Fabrication and Testing of Large Flats

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August 28, 2007

Introduction

- We developed techniques for measuring and figuring large optical flats
    - Scanning pentaprism slope measurmeents
    - Vibration insensitive subaperture Fizeau interferometry
    - Computer controlled polishing
- These are demonstrated on a 1.6-m flat, and can be applied to much larger mirrors

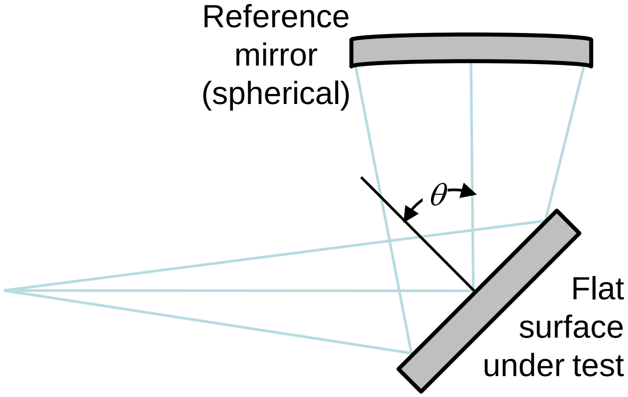
Current State-of-the-Art for Flat Fabrication

Continuous polishing machines are currently used to make good flat mirrors

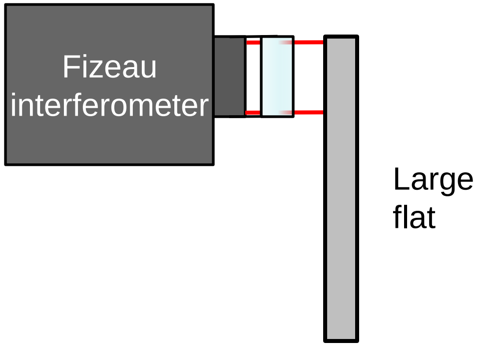
- Advantages
  - Simultaneous multiple mirror production – cost effective
  - Mirror edges are automatically controlled
- Disadvantage
  - Limited in size (~ 1 m)
  - 1/3 of the lap size

Conventional Optical Testing of Large Flats

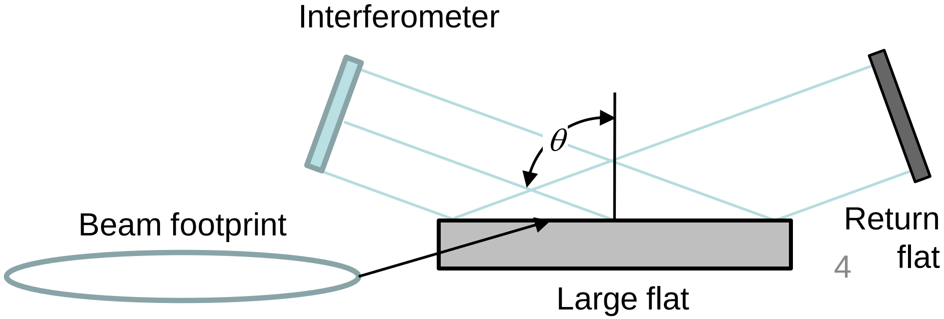
- **Ritchey-Common test**
  - Requires a spherical mirror larger than the flat
  - Difficult test to accomplish on a large scale
  - Creates a large air path



- **Fizeau test with subaperture stitching**
  - Commercial Fizeau interferometers are limited in size (10-50 cm)
  - The accuracy of the test suffer as the size of the subaperture becomes small compared to the size of the test mirror
  - Vibration is difficult to control for large scale systems

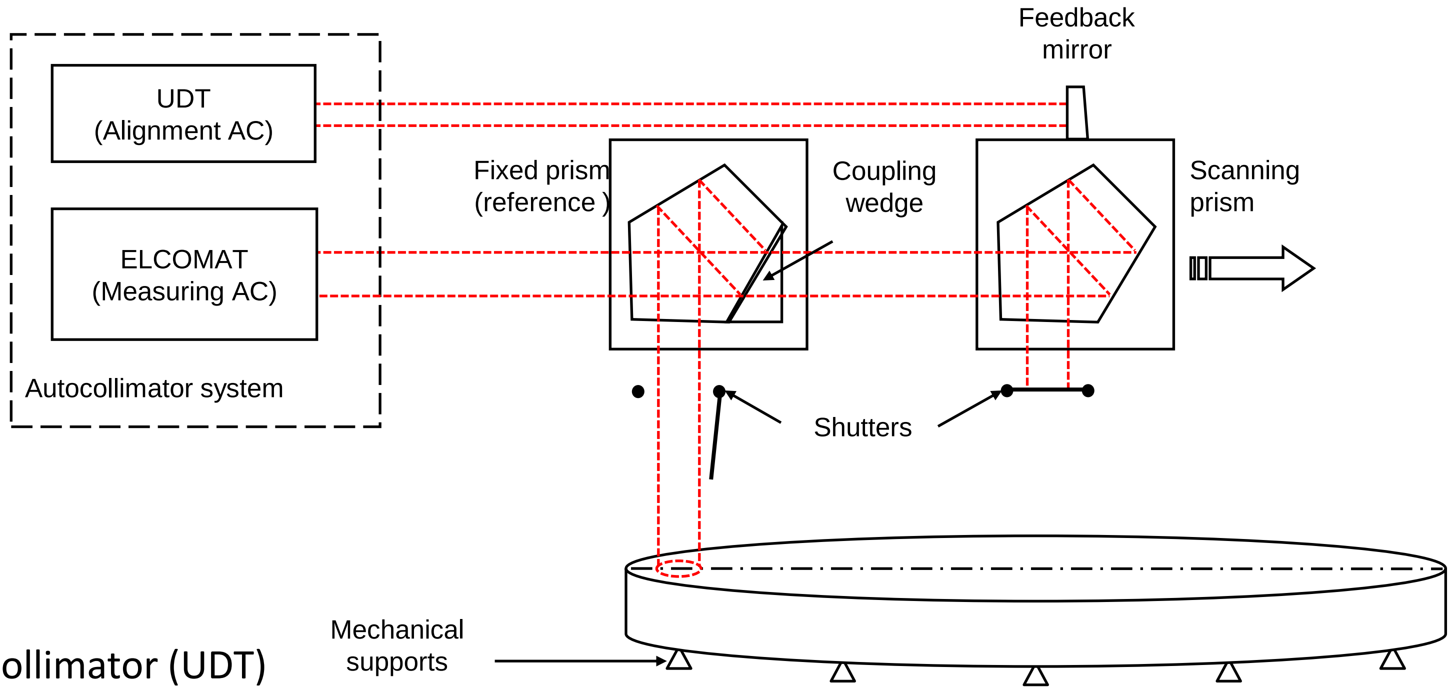


- **Skip flat test**
  - Also performs subaperture testing at oblique angles
  - The accuracy of the test suffer as the size of the subaperture becomes small



Scanning Pentaprism Test

- Two pentaprisms are co-aligned to a high resolution autocollimator
- The beam is deviated by 90° to the test surface
- Any additional deflection in the return beam is a direct measure of surface slope changes
- Electronically controlled shutters are used to select the reference path or the test path
- One prism remains fixed (reference) while the other scans across the mirror

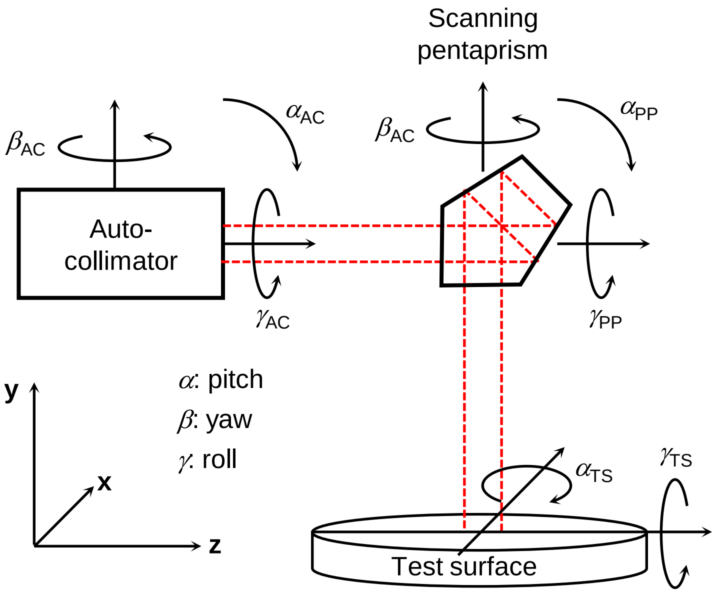


- A second autocollimator (UDT) maintains angular alignment of the scanning prism through an active feedback control

Coupling of Prism Errors into Measurements

<u>Pentaprism motions:</u>

- Small <u>pitch</u> motion does not effect in-scan reading (90° deviation is maintained)
- Angle readings are coupled linearly for <u>yaw</u> motion
- Angle readings are coupled quadratically for <u>roll</u> motion



Degrees of freedom defined

<u>Contributions to in-scan line-of-sight errors:</u>

- First order errors (α_{AC}) are eliminated through differential measurements
- Second order errors affect the measurements (γ_{PP}^2, $\gamma_{AC} \cdot \gamma_{PP}$, $\gamma_{AC} \cdot \beta_{PP}$)
- The change in the in-scan LOS can then be derived as:

$$\Delta\alpha_{LOS} \approx 2\gamma_{PP} \cdot \Delta\gamma_{PP} + \gamma_{AC}\left(\Delta\gamma_{PP} + \Delta\beta_{PP}\right) + \Delta\gamma_{AC}\left(\gamma_{PP} + \beta_{PP}\right) \approx 18 \text{ nrad rms}$$

Alignment Errors

Alignment errors for the pentaprism/autocollimator system

Parameter	Description	Tolerance
γ_{PP}	Initial misalignment of the prism roll	< 0.13 mrad
$\Delta\gamma_{PP}$	Variation in prism roll	< 0.05 mrad rms
γ_{AC}	Misalignment of the autocollimator roll relative to direction of motion	< 0.10 mrad
$\Delta\gamma_{AC}$	Variation in autocollimator roll	< 0.05 mrad rms
β_{PP}	Initial misalignment of the prism yaw	< 0.13 mrad
$\Delta\beta_{PP}$	Variation in prism yaw	< 0.05 mrad rms

Misalignment and perturbation influences on the line-of-sight

Contribution (terms from Eq. 4)	Amount of line of sight deviation (nrad rms)
$2\gamma_{PP} \times \Delta\gamma_{PP}$	13
$\Delta\gamma_{AC} \times \gamma_{PP}$	7
$\Delta\gamma_{AC} \times \beta_{PP}$	7
$\gamma_{AC} \times \Delta\gamma_{PP}$	5
$\gamma_{AC} \times \Delta\beta_{PP}$	5
RSS	**18**

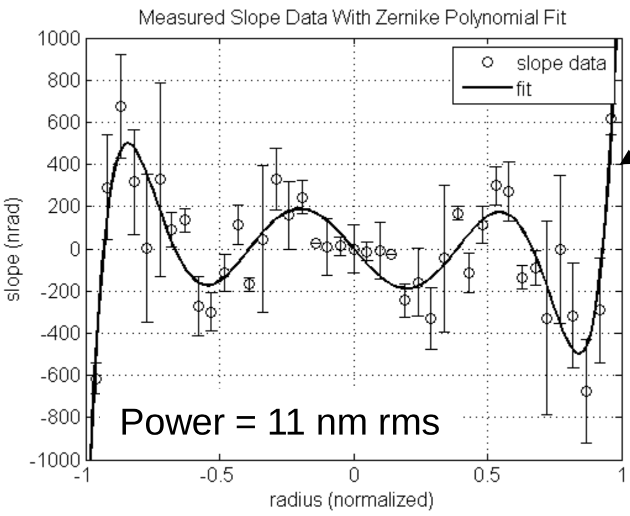
Error Analysis

- Errors from angular motions of the PP and AC ~ 18 nrad rms
- Mapping error ~ 4 nrad rms
- Thermal errors ~ 34 nrad rms
- Errors from coupling lateral motion of the PP ~ 80 nrad rms
- Measurement uncertainty from the AC ~ 160 nrad rms
- Beam divergence coupling into lateral motion of the PP limits the power measurement accuracy to 9 nm rms
- **Combine errors** ~ 190 nrad rms from one prism
  - Monte Carlo analysis showed we can measure a 2 m flat to 15 nm rms of low-order aberrations assuming 3 lines scans and 42 measurement points per scan

Results for a 1.6 m Flat

Scanning mode

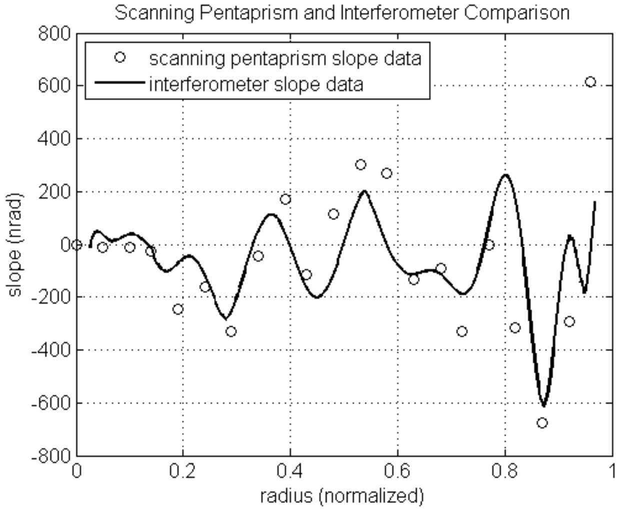
(single line scan)



Power = 11 nm rms

Finished mirror

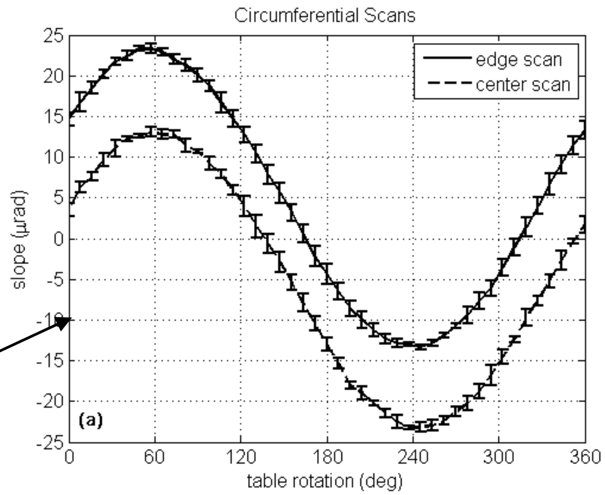
Comparison to interferometer data



Staring mode

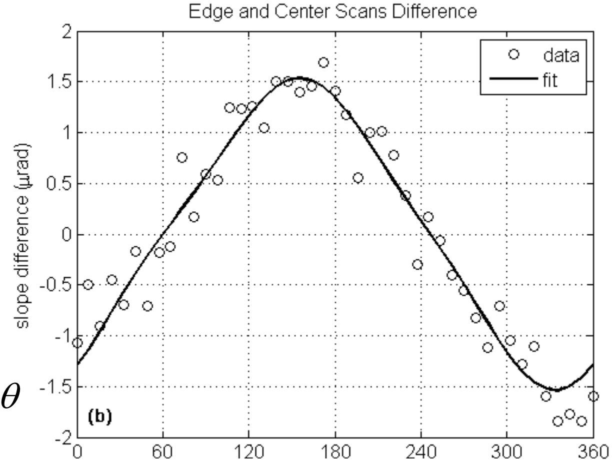
(measures θ dependent aberrations)

While in production



Fitting function used:

$$f(\theta) = a_0 + a_1 \sin\theta + b_1 \cos\theta + a_2 \sin 2\theta + b_2 \cos 2\theta + a_3 \sin 3\theta + b_3 \cos 3\theta$$



Astigmatism (2θ): 15 nm rms
Trefoil (3θ): 18 nm rms

Scanning Pentaprism - Conclusion

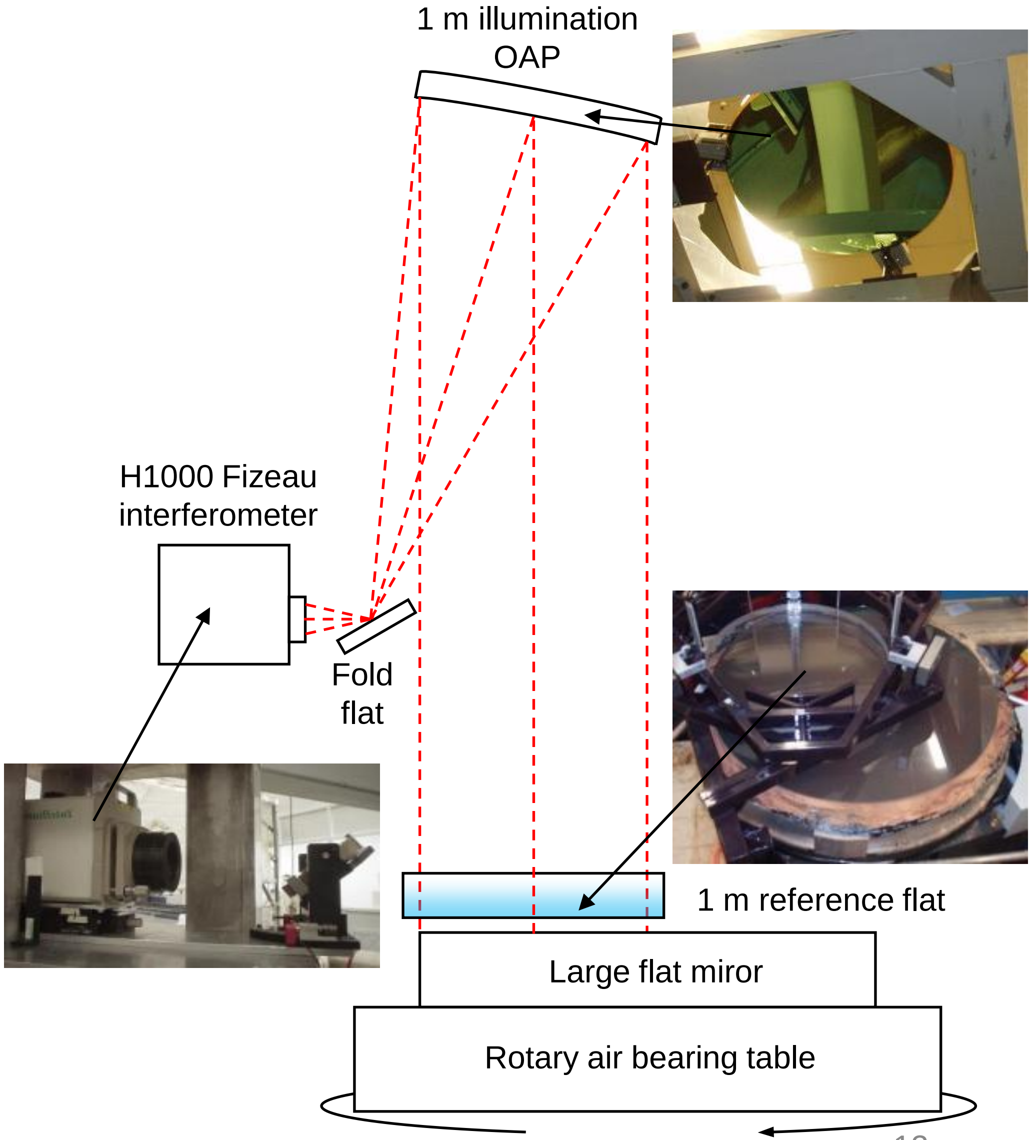
- Highly accurate test system used to measure large flats
  - Accuracy limited only by second order influences; these are minimized through careful alignment and active control of the prism
- Can be used in scanning or staring mode
- Can measure a 2 m flat to 15 nm rms of low-order aberrations
- Measurement accuracy for power is limited to 9 nm rms for a 2 m flat
- Absolute testing of large flats

1 m Vibration-Insensitive Fizeau

- Provided 1 m aperture sampling
- Provided efficient, accurate, and *in-situ* testing
- Used custom collimating optics and reference flat
- Short air gap between the reference and test surface and use of polarization for instantaneous phase shifting gave high accuracy in the presence of vibrations and thermal effects

1-m Fizeau aperture interferometer

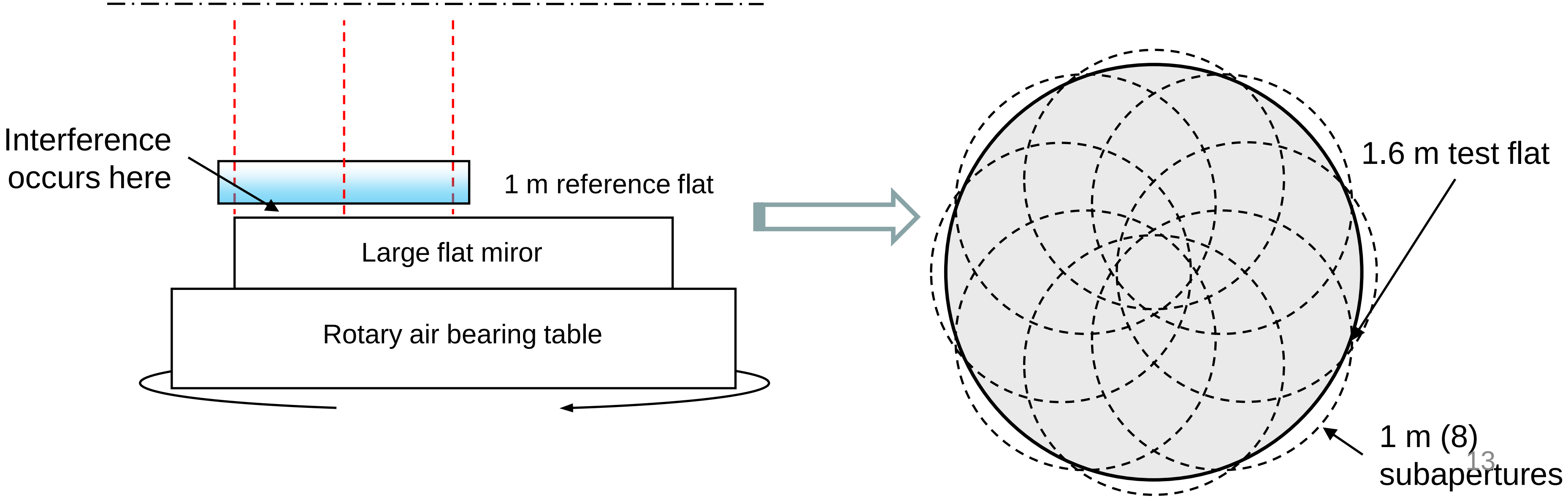
- Commercial instantaneous Fizeau interferometer (emitted 2 circularly polarized beams)
- Standard diverger and 1 m OAP formed the collimating optics
- A 6-in flat folded the beam
- A 1 m external reference flat was suspended a few cm over the test flat and provided six equally spaced rotations
- Test flat rested on polishing supports and air bearing table



Principle of Operation

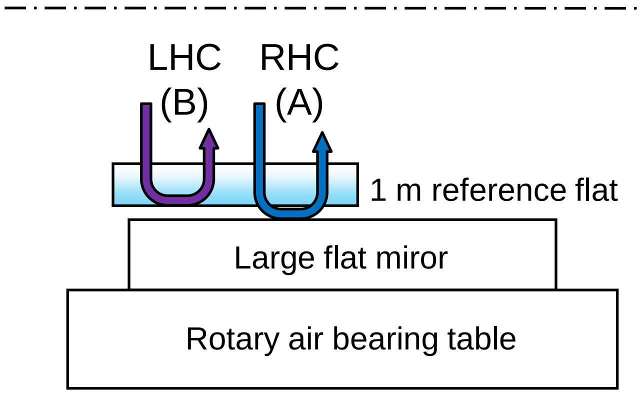
- A Fizeau test requires a collimated beam and a reference flat surface
- To get complete coverage of the 1.6 m test flat, the test flat is rotated underneath the reference flat
- Subaperture measurements are combined to get a full surface map
  - Maximum likelihood estimation method to estimate the reference and test surfaces [P. Su]

Requires 8 subaperture measurements to get complete coverage

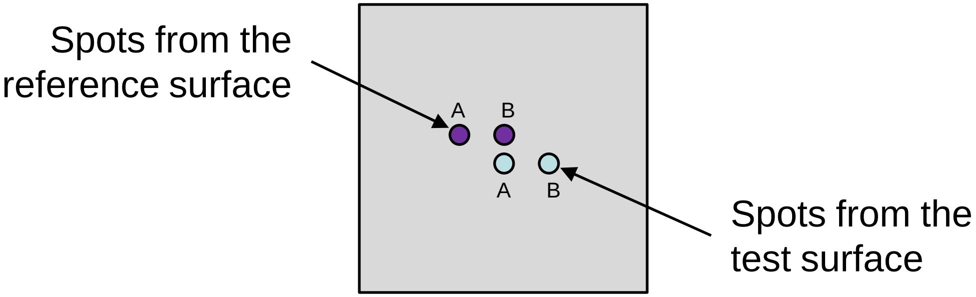


Vibration Insensitive System

- The system provides simultaneous phase-shifting using polarization and polarizing elements
- Orthogonal polarizations from the reference and test surfaces are combined to get interference and phase shifting



Alignment mode

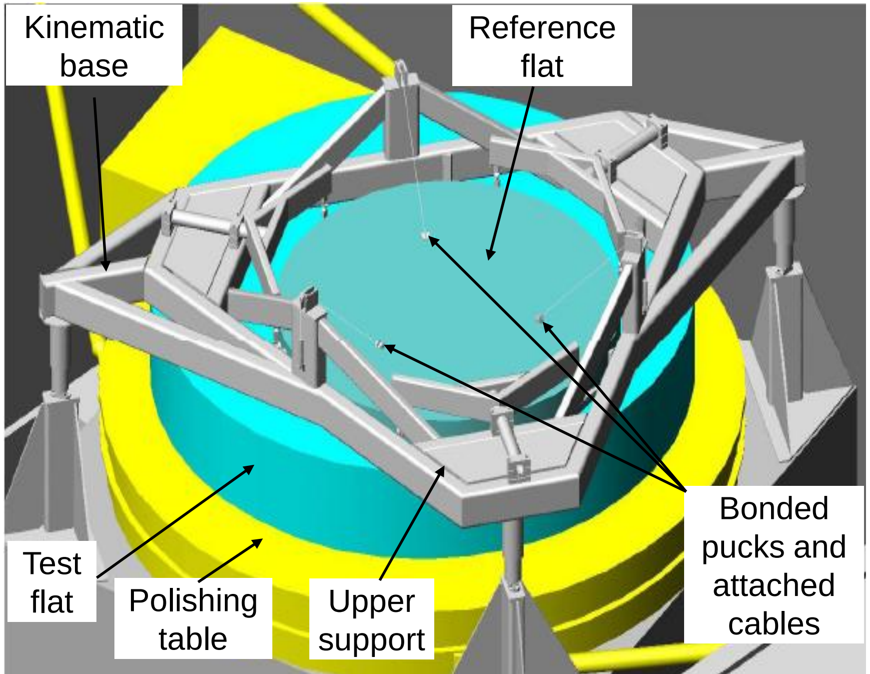


Software screen

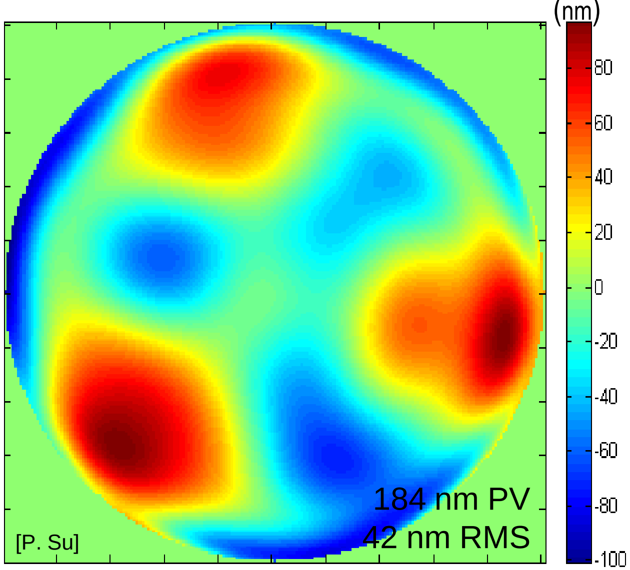
- The beams are circularity polarized to reduce the effect of birefringence through the 11 cm thick reference flat [C. Zhao]

Support of 1 m Reference Flat

- 1 m fused silica polished to 100 nm P-V
- Mechanically stable and kinematic mount held the reference flat
  - Three counter balanced cables attached to pucks bonded to the reference flat surface
  - Six tangential edge support
  - Provide six equally spaced rotations and good position repeatability of the reference flat



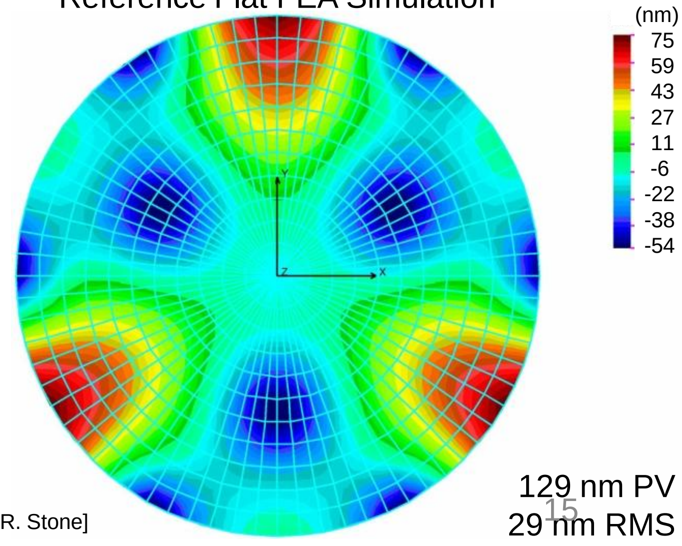
Reference Flat Surface measurement



184 nm PV
42 nm RMS

[P. Su]

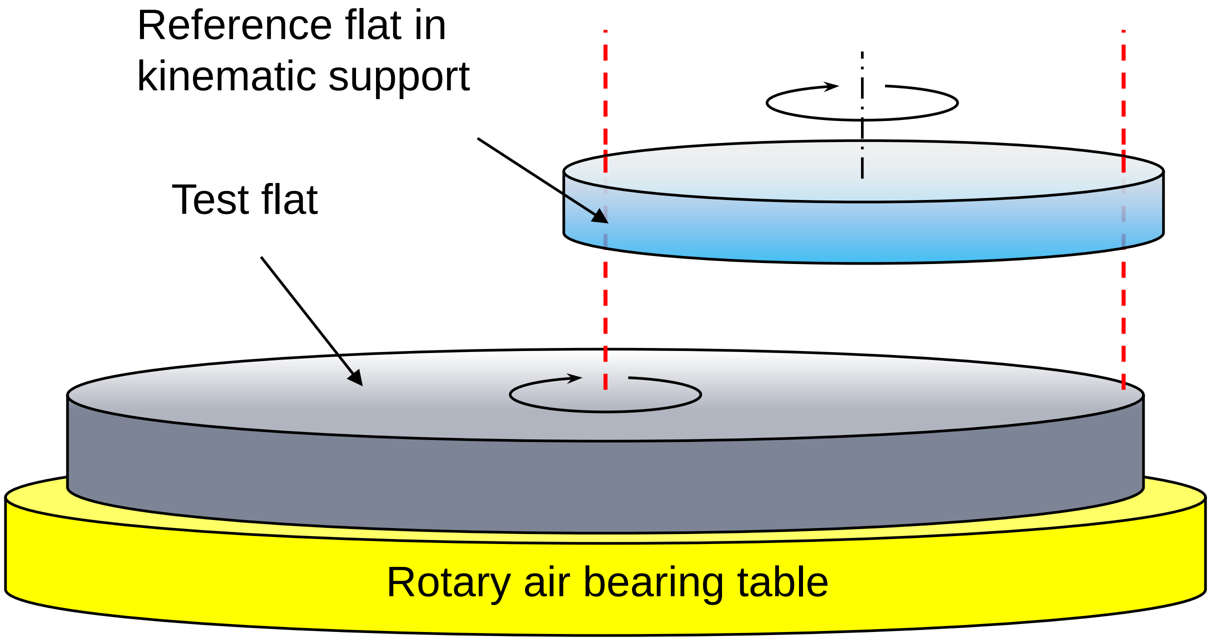
Reference Flat FEA Simulation



[R. Stone]

129 nm PV
29 nm RMS

System Calibration



- Surface irregularity calibration
  - Multiple rotations of the reference and test surfaces to get unbiased estimate of the two surfaces (MLE method)
  - This method did not calibrate power
- Surface power calibration
  - Used the scanning pentaprism to measure power in the test flat

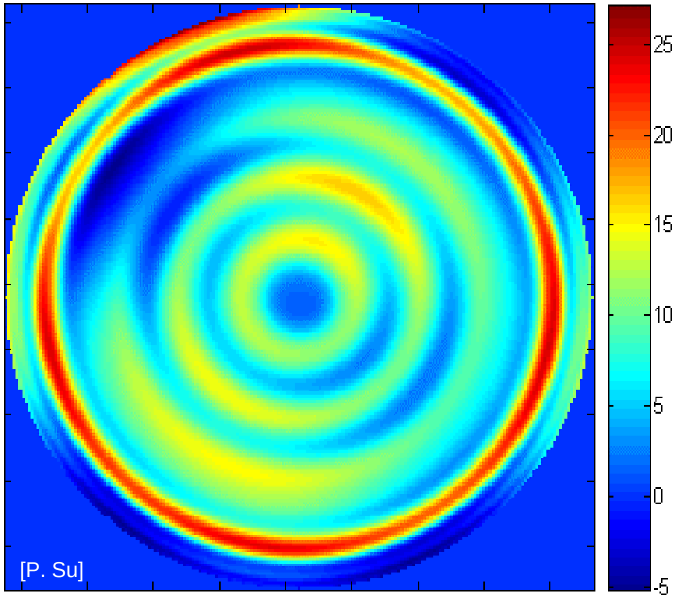
Summary of Maximum Likelihood Estimation and Stitching

- Maximum likelihood estimation (software developed by UA [P. Su])
  - Initially, neither the reference surface nor the test surface is known
  - Modulate the subaperture data through multiple rotations of the reference and test surfaces
  - Create a global maximum likelihood solution for combining the subaperture data and reconstructing the reference and test surfaces
  - Reference and test surface estimated to 3 nm rms – through repeatability of the measurements
- Subaperture stitching (commercially available software MBSI)
  - Stitching can be used after determination of the reference surface
    - Relies on the MLE solution for the reference surface
  - Rotate each subaperture measurement to the global coordinate system
  - Match the overlapping regions in piston and tilt
  - Errors from stitching was about 2 nm rms

Results on the Finished Mirror

- Comparison of results from MLE and stitching
  - The same zonal features are observed in both
  - The stitched map preserves higher frequency errors

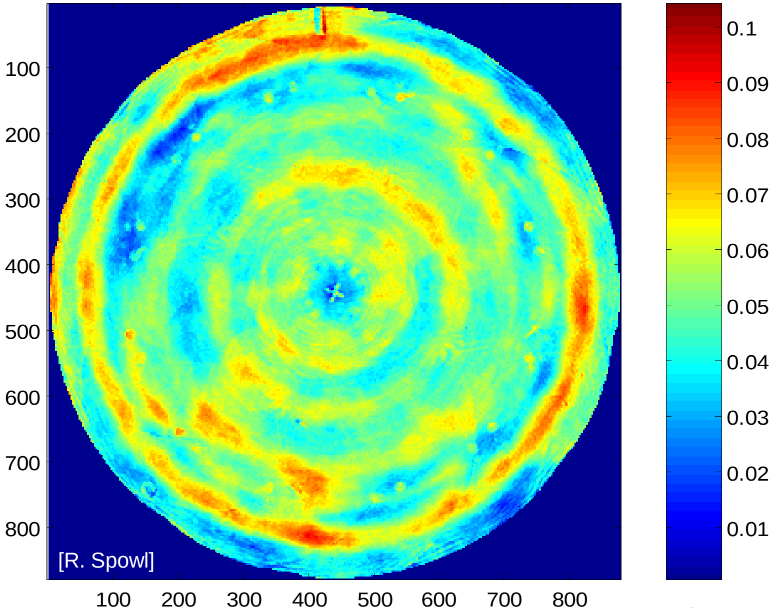
1.6 m flat surface by MLE



[P. Su]

6 nm rms after removing power & astigmatism

1.6 m flat surface by stitching



[R. Spowl]

7 nm rms after removing power & astigmatism

Error Analysis

- Error budget for the test
  - Interferometer noise ~ 3 nm rms per measurement
  - Illumination/alignment errors ~ 3 nm rms
  - Distortion (mapping errors) ~ 1 nm rms
  - Calibration ~ 1 nm rms
  - Combining subapertures ~ 2 nm rms
- **Combined errors** ~ 4.9 nm rms (assumes no averaging)
- MLE showed using 24 measurements the test is better than this due to averaging (3 nm rms)

1 m Fizeau Interferometer – Conclusion

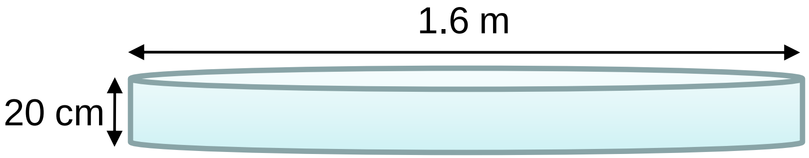
- Provided accurate and efficient testing
- Larger aperture provided more surface coverage – reduces stitching errors
- Multiple rotations of the reference and test surface and measurement redundancy isolated errors from both surfaces through MLE
- *In-situ* test with kinematic reference flat
- Test on final surface or guide fabrication

Advanced Fabrication Technologies

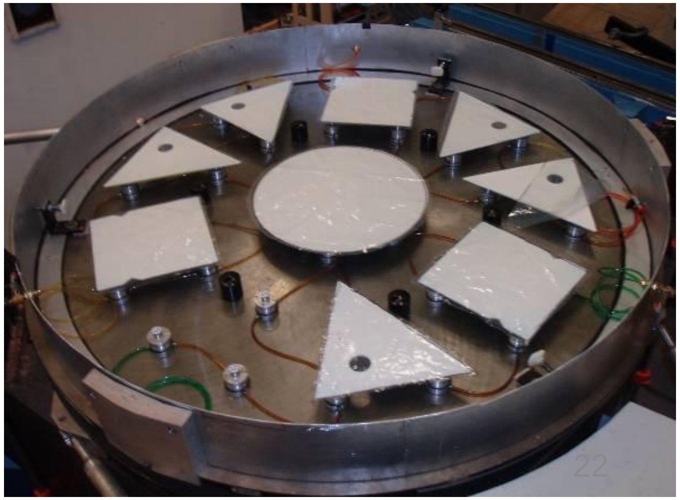
- Classical polishing alone do not enable fabrication of quality large flats
- We developed a computer controlled polishing that used polishing simulation software combined with accurate and efficient metrology
  - Rapid convergence of the surface error
- Key advantage of our method over classical polishing is our method is scalable to larger flats

Mirror Geometry and Supports

- Mirror geometry
  - Solid Zerodur
    - 1.6 m diameter, 20 cm thick
    - 1034 kg



- Mirror polishing supports
  - 36 point support arranged on three rings based on Nelson’s model for minimum surface deflection (< 3 nm rms)
  - Hydraulic piston type actuators

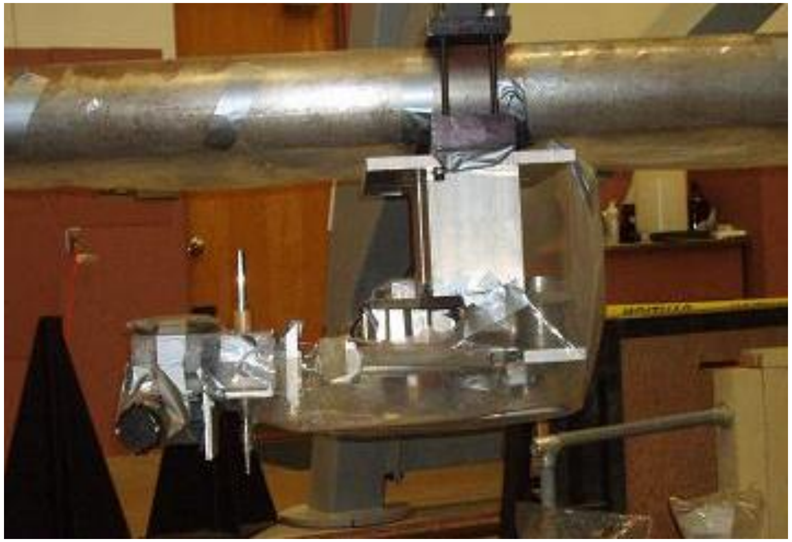


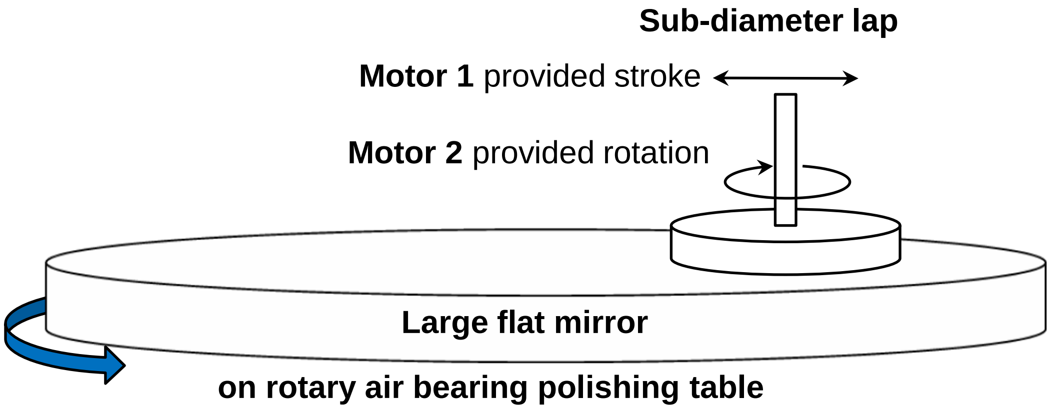
Large Tool Polishing and Efficient Metrology

- Initial polishing was performed with a 40-in tool
  - Molded pitch with Barnesite as slurry
  - About 0.3 pounds per square inch (psi) on the mirror
  - Random motion of the tool to avoid large zonal errors
  - Closely monitored the edges with a test plate
- Electronic levels were used to monitor global changes in the mirror surface

Surface Finishing with Smaller Tools

- Retrofitted a Draper machine with a radial stroker
  - Two motors on the radial stroker provided variable tool stroke and rotation
  - Radial stroker was attached to the rail of Draper machine
  - Radial stroker was positioned over the surface zone by moving the rail, which normally would provide stroke for large tools
- Drove tool sizes ranging from 6- to 16-in at 0.2 to 0.3 psi





Sub-diameter lap

Motor 1 provided stroke

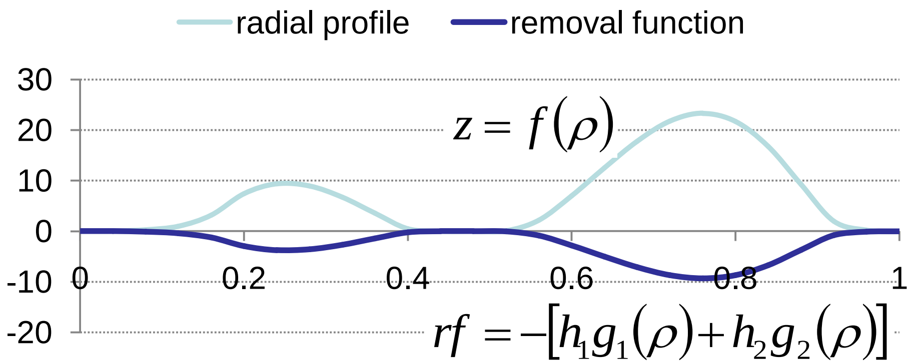
Motor 2 provided rotation

Large flat mirror

on rotary air bearing polishing table

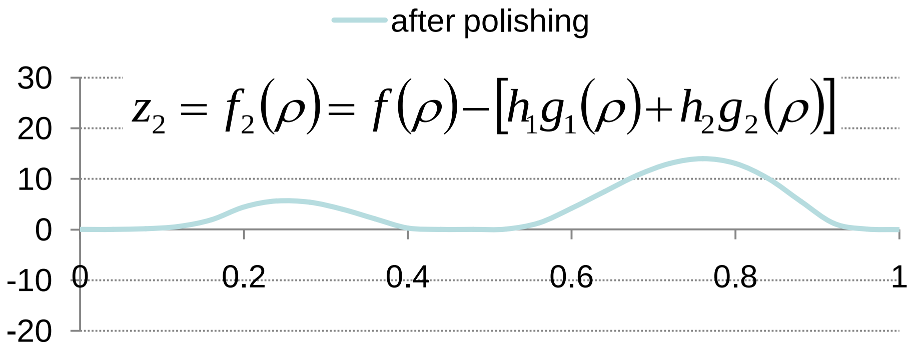
Surface Finishing – Computer Controlled Polishing

Example of using the software



$$z = f(\rho)$$

$$rf = -\left[h_1 g_1(\rho) + h_2 g_2(\rho)\right]$$

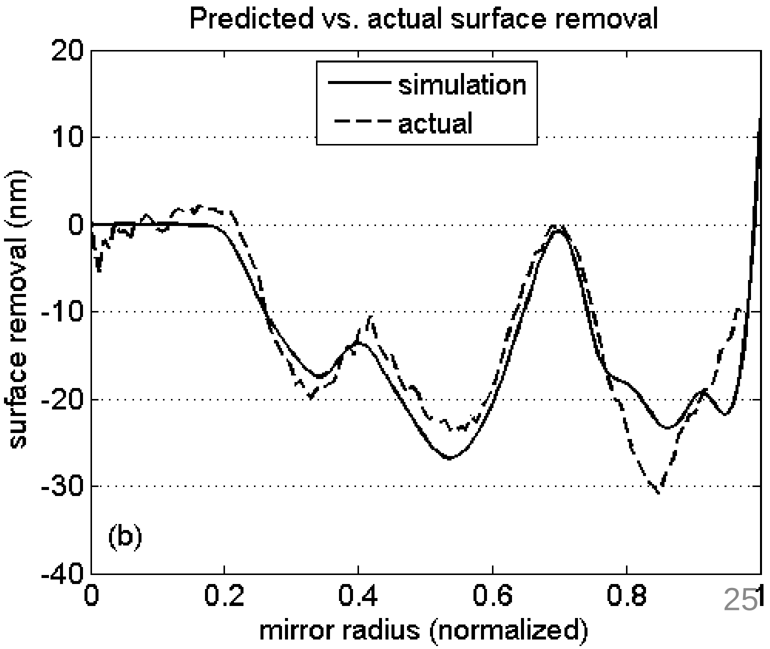


$$z_2 = f_2(\rho) = f(\rho) - \left[h_1 g_1(\rho) + h_2 g_2(\rho)\right]$$

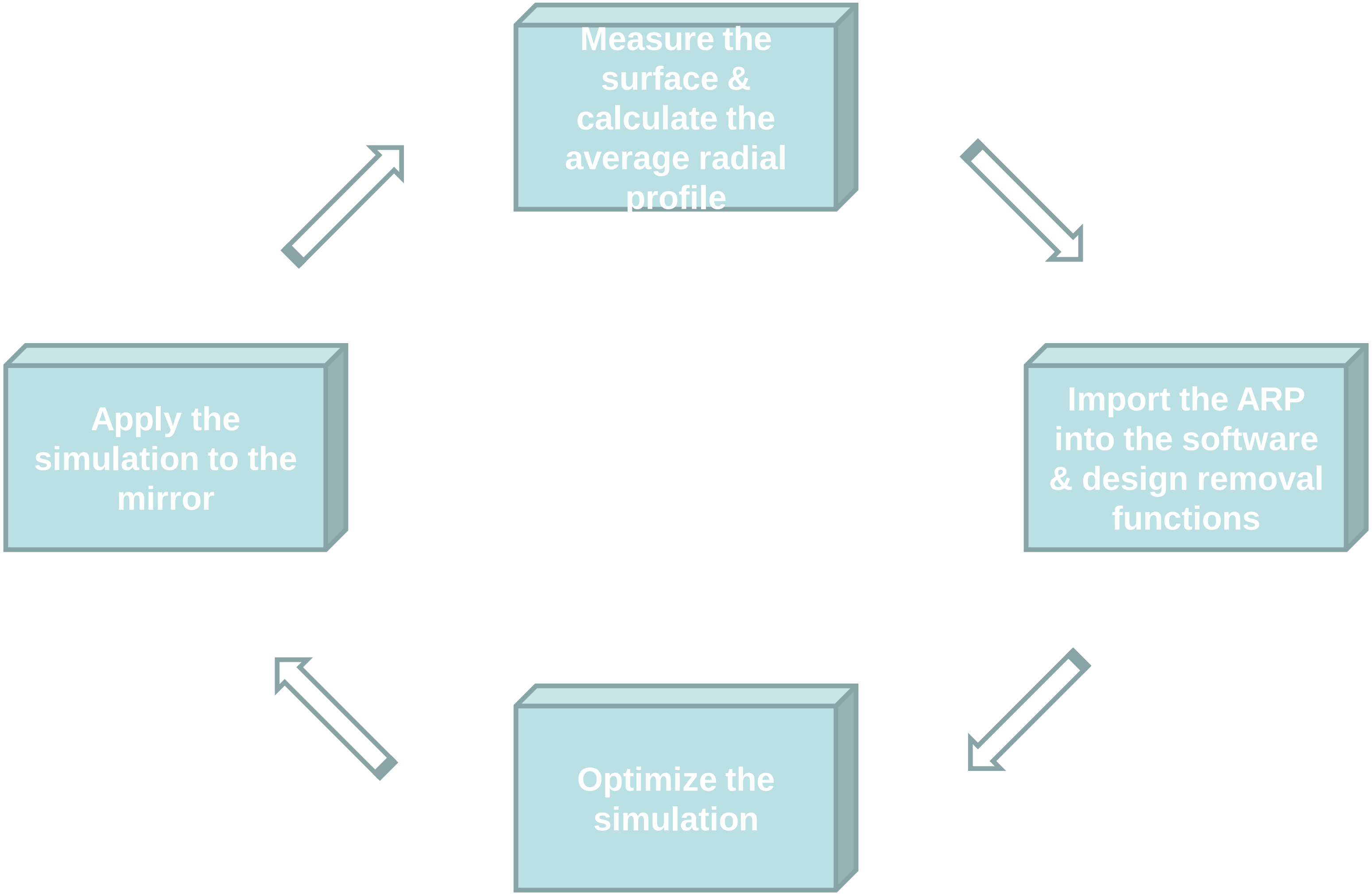
After applying *N* different removal profiles:

$$z_N = f_N(\rho) = f(\rho) - \sum_{i=1}^{N} h_i \times g_i(\rho)$$

- Polishing simulation software
  - Uses Preston’s relation for surface removal ($R = K \times p \times v$)
  - Removal function varies significantly with tool position on the mirror



Closed-Loop Computer Controlled Polishing



Measure the surface & calculate the average radial profile

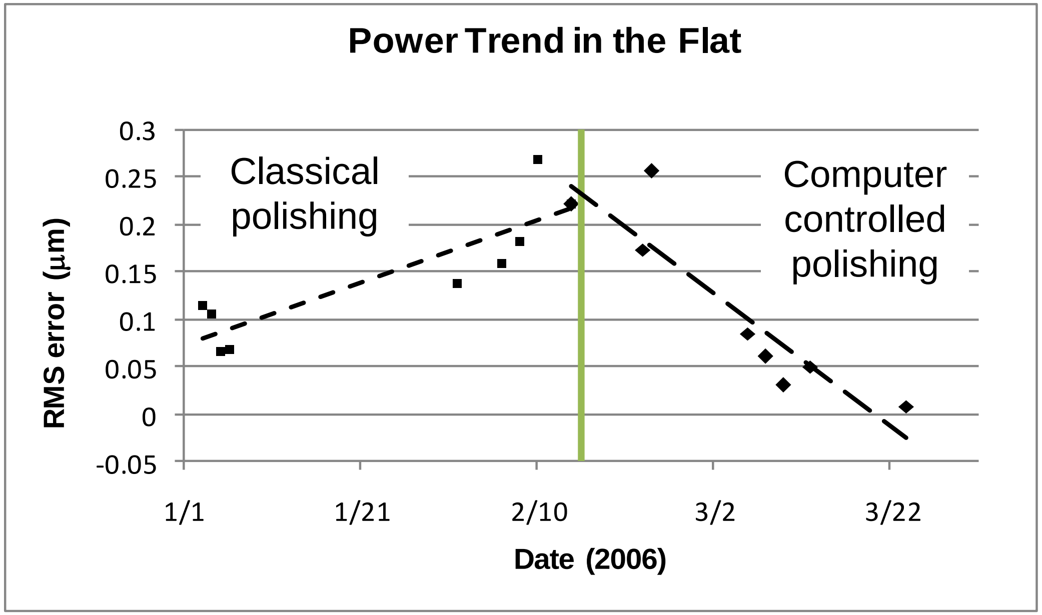
Import the ARP into the software & design removal functions

Optimize the simulation

Apply the simulation to the mirror

Power Trend in the 1.6 m Flat

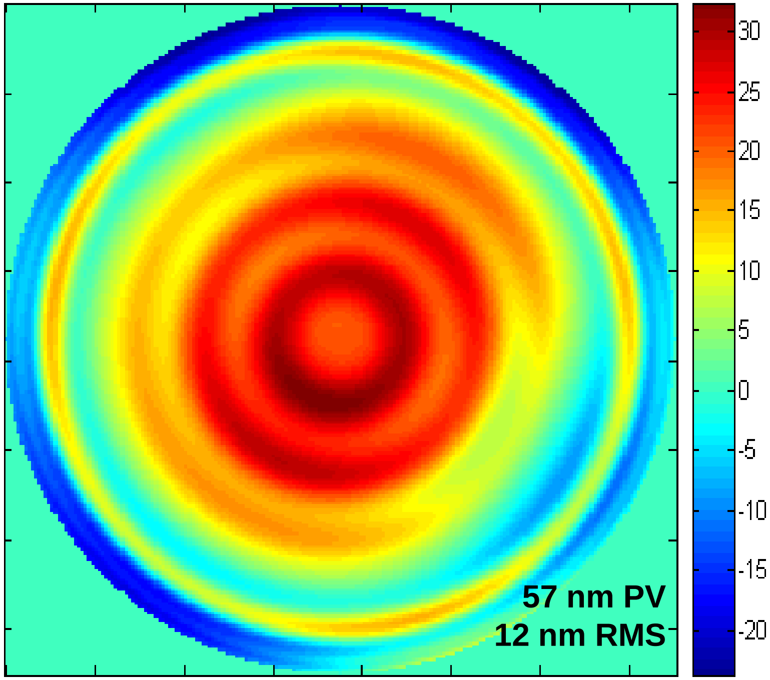
- Measured with the scanning pentaprism
- Shows the point when the computer assisted polishing was implemented



Surface Figure on the Finished Mirror

- Combined results from the Fizeau and scanning pentaprism tests

- **11 nm rms** power
- **6 nm rms** irregularity
- 12 nm rms overall surface

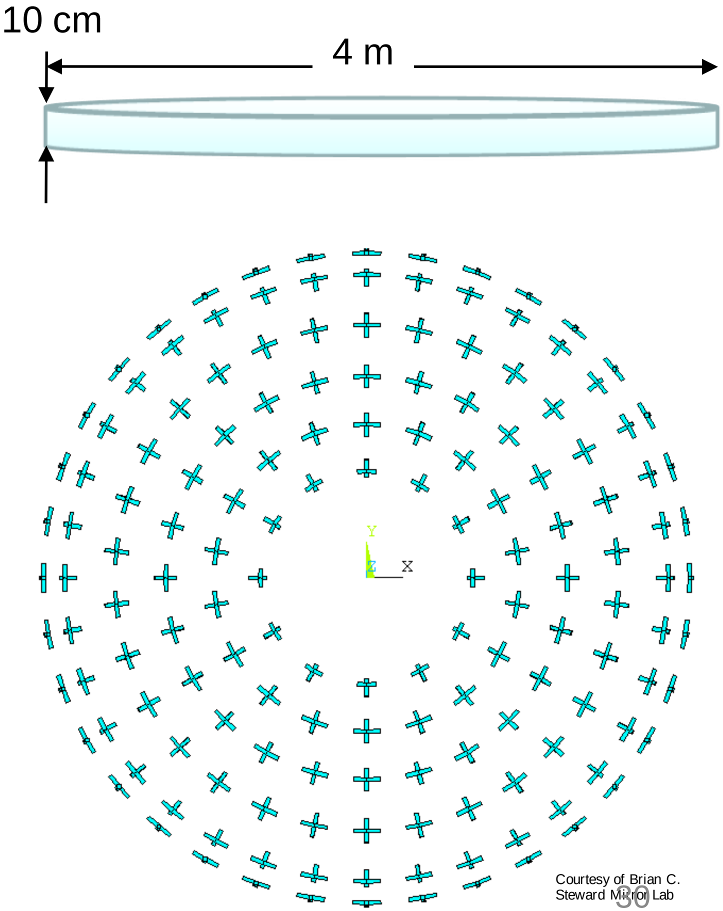


1.6 flat Mirror – Conclusion

- Classical polishing alone did not enable fabrication of high performance flat
- Developed a computer controlled polishing combined with efficient and accurate metrology
  - Resulted in rapid convergence of the surface error
- This is the best large flat mirror we know about.
- There is no reason to believe that we coul

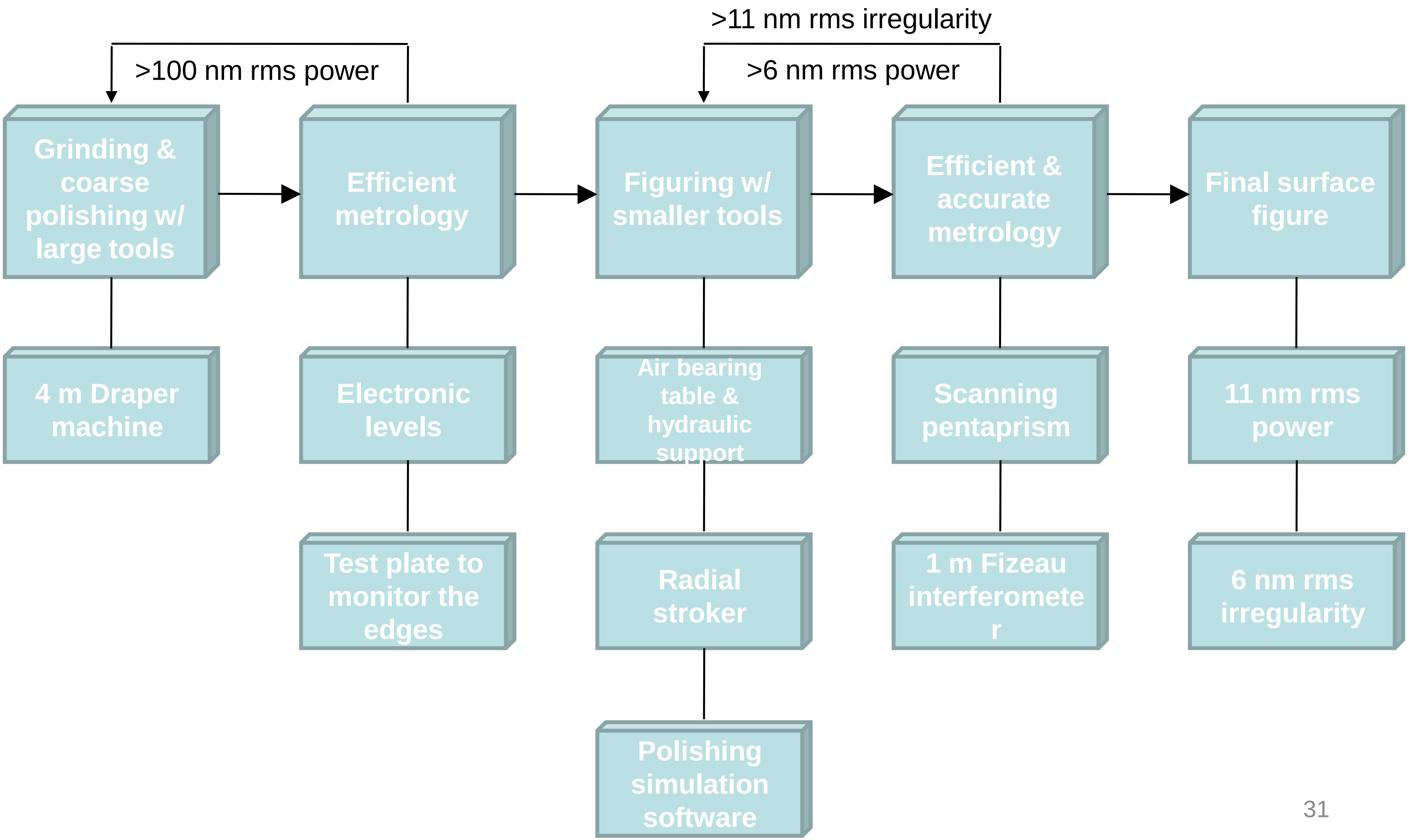
Mirror Geometry and Supports Example for 4 m Flat

- Mirror geometry example
  - Solid Zerodur
  - 4 m diameter, 10 cm thick
- Mirror supports example
  - 120 support points arranged on 5 rings
  - Surface deflection (distortion) maintained to 12 nm rms



Courtesy of Brian C.
Steward Mirror Lab

Manufacturing Plan for a 4 m Flat



>11 nm rms irregularity

>100 nm rms power

>6 nm rms power

Grading & coarse polishing w/ large tools → Efficient metrology → Figuring w/ smaller tools → Efficient & accurate metrology → Final surface figure

- Grinding & coarse polishing w/ large tools
  - 4 m Draper machine
- Efficient metrology
  - Electronic levels
  - Test plate to monitor the edges
- Figuring w/ smaller tools
  - Air bearing table & hydraulic support
  - Radial stroker
  - Polishing simulation software
- Efficient & accurate metrology
  - Scanning pentaprism
  - 1 m Fizeau interferometer
- Final surface figure
  - 11 nm rms power
  - 6 nm rms irregularity

Limitations

- Fabrication
  - Limited polishing tool selection
- Electronic levels
  - Measures slopes, therefore, measurement accuracy decreases for larger mirrors
- Scanning pentaprism
  - Similarly, measurement accuracy decreases for larger mirrors
  - Current rails limited to 2.5 m
- 1 m Fizeau interferometer
  - Reference is constrained in lateral motion
  - More subapertures to combine

Conclusion

- Developed and implemented a method for making large high performance flats
  - Efficient and accurate metrology
  - Closed-loop computer controlled polishing
- Method lead to making the world's best 2 m class flat
- Laid foundation for fabricating large flat mirror as large as 8 m