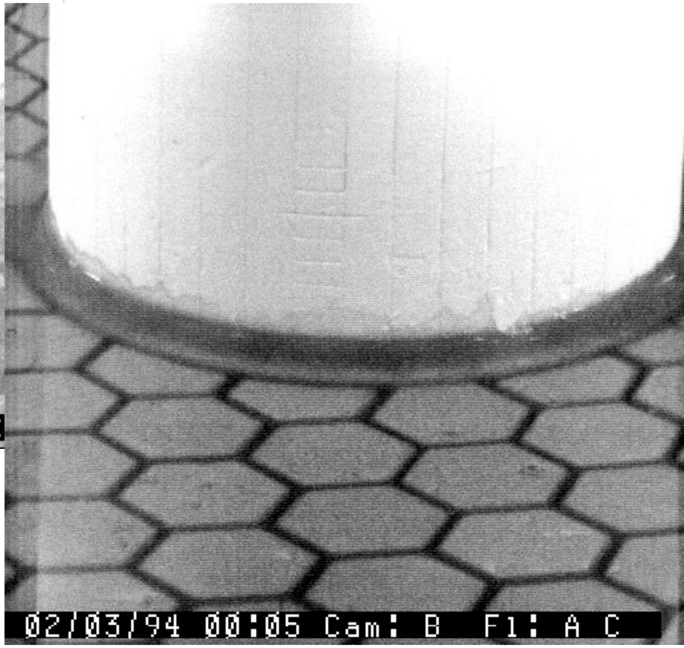
Inspect, weigh, and load 18 tons of Ohara E6 borosilicate glass in ~5 kg blocks.

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







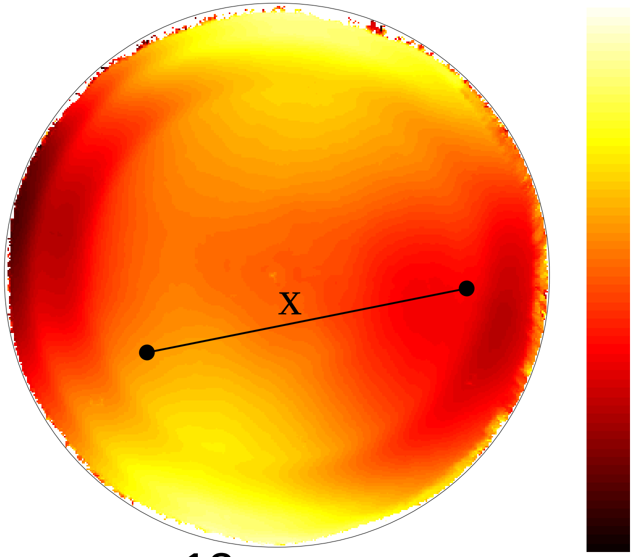
UV cameras mounted in the furnace lid monitor the casting.

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.

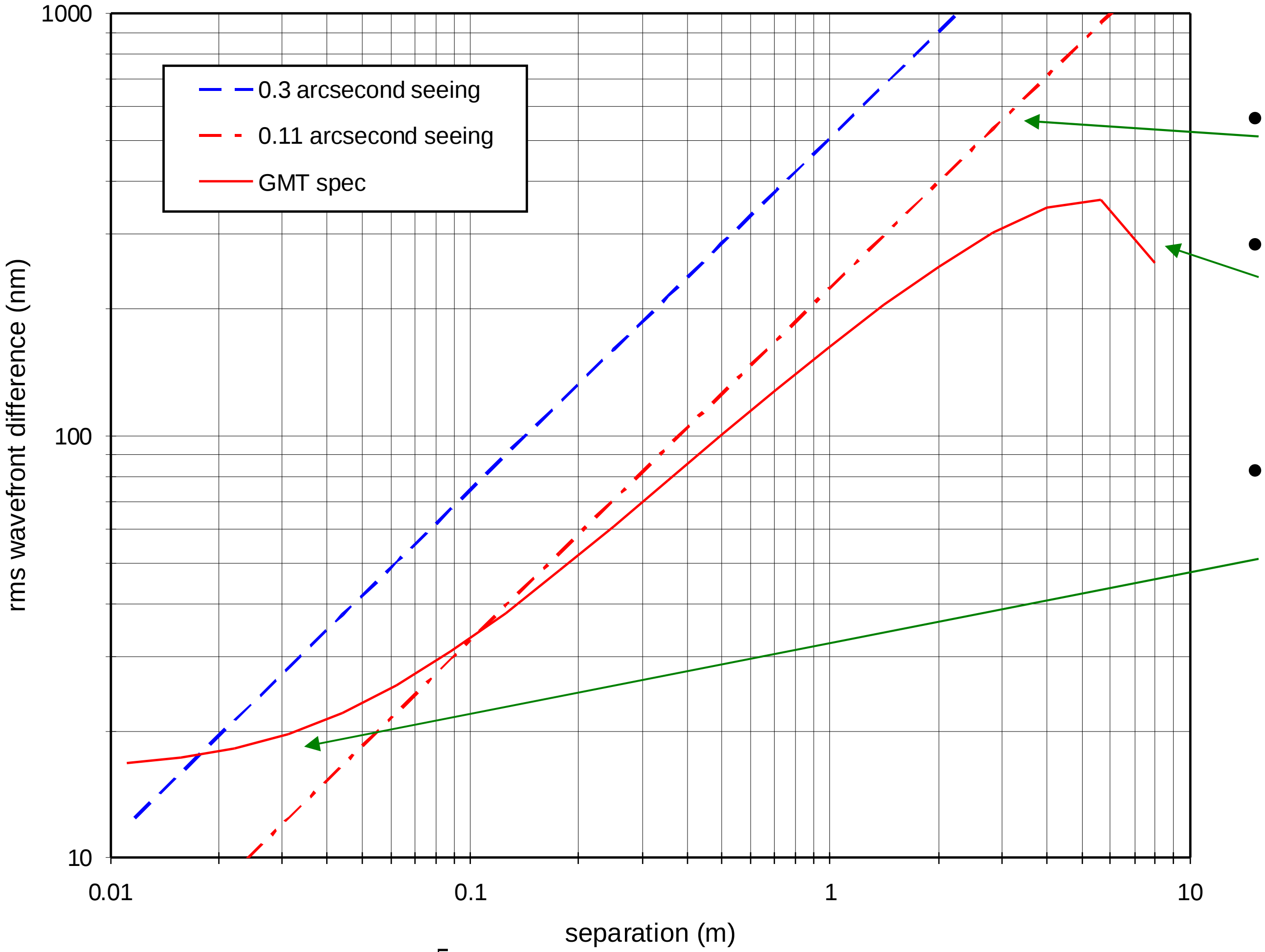
First GMT mirror blank

Manufacturing: Accuracy requirements

- 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.
- “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.
- 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



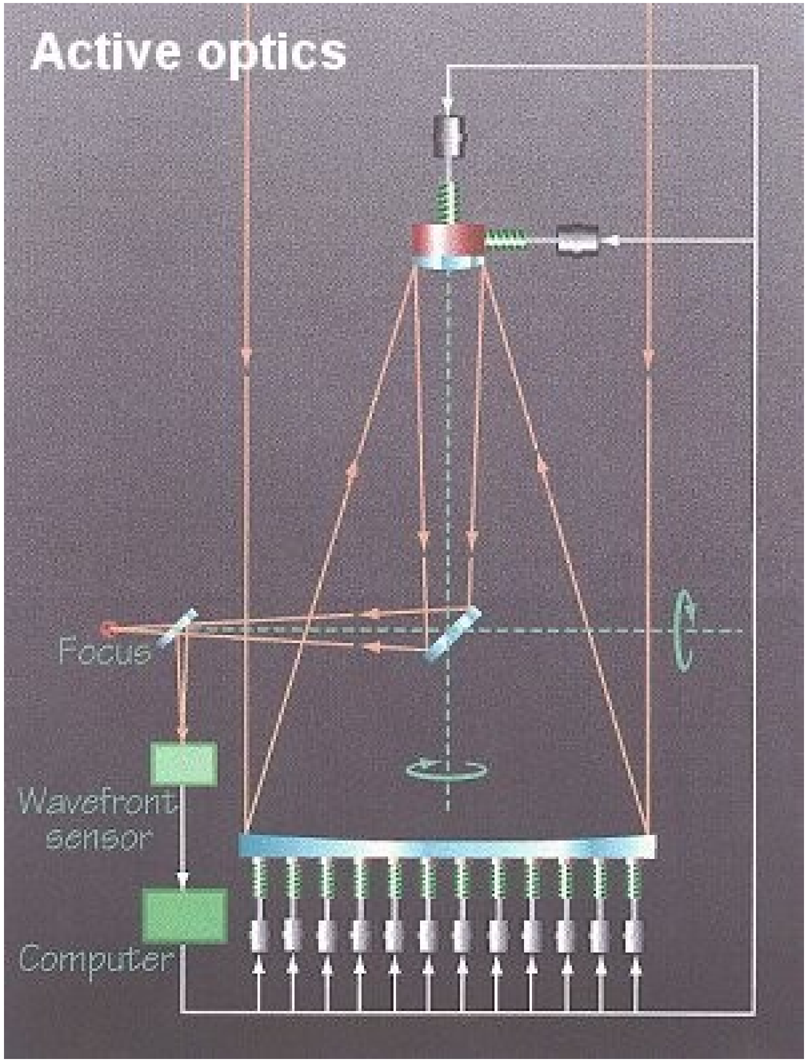
- Start with 0.11 arcsecond seeing.
- Eliminate tilt across full pupil: tighten on large scales.
- Add allowance for 2% scattering loss due to 16 nm rms WFE on small scales.

$$\delta^2(x) = \left(\frac{\lambda}{2\pi}\right)^2 6.88 \left(\frac{x}{r_0}\right)^{\frac{5}{3}}$$

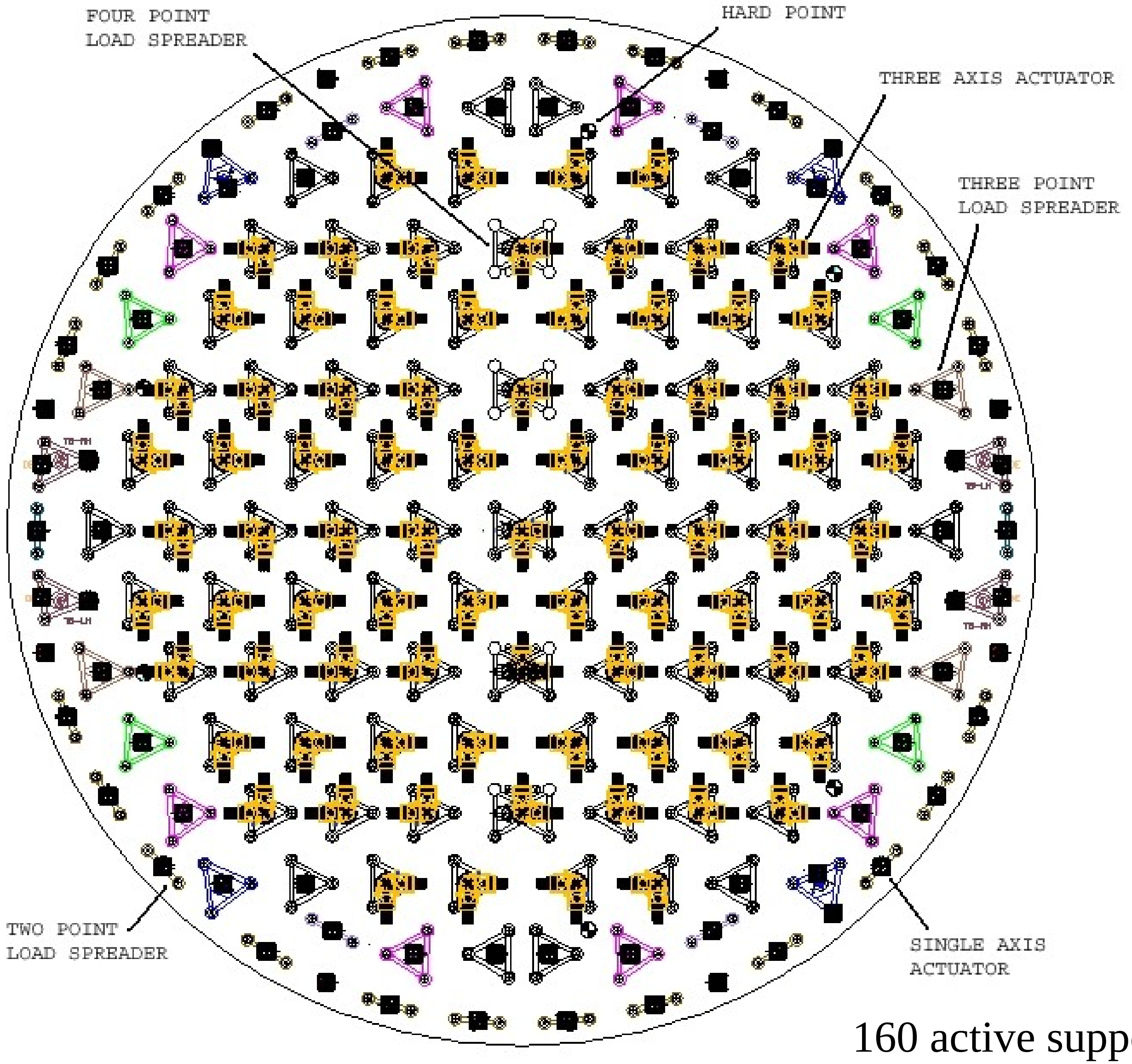
$$\theta = 0.98\frac{\lambda}{r_0}$$

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 the large-scale errors that are least stable.
- Implication for manufacturing:
  - No need to completely eliminate all low-order shape errors, because they will be controlled with active optics at telescope.
  - In fact, no point in it.
- Manufacturing requirement is to control all aberrations 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.



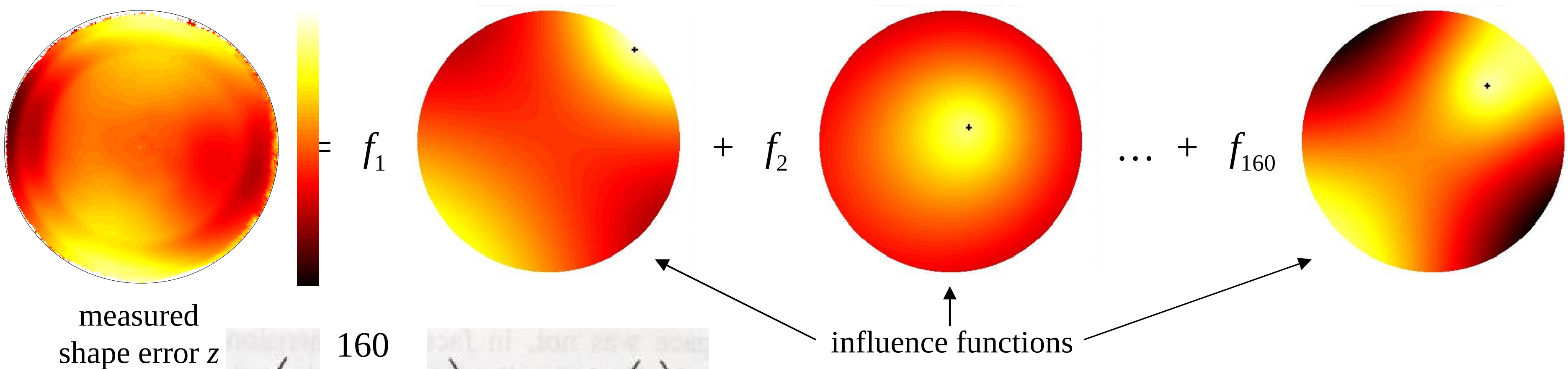
GMT mirror support layout

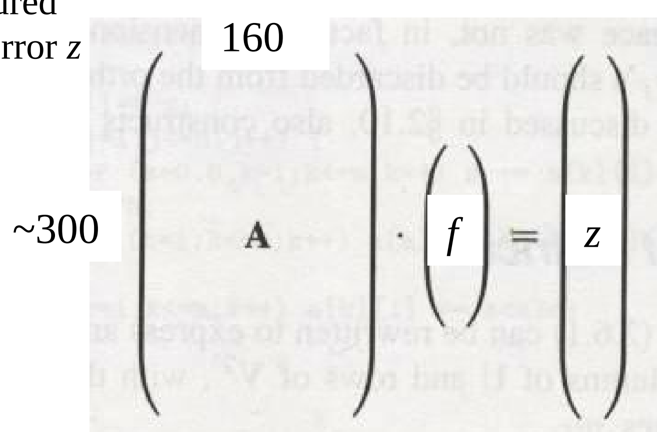


160 active support actuators

Active optics as a model-fitting problem

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





- 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.

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 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….

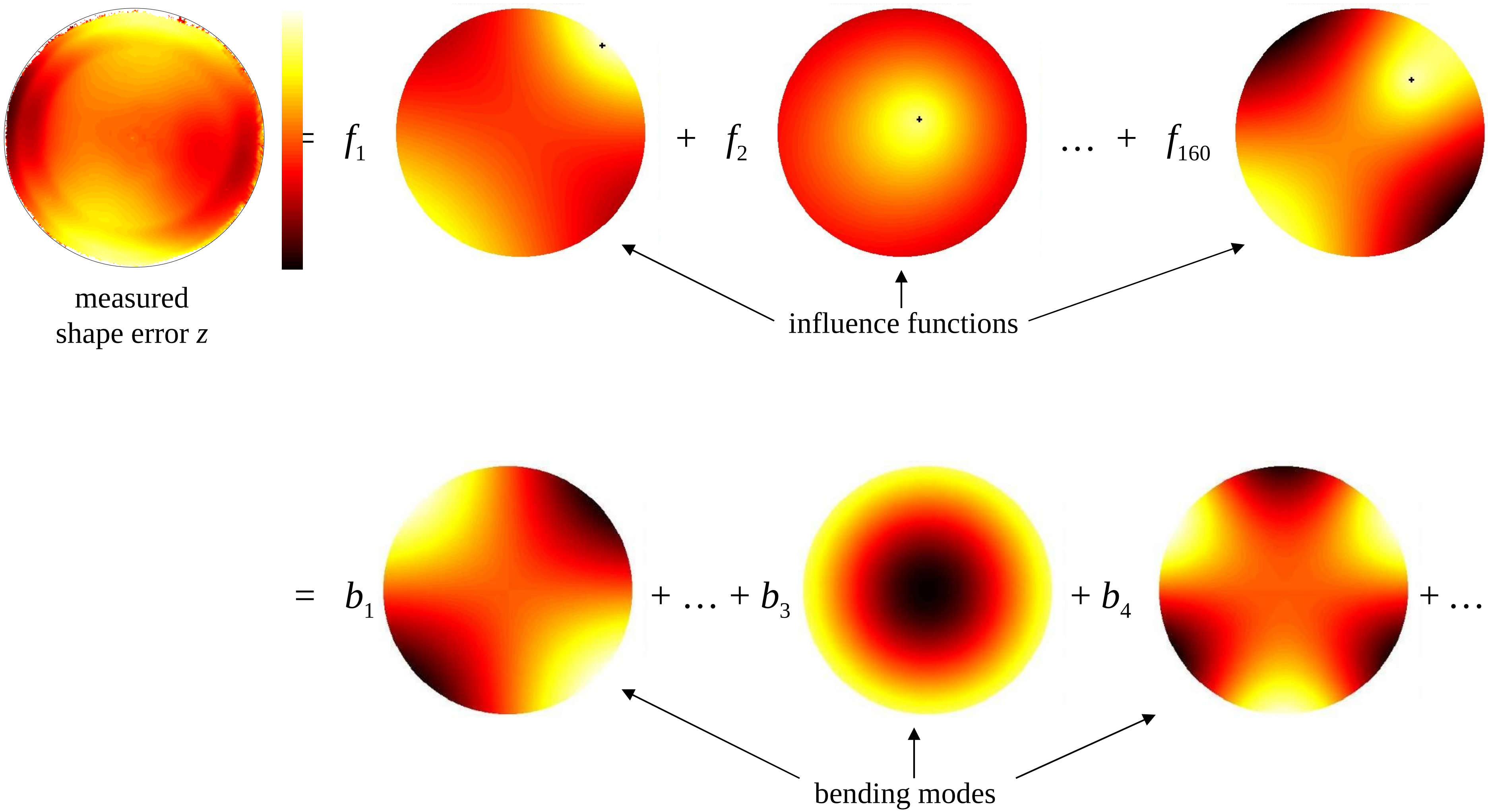
Singular-value decomposition

- From *Recipes*:

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

- Interpret these factors in physical terms:
- ***U*** has same dimensions as ***A***. 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

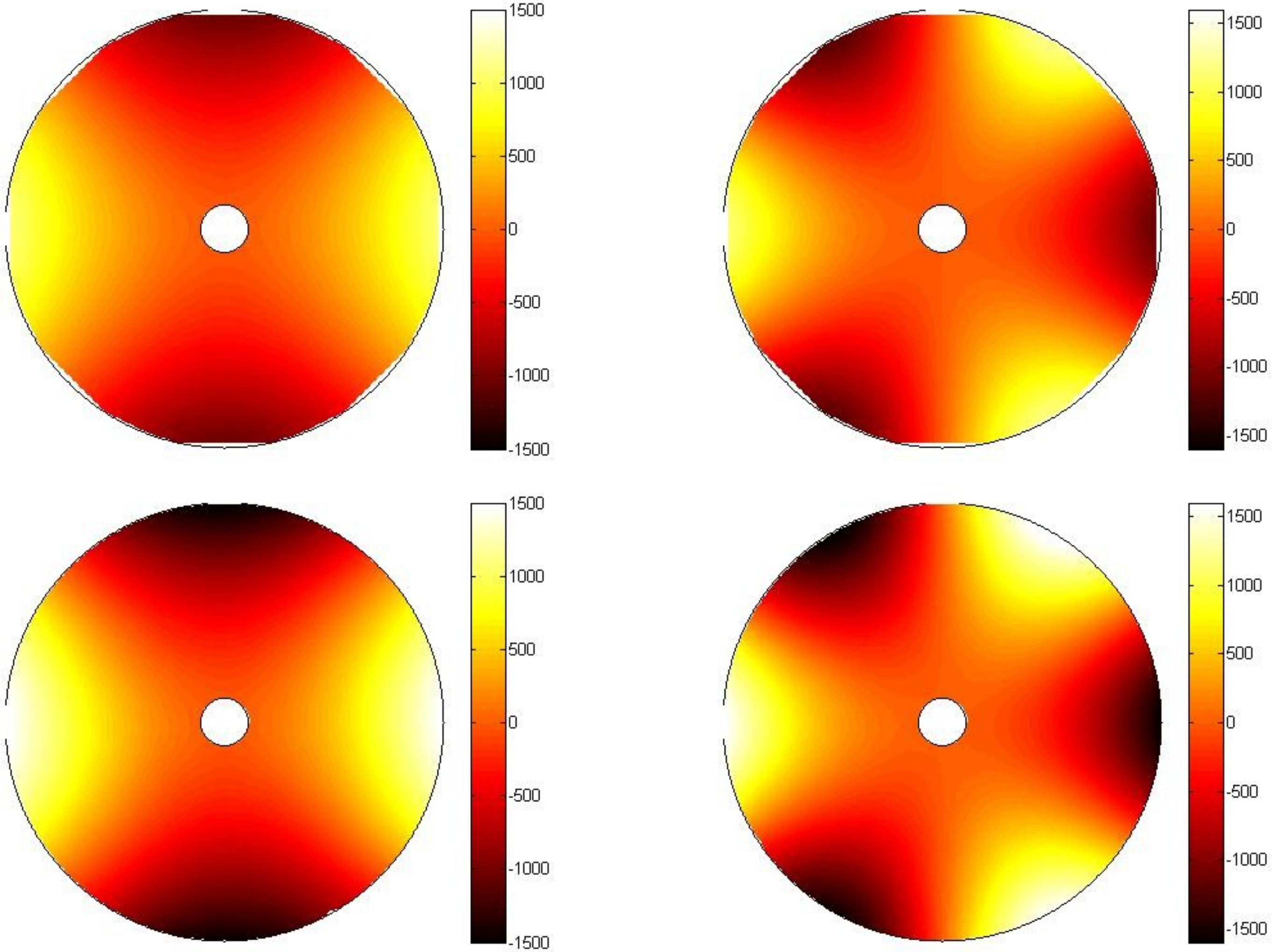
$$\begin{pmatrix} f \end{pmatrix} = \begin{pmatrix} \mathbf{V} \end{pmatrix} \cdot \begin{pmatrix} \mathrm{diag}(1/w_j) \end{pmatrix} \cdot \begin{pmatrix} \mathbf{U}^T \end{pmatrix} \cdot \begin{pmatrix} z \end{pmatrix}$$

- 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).
  1. Multiply each mode coefficient by stiffness $1/w_j$.
     - Resulting vector tells how much of each force mode.
  1. Convert from force modes to actuator forces.
- If there is redundancy, some $w_j = 0$.
  - Corresponding columns of ***V*** are the force vectors that cause no displacement: the *nullspace* of ***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



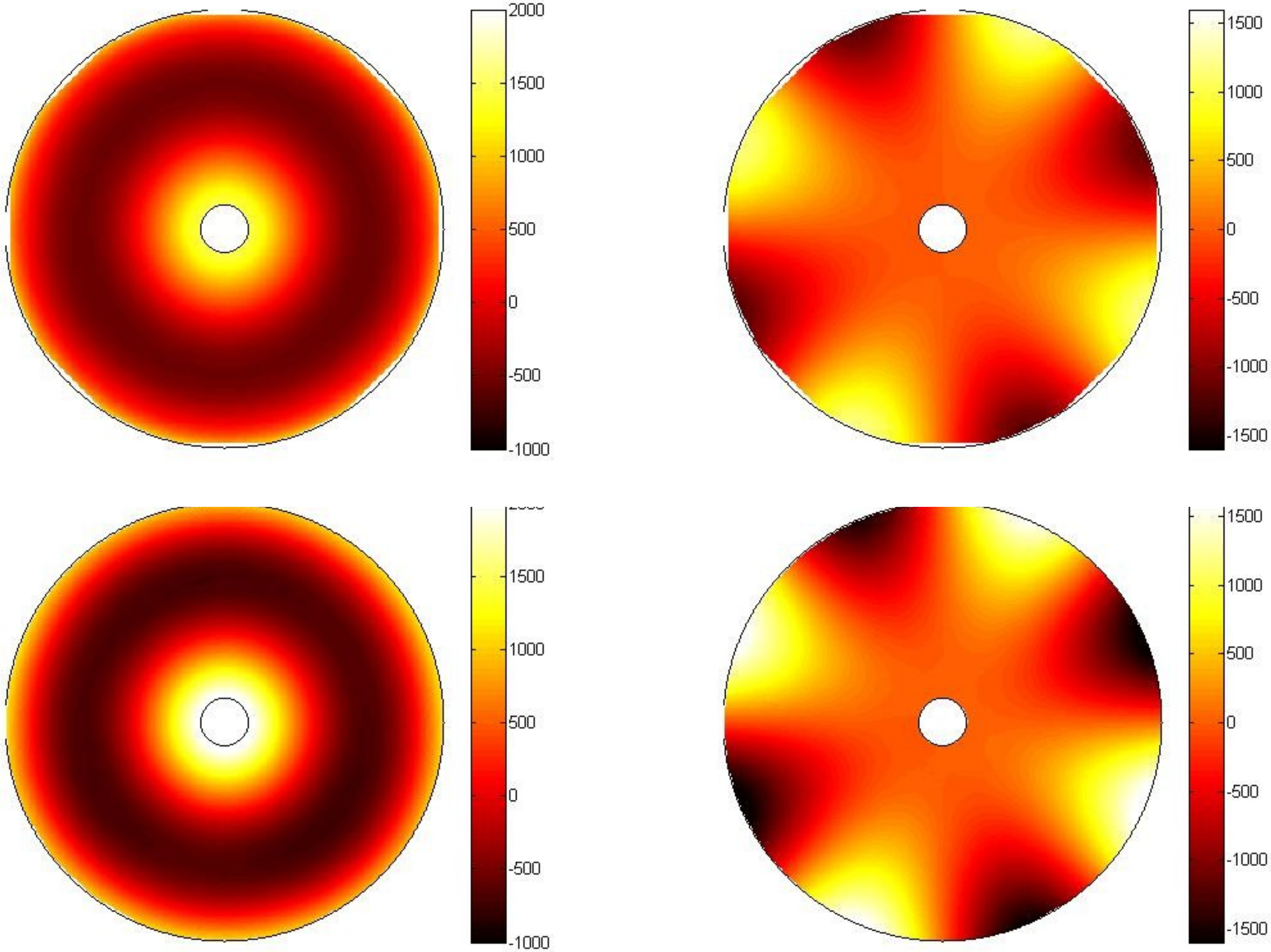
mode 1
5 N rms force

mode 3
30 N rms force

Measured bending modes for LBT primary mirror

calculated

measured



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.