Fabrication and Testing of Large Flats

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Introduction

- We developed techniques for measuring and figuring large optical flats
  - Scanning pentaprism slope measurements
  - 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 $90^\circ$ 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

Pentaprism motions:
- Small pitch motion does not effect in-scan reading (90° deviation is maintained)
- Angle readings are coupled linearly for yaw motion
- Angle readings are coupled quadratically for roll motion

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

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

Alignment errors for the pentaprism/autocollimator system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{PP}$</td>
<td>Initial misalignment of the prism roll</td>
<td>$&lt; 0.13$ mrad</td>
</tr>
<tr>
<td>$\Delta \gamma_{PP}$</td>
<td>Variation in prism roll</td>
<td>$&lt; 0.05$ mrad rms</td>
</tr>
<tr>
<td>$\gamma_{AC}$</td>
<td>Misalignment of the autocollimator roll relative to direction of motion</td>
<td>$&lt; 0.10$ mrad</td>
</tr>
<tr>
<td>$\Delta \gamma_{AC}$</td>
<td>Variation in autocollimator roll</td>
<td>$&lt; 0.05$ mrad rms</td>
</tr>
<tr>
<td>$\beta_{PP}$</td>
<td>Initial misalignment of the prism yaw</td>
<td>$&lt; 0.13$ mrad</td>
</tr>
<tr>
<td>$\Delta \beta_{PP}$</td>
<td>Variation in prism yaw</td>
<td>$&lt; 0.05$ mrad rms</td>
</tr>
</tbody>
</table>

## Misalignment and perturbation influences on the line-of-sight

<table>
<thead>
<tr>
<th>Contribution (terms from Eq. 4)</th>
<th>Amount of line of sight deviation (nrad rms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\gamma_{PP} \times \Delta \gamma_{PP}$</td>
<td>13</td>
</tr>
<tr>
<td>$\Delta \gamma_{AC} \times \gamma_{PP}$</td>
<td>7</td>
</tr>
<tr>
<td>$\Delta \gamma_{AC} \times \beta_{PP}$</td>
<td>7</td>
</tr>
<tr>
<td>$\gamma_{AC} \times \Delta \gamma_{PP}$</td>
<td>5</td>
</tr>
<tr>
<td>$\gamma_{AC} \times \Delta \beta_{PP}$</td>
<td>5</td>
</tr>
<tr>
<td>RSS</td>
<td>18</td>
</tr>
</tbody>
</table>
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

**Fitting function used:**
\[ f(\theta) = a_0 + a_1 \sin \theta + b_1 \cos \theta + a_2 \sin 2\theta + b_2 \cos 2\theta + a_3 \sin 3\theta + b_3 \cos 3\theta \]

**Staring mode**
(measures $\theta$ dependent aberrations)

Finished mirror

While in production

Astigmatism ($2\theta$): 15 nm rms
Trefoil ($3\theta$): 18 nm rms
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].
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.
- 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
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

1.6 m flat surface by stitching

6 nm rms after removing power & astigmatism

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
• 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
Surface Finishing – Computer Controlled Polishing

Example of using the software

- 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

After applying \( N \) different removal profiles:

\[
z_N = f_N(\rho) = f(\rho) - \sum_{i=1}^{N} h_i \times g_i(\rho)
\]
Closed-Loop Computer Controlled Polishing

1. Measure the surface & calculate the average radial profile
2. Import the ARP into the software & design removal functions
3. Optimize the simulation
4. 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

![Graph showing Power Trend in the Flat](image-url)
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
Manufacturing Plan for a 4 m Flat

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

4 m Draper machine → Electronic levels → Test plate to monitor the edges

>100 nm rms power → >6 nm rms power

Air bearing table & hydraulic support → Radial stroker → 1 m Fizeau interferometer

>11 nm rms irregularity → 11 nm rms power

Scanning pentaprism → 6 nm rms irregularity

Polishing simulation software
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