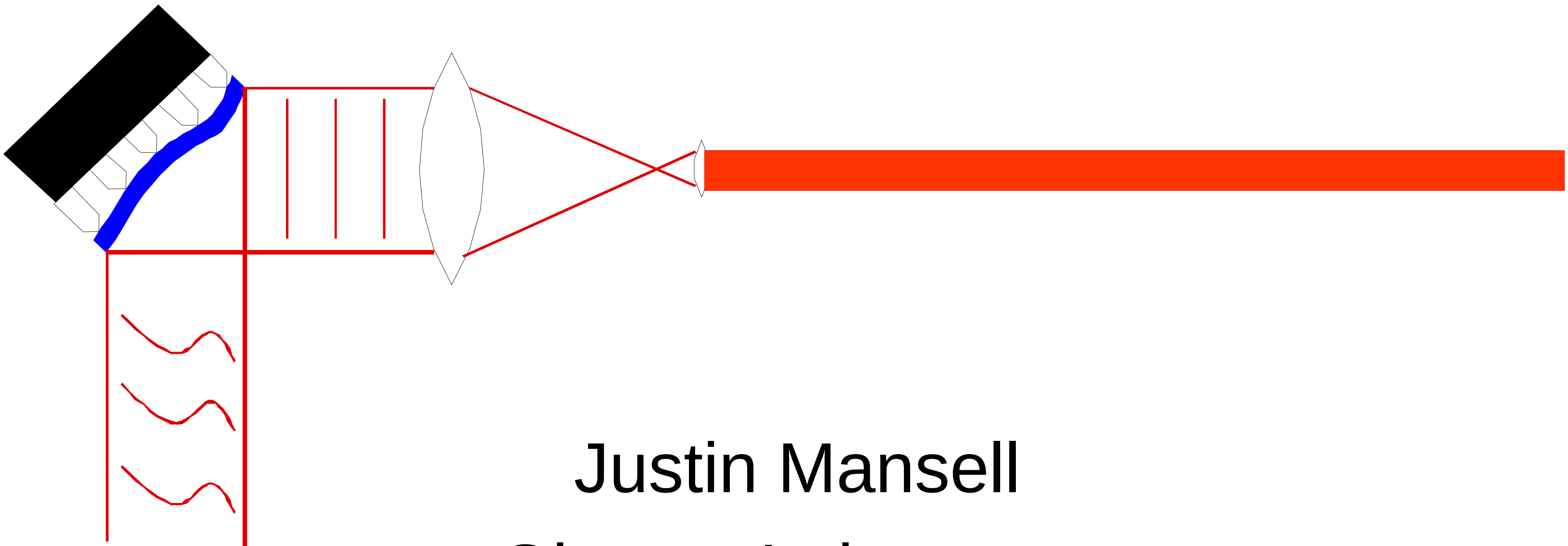
Adaptive Optics for LIGO



Justin Mansell

Ginzton Laboratory

Stanford University

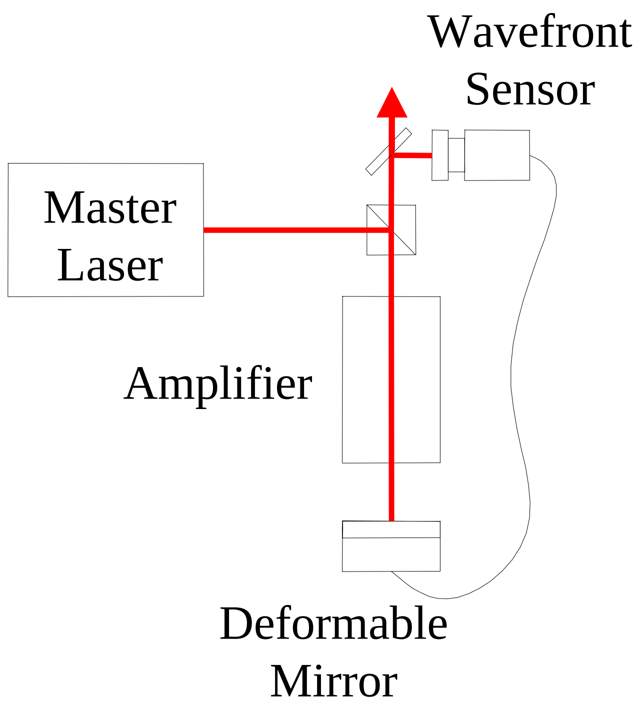
LIGO-G990022-39-M

Outline

- Motivation
- Wavefront Sensor
  - Characterization
  - Enhancements
  - Modeling Projections
- Adaptive Optics Results
  - Effects of Thermal Lensing
  - Characterization
- Conclusions

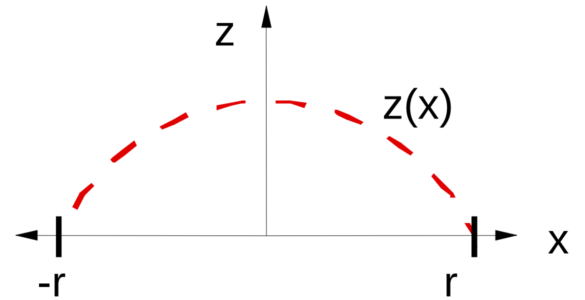
Motivation

- Optical Metrology
  - Measuring LIGO Mirrors
- Laser Beam Characterization
- Laser Spatial-Mode Control
  - Thermal Lens Compensation
  - Amplifier Aberration Compensation
- Other Areas
  - Contact Lenses
  - Direct Eye Measurement
  - Astronomy
  - Hard-disk drives
  - Windshield Manufacturing



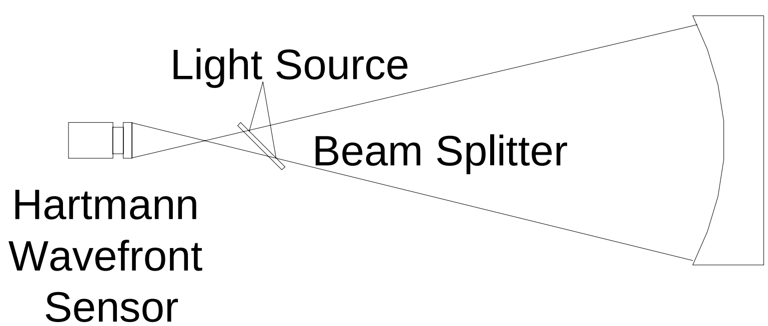
Optical Metrology

- Wavefront Error (Optic Surface Figure)
  - $F_{zonal} \approx 3.5$
  - $F_{modal} \approx 1.0$
- Optic Radius of Curvature (ROC)



$$\left\langle z^2 \right\rangle = F \cdot \frac{d}{f} \cdot \left\langle \Delta x^2 \right\rangle$$

$$ROC \approx \frac{r^2}{2 \cdot \left| z(r) - z(0) \right|}$$



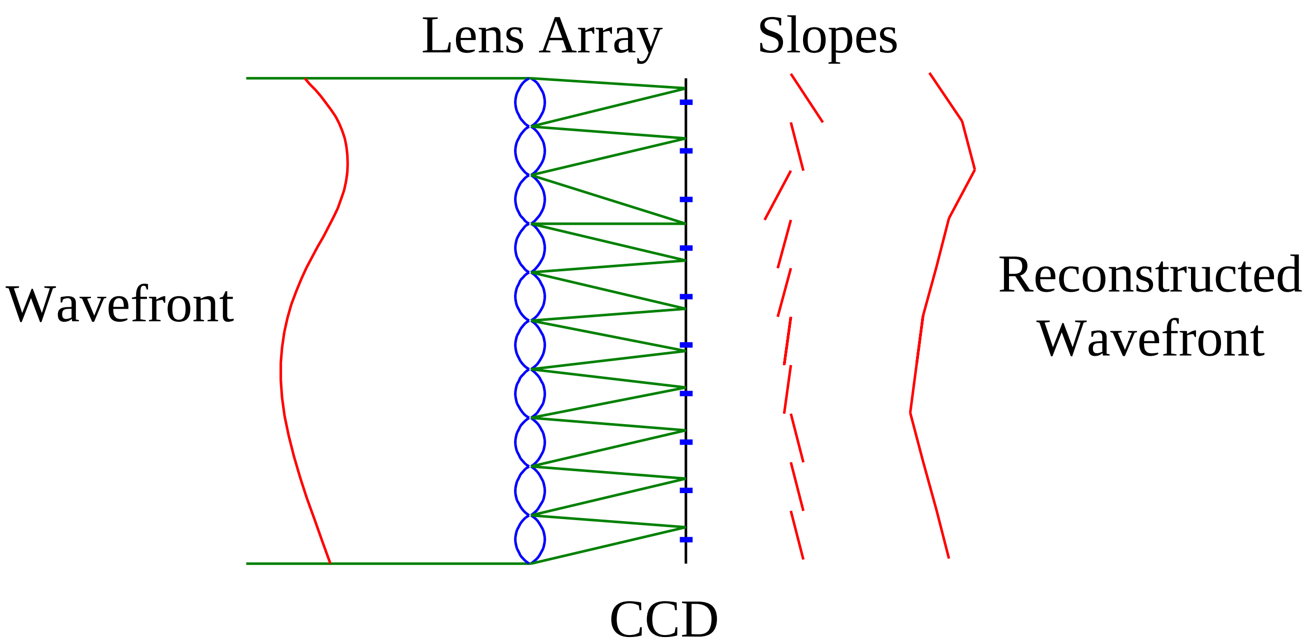
Variables

z = wavefront distortion
F = reconstructor constant
Δx = spot position shift
d = lens diameter
f = lens focal length

Justin Mansell - jmansell@stanford.edu
Stanford University

Shack-Hartmann Wavefront Sensor

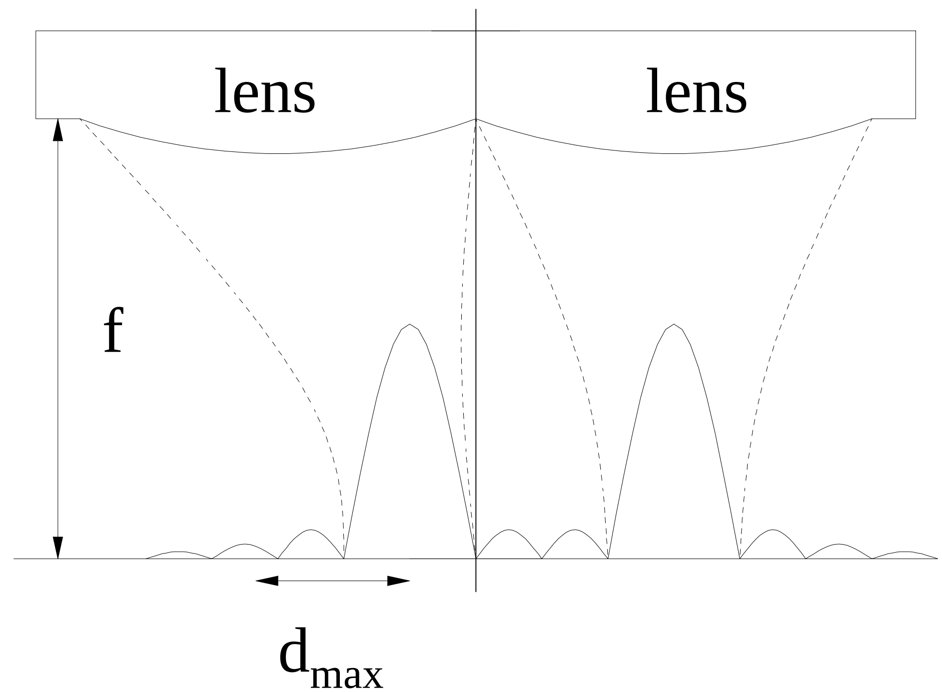
- Each lens measures average slope across that lens.
- Phase slope is spot displacement over focal length.
- Wavefront is reconstructed by integrating.



Justin Mansell - jmansell@stanford.edu
Stanford University

Hartmann Sensor Characteristics

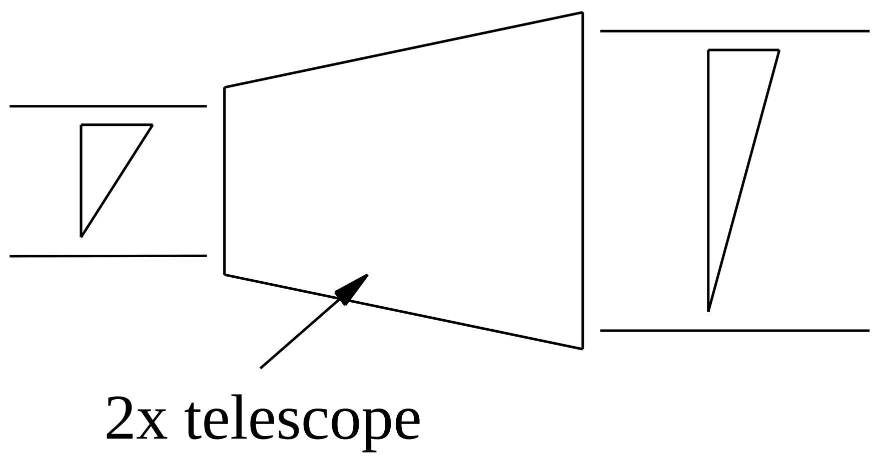
- Tip-Tilt Sensitivity
  - Limit: Spot Position Determination Accuracy
- Dynamic Range
  - Limit: Excessive Spot Motion
- Resolution
  - Limit: Lens Size
- Example:
  - f=8mm, d=144 micron
  - spot position: 0.2 um so 25 microrads
  - dynamic range: 4.5 mrads



Justin Mansell - jmansell@stanford.edu
Stanford University

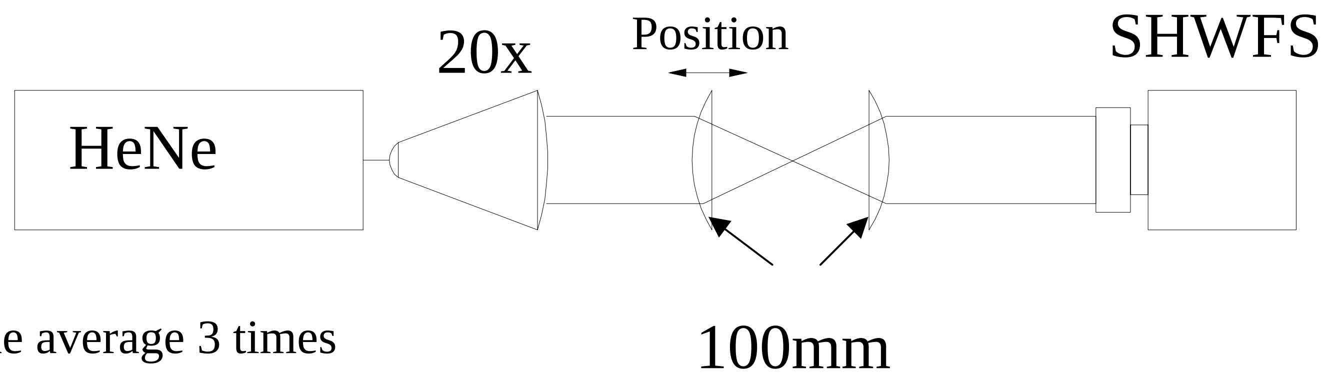
Effects of Magnification

- Magnification defined as times image increases in size (20x = 20 times bigger)
- Magnification linearly increases resolution and decreases sensitivity
- **Conclusion: SHWFS good at measuring large optics**



Justin Mansell - jmansell@stanford.edu
Stanford University

Measured ROC Wavefront



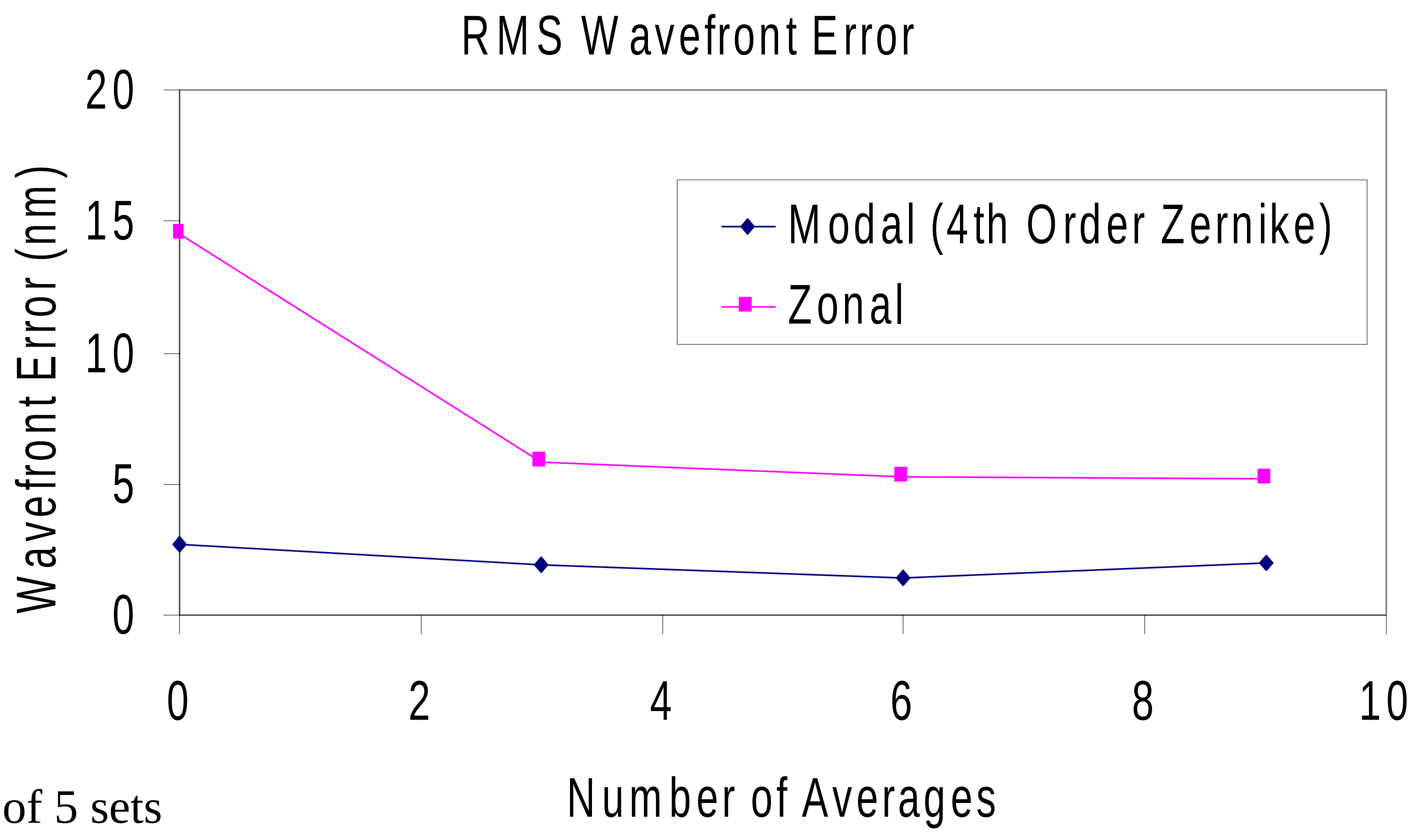
10-frame average 3 times

Position (microns)	Theoretical ROC (m)	Measured ROC (m)	Std. Dev. (m)	Std. Dev. Sag Difference (nm)
0	Infinity	2157	724	4.4
10	999.9	587	83	6.1
20	499.9	344	20	4.3
30	333.23	249	12	4.9
40	249.9	202	10	6.3
50	199.9	168	3	2.7
100	99.9	89	0.7	2.1

Shack-Hartmann Performance

- Wavefront sensor accuracy limited by ability to measure focal spot positions.
  – Our sensor had 100nm focal spot accuracy and measured ~5nm RMS wavefront error over 1cm (~λ/200).
- Modeling shows:
  – Coherent crosstalk between adjacent lenses limits sensor accuracy.
  – Camera noise sets next accuracy limit.

Measured Flat Wavefront Error

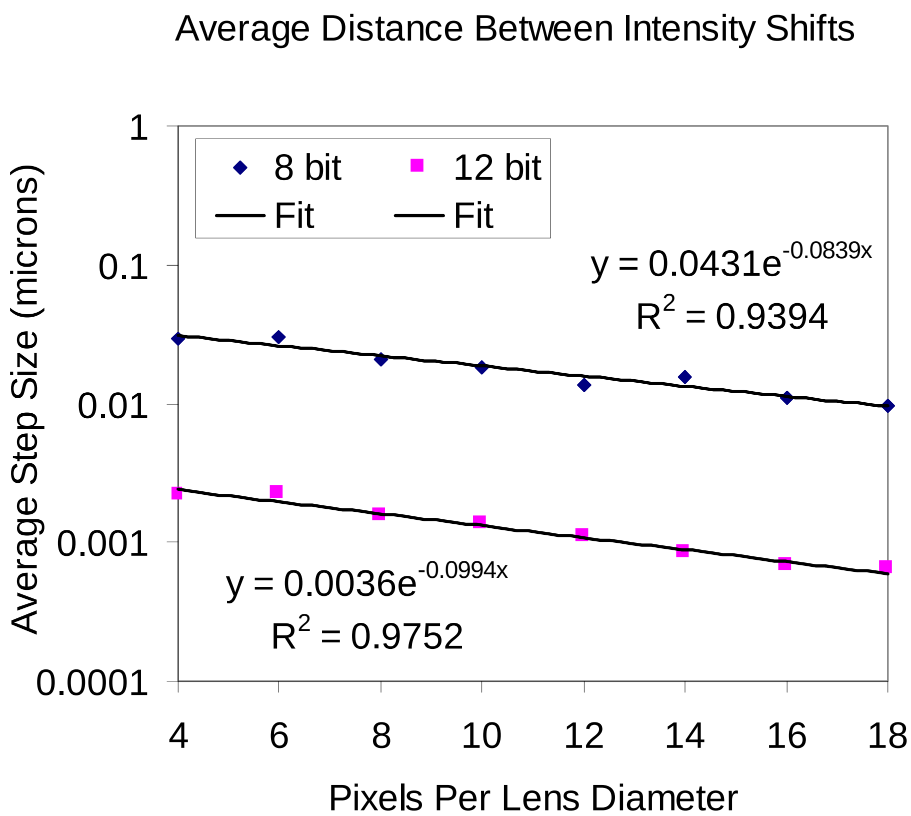


Average of 5 sets

Justin Mansell - jmansell@stanford.edu
Stanford University

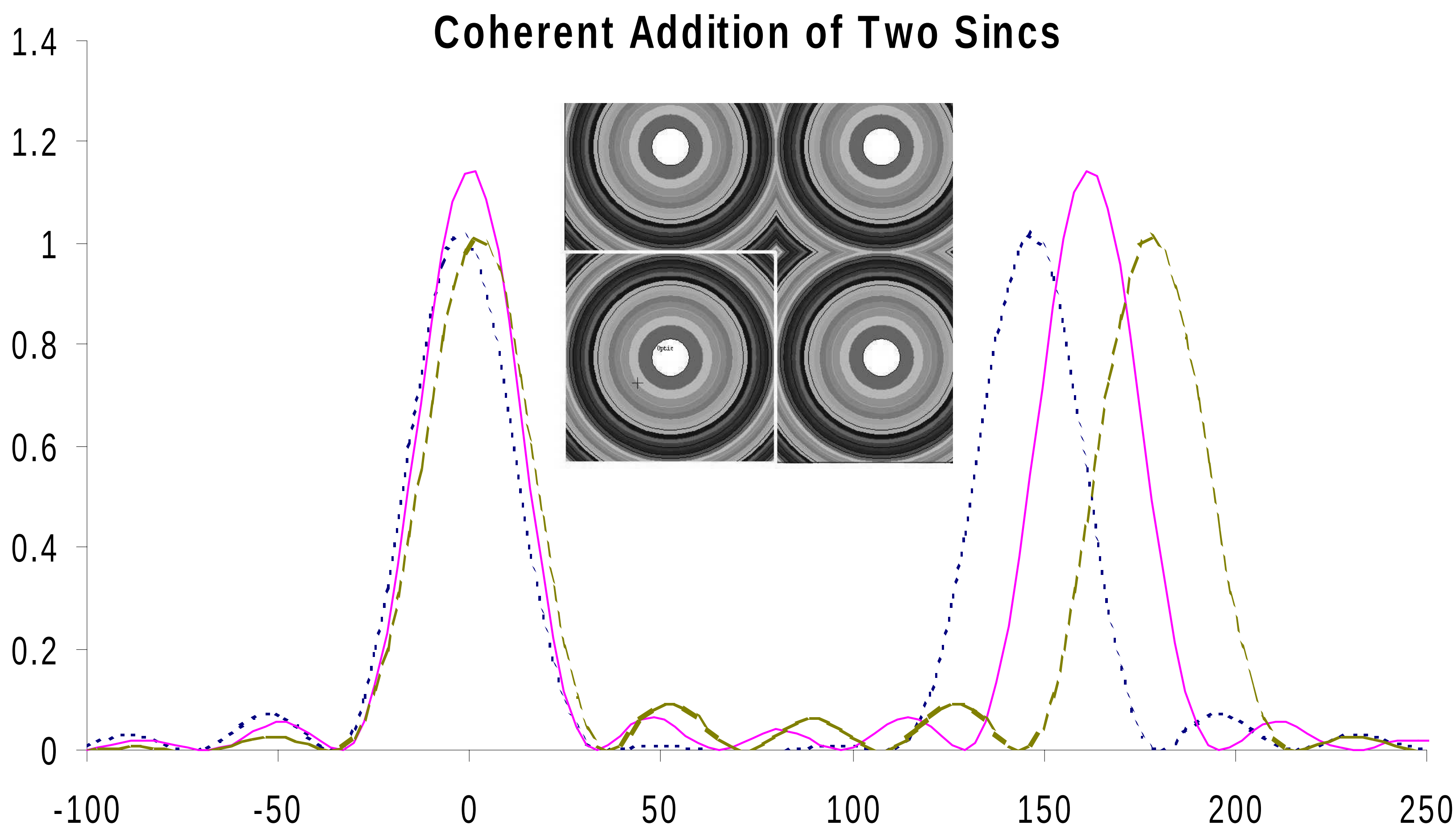
Modeling

- Assumed E-field known
- E-field is coherent sum from all lenses
- Pixelated by sampling 100 points
- Digitized by rounding to nearest 2^{bits}
- Moved center focal spot of 5x5 array by 0.1nm to 100nm and looked for intensity shift.



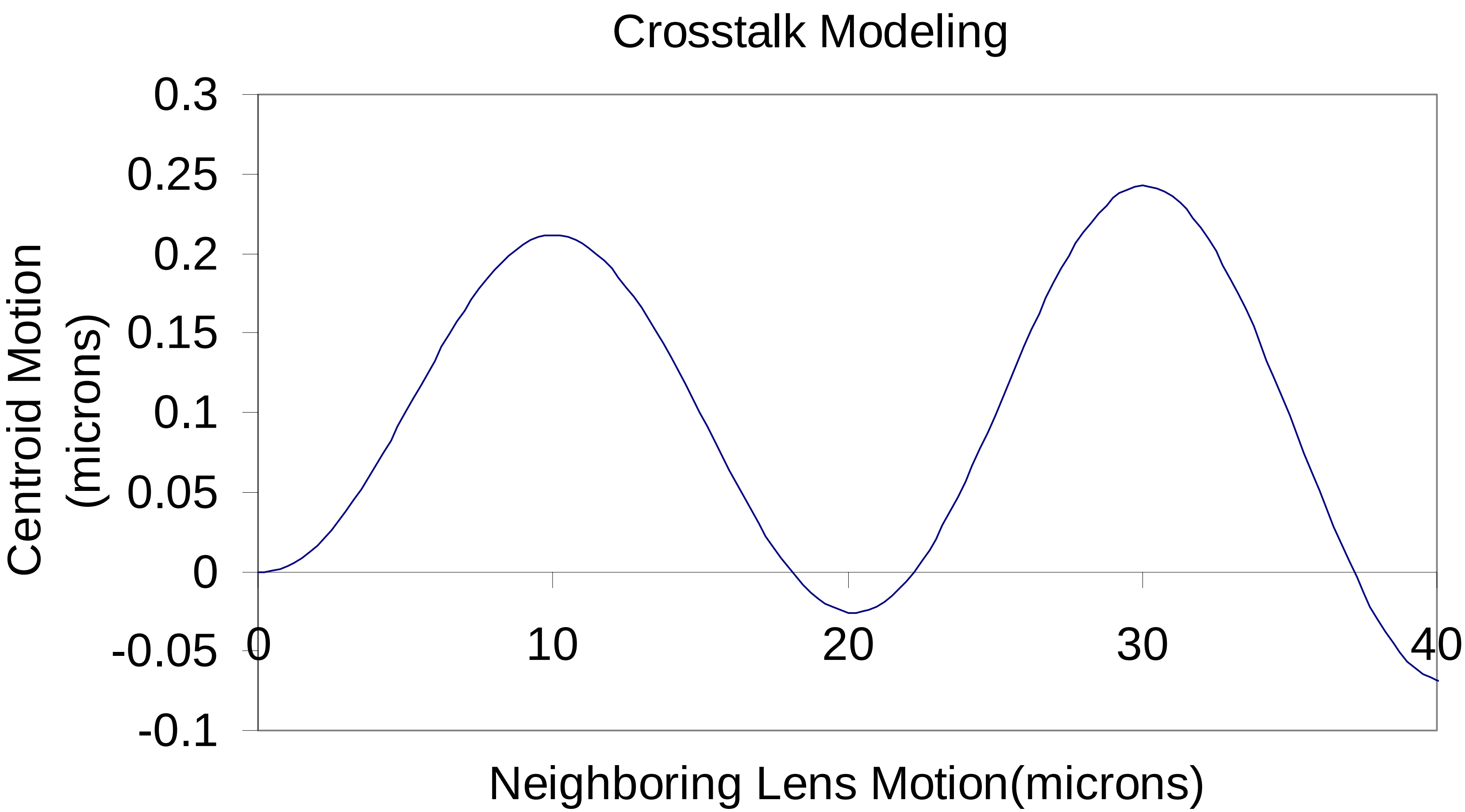
Justin Mansell - jmansell@stanford.edu
Stanford University

Effect of Coherent Crosstalk



Justin Mansell - jmansell@stanford.edu
Stanford University

Diffraction Modeling



Justin Mansell - jmansell@stanford.edu
Stanford University

Future Wavefront Sensor Performance

Wavefront Error

Perturbation	Effect on SHWFS
8 to 12-bit camera	Improve Tilt Sensitivity by 16x

Estimated RMS Wavefront Error: 0.3nm (~ λ / 3000)

Radius of Curvature

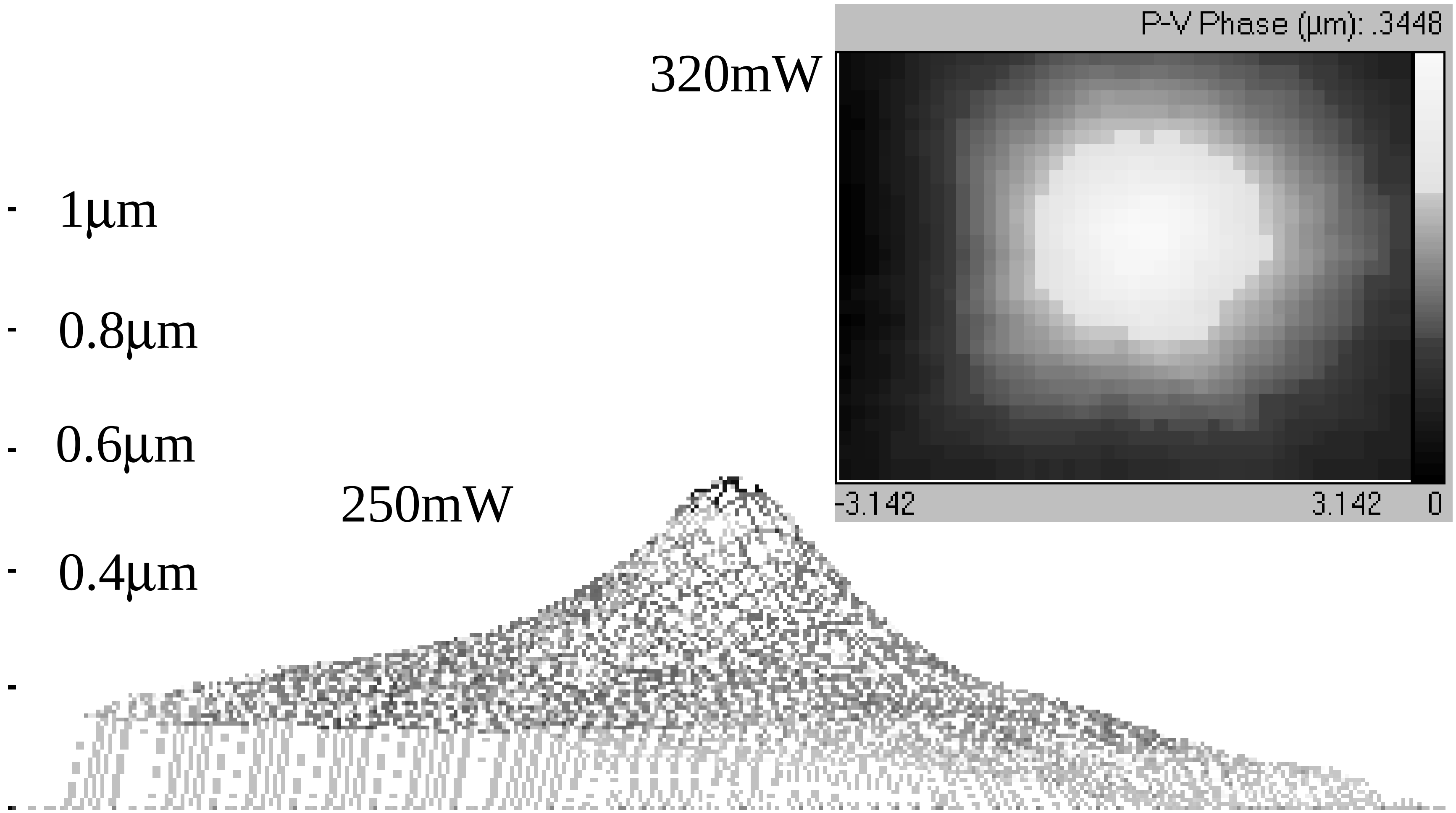
1/20x Magnification	Tilt Amplification by 20x

Estimated ROC : 10,000 ± 6.25 meters

Outline

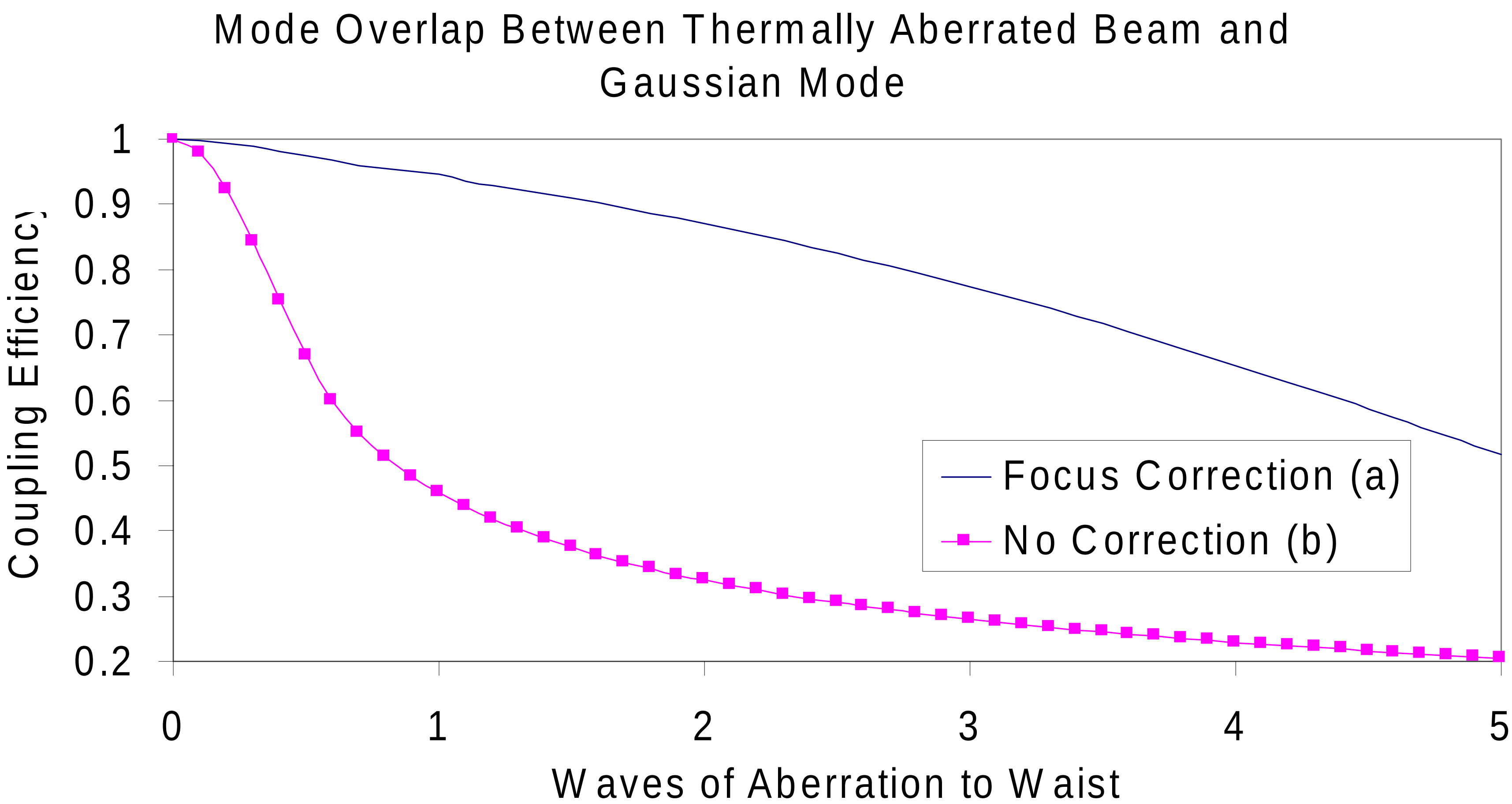
- Motivation
- Wavefront Sensor
  - Characterization
  - Enhancements
  - Modeling Projections
- **Adaptive Optics Results**
  - Effects of Thermal Lensing
  - Characterization
- Conclusions

$LiNbO_3$ Thermal Lenses



Justin Mansell - jmansell@stanford.edu
Stanford University

Effects of Thermal Lensing

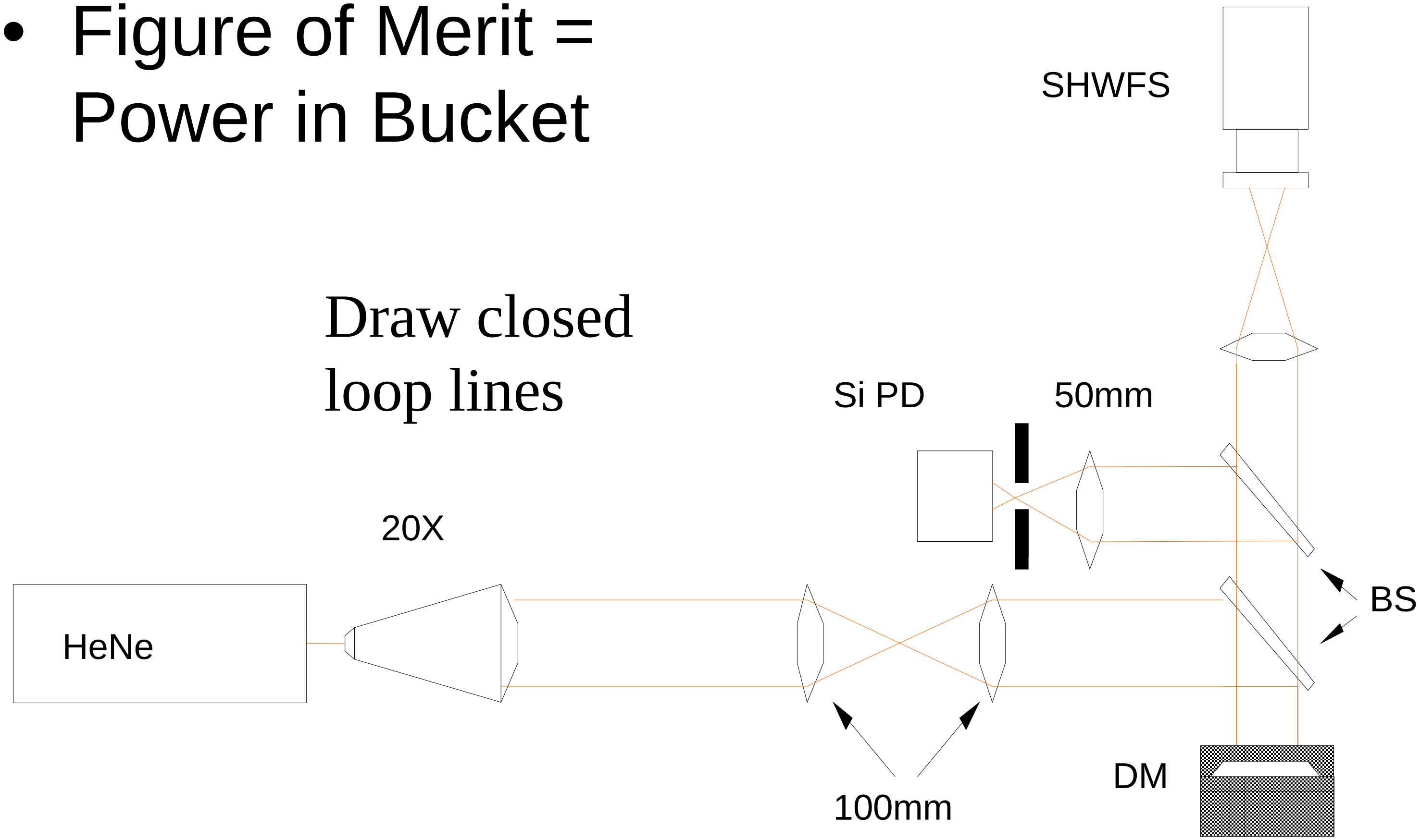


Justin Mansell - jmansell@stanford.edu
Stanford University

Adaptive Optics System

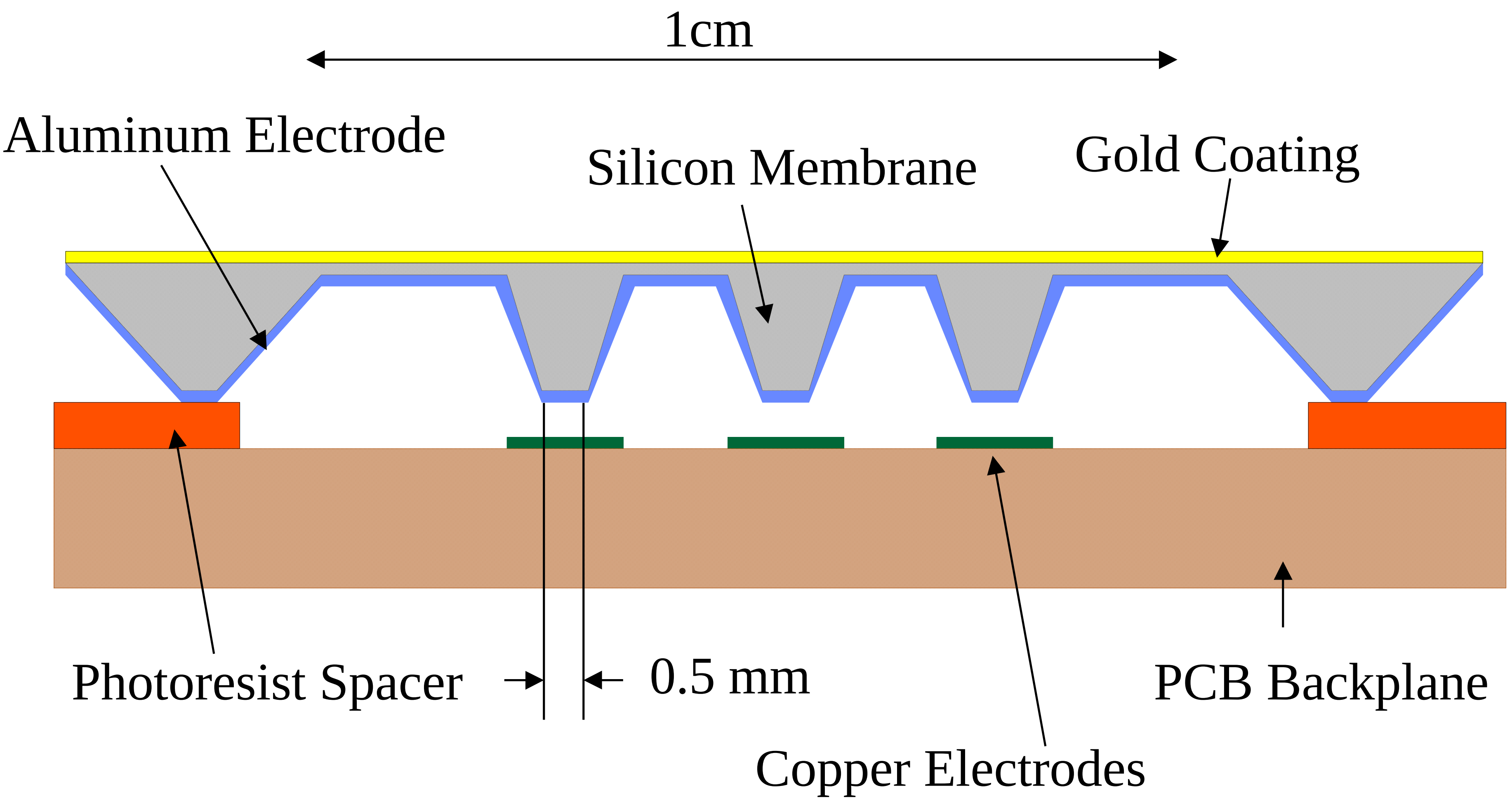
- Figure of Merit = Power in Bucket

Draw closed loop lines



Justin Mansell - jmansell@stanford.edu
Stanford University

Mirror Architecture



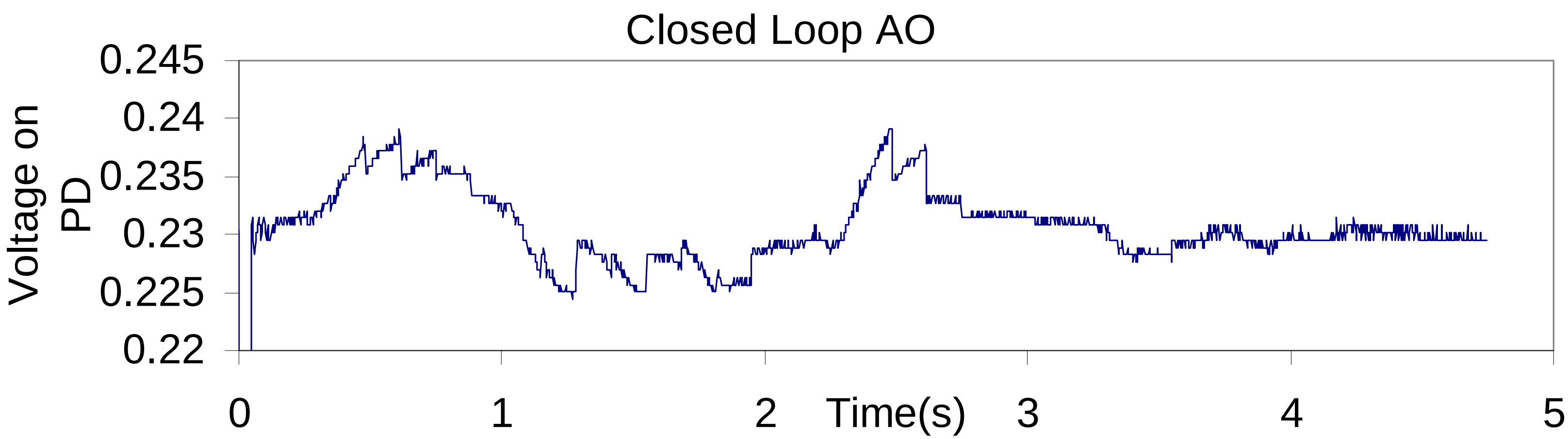
Patent Pending

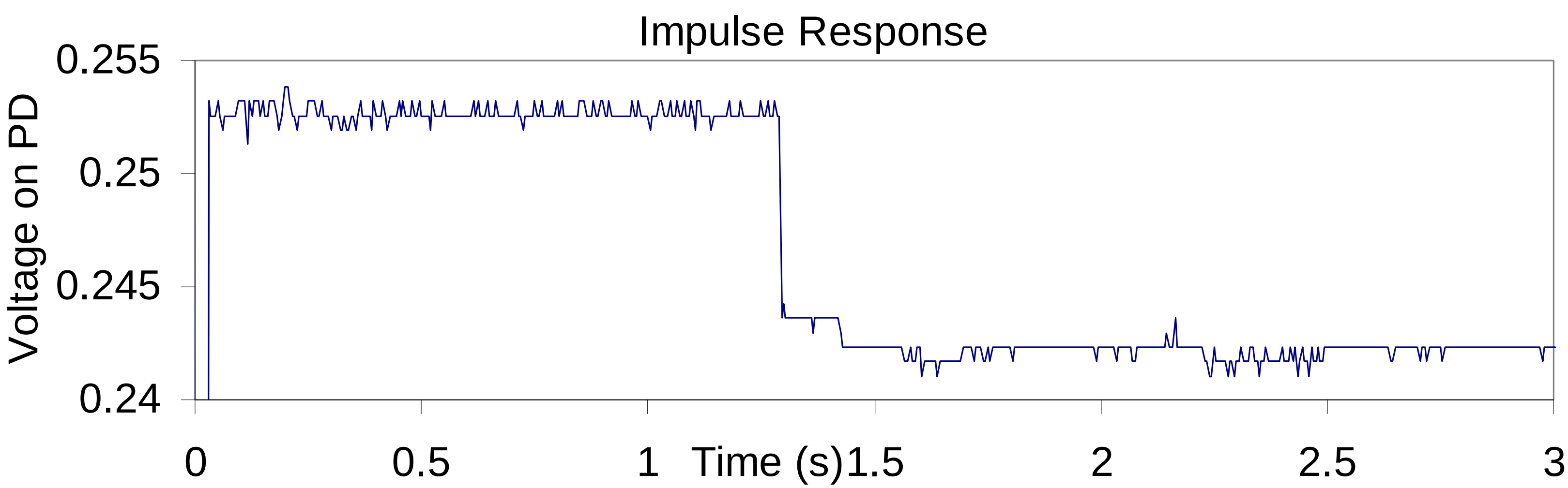
Justin Mansell - jmansell@stanford.edu
Stanford University

System Characteristics

- DM Characteristics
  – 1kHz Resonance
  – 200V moved DM 1.25 microns
  – 30um thick
- Sensor Characteristics
  – 15Hz Max Frame Rate
  – 1200 lenses = 5Hz
  – 300 lenses = 10Hz

AO System Results





Justin Mansell - jmansell@stanford.edu
Stanford University

AO Conclusions

- Sensor promising for core-optic compensation
- Simple adaptive optics system shows promise for laser amplifier and thermal lens correction

Note 1, LIGO, 03/18/99 09:40:50 AM
LIGO-G990022-39-M