

---

# Low Cost Adaptive Optics

or, doing significant research on a budget much less than 6 figures

Robert K. Tyson

Associate Professor of Physics and Optical Science

---



---

# Contents:

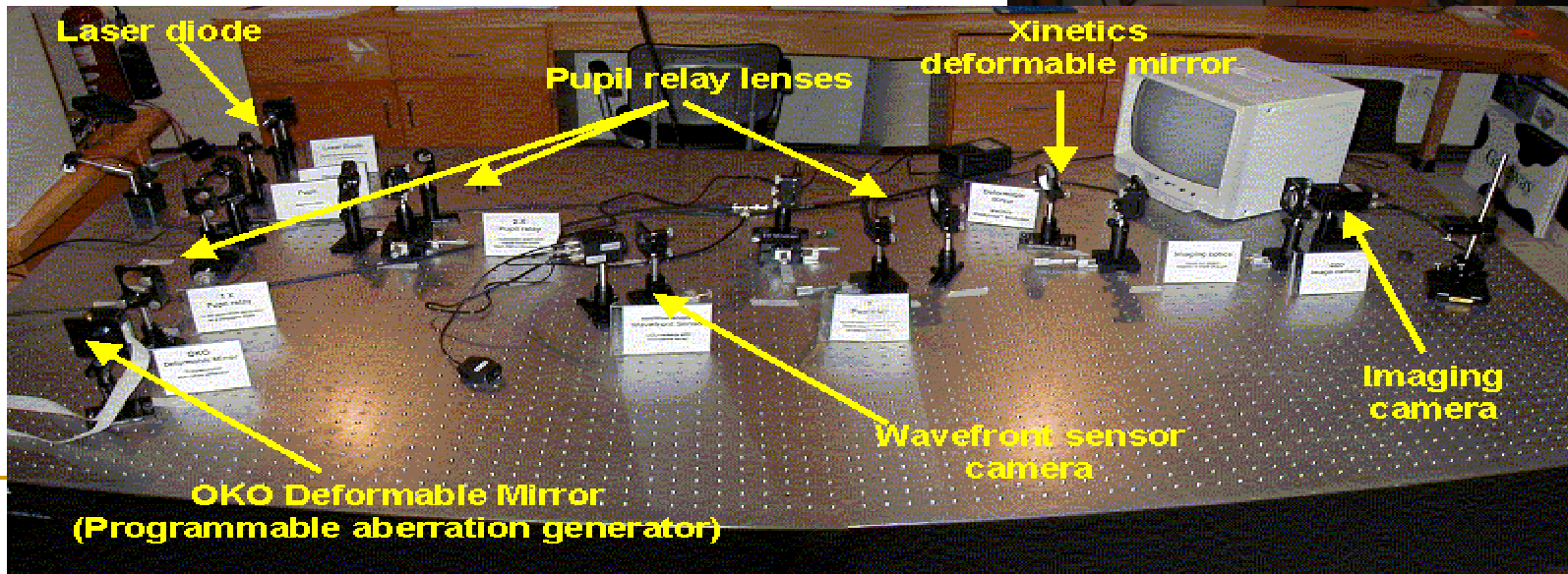
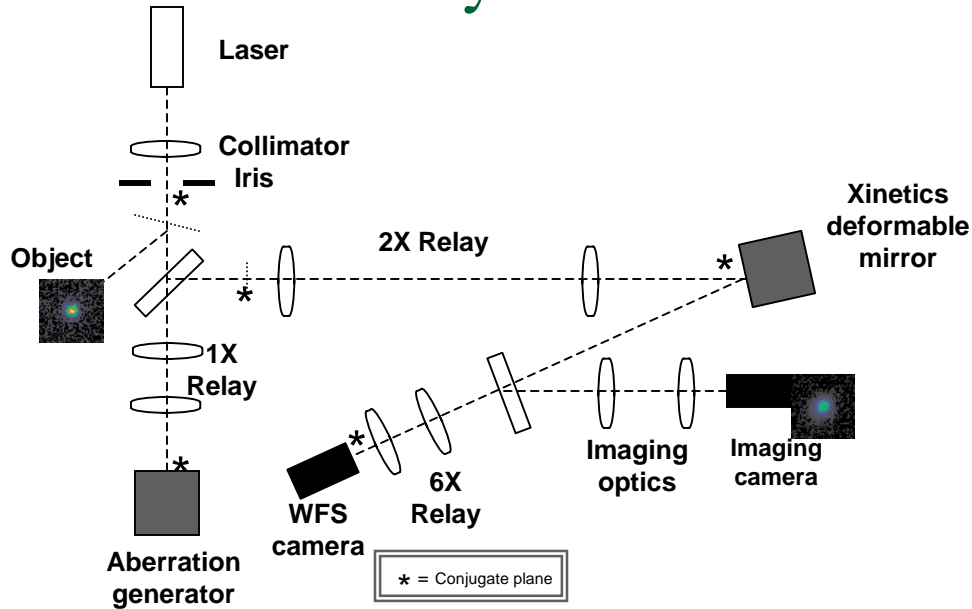
- What is “low” cost?
  - An Adaptive Optics Sandbox
  - Research, a specific problem or set of problems
    - Astronomy?
    - Medical imaging?
    - High-energy laser propagation?
    - Free-space laser communications?
  - Development of Bit-Error Rate diagnostics
  - The Low-order AO experiment
  - The Atmospheric Turbulence Phase Plate
  - The High-order Adaptive Optics System
  - The High-order AO experiment
-

---

# Low Cost

- Components can be very low cost.
  - Deformable mirrors for a few hundred dollars.
  - Wavefront sensor cameras for a few hundred dollars.
  - Multi-purpose computers
  - Infrastructure
-

# Laboratory Infrastructure



---

# A specific problem -Lasercom

- Free-space optics (FSO) is the propagation of light through the atmosphere.
  - Can include terrestrial, terrestrial-satellite, terrestrial-aircraft, aircraft-aircraft, and LEO inter-satellite links.
  - FSO systems typically operate in the nonvisible infrared electromagnetic terahertz spectrum.
  - First employed by the military and NASA, FSO has been around for more than 30 years.
  - Current commercially available systems such as those by LightPointe operate at up to 2.5 Gbs/sec (OC-48).
-

# Theory

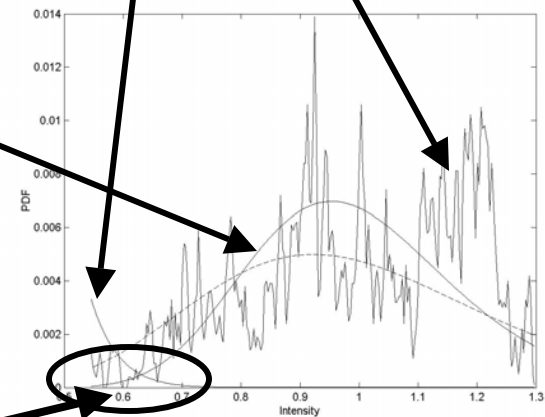
$$\text{BER(OOK)} = \frac{1}{2} \int_0^{\infty} p_I(s) \operatorname{erfc} \left( \frac{\langle \text{SNR} \rangle s}{2\sqrt{2} \langle i_s \rangle} \right) ds$$

**Probability distribution  
( optical scintillation noise )**

**Receiver electronic noise**

Gamma-gamma

$$p_I(s) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)\langle i_s \rangle} \left( \frac{s}{\langle i_s \rangle} \right)^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta} \left( 2\sqrt{\frac{\alpha\beta s}{\langle i_s \rangle}} \right)$$



**Overlap is the bit-error rate**

# How the AO works...

**Adaptive optics spatial filter modifies the optical noise**

$$\sigma_1^2 = \frac{2.606}{2\pi} k^2 C_n^2 \int_0^{2\pi} \int_0^{\infty} \left[ L - \frac{k}{\kappa^2} \sin\left(\frac{L\kappa^2}{k}\right) \right] \kappa^{-8/3} \left[ 1 - \sum_{i=1}^N F_i(\kappa, D, \phi) \right] d\kappa d\phi$$

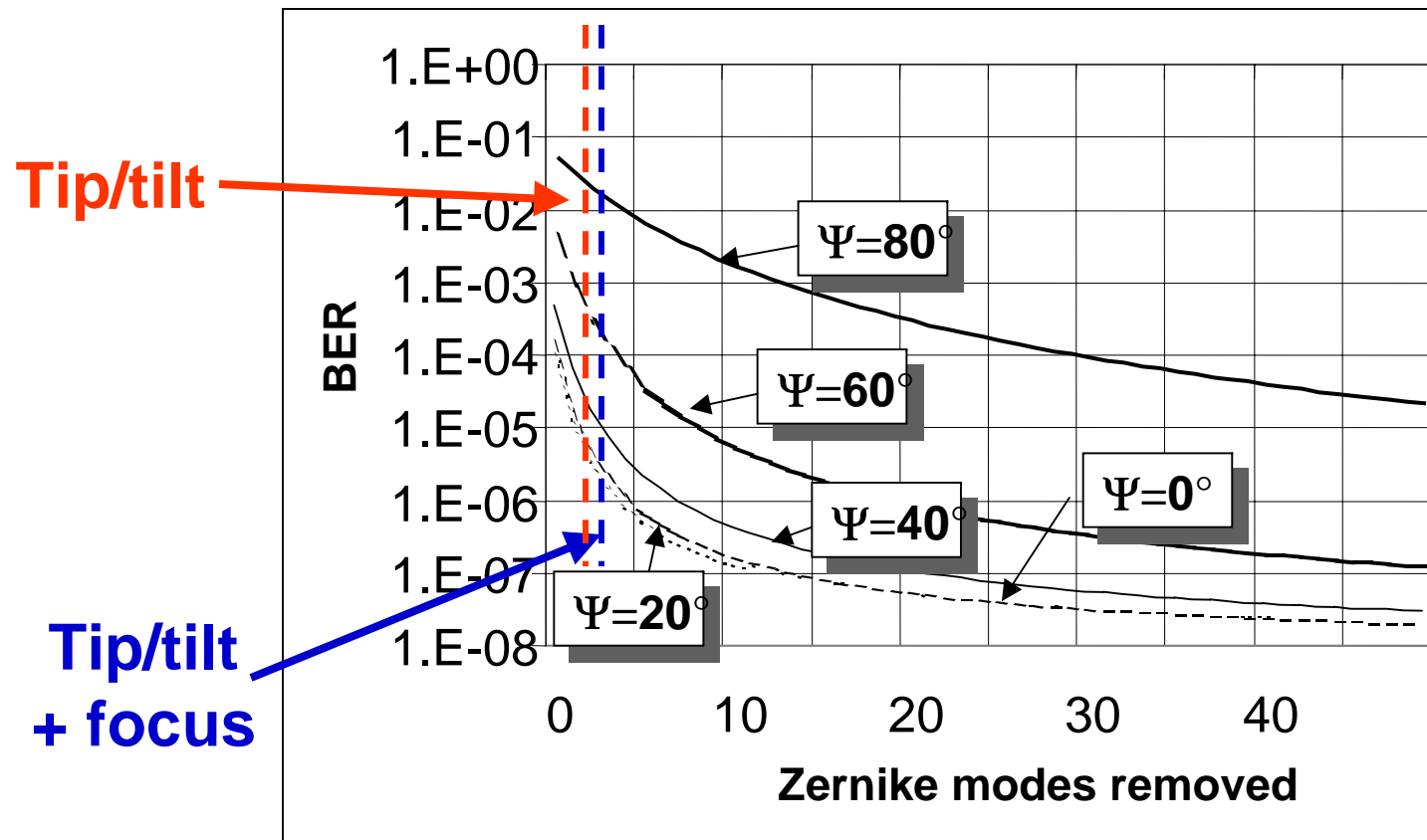


**Spatial filter for  
2 axes of tilt removed**

$$\left[ 1 - 2(2) \left[ \frac{2J_2(\kappa D/2)}{\kappa D/2} \right]^2 \right]$$

# Theoretical Predictions

Theoretical improvement for free-space laser communications



---

# Bit-Error Rate (BER) Diagnostics

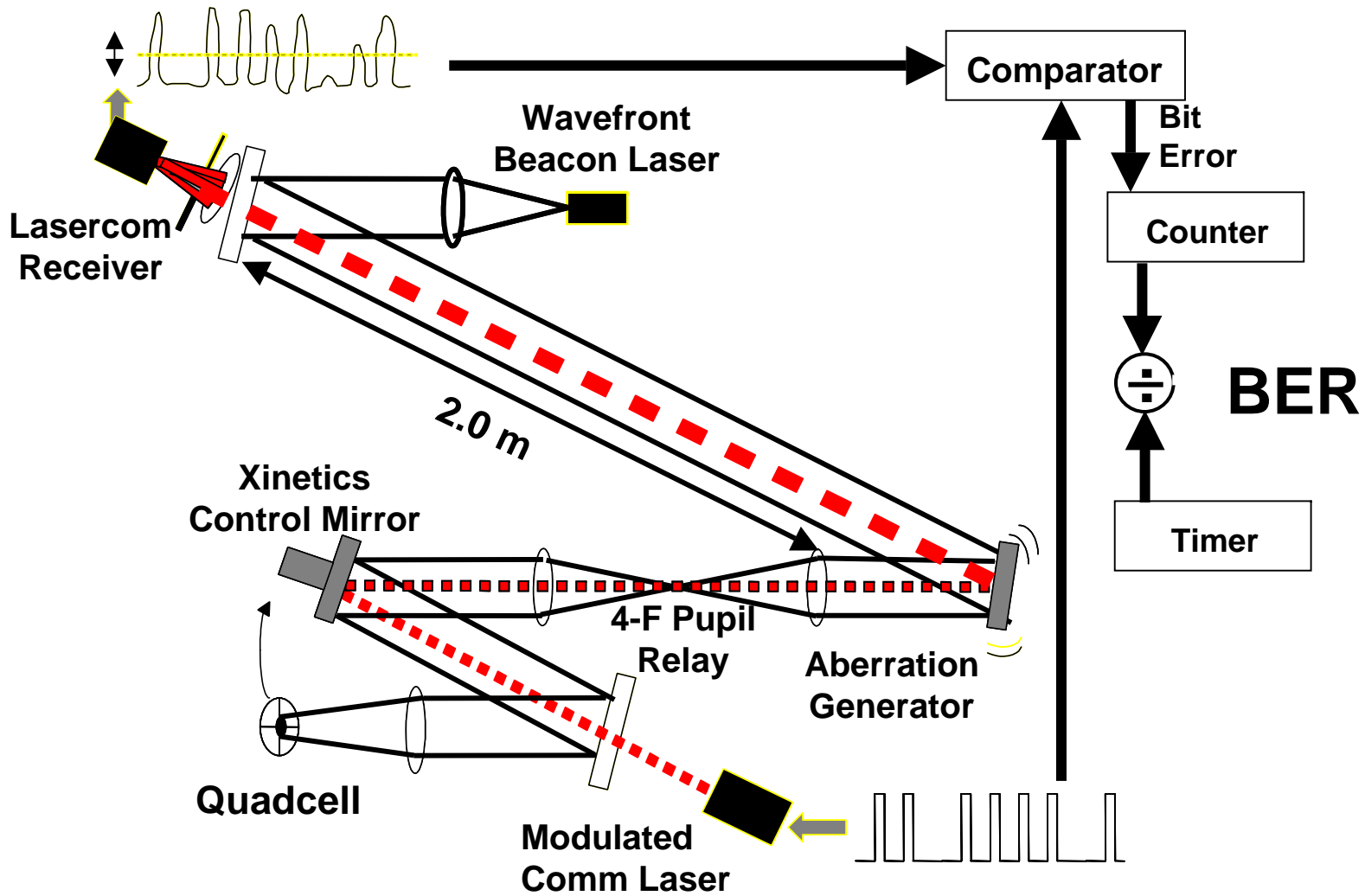
- In the transmission of digital data, the bit error rate (BER) is the ratio of bits received in error relative to the total number of bits received.
  - The BER is commonly expressed as ten to a negative power. A BER of 10 to the minus 6 means that out of 1,000,000 bits received, one bit was in received incorrectly.
  - We need to compare the transmitted signal to the received signal.
-

---

# Scintillation

- Even though dynamic refractive index variations are small, propagating an optical wave through a large number of inhomogeneities over distance can result in significant distortions of the wavefront.
  - Turbulence-caused phase variations manifest at a distance as intensity variation, known as scintillation, which degrades the link.
-

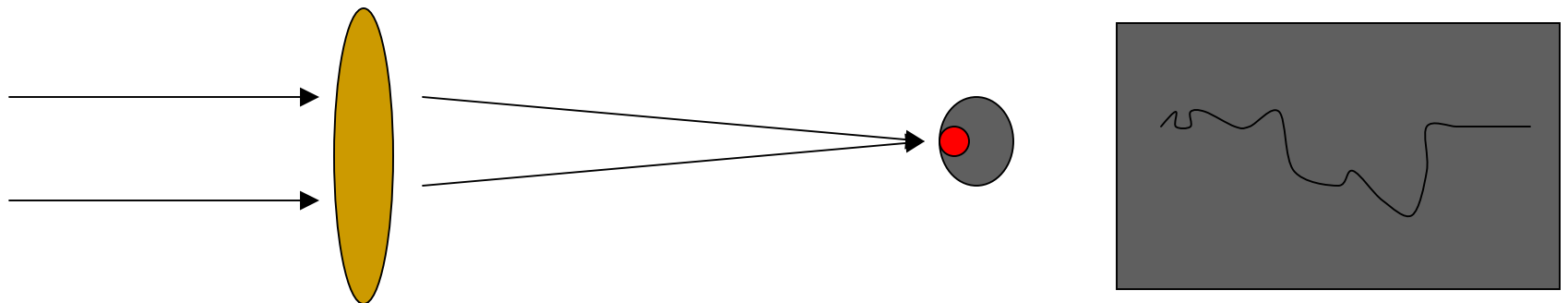
# Tip/tilt experimental layout

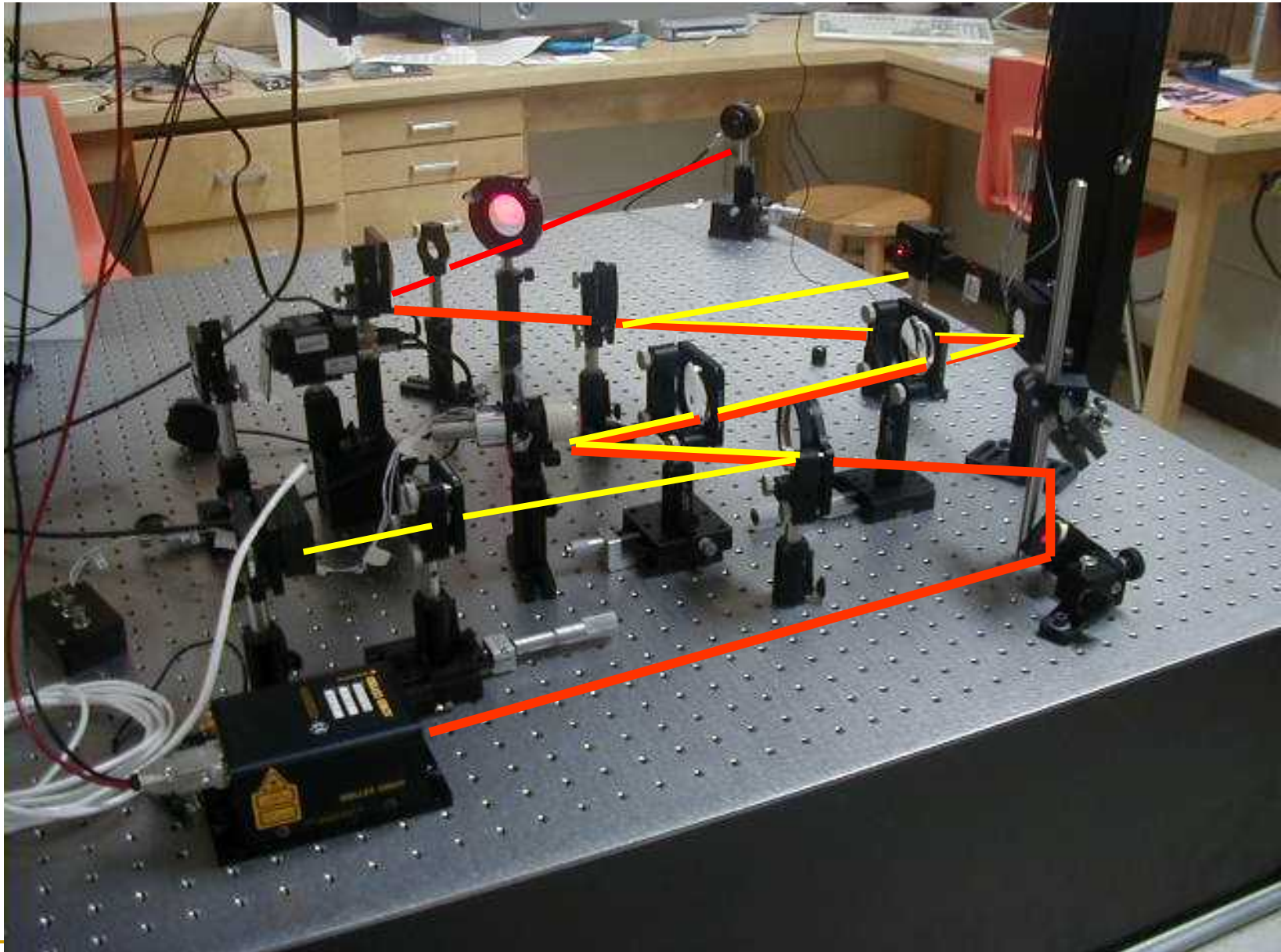


---

# Simulated Scintillation

- The aberration mirror was moved via commands that were generated with Gaussian statistics with Labview.
- The beam spot moving partially on & off the photodiode detector resulting in amplitude fluctuations resembling real-world scintillation.





---

# BER Measurements

- Pin Photodiode used to measure lasercom signal with Labview driven NI5112 8-bit digitizer.
  - Labview driven NI PCI-6713 I/O card used to generate, measure (Quadcell), and control active mirrors.
  - Matlab to condition the data.
-

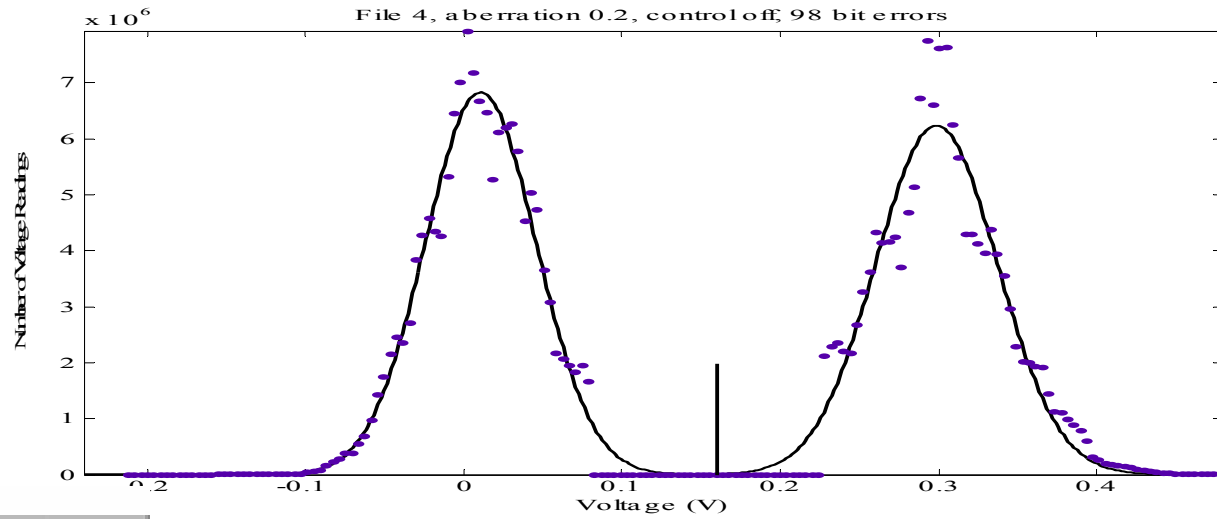
---

# BER Data Collection Electronics

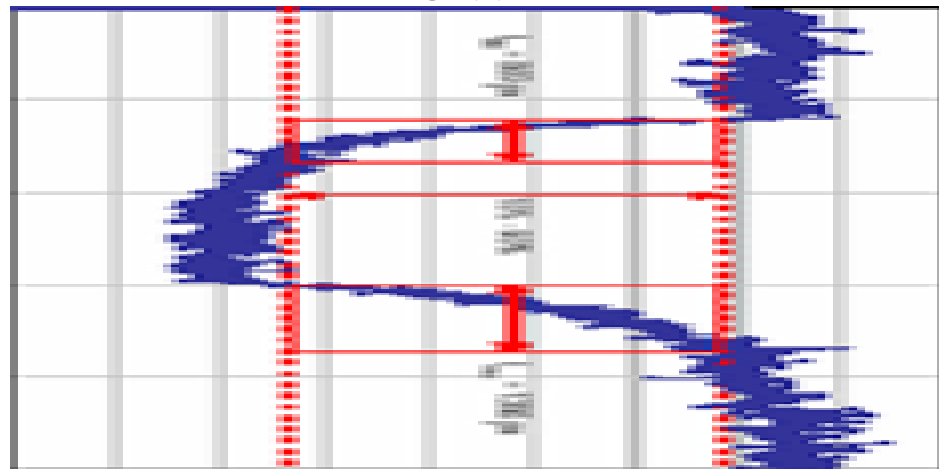
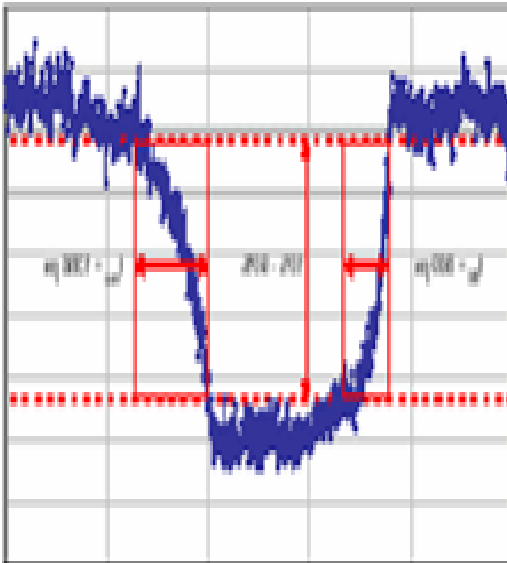
- Bit determinations made near center of bit.
  - Threshold detector output held in latch.
  - Transmitted bit held in latch.
  - Contents of the two latches sent to comparator.
  - Output of comparator counted as bit errors.
-

# Data

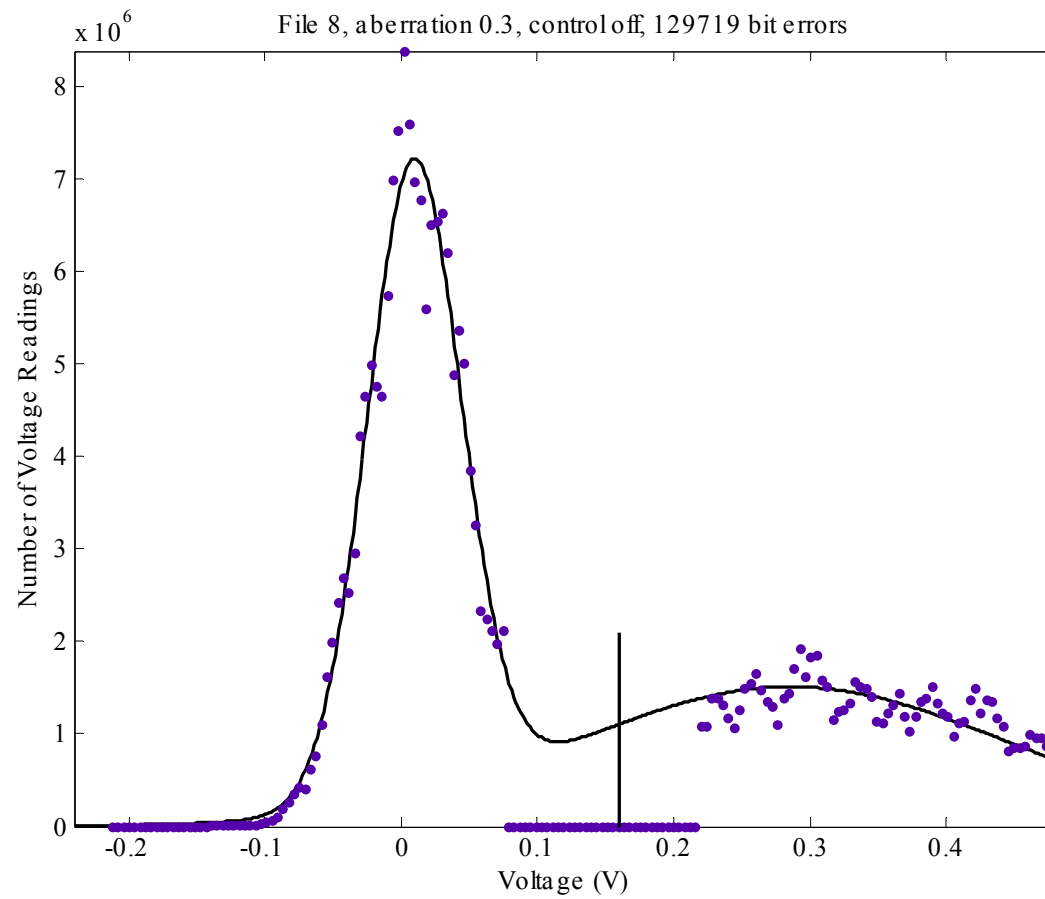
## Probability Density Function



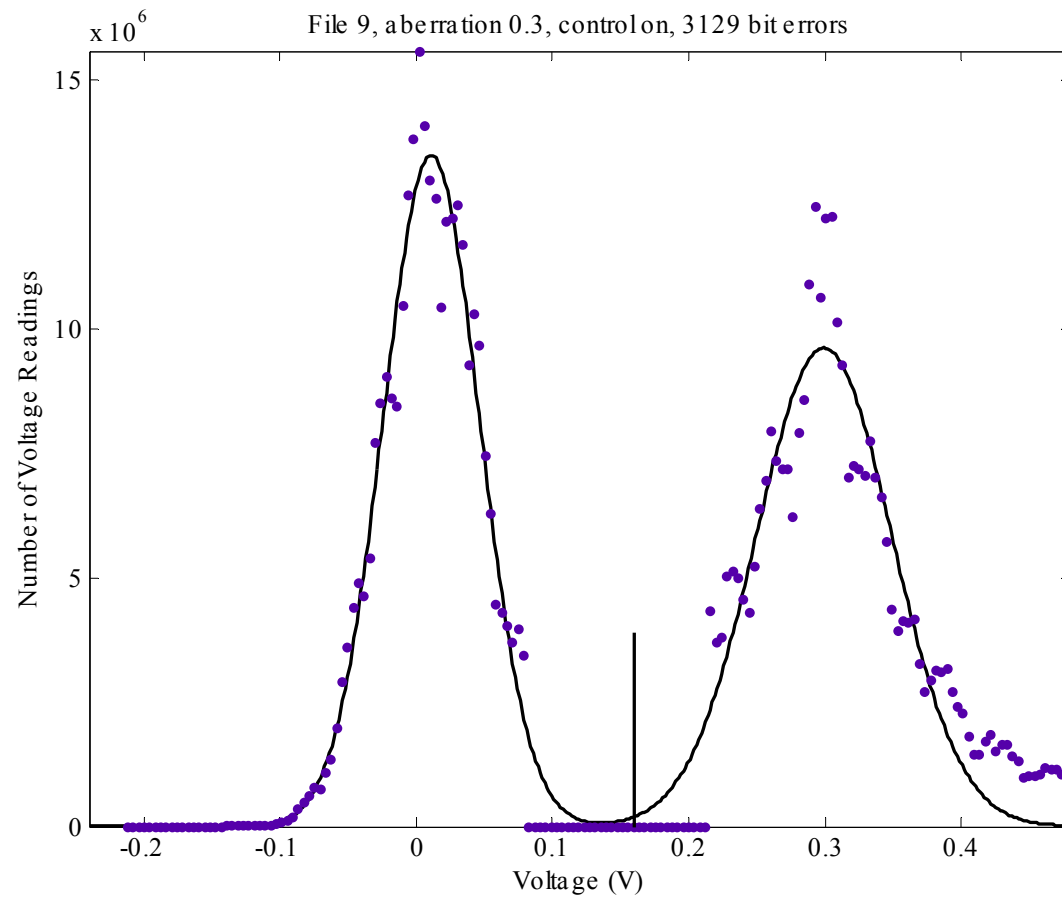
Signal



# Uncorrected Turbulence



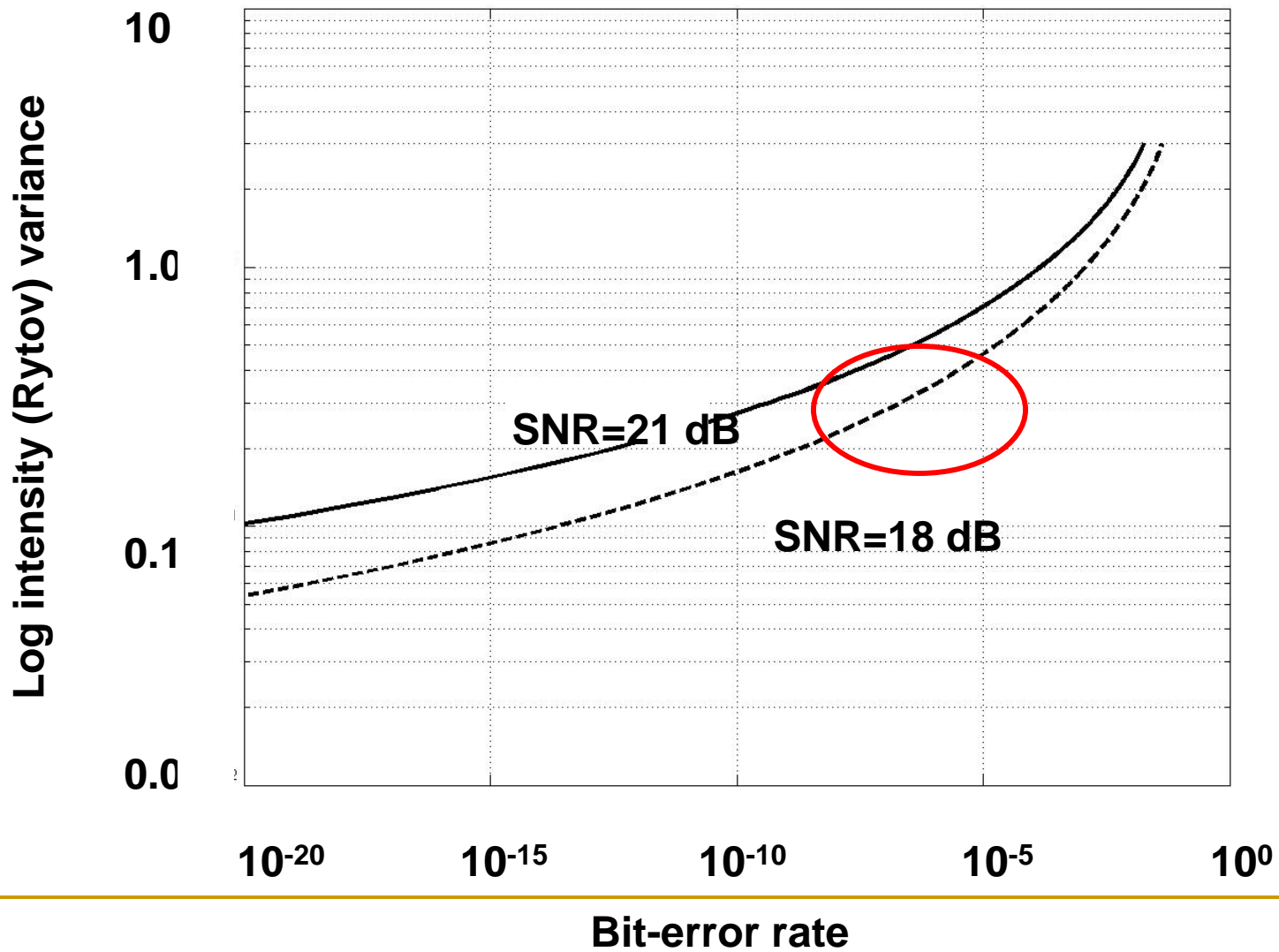
# Corrected Turbulence



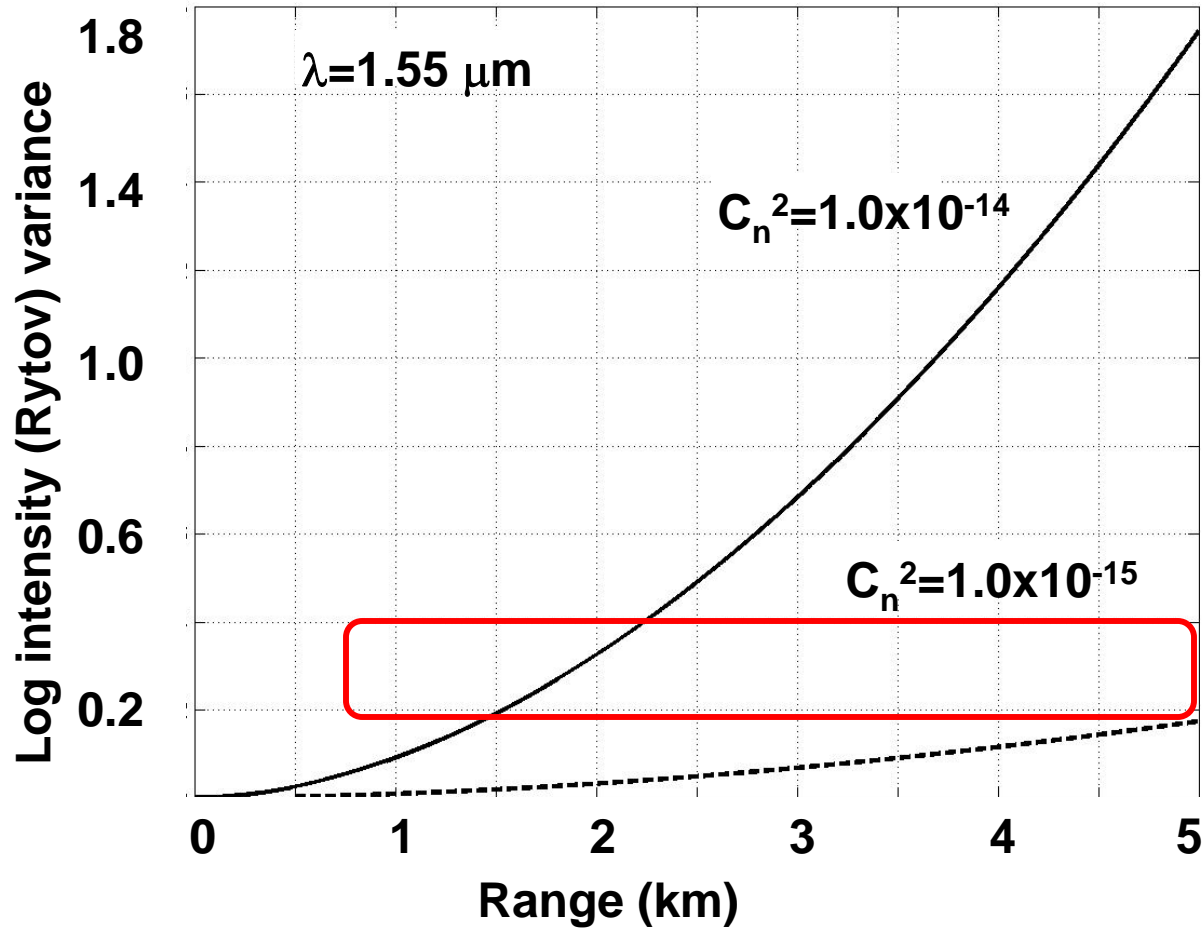
# Tip/tilt Results

Aberration level (arbitrary units)	Control	SNR(dB)	BER	BER improvement
0.20	Off	20.9	$3.7 \times 10^{-7}$	
0.20	On	20.5	$3.2 \times 10^{-7}$	1.2 X
0.25	Off	19.3	$1.3 \times 10^{-6}$	
0.25	On	19.9	$5.6 \times 10^{-7}$	2.3 X
0.25	Off	7.8	$5.4 \times 10^{-4}$	
0.25	On	18.3	$1.3 \times 10^{-5}$	42 X

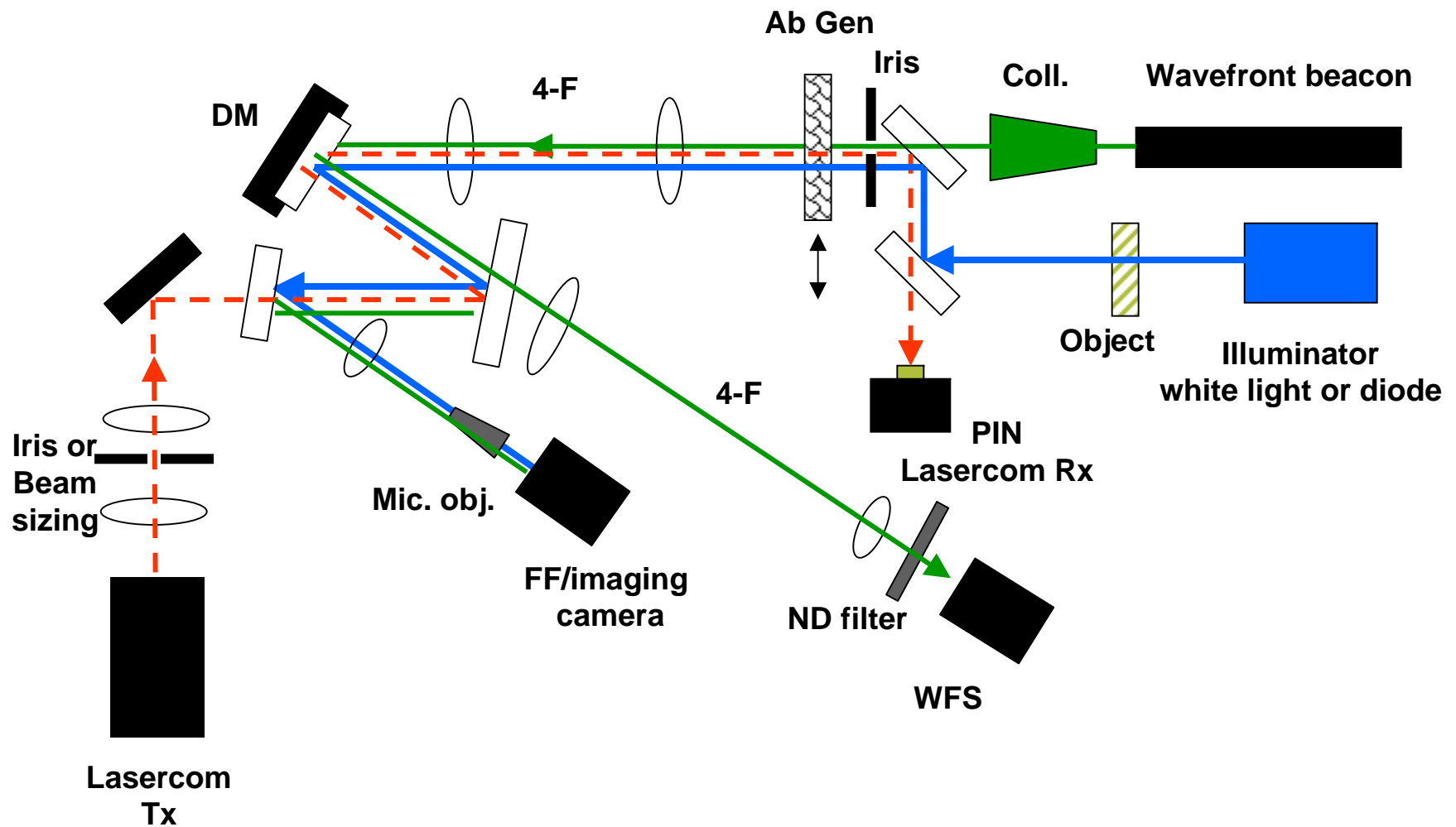
# Comparison to theory



# Where it fits in the real world

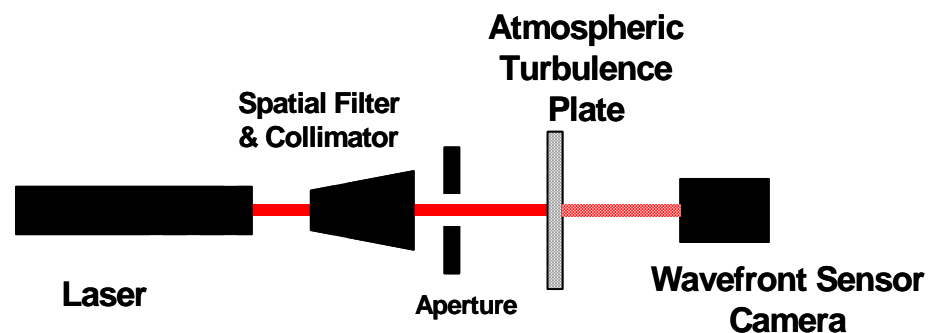
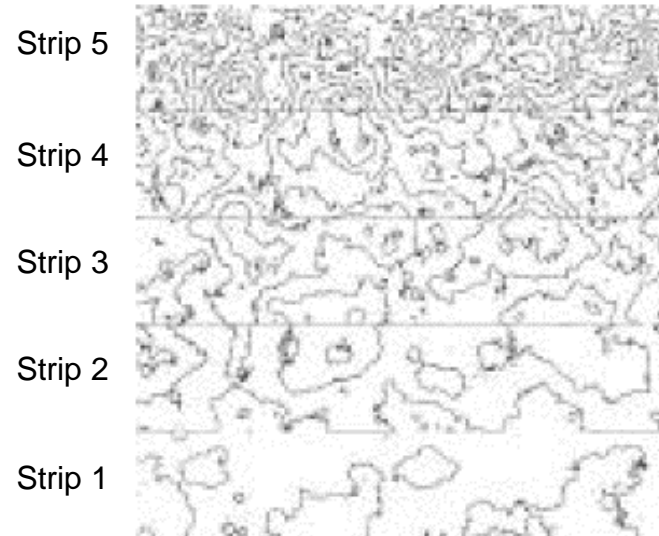


# Multipurpose configuration: *sandbox*



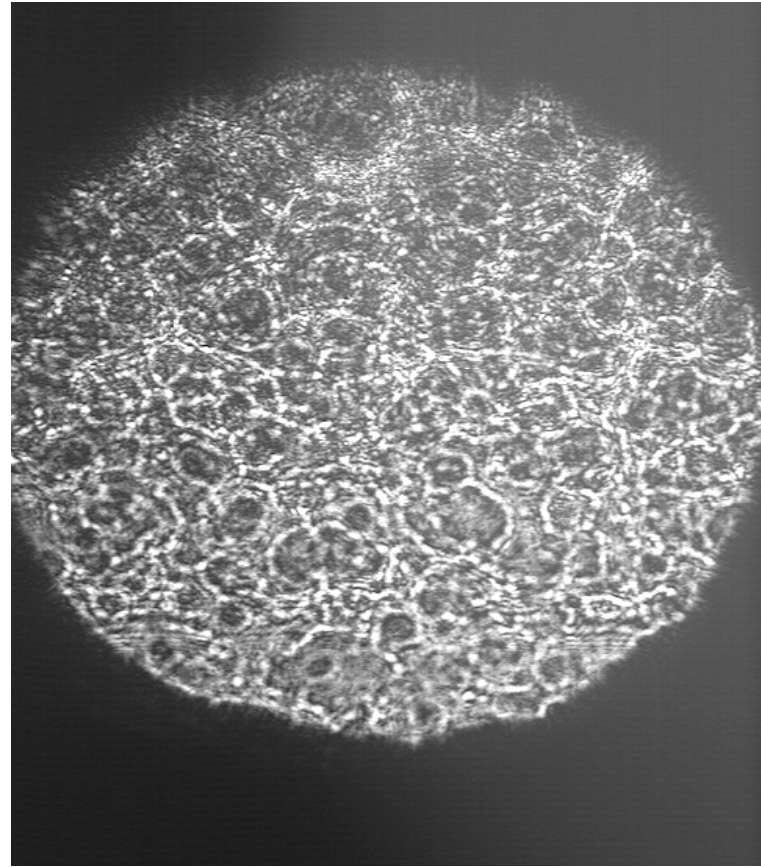
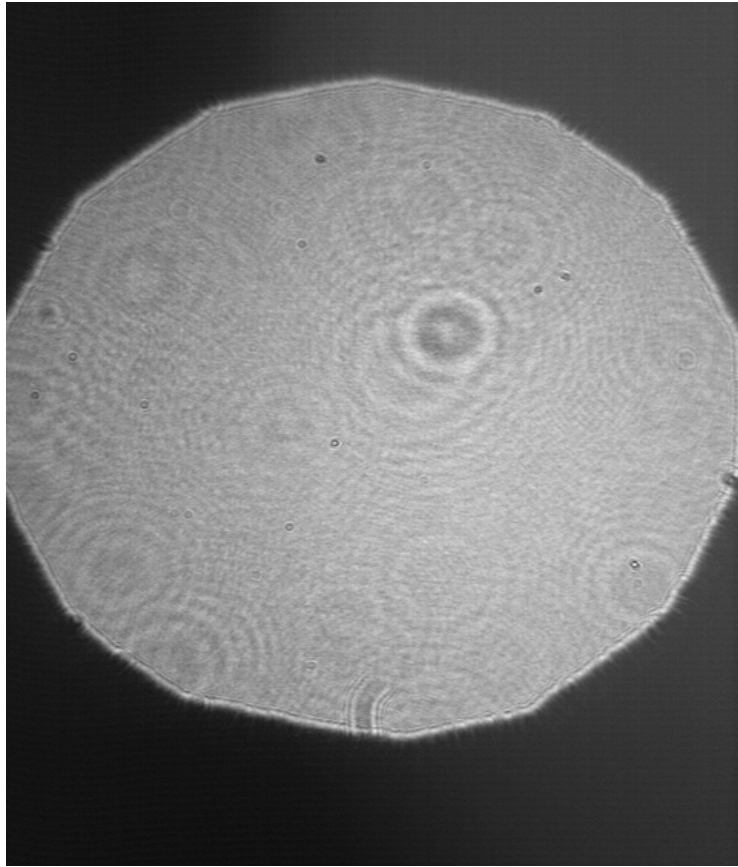
# Atmospheric Turbulence Phase Plate

- ATPP Purchased to Simulate Repeatable Atmospheric Turbulence
- ATPP to be Measured to Compare our Data with the Design Data



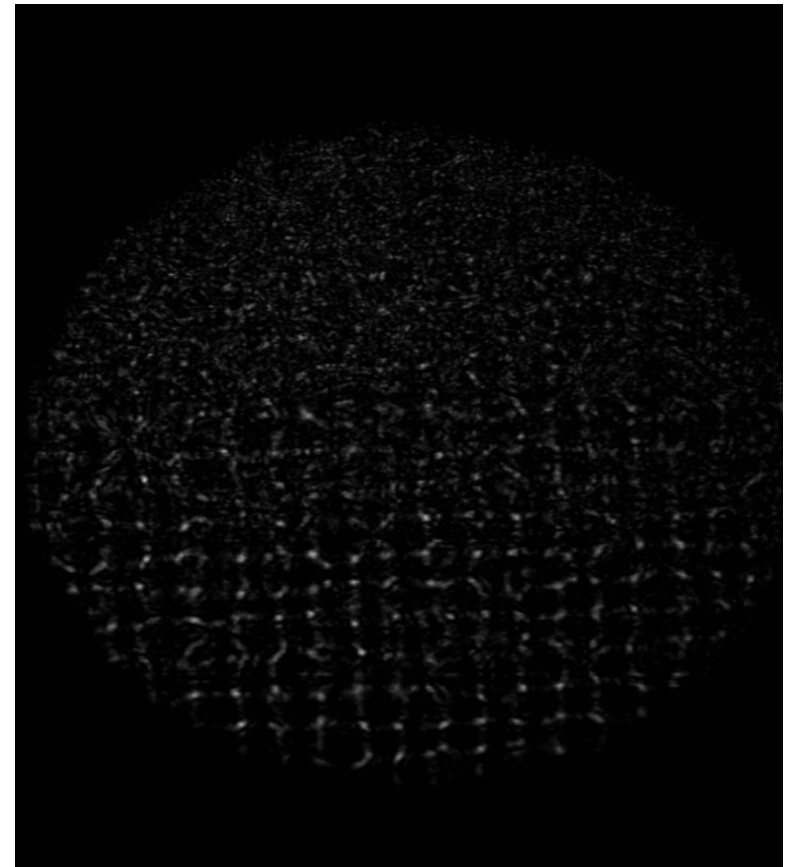
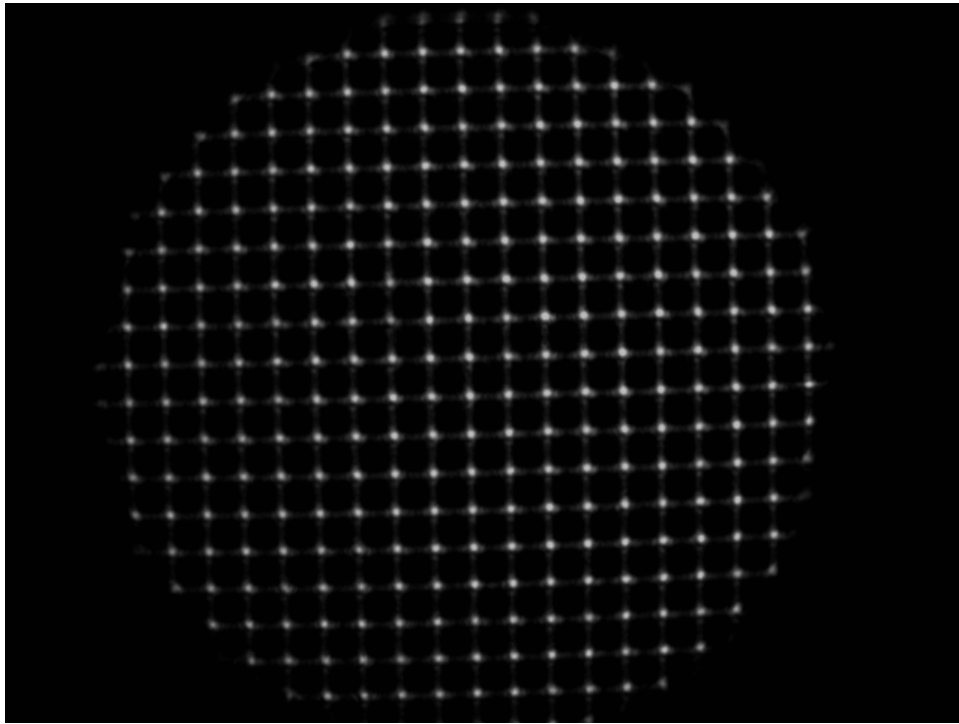
---

# Atmospheric Turbulence Phase Plate



---

# Hartmann Spots for Atmospheric Turbulence Phase Plate

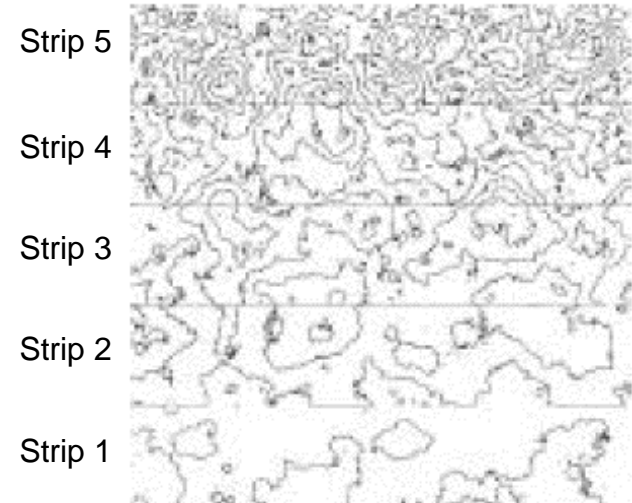


---

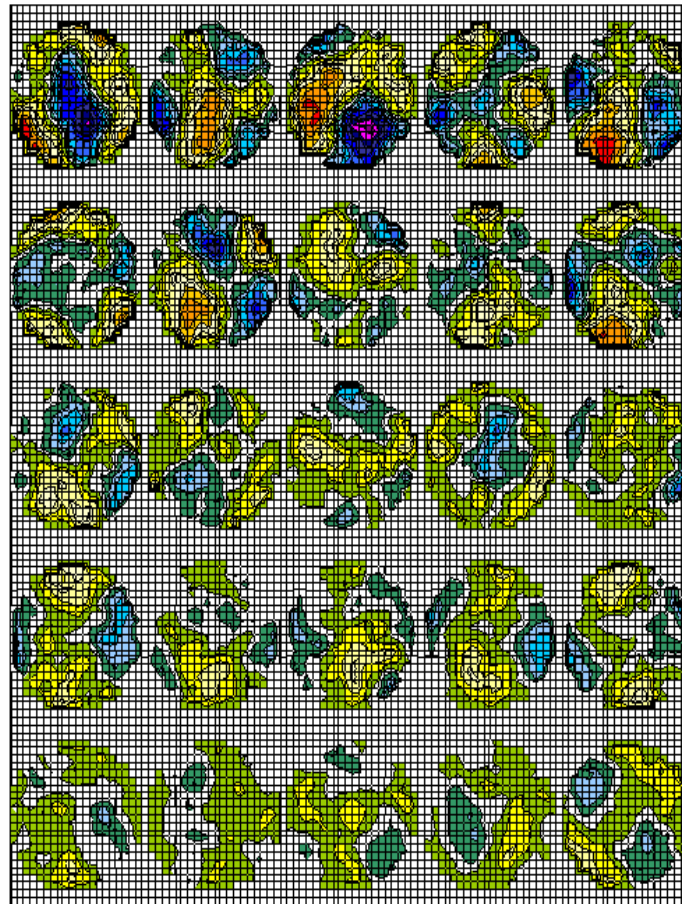
# Atmospheric Turbulence Phase Plate

## ■ Design Data

- ❑ Linear Dimension : 26mm x 26mm
- ❑ 5 Regions of Turbulence
- ❑ 5200 x 5200 Matrix for Numeric Realization
- ❑ Designed Using Kolmogorov Structure Function as Basis for Turbulence Model
- ❑ *NOT* low cost



# Atmospheric Turbulence Phase Plate



■ 1.2-1.4 microns

■ 1-1.2

■ 0.8-1

■ 0.6-0.8

■ 0.4-0.6

■ 0.2-0.4

■ 0-0.2

■ -0.2-0

■ -0.4--0.2

■ -0.6--0.4

■ -0.8--0.6

■ -1--0.8

■ -1.2--1

■ -1.4--1.2

■ -1.6--1.4

■ -1.8--1.6

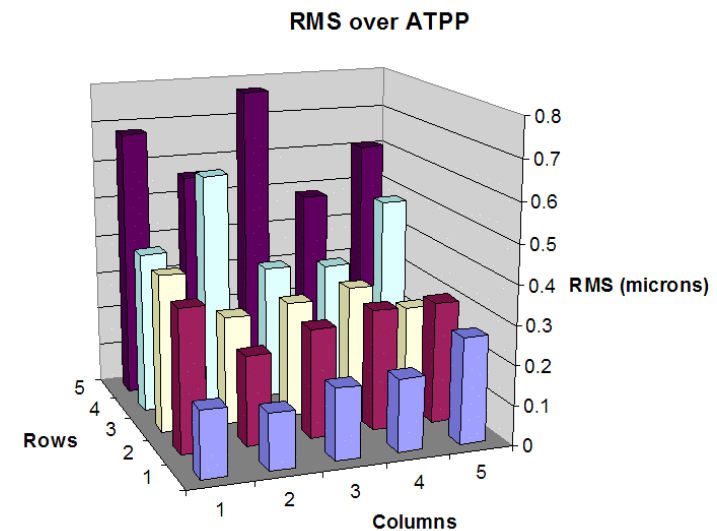
■ -2--1.8

Measured Data Contour

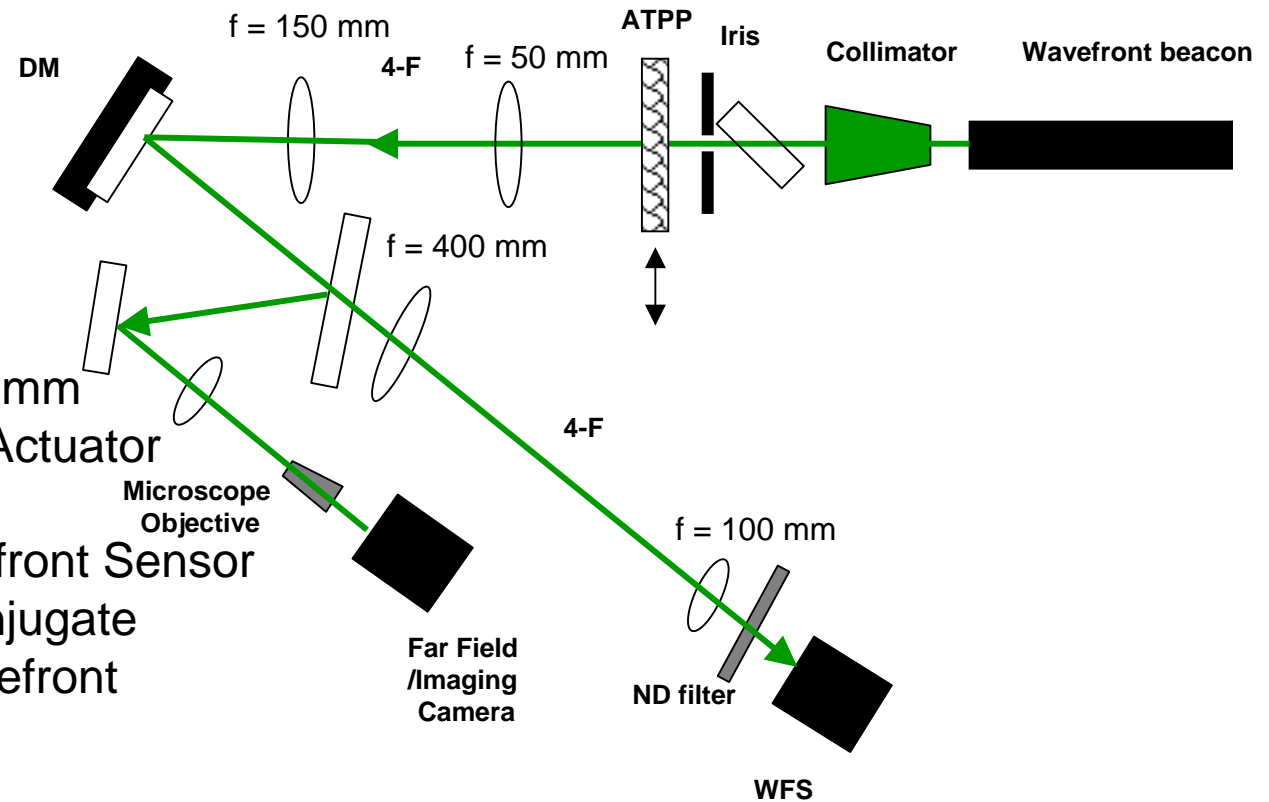
# Atmospheric Turbulence Phase Plate

- $D/r_0$  is Value Important in Adaptive Optics
- $D/r_0$  Values Scalable Using Linear Scaling Laws
  - To Measure ATPP, a 5mm Beam Diameter was Used
  - Measured Values for  $D/r_0$  for Each Strip:

$D / r_0$ (uncompensated)
2.10
3.60
3.80
5.80
8.90



# High-order Adaptive Optics System (subset of *Sandbox*)

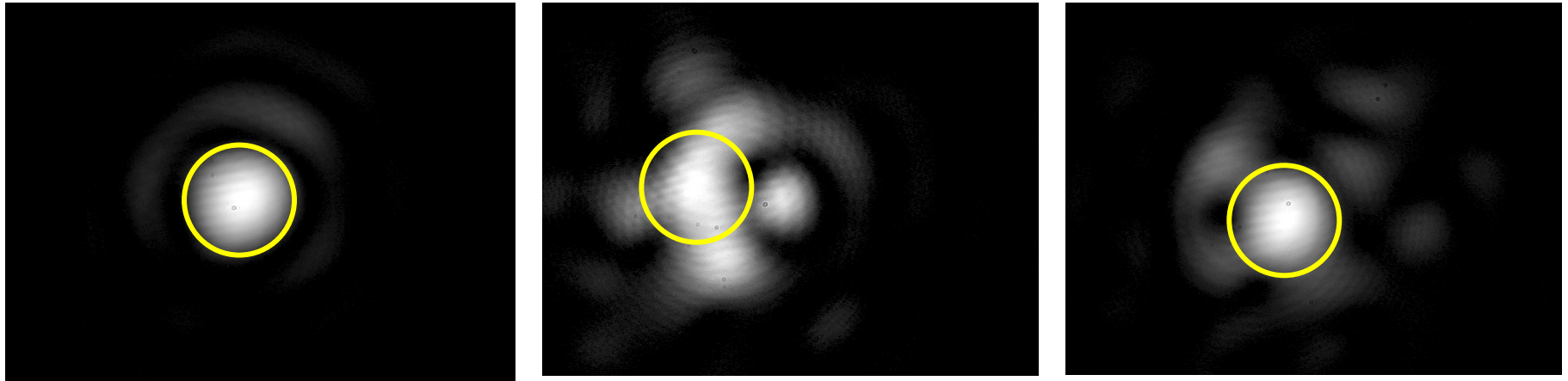


- Beam Diameter set to 2mm
- OKO Technologies 37 Actuator Deformable Mirror
- Shack-Hartmann Wavefront Sensor
- 4F System Used to Conjugate ATPP Wavefront to Wavefront Sensor

---

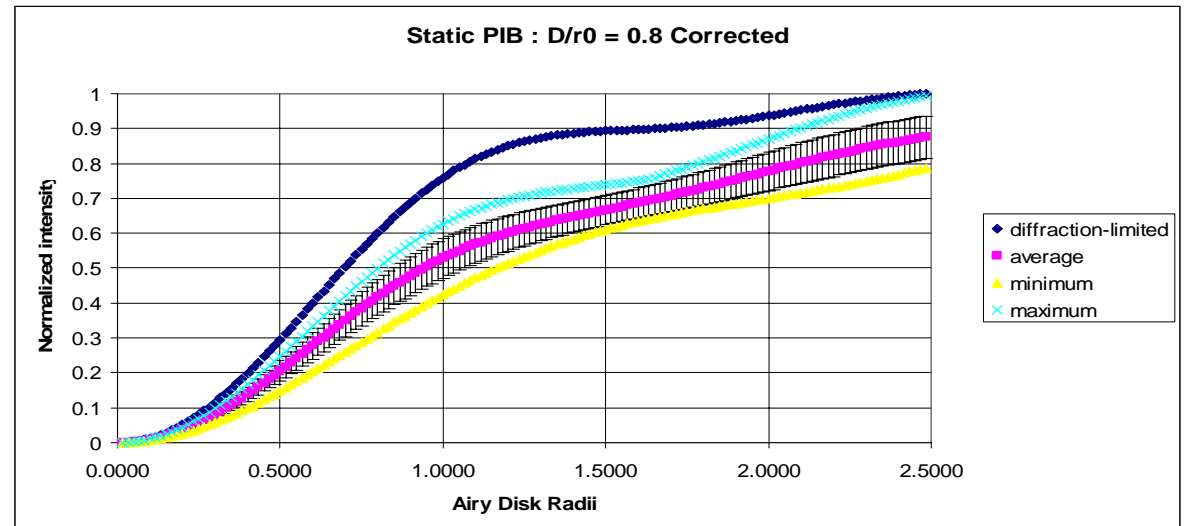
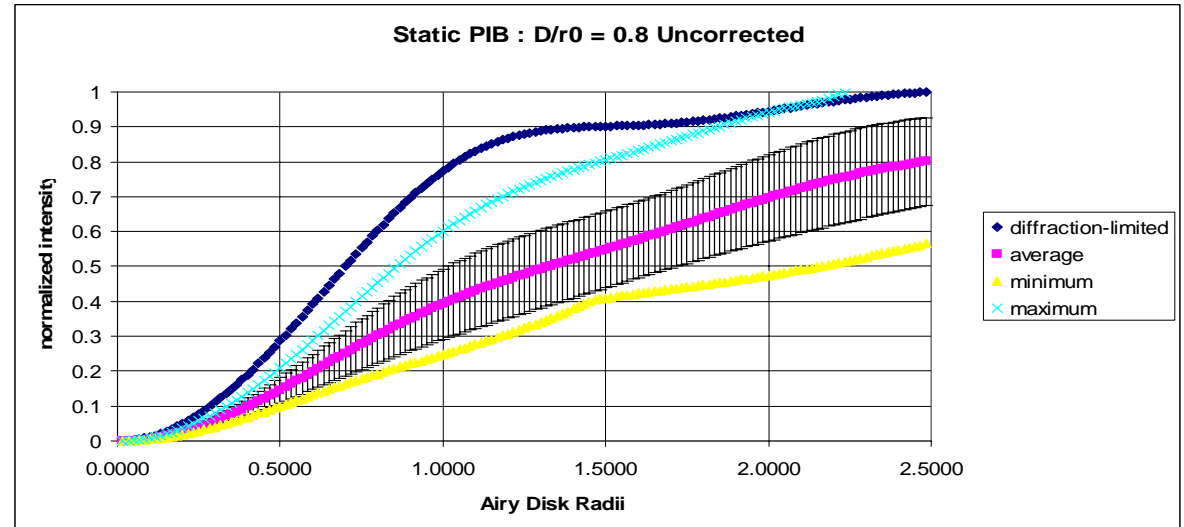
# Adaptive Optics System

- Measure Static and Dynamic Response of System to Turbulence
- Using Far-Field Image as Diagnostic
  - Power in the Bucket
  - Strehl Ratio



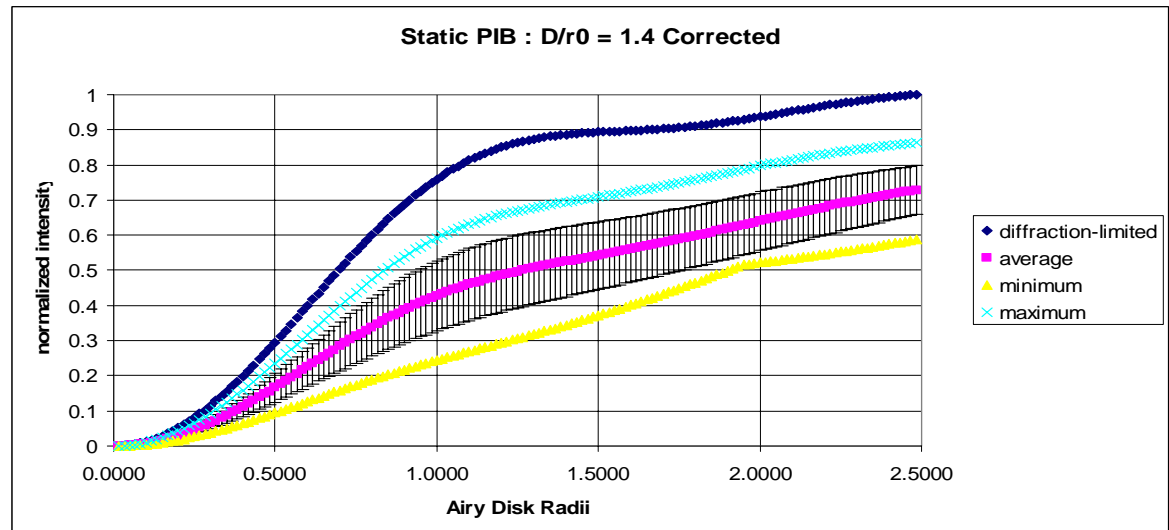
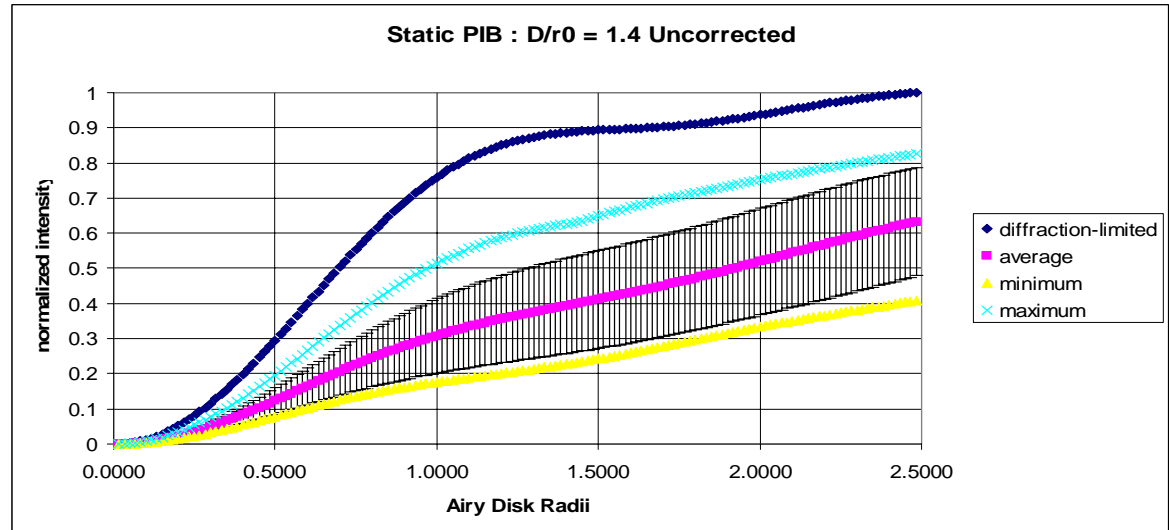
# AO System Static Performance

- Temporally Static Results
- $D/r_0 = 0.8$



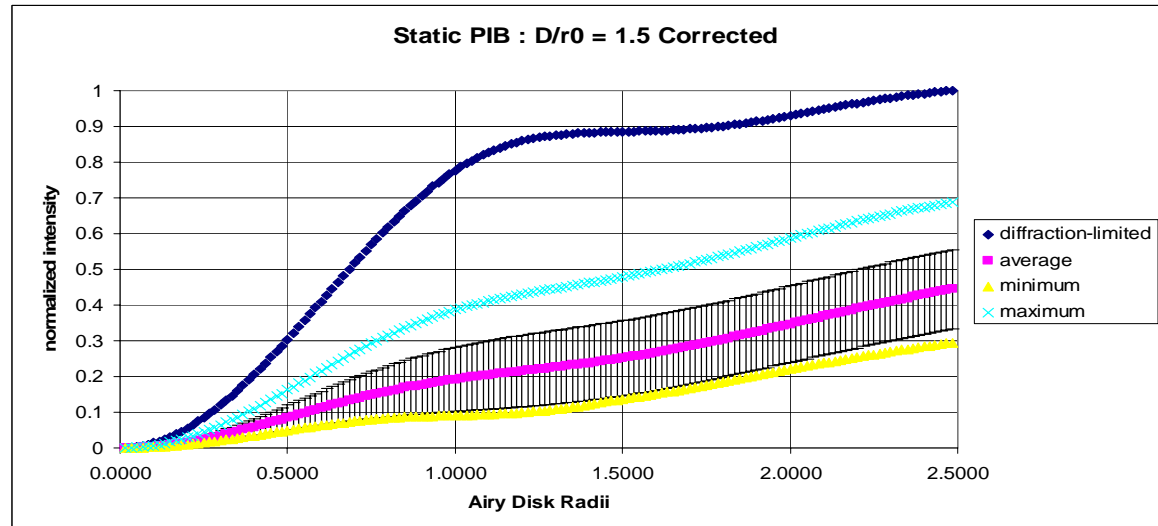
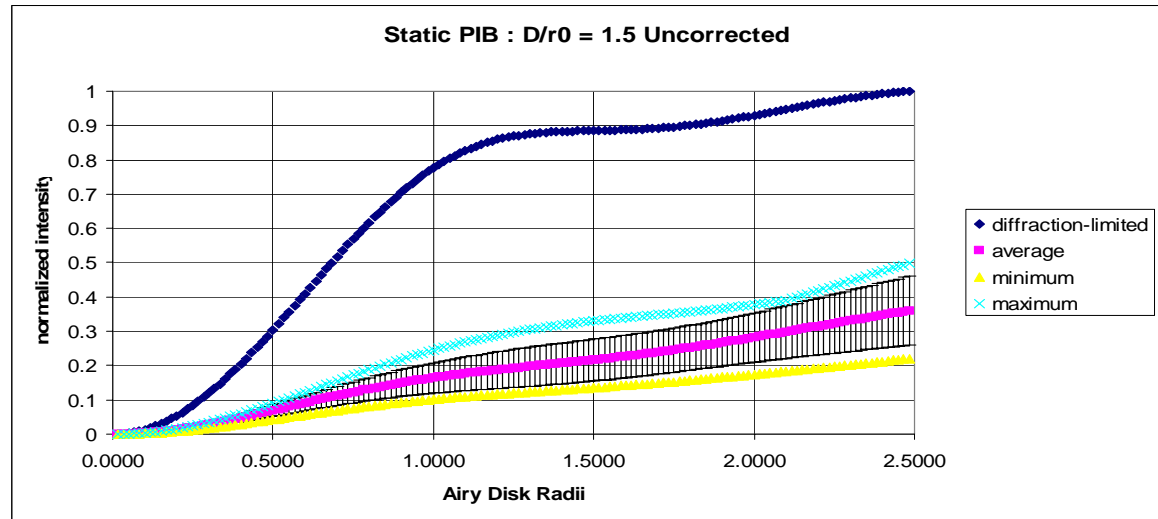
# AO System Static Performance

■  $D/r_0 = 1.4$



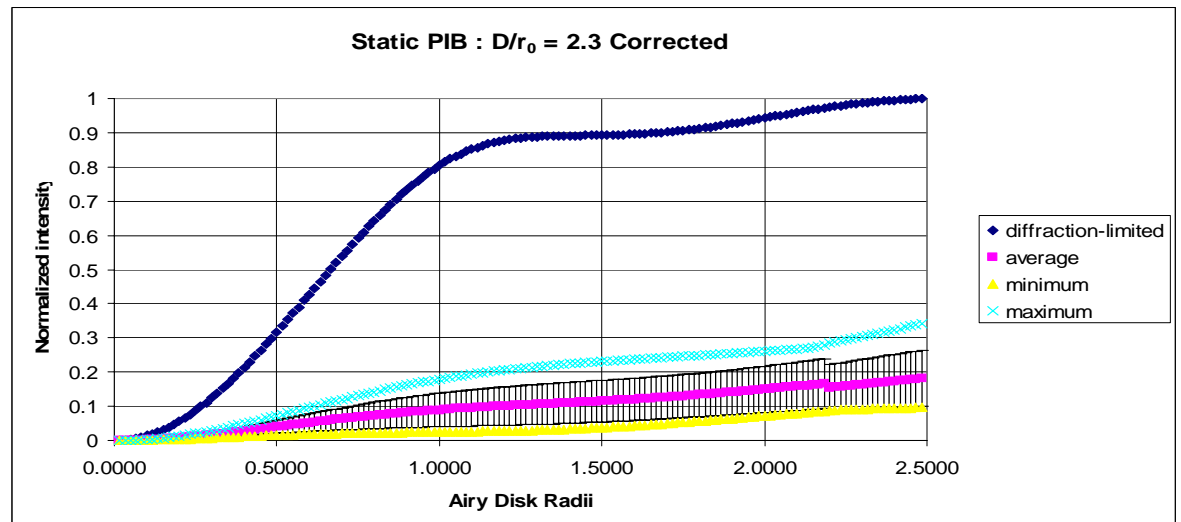
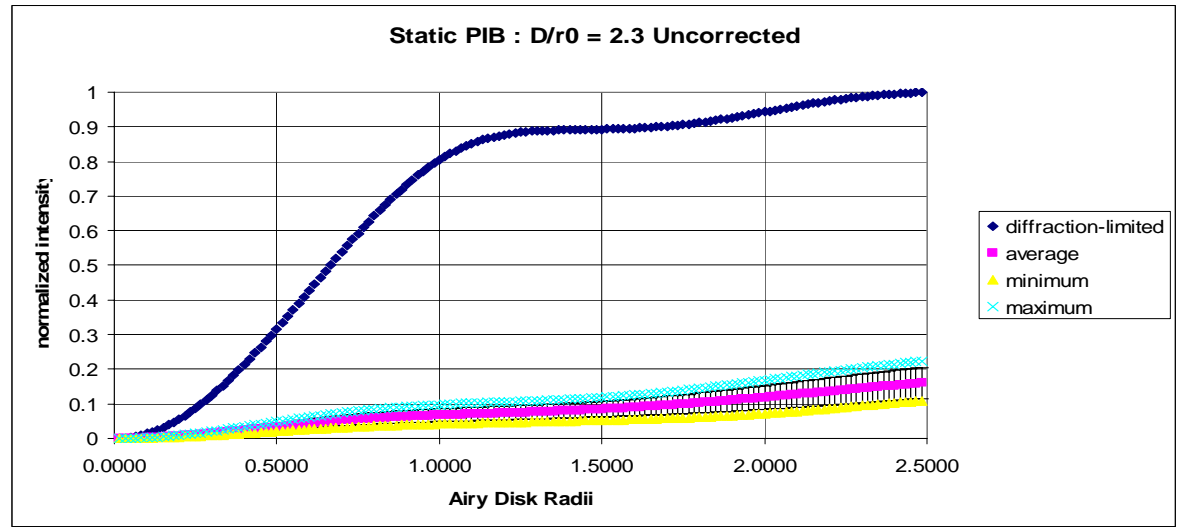
# AO System Static Performance

■  $D/r_0 = 1.5$



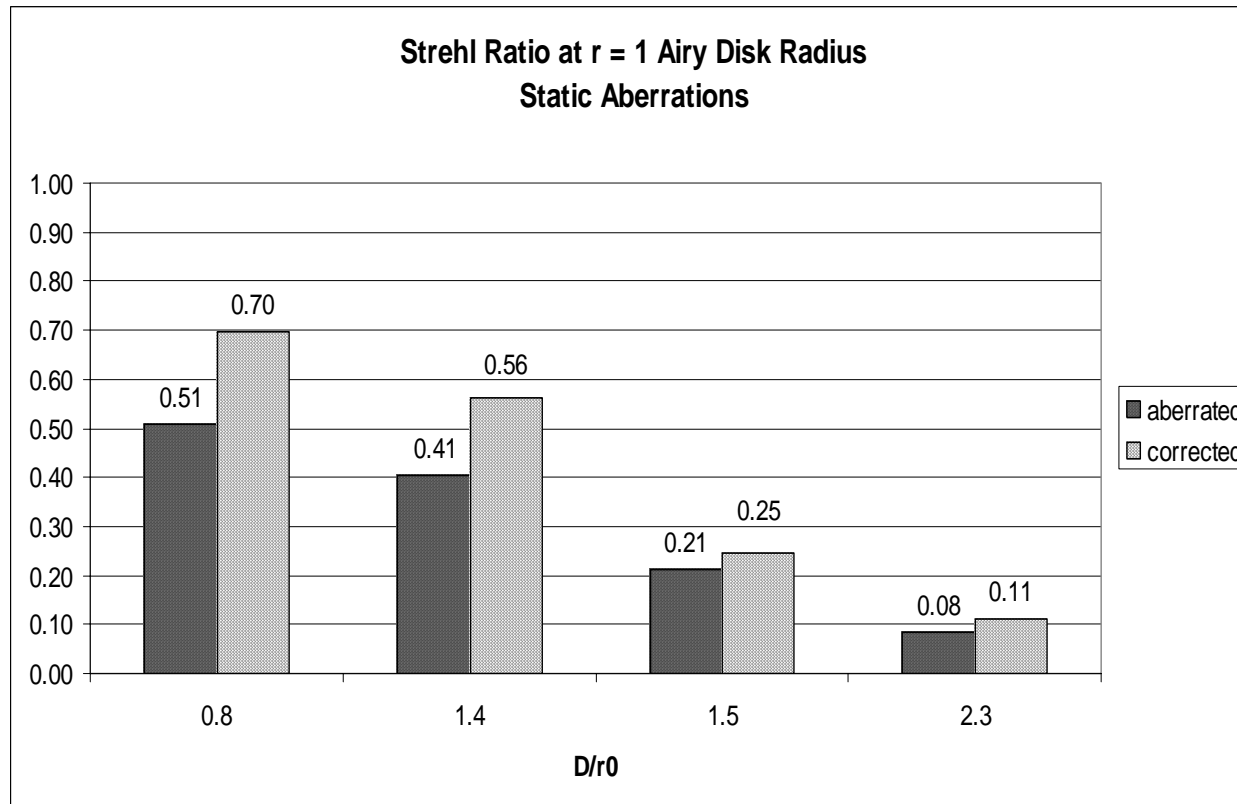
# AO System Static Performance

■  $D/r_0 = 2.3$



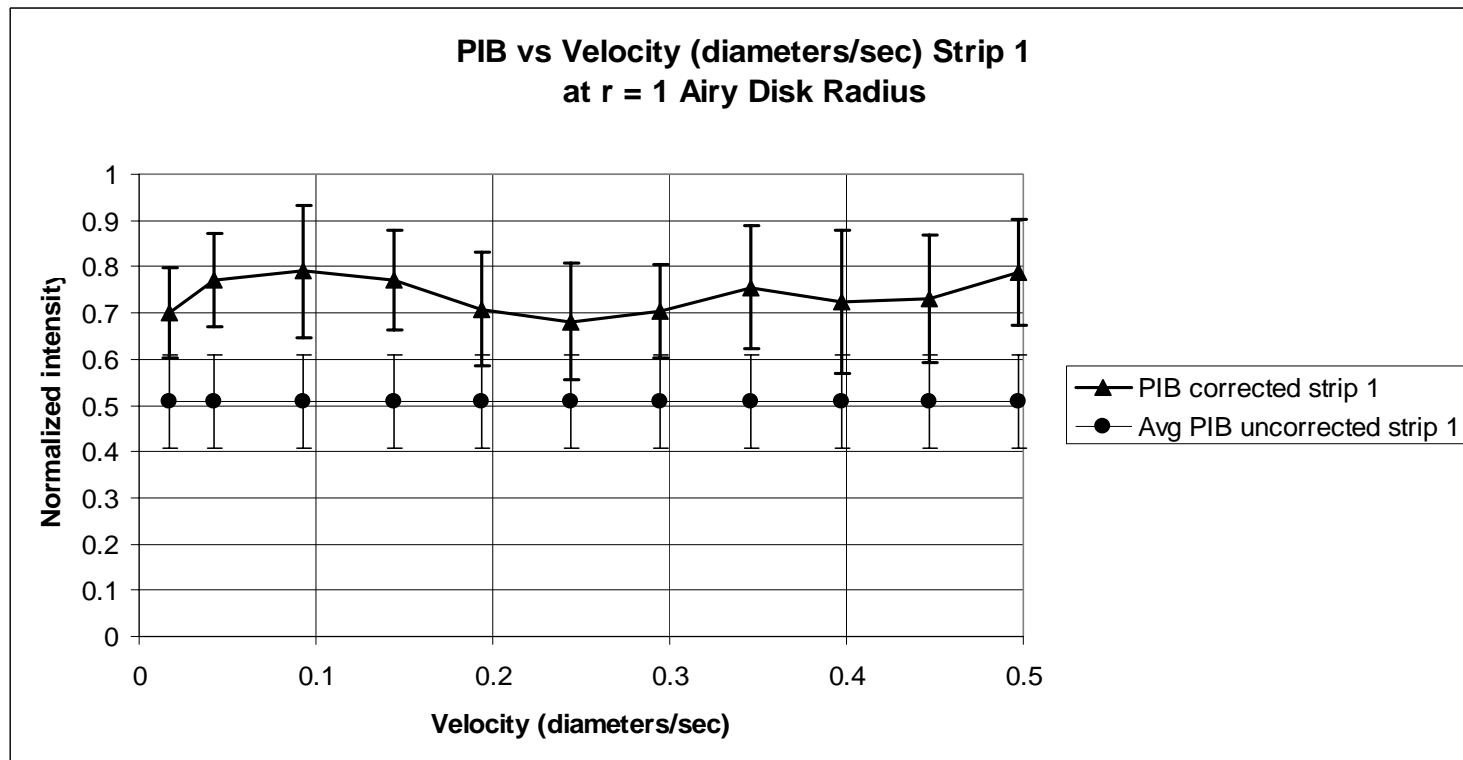
# AO System Static Performance

## ■ Strehl Ratio Improvements

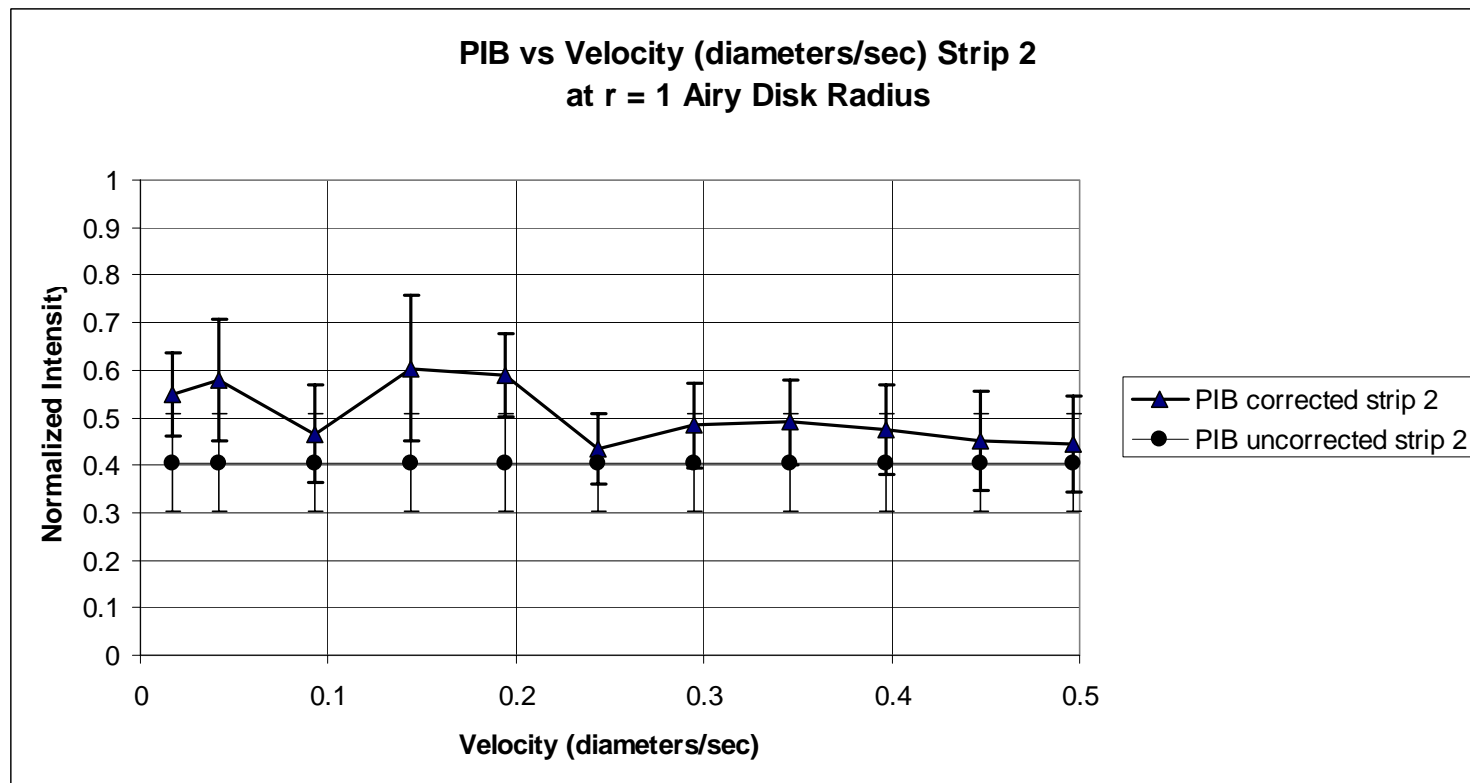


# AO System Dynamic Performance

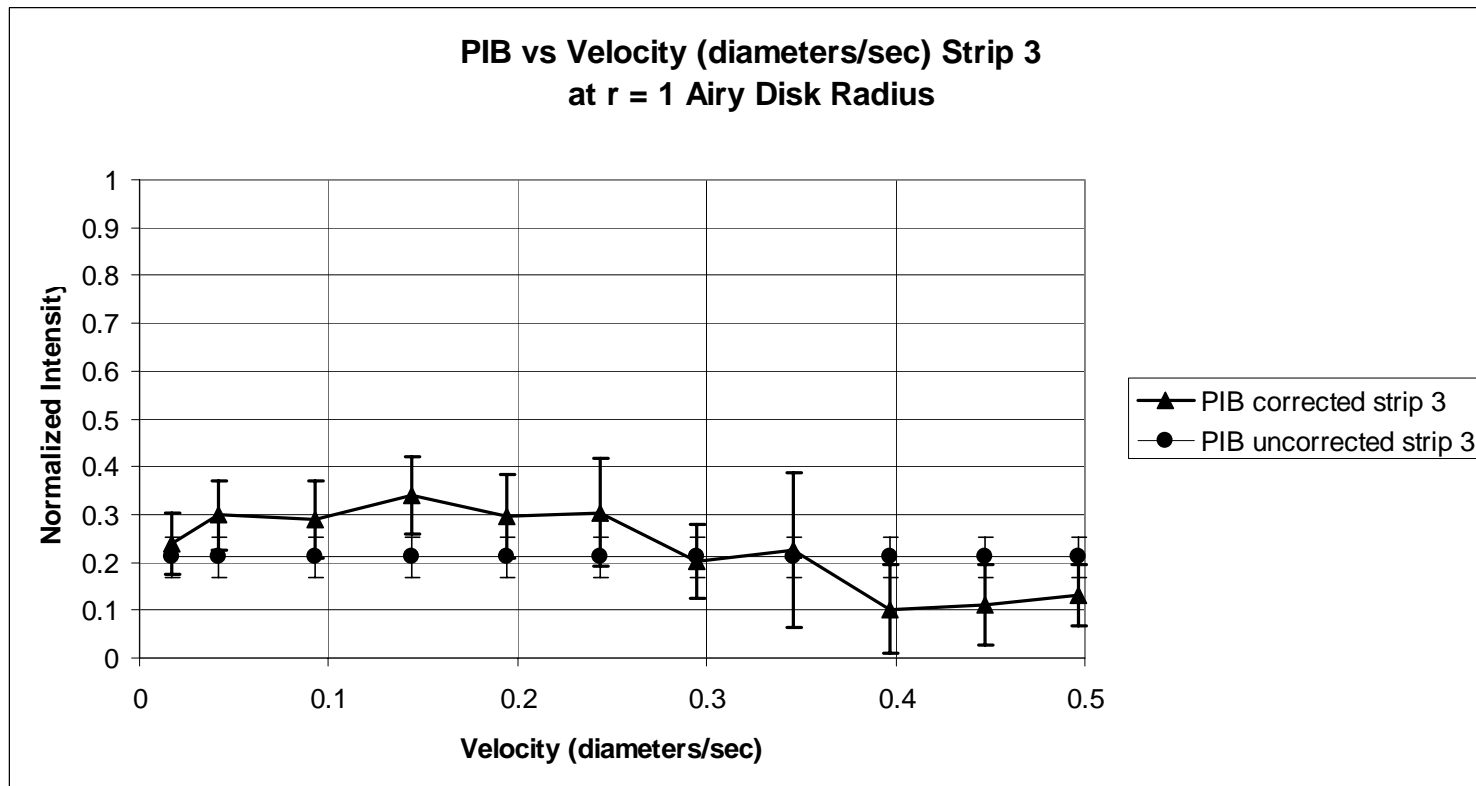
- Temporally Dynamic Results for Velocities up to .50 Beam Diameters per Second



# AO System Dynamic Performance

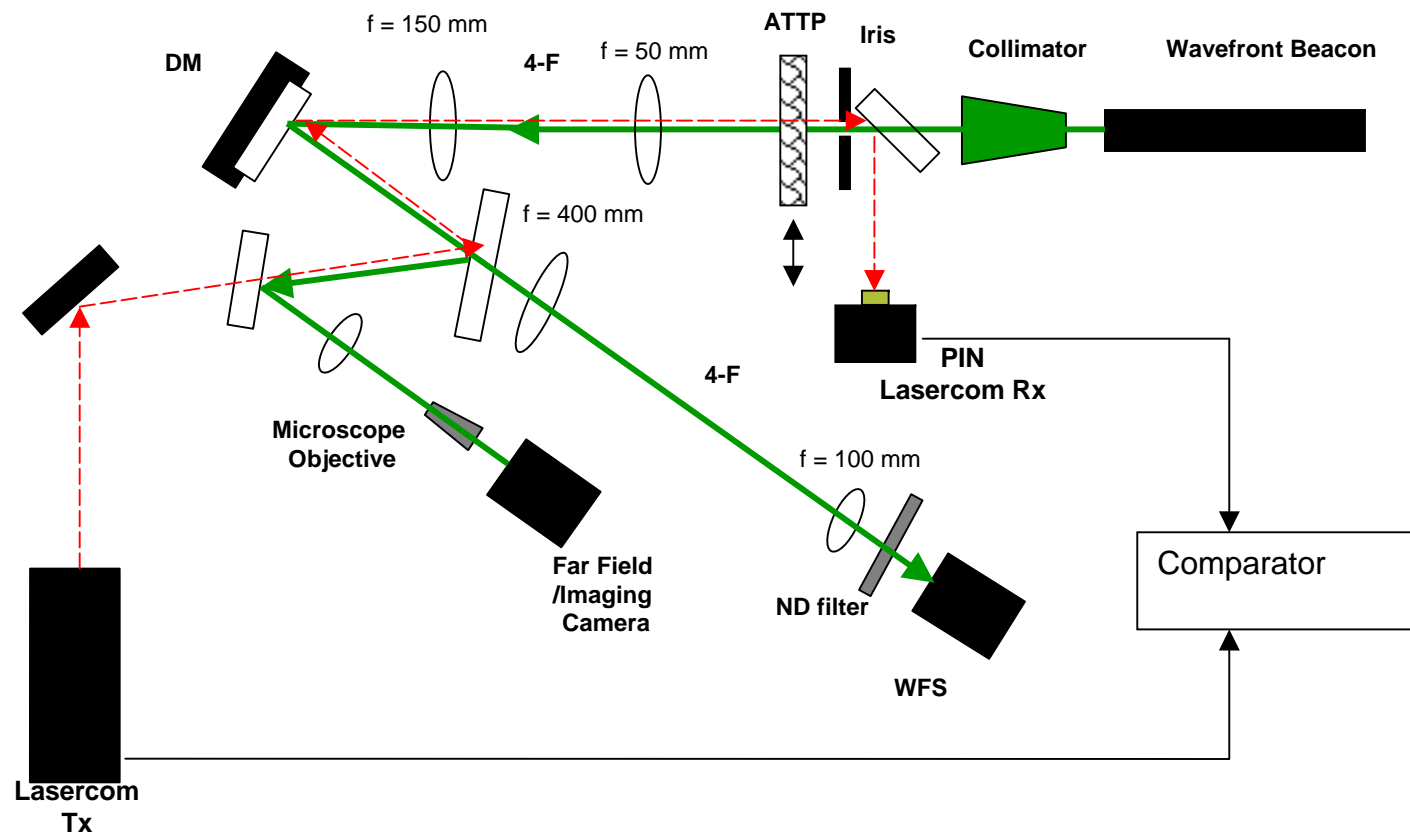


# AO System Dynamic Performance



# AO System BER Measurement

## ■ 2kHz Bit Rate



# AO System BER Measurement

Aberration level ( $D/r_0$ )	Uncorrected BER	Corrected BER	BER improvement
0.8	$2.3 \times 10^{-2}$	$5.49 \times 10^{-4}$	41.5 X
1.4	$1.46 \times 10^{-1}$	$1.03 \times 10^{-1}$	1.4 X
1.5	$2.25 \times 10^{-2}$	$1.03 \times 10^{-2}$	2.2 X
2.3	$3.38 \times 10^{-2}$	$2.34 \times 10^{-2}$	1.4 X

---

# High-order AO System BER Results

- Static Correction Averaged a Consistent 37% Improvement in Strehl Ratio
  - Dynamic Correction Averaged Similar Improvement up to a Velocity of .35 Beam Diameters per Second at a  $D/r_0 = 1.5$
  - BER Improvement by Higher Order AO was Improved most for  $D/r_0 = 0.8$  (~42X)
-

For a few dollars more ...

## Bistatic Experiment

