Characterization Of A Novel Electro-Static Membrane Mirror Using Off-the-Shelf Pellicle Membranes

David C. Dayton
Applied Technology Associates, 1300 Britt Street, SE, Albuquerque, NM 87123

Justin D. Mansell
Active Optical Systems, 2021 Girard Blvd. SE, Ste 150, Albuquerque, NM 87106

John D. Gonglewski
Air Force Research Laboratory, AFRL/DESE, 3550 Aberdeen SE, Kirtland AFB, NM 87117

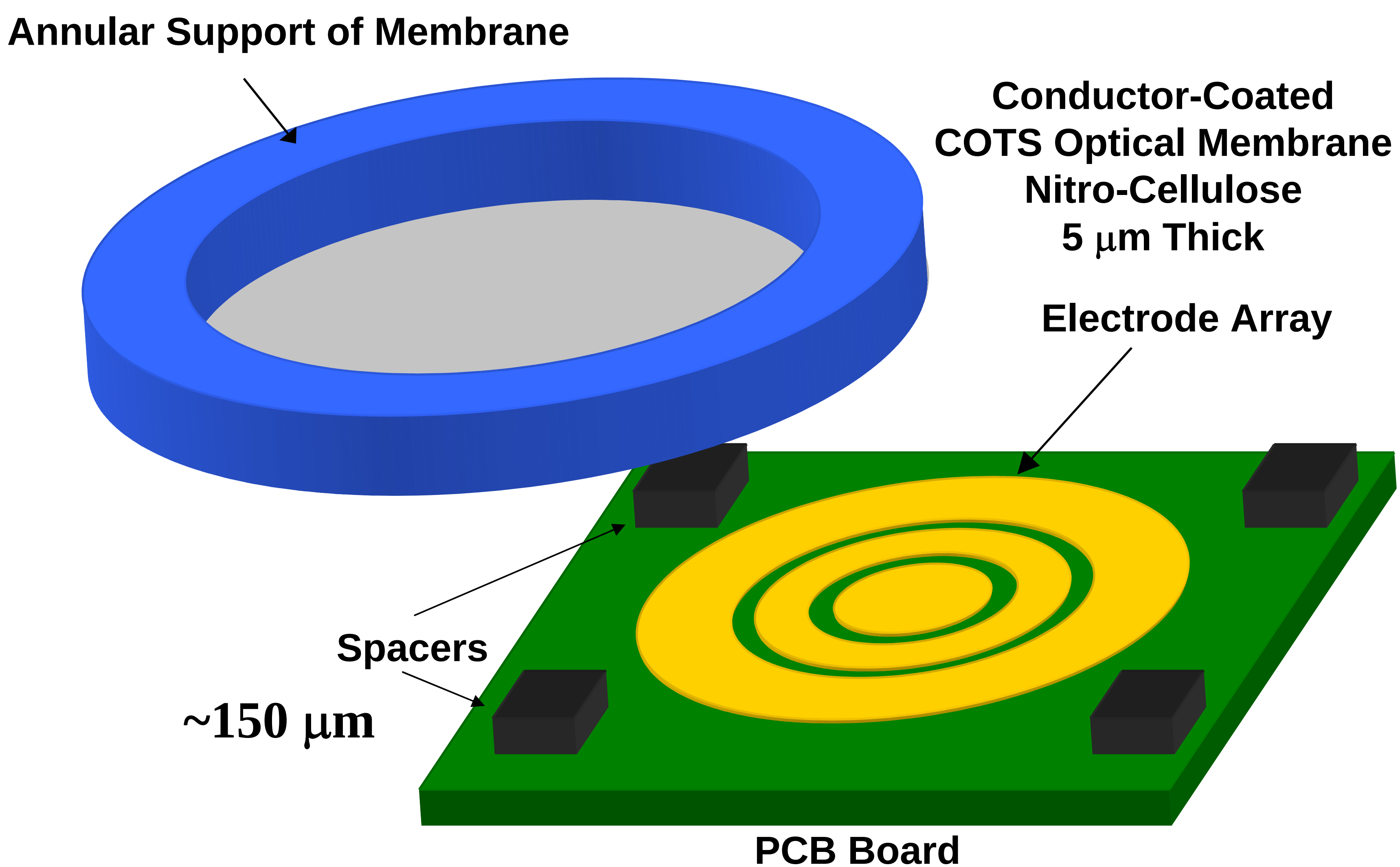
Bob Praus
MZA Associates Corp., 2021 Girard Blvd. SE, Ste 150, Albuquerque, NM 87106

International Workshop on Adaptive Optics in Industry and Medicine, Galway, IE, June 12, 2007

Introduction

- **Membrane Mirrors**
  - Low Cost, Compact Alternative for AO
  - ~$10/Actuator vs ~$1000/Actuator
- **Commercial Off-the-Shelf (COTS) Pellicle Membrane**
  - Reduces Production Costs
  - No Foundry Required
  - Rapid Low Cost Prototyping of Custom Configurations
  - Different Coatings Including Multi-layer Dielectric
  - Different Membrane Materials Possible for Different Applications
- **Proof-of-Concept Lab Investigation of Device Performance**
  - Investigate Utility of Devices for AF Projects
  - Static Measurements
  - Dynamic Closed Loop Performance
- **Applications**
  - Laser Com-Beam Control-Ophthalmology-Atmospheric Imaging

Low-Cost Polymer Deformable Mirror



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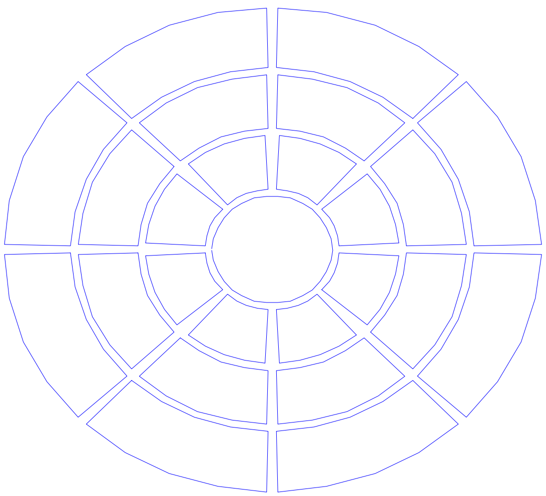
Packaged Device

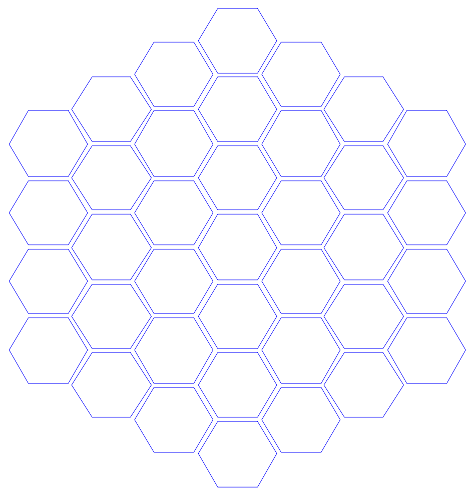
AIR FORCE RESEARCH LABORATORY

Examples of Actuator Configurations

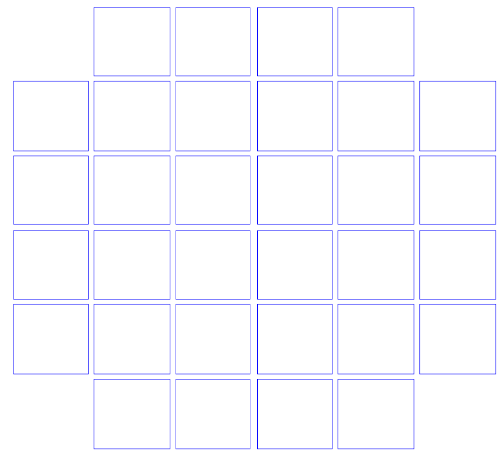
Segmented Annular



Hex

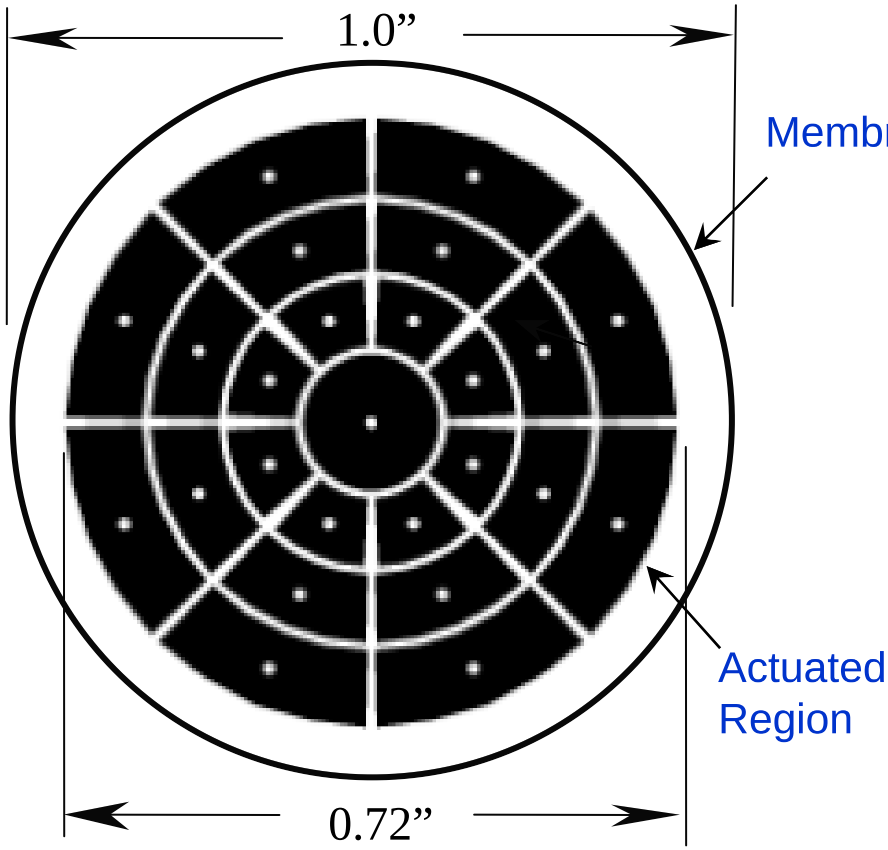


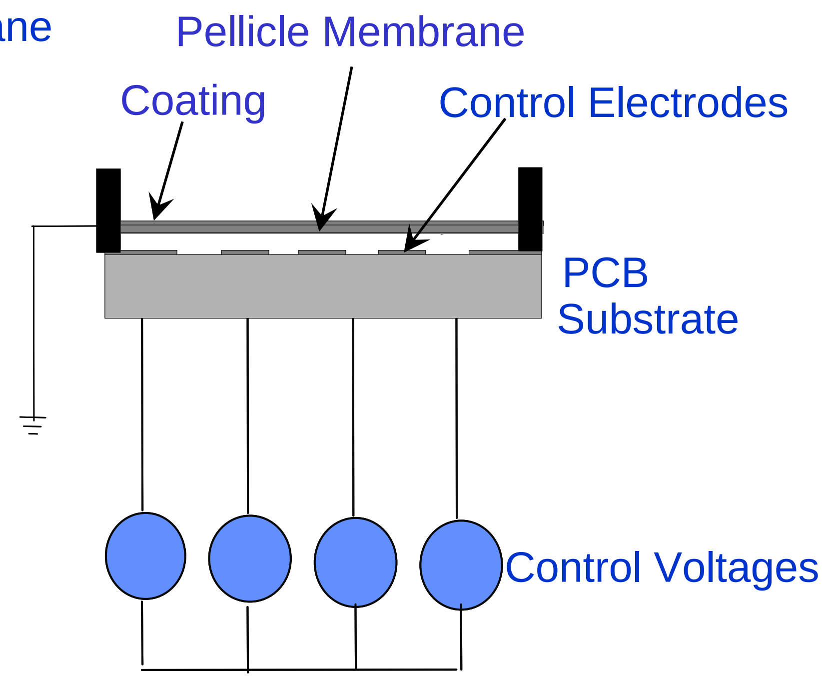
Square



Proto-Type Device Used in Tests Presented Here

AOS COTS Pellicle Membrane Mirror



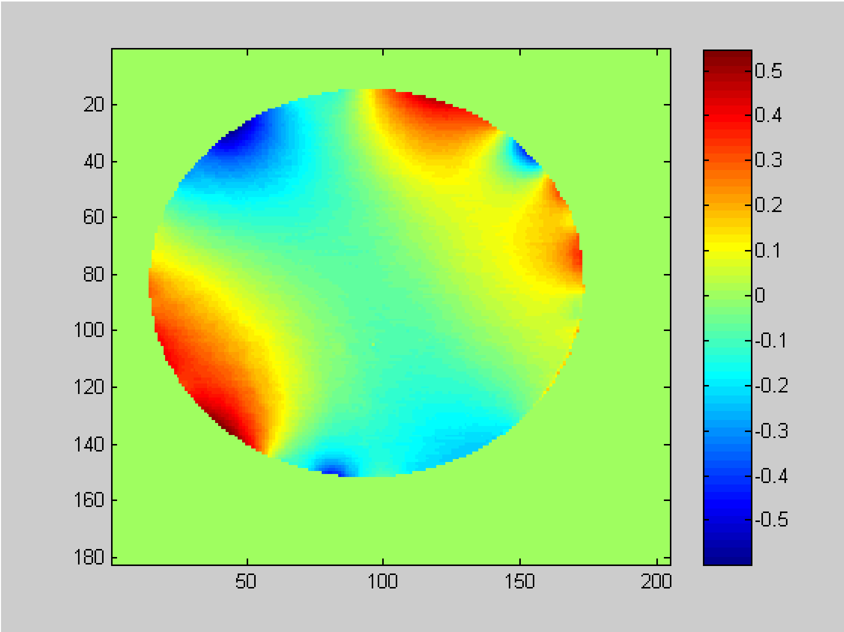


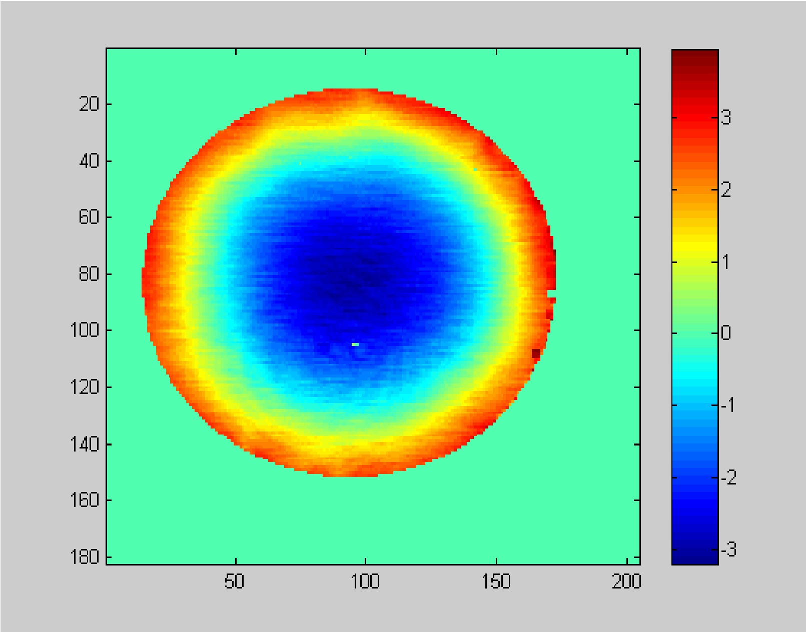
- 5 μm Polymer Membrane Stretched Over Voltage Pads
- 25 Actuators
- ~ 500 Hz First Membrane Resonance

- Actuators Can Only Pull
  Operate Around a Static Bias
- Designed for 300 V Max
  280 V Used in Tests

Mirror Surface Measurements (Mechanical)

Phase Shift Interferometer Measurement
632 nm





0 Volts to All Actuators
Peak-Valley 1.14 Waves

280 Volts to All Actuators
Peak-Valley 7 Waves
Static Aberration Subtracted

Influence Function Calculation

$$\nabla^2 S(\rho,\theta) = -F / T(\rho,\theta)$$ **Poisson Equation**

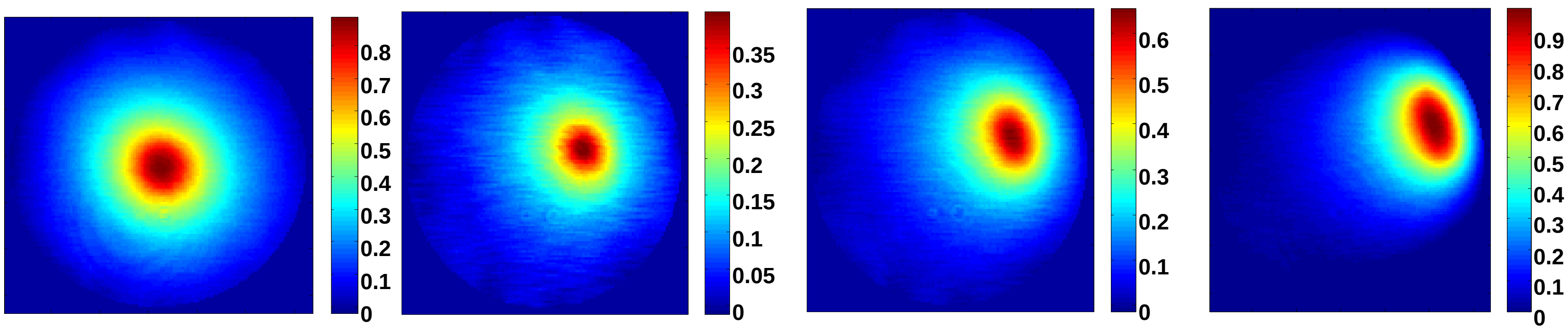
$$F = -\frac{\varepsilon_0}{2}\left(\frac{V}{d}\right)^2$$ **Ideal Capacitor Equation**

Solve Subject to Boundary Condition of Fixed Annular Support

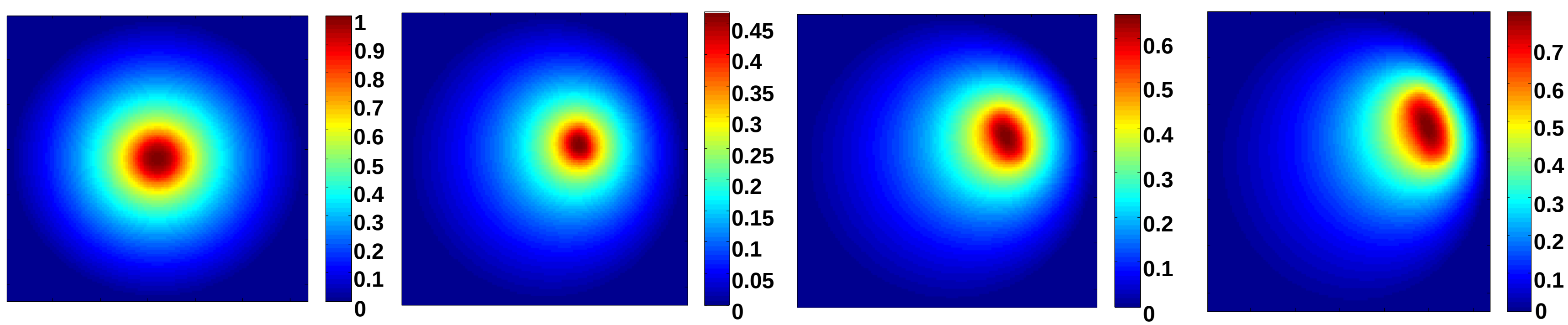
Numerical Solution Outlined in Claflin & Bareket JOSA (1986)

Influence Functions Along One Radial

Center | **1st Ring** | **2nd Ring** | **Outer Ring**



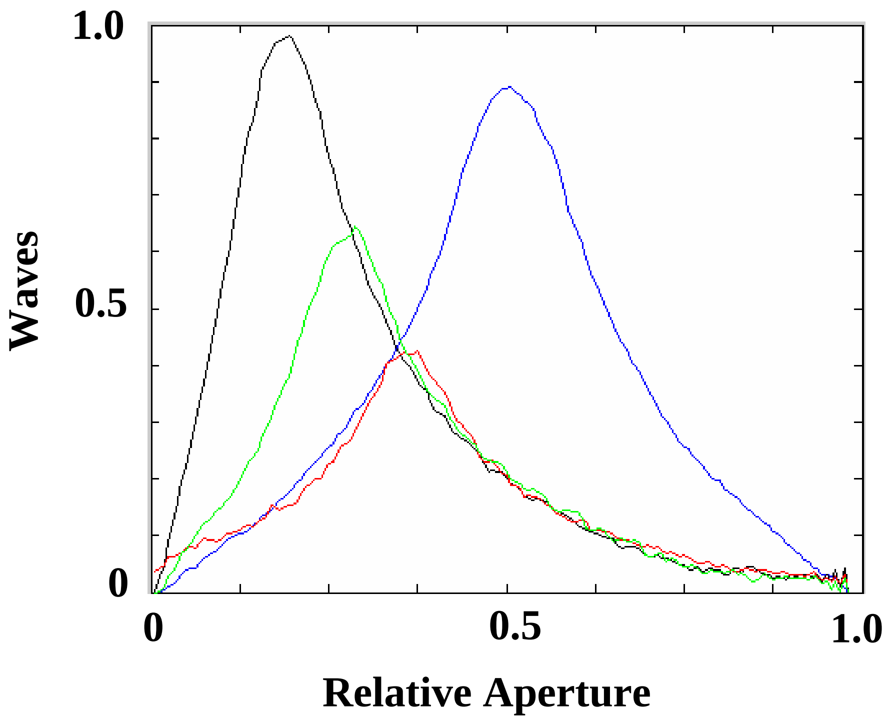
Measured -- Static Aberration Subtracted



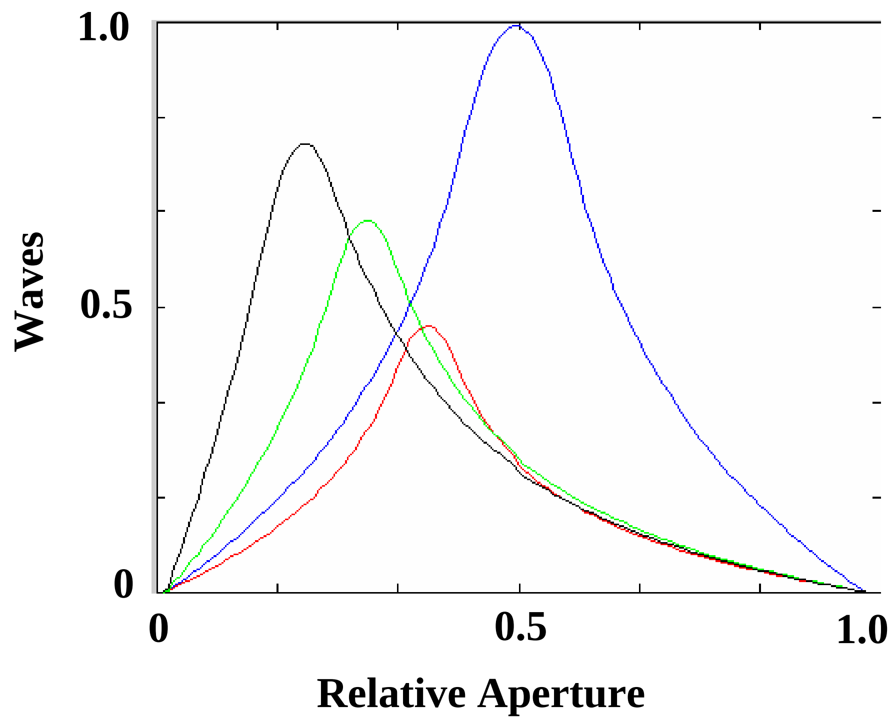
Theoretical

Influence Functions

Close Comparison - Shape of Measured and Theoretical Modes
Some Variations in Electrode Response



Cross-Section
Measured Influence Functions

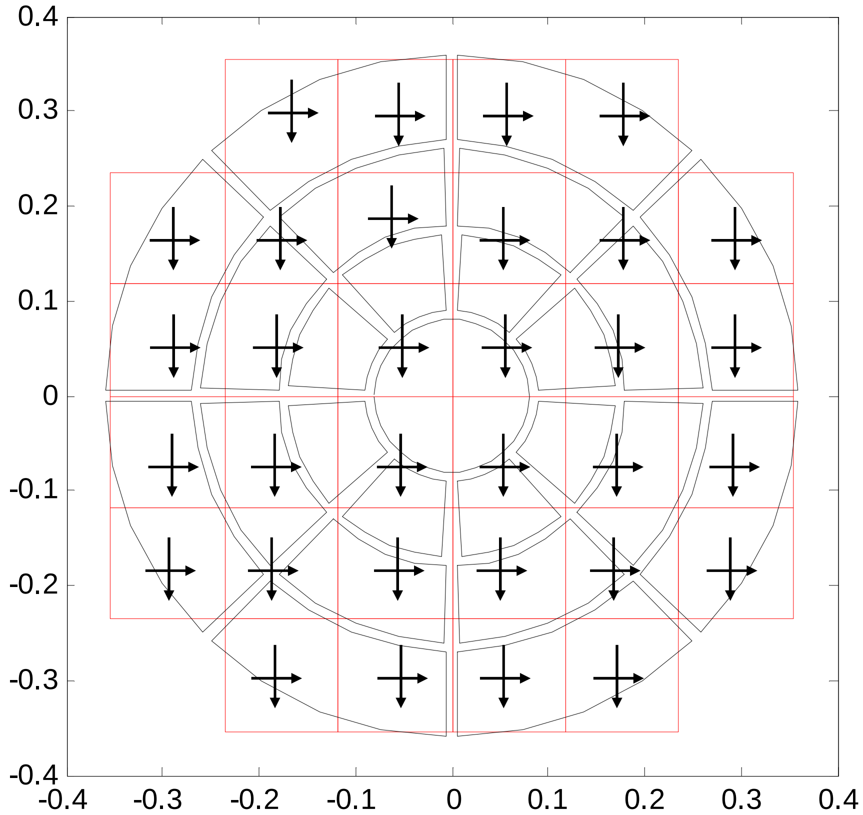


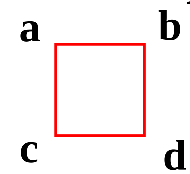
Cross-Section
Calculated Influence Functions

Shack-Hartmann Lensletts

-Shack-Hartmann WFS Measures Slopes Over Lenslet Apertures

-Fried Approximation





$$\nabla_x = \frac{(b-a)+(d-c)}{2}$$

$$\nabla_y = \frac{(c-a)+(d-b)}{2}$$

$$\left[\frac{\nabla_X}{\nabla_Y}\right] = \Gamma_{WFS}\left[Wavefront\right]$$

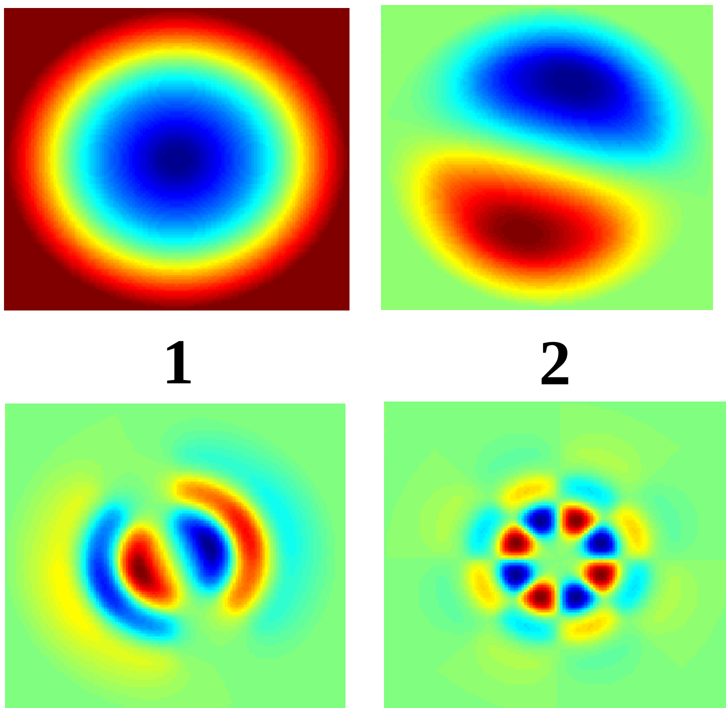
$$Wavefront = \sum_{i=1}^{25} a_i Mode_i$$

SVD Approach to Controller Derivation

$$H = (\Gamma_{WFS} Wavefront)^{-1}$$

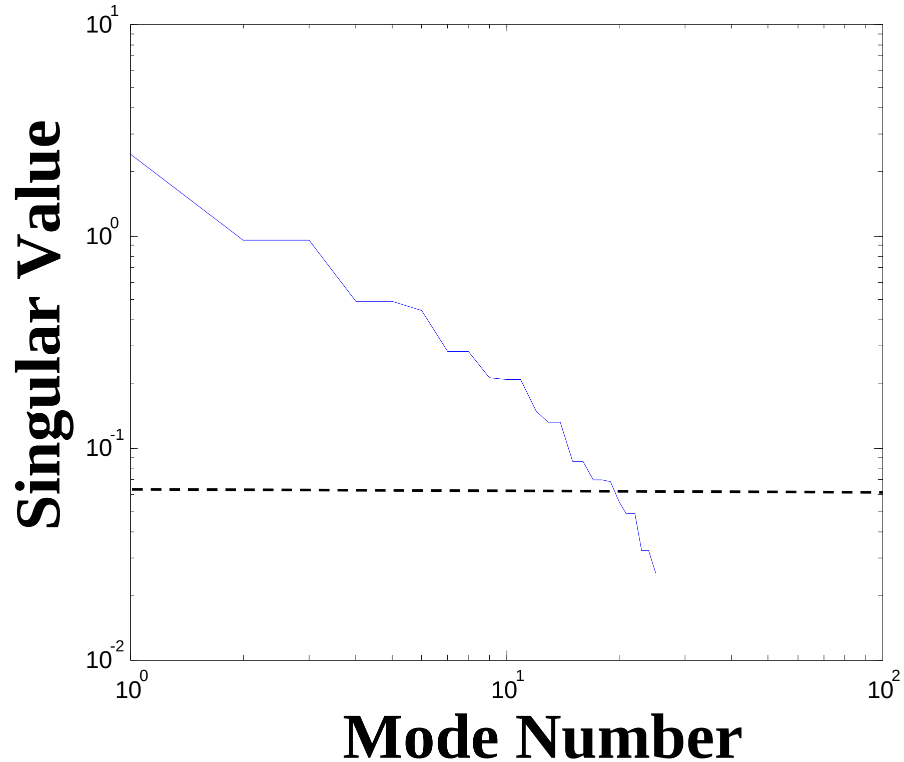
- **Natural Mirror Modes Not Orthogonal**
- **Singular Value Decomposition for Pseudo-Inverse**
  - Derive a Set of Orthogonal Modes Spanning Same Space
  - Expand Mirror Modes in Terms of Orthogonal Modes
  - Discard Modes with Low Singular Values to Improve Stability
  - Calculations in MATLAB

SVD Modes



1 2

17 25

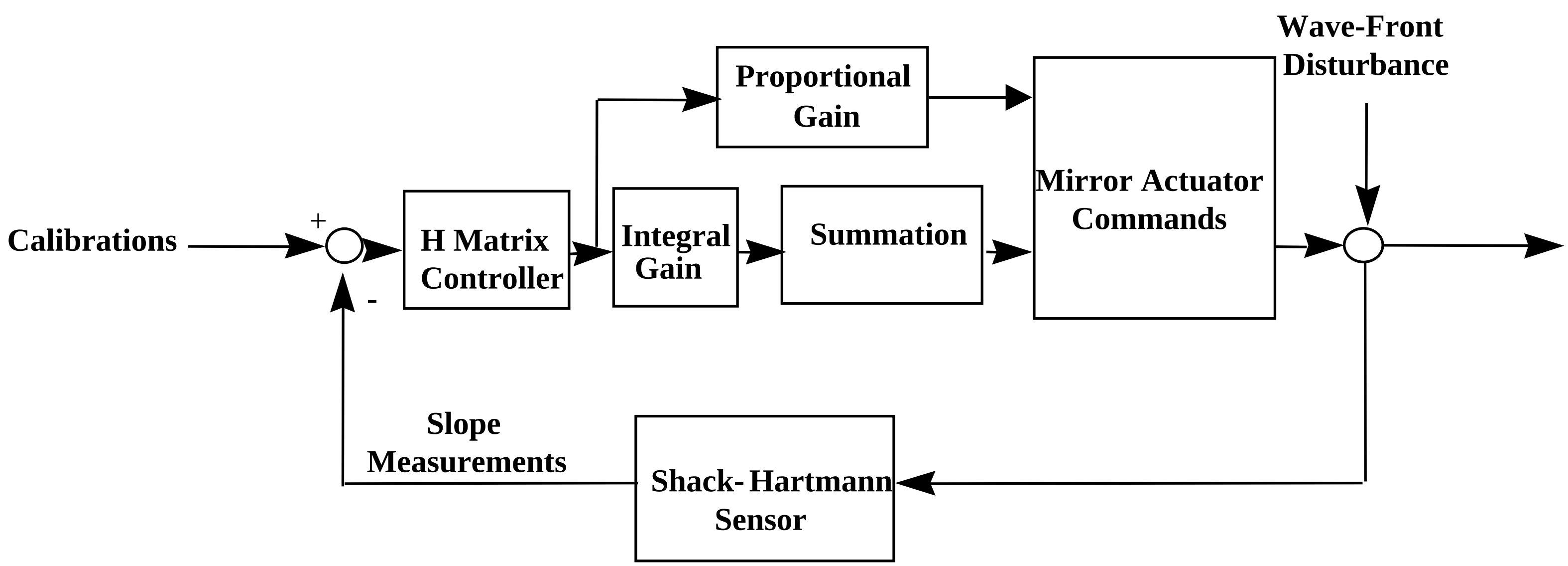


Stability Improved By Discarding Modes With Low S.V.

At Expense of Fewer Degrees of Freedom 20 Modes Used

Correct D/r0~5 With this Number of Modes

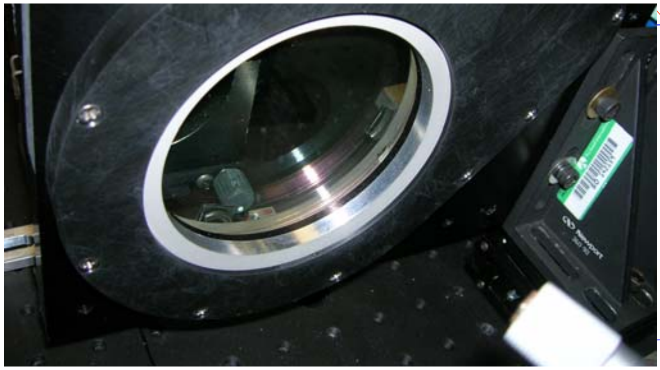
Control Algorithm

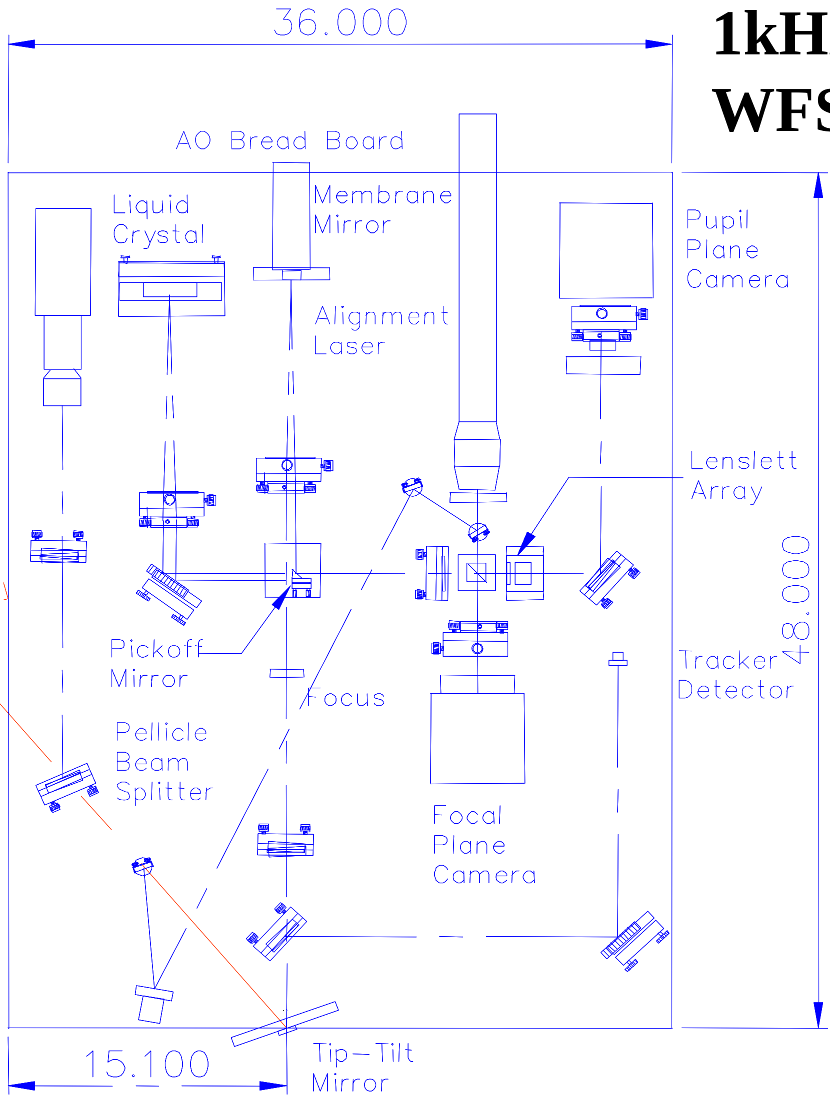


1000 Hz WFS Sample Rate
1 msec Loop Time
1 Time Step Latency

MEMS AO Test Bed

Lexitek Spinning Phase Plate
Variable Rate Dynamic Disturbance

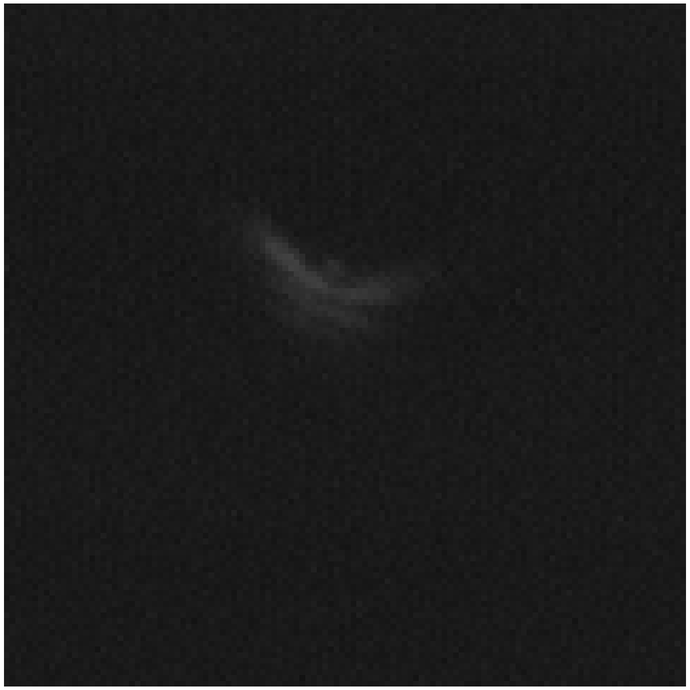


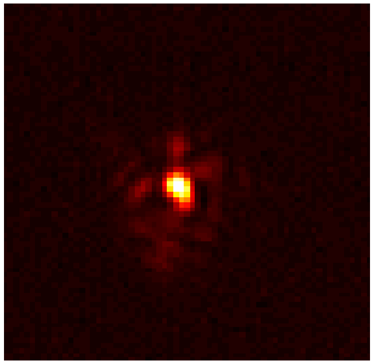


1kHz Low Noise WFS Camera

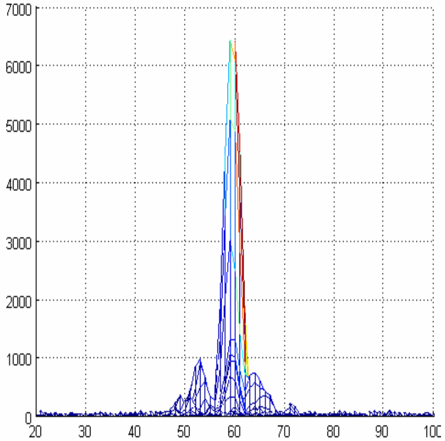
Closed Loop Experiments No Disturbance

Correct Static Aberrations



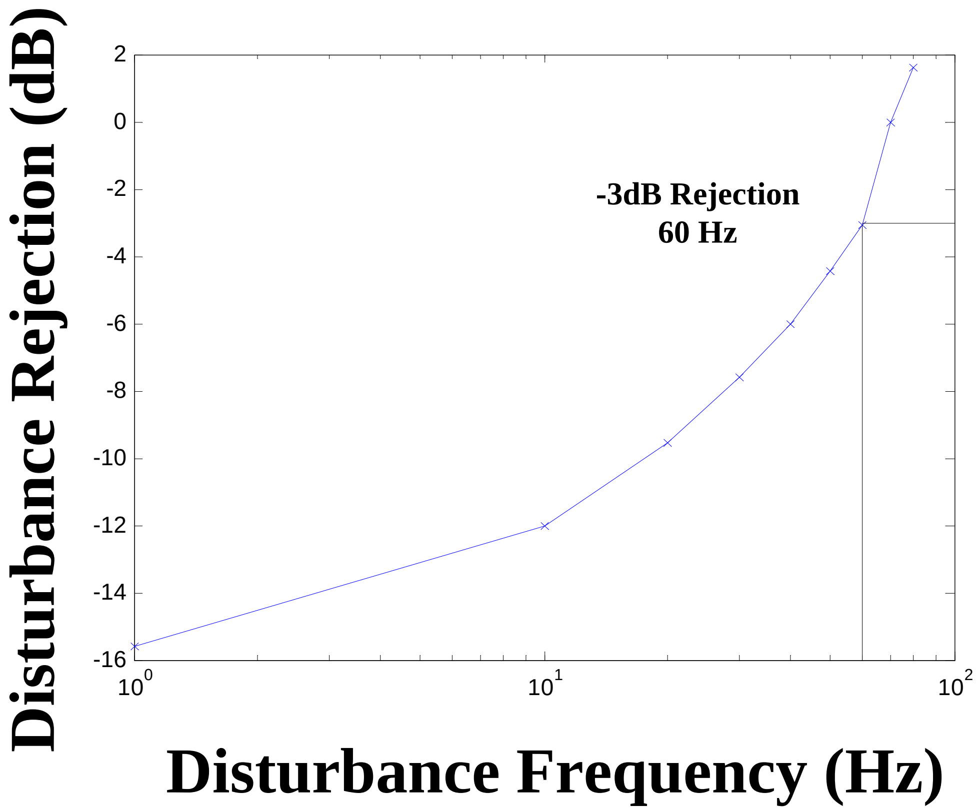


Strehl=.58



Closed Loop Temporal Bandwidth

Tilt Disturbance Rejection



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Strehl Predictions

$$\text{Strehl} \cong e^{-\sigma^2} \qquad \sigma^2 = \sigma_{static}^2 + \sigma_{fit}^2 + \sigma_{temp}^2 + \sigma_{snr}^2$$

$$\sigma_{fit}^2 \cong \alpha \left(\frac{r_s}{r_0} \right)^{5/3} \qquad \alpha = .4$$

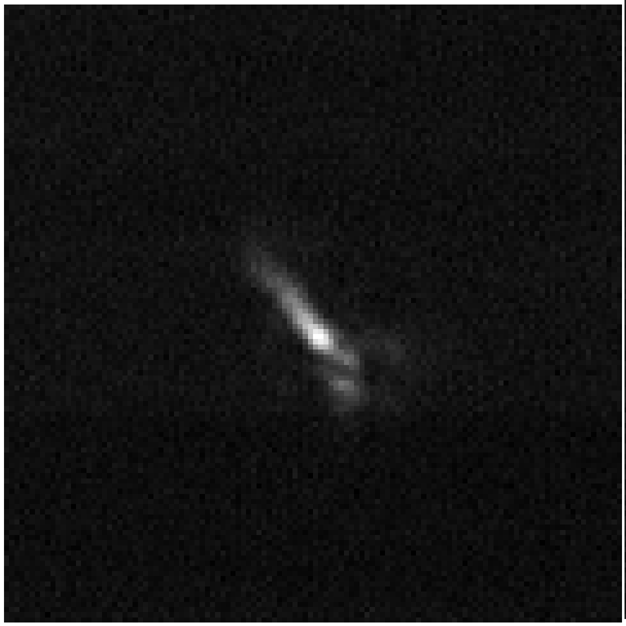
Membrane Mirror

$$\sigma_{temp}^2 \cong \left(\frac{f_G}{f_{3dB}} \right)^{5/3} \qquad \sigma_{snr}^2 \cong .35 \frac{\pi^2}{4\,SNR^2}$$

Strehl Ratio Predictions

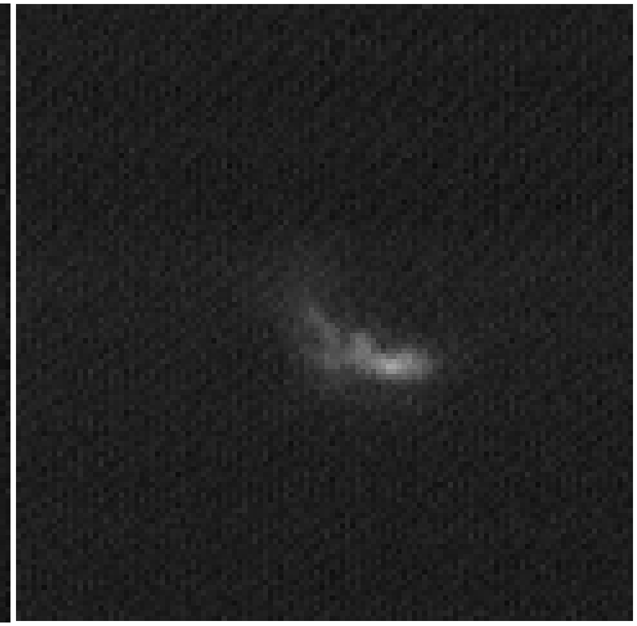
.37	.25	.16
10 Hz	40 Hz	60 Hz

Closed Loop Experiments Dynamic Disturbance



10 Hz Greenwood Frequency

40 Hz

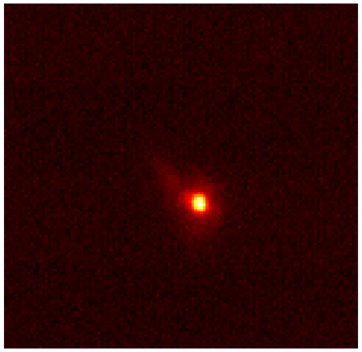


60 Hz

D/r0=5 Dynamic Disturbance (Spinning Phase Plate)
Different Greenwood Frequencies

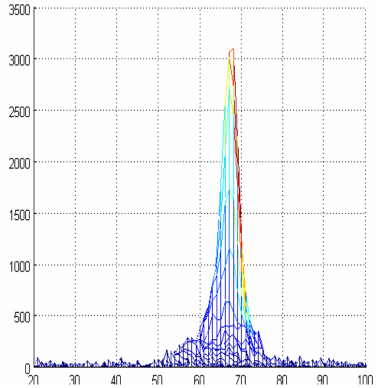
Some Residual Error Due to Uncorrected Static Aberration

Long Exposure
Closed Loop Strehl Ratio

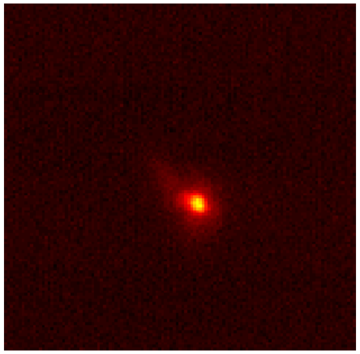


Strehl=0.28

(0.37)

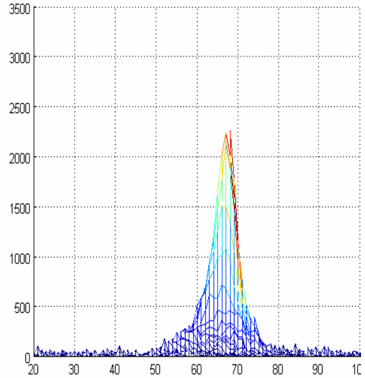


10 Hz



Strehl=0.20

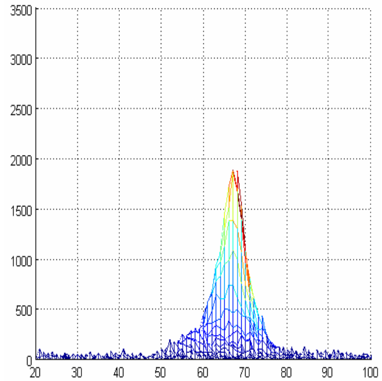
(0.25)



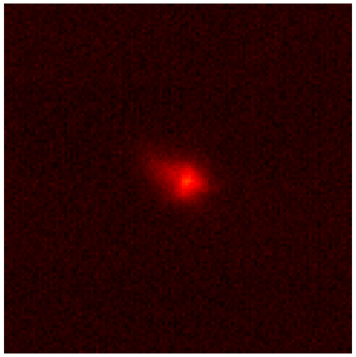
40 Hz

Strehl=0.15

(0.16)

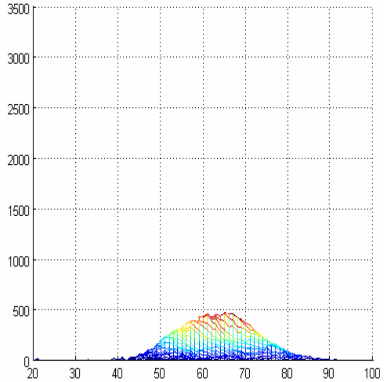


60 Hz



Strehl=.05

Predicted Strehl

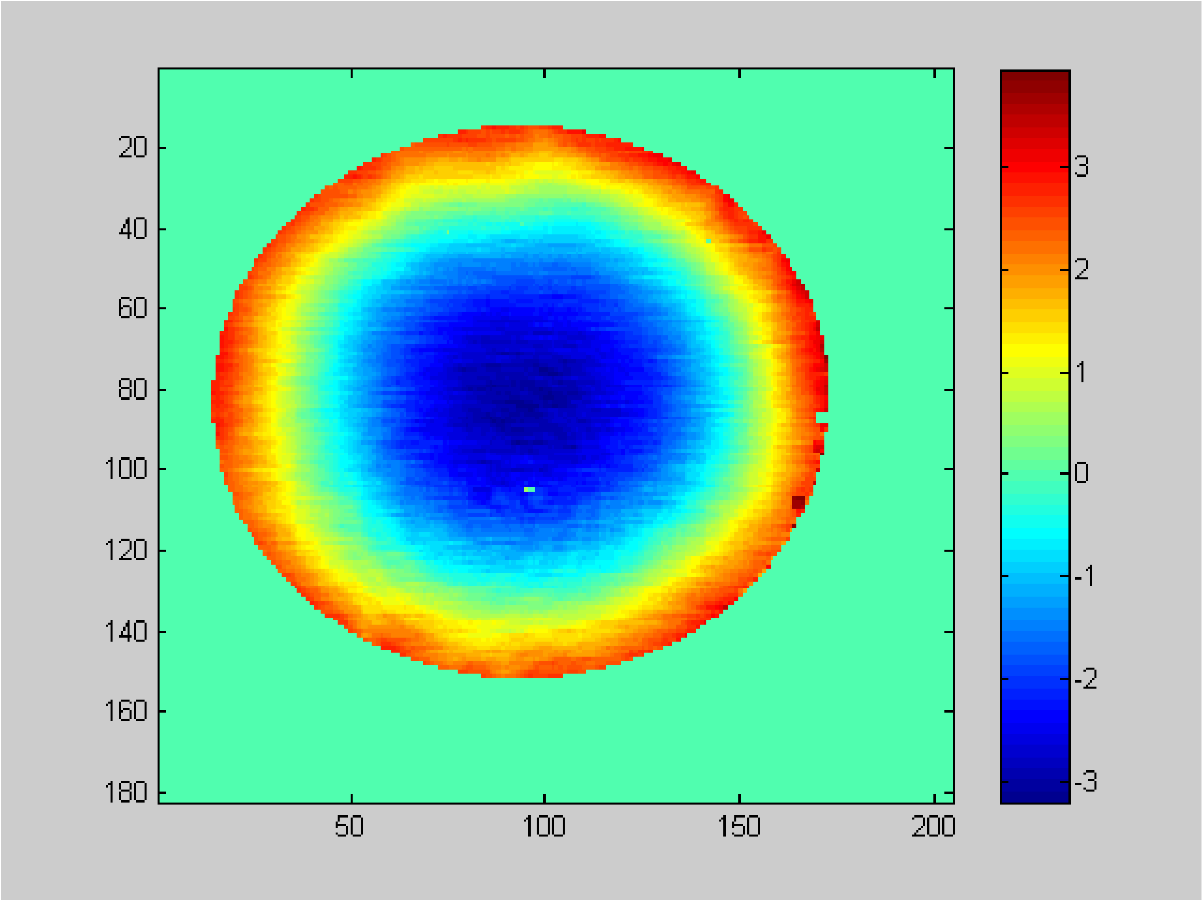


Open Loop

Conclusions

- **Membrane Mirror AO Devices**
  - Less Expensive, Low Power, Compact
- **Pellicle Membrane Mirror**
  - COTS Pellicle Nitro-Cellulose 5 μm Membrane
  - Different Membranes and Coatings for Different Applications
  - ~1 Wave (Mechanical) P-V Static Aberration
  - 500 Hz 1st Resonance
- **Proof of Concept Demonstration**
  - First High Speed Closed Loop Demo 60Hz - 3dB B.W.
  - Correction of D/r0~5 Dynamic Disturbance with 25 Actuators
  - Static Aberrations Degrade Performance-Use up Dynamic Range
  - Increase Dynamic Range to Correct Static Aberration
  - Work With Other Actuator/WFS Configurations

Full Stroke Mirror Surface



280 Volts to All Actuators
Peak-Valley 7 Waves@ 623 nm
Static Aberration Subtracted

Pellicle Mirror Measured Influence Functions