10.0 Absolute Measurements

Computers make it possible to perform measurements more accurate than the reference surface
10.0 Absolute Measurements

- 10.1 Flat Surfaces
- 10.2 Spherical Surfaces
  - 10.2.1 Three Measurements of Spherical Mirror
  - 10.2.2 Ball Averager
- 10.3 Surface Roughness
  - 10.3.1 Perfect Mirror
  - 10.3.2 Generate Reference
  - 10.3.3 Absolute rms Measurement
Absolute Surface Shape Measurement

- Perform measurements more accurate than the reference surface
- Removing system aberrations & reference surface effects
- Improves measurement accuracy
- Tests for
  - Flats
  - Spheres
  - Surface roughness
10.1 Flat Surfaces

- For an absolute measurement of flat surfaces, need at least three flats:
  - Compare flat A with flat B
  - Compare flat A with flat C
  - Compare flat B with flat C

- Can get null test for all three measurements. All three flats must indeed be flat.
Measurements Required for Three-Flat Test

\[
\begin{align*}
B \text{ Inverted} & \times & A \\
C \text{ Inverted} & \times & B \text{ Rotated}
\end{align*}
\]
Three-Flat Test Equations

Make 4 Measurements

\[ G_{AB}(x,y) = f_A(x,y) + f_B(-x,y) \]
\[ G_{AC}(x,y) = f_A(x,y) + f_C(-x,y) \]
\[ G_{BC}(x,y) = f_B(x,y) + f_C(-x,y) \]
\[ G_{BC'}(x,y) = f_B(-x,-y) + f_C(-x,y) \]
Three-Flat Test - X Line

\[ f_A(x,0) = \frac{G_{AB}(x,0) + G_{AC}(x,0) - G_{BC'}(x,0)}{2} \]

\[ f_B(x,0) = \frac{G_{AB}(x,0) - G_{AC}(x,0) + G_{BC'}(x,0)}{2} \]

\[ f_C(x,0) = \frac{-G_{AB}(x,0) + G_{AC}(x,0) + G_{BC'}(x,0)}{2} \]
Three-Flat Test - Y Line

\[ f_A(0, y) = \frac{G_{AB}(0, y) + G_{AC}(0, y) - G_{BC}(0, y)}{2} \]

\[ f_B(0, y) = \frac{G_{AB}(0, y) - G_{AC}(0, y) + G_{BC}(0, y)}{2} \]

\[ f_C(0, y) = \frac{-G_{AB}(0, y) + G_{AC}(0, y) + G_{BC}(0, y)}{2} \]
Three-Flat Test - Flat A

X Scan
p-v: 0.021
rms: 0.022

Y Scan
p-v: 0.085
rms: 0.019
Three-Flat Test - Flat B

**X Scan**
- PV: 0.035
- RMS: 0.009

**Y Scan**
- PV: 0.048
- RMS: 0.012

**THREE FLAT**

wv: 633.0 nm
pupil: 100%

**Normalized 1.00**
Three-Flat Test - Flat C

X Scan
r-m: 0.016
rms: 0.002

Y Scan
r-m: 0.033
rms: 0.007

THREE FLAT
wv: 633.0 nm
pupil: 100%

3-FLATS 03:07 03/16/89
(Flat C)
Question

What is wrong with the following approach for performing an absolute measurement of a flat??

1. Measure a flat in a Twyman-Green or laser based Fizeau interferometer.
2. Move the flat a small distance in the horizontal direction and make a second measurement.
3. Subtract these two measurements. All the errors coming from the interferometer for the two measurements are common and subtract out and we are left with the equivalent of a lateral shear interferogram for the flat.
4. This could be repeated to obtain a lateral shear interferogram having orthogonal shear.
5. Analyze the two lateral shear interferograms to determine the errors in the flat.
10.2 Absolute Sphere Testing

- 10.2.1 Three Measurements of Spherical Mirror
- 10.2.2 Ball Averager
10.2.1 Three Measurements of Spherical Mirror

$W_{0^\circ}$

$W_{180^\circ}$

$W_{\text{focus}}$
Absolute Sphere Testing (Equations)

\[ W_0 \left[ x, y \right] = 2W_{surf} \left[ x, y \right] + W_{ref} \left[ x, y \right] + 2W_{div} \left[ x, y \right] \]
\[ W_{180} \left[ x, y \right] = 2W_{surf} \left[ -x, -y \right] + W_{ref} \left[ x, y \right] + 2W_{div} \left[ x, y \right] \]
\[ W_{focus} \left[ x, y \right] = W_{ref} \left[ x, y \right] + W_{div} \left[ x, y \right] + W_{div} \left[ -x, -y \right] \]

Combining the three measurements yields

\[ W_{surf} \left[ x, y \right] = \frac{1}{4} \left( W_0 \left[ x, y \right] + W_{180} \left[ -x, -y \right] - W_{focus} \left[ x, y \right] - W_{focus} \left[ -x, -y \right] \right) \]

\([-x, -y]\) in the last equation means we are rotating the data 180° in the computer.
Single Measurement of Sphere

TILT, POWER REMOVED
INTERVAL = 0.025
RMS = 0.014 WAVES
P-V = 0.121 WAVES

FIZEAU INTERFEROMETER, F/1.1 REF. SPHERE
Flat at Focus f/1.1 Diverger

TILT, POWER, COMA REMOVED
INTERVAL = 0.05
RMS = 0.027 WAVES
P-V = 0.243 WAVES
Absolute Reference

TILT, POWER REMOVED
INTERVAL = 0.025
RMS = 0.010 WAVES
P-V = 0.084 WAVES
Absolute Measurement of Sphere

TILT, POWER REMOVED
INTERVAL = 0.025
RMS = 0.011 WAVES
P-V = 0.081 WAVES
10.2.2 Absolute Sphere Testing Using Ball Averager

Calibration ball sitting on a three point kinematic mount with the green cone representing the light from the transmission sphere focused at the center of the ball.

Actual Hardware

Take many measurements for different rotations of ball and average results to average out errors in the ball.
10.3 Absolute Measurement of Surface Roughness

- 10.3.1 Perfect mirror
- 10.3.2 Generate reference
- 10.3.3 Absolute rms measurement
Absolute Surface Roughness Measurement Assumptions

- Surface height is random
- Statistics do not vary over surface
- Each measurement = Test + Reference
- Test and reference uncorrelated
Effect of Reference Surface on Measurement

Error in measured rms for 5 A rms reference surface

<table>
<thead>
<tr>
<th>Rms roughness of test surface (Å)</th>
<th>Error (Å)</th>
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<tbody>
<tr>
<td>0</td>
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</tr>
<tr>
<td>30</td>
<td>0.1</td>
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</table>
10.3.1 Perfect Mirror

I have never seen a perfect mirror, but if we could get one we could measure it to calibrate the system.
10.3.2 Generate Reference

- Average many measurements
- Move random surface > correlation length between measurements
- Effects of random surface reduce as square root of number of measurements
Generate Reference and Subtract

Surface + Reference

Reference

Surface (0.071 nm)
10.3.3 Absolute RMS Measurement

- Make 2 measurements where surface moved > correlation length between measurements
- Subtract measurements and divide by square root of 2
- Reference cancels and obtain
- RMS of test surface

\[
\text{Diff} = \text{Test}_1 + (-\text{Test}_2) \\
\text{RMS}_{\text{Test}} = \frac{1}{\sqrt{2}} \text{RMS}_{\text{Diff}}
\]
Generate Reference and Absolute RMS Comparison

Generate Reference

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>RMS</td>
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</table>

Absolute RMS

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
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</thead>
<tbody>
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<td>RMS</td>
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