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Wavefront Amplitude Variation of TPF's High Contrast Imaging Testbed - Modeling and Experiment

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Wavefront Amplitude Error

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- Complex wavefront

$$E(x,y) = A(x,y)e^{-ik\phi}$$

- For small amplitude and phase error

$$E(x,y) = A_0(1+a)\cdot(1-ik\phi) = A_0(1+a-ik\phi)$$

- The fractional residual scatter light from both a and $k\phi$ is then
  - Amplitude $a = 1\%$ ⇔ Phase $\phi = \lambda/630$

$$\frac{I}{I_0} = \frac{|FT(a)|^2}{A_0^2} + \frac{|FT(k\phi)|^2}{A_0^2} + \frac{ct}{A_0^2}$$

- Source causes amplitude error at HCIT:
  - Source illumination
  - Optical coating non-uniformity
  - Mixing from phase error from the optical components
  - Ghost / scatter light interference

- Knowledge of amplitude error is critical for TPF's High Contrast Imaging Testbed
  - Half-dark hole for amplitude error compensation
  - Wavefront sensing using pupil image
  - Multi-conjugate DMs for full-dark hole

Study of HCIT Wavefront Amplitude Variation

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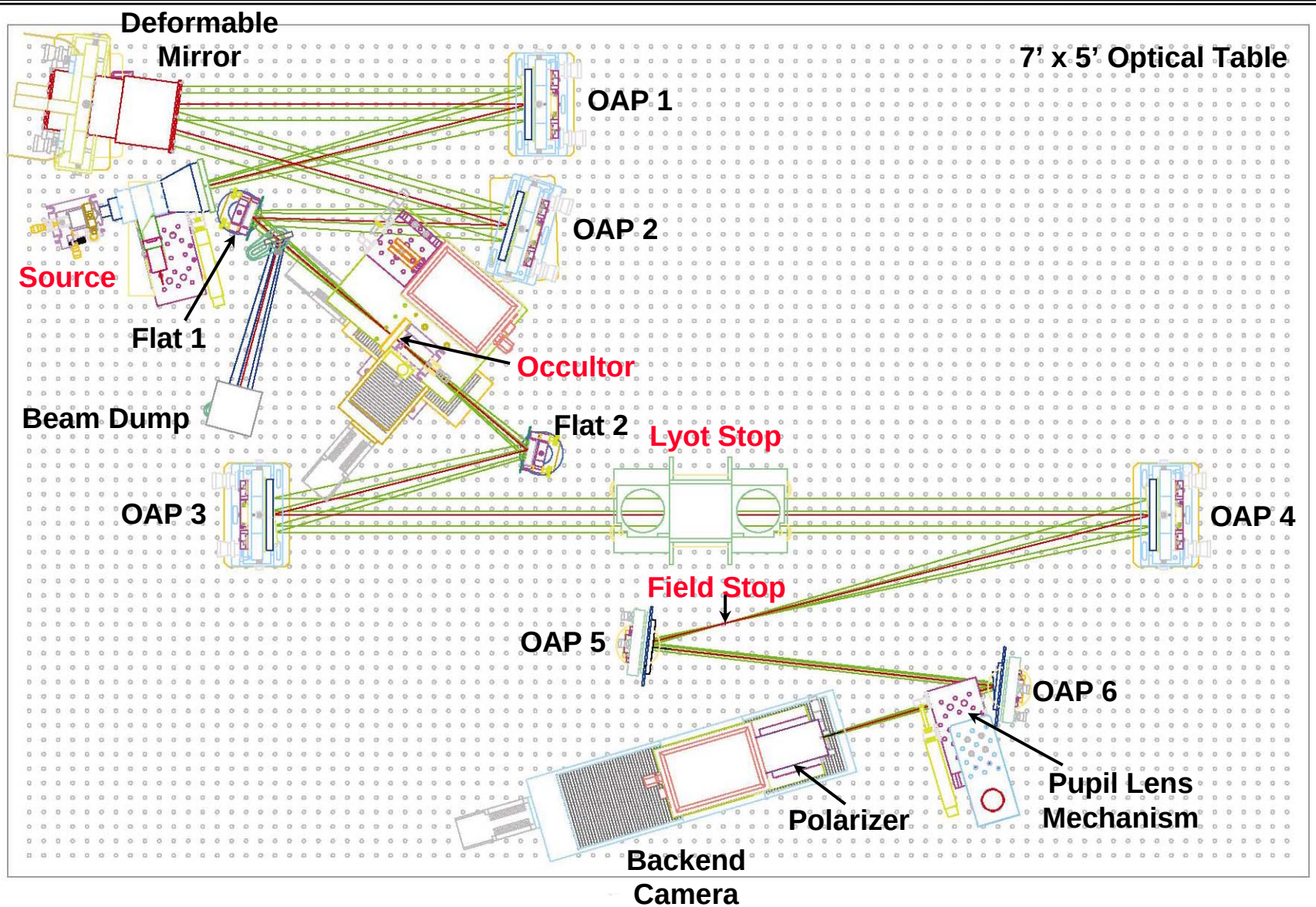
- **Modeling of High Contrast Imaging Testbed**
  - Investigate the effect of phase error mixing
    - HCIT mirror surface Zygo measurement
    - Amplitude variation response of spatial frequency of WF phase
- **Experiments on High Contrast Imaging Testbed**
  - Measuring wavefront amplitude variation of HCIT
    - Pupil imaging system
    - Direct imaging at Lyot plane
    - Lyot plane fiber scanning

HCIT: Testbed Layout



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HCIT: Photo

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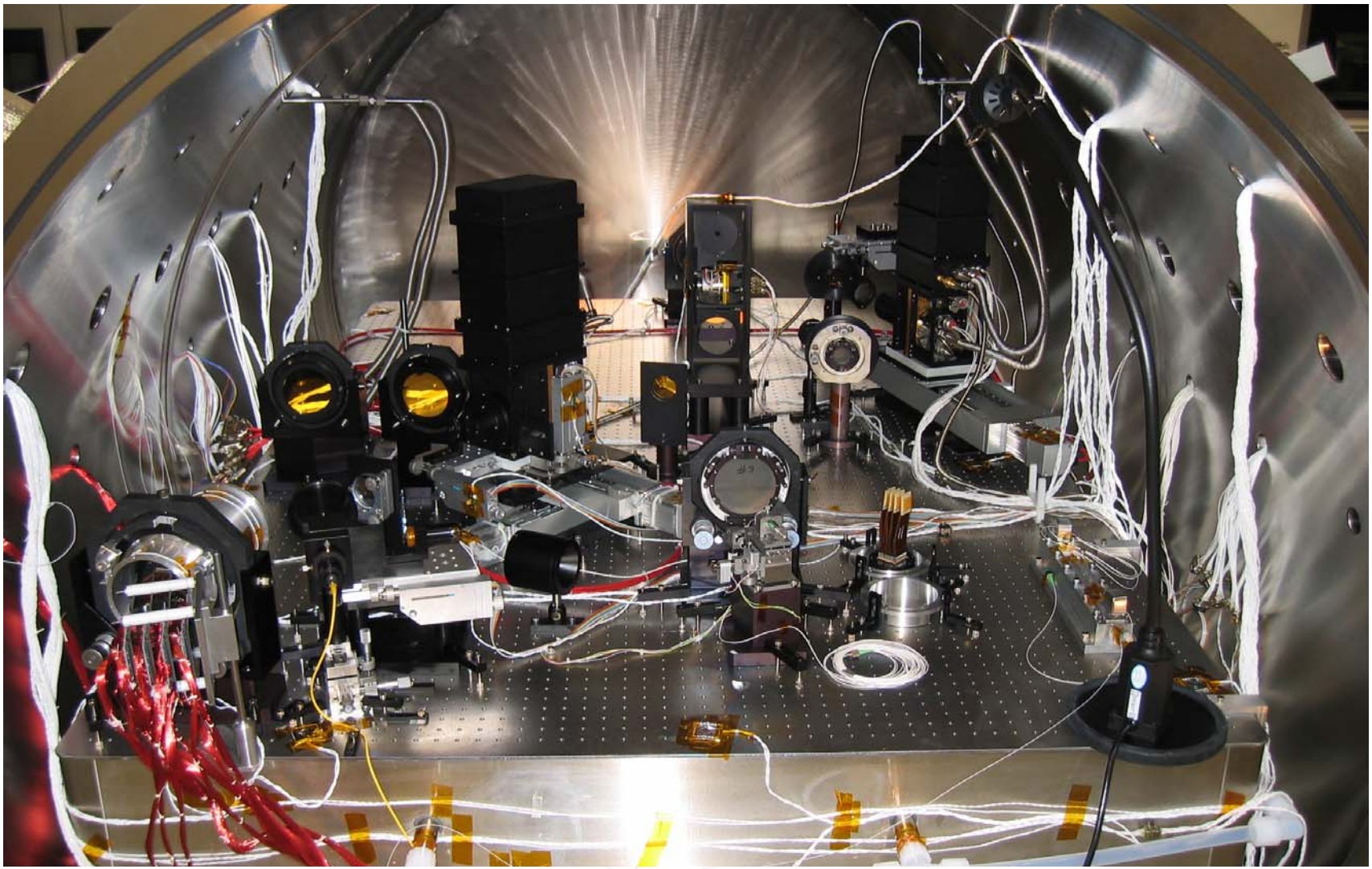

HCIT Modeling: Setup

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- **Purpose: to investigate the amplitude error caused by mirror figure error (phase) due to the diffraction mixing**
  - Optical component requirement
  - Second DM
- **HCIT MACOS model**
  - Full diffraction propagation for front end optics
- **Amplitude calculation method**
  - Complex amplitude output at back-end exit pupil: $E = Ae^{i\phi}$
    - No back-end optical aberrations
  - Use ideal case (no-aberrations) as the reference: $E_0 = A_0 e^{i\phi 0}$
    - A_0 may contain Gaussian illumination
  - Amplitude variation:
    - $\delta = (|E| - |E_0|) / |E_0| = (A - A_0) / A_0$
- **Mirror aberrations:**
  - Zygo measurements applied to front-end optics
  - Periodic phase errors applied on each front-end optic

HCIT MACOS Modeling: Effect of Mirror Figure Error as Measured by Zygo

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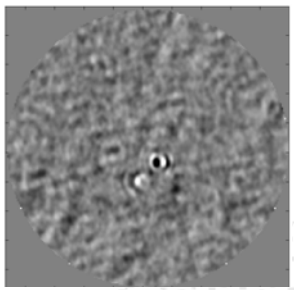
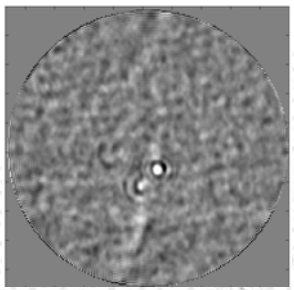
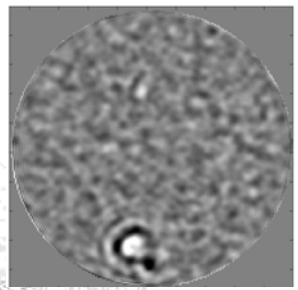
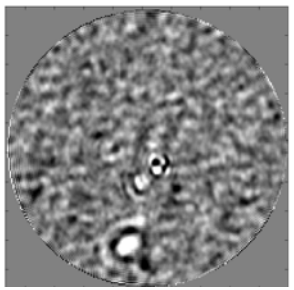
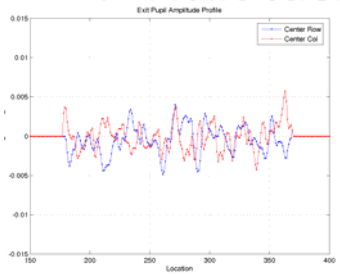
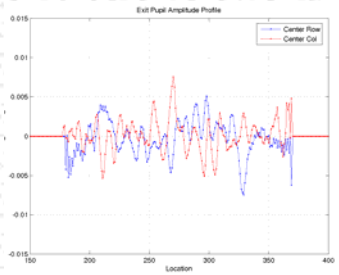
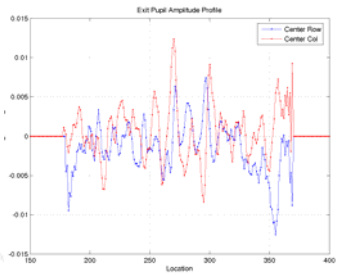
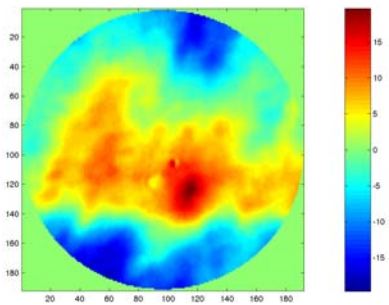
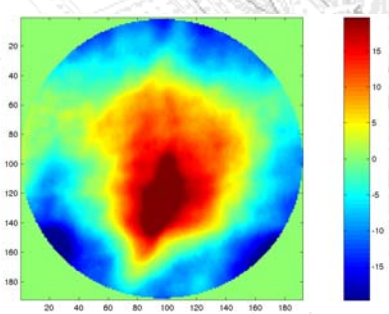
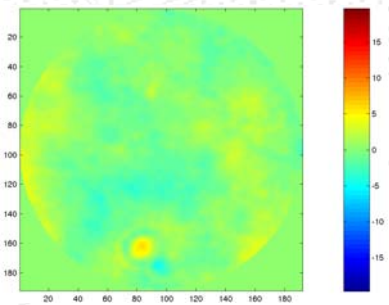
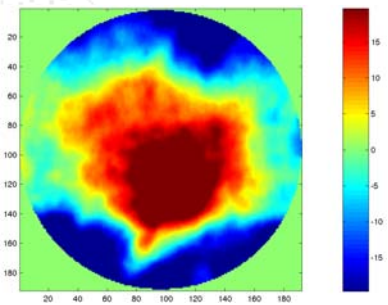
	OAP-1	OAP-2	FM-1	All Front-end
Amplitude				
	Rms=1.30%	Rms=0.24%	Rms=0.23%	Rms=1.33%
Amp Profile				
Phase				
	Rms=7.3nm	Rms=9.5nm	Rms=1.3nm	Rms=14.9nm

HCIT MACOS Modeling: Effect of Mirror Figure Error as Measured by Zygo

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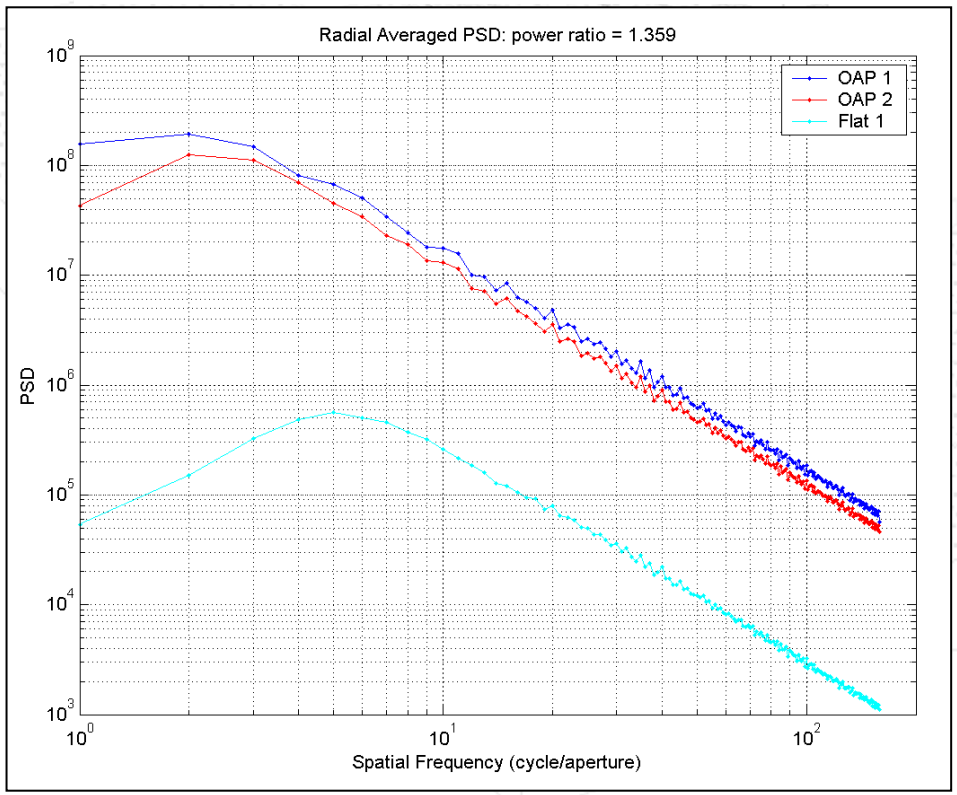
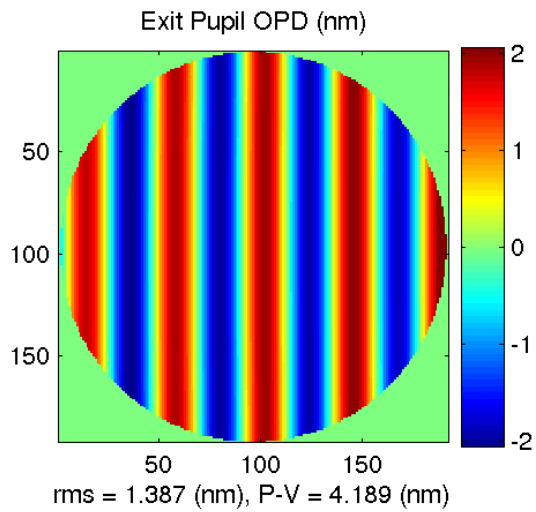
- Zygo measurement shows that OAP #1 has more power in high frequency
- OAP #1 has larger amplitude error contribution even it has similar Fresnel number

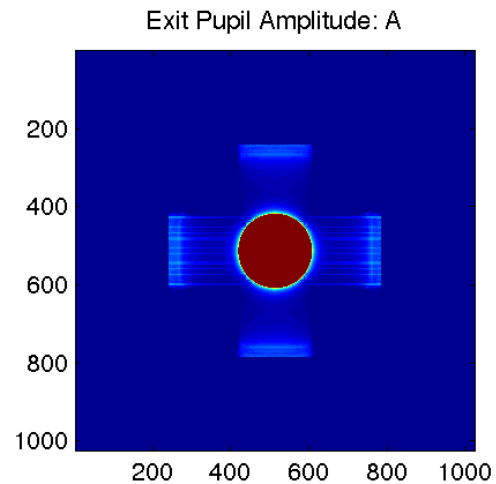
PSD of Mirror Surfaces Measured by Zygo



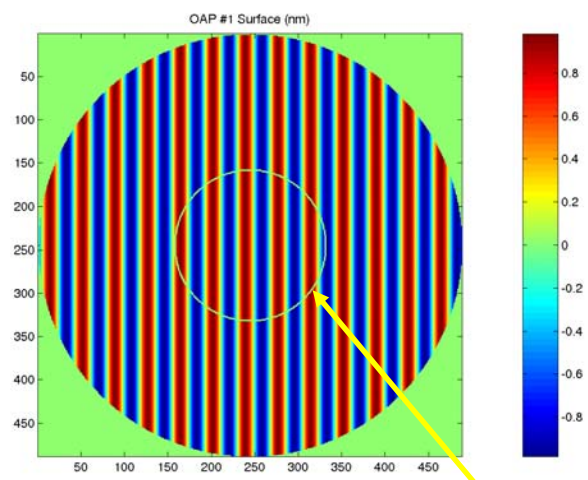
Macos Modeling: Spatial Frequency Response

- Periodic phase errors with different spatial frequencies are applied to each of HCIT front-end optics
- Fresnel numbers of optics:
  - OAP 1: $F_n \sim 100$
  - OAP 2: $F_n \sim 100$
  - Flat 1: $F_n \sim 50$

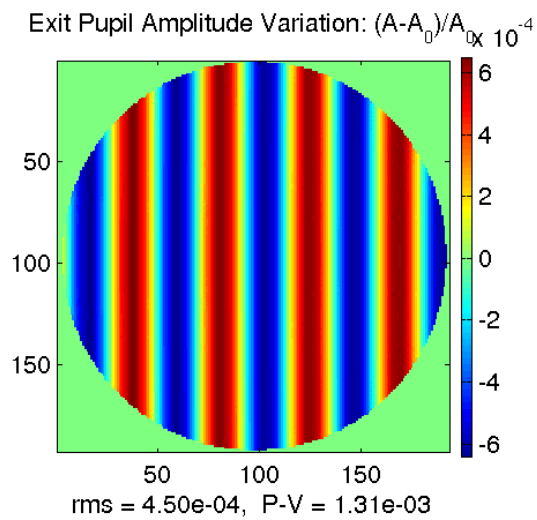


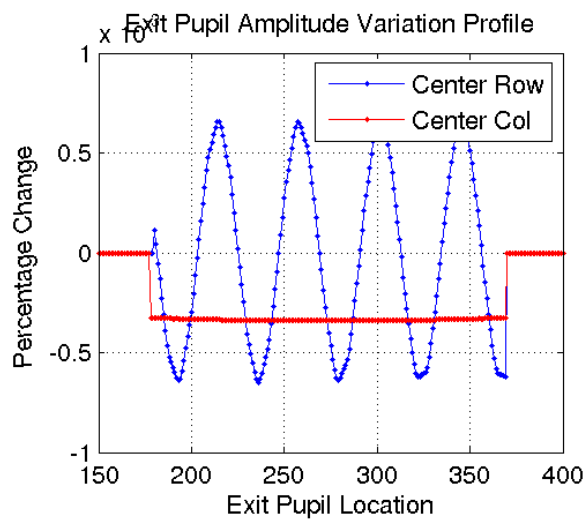


Sinusoidal Phase Error on Mirror



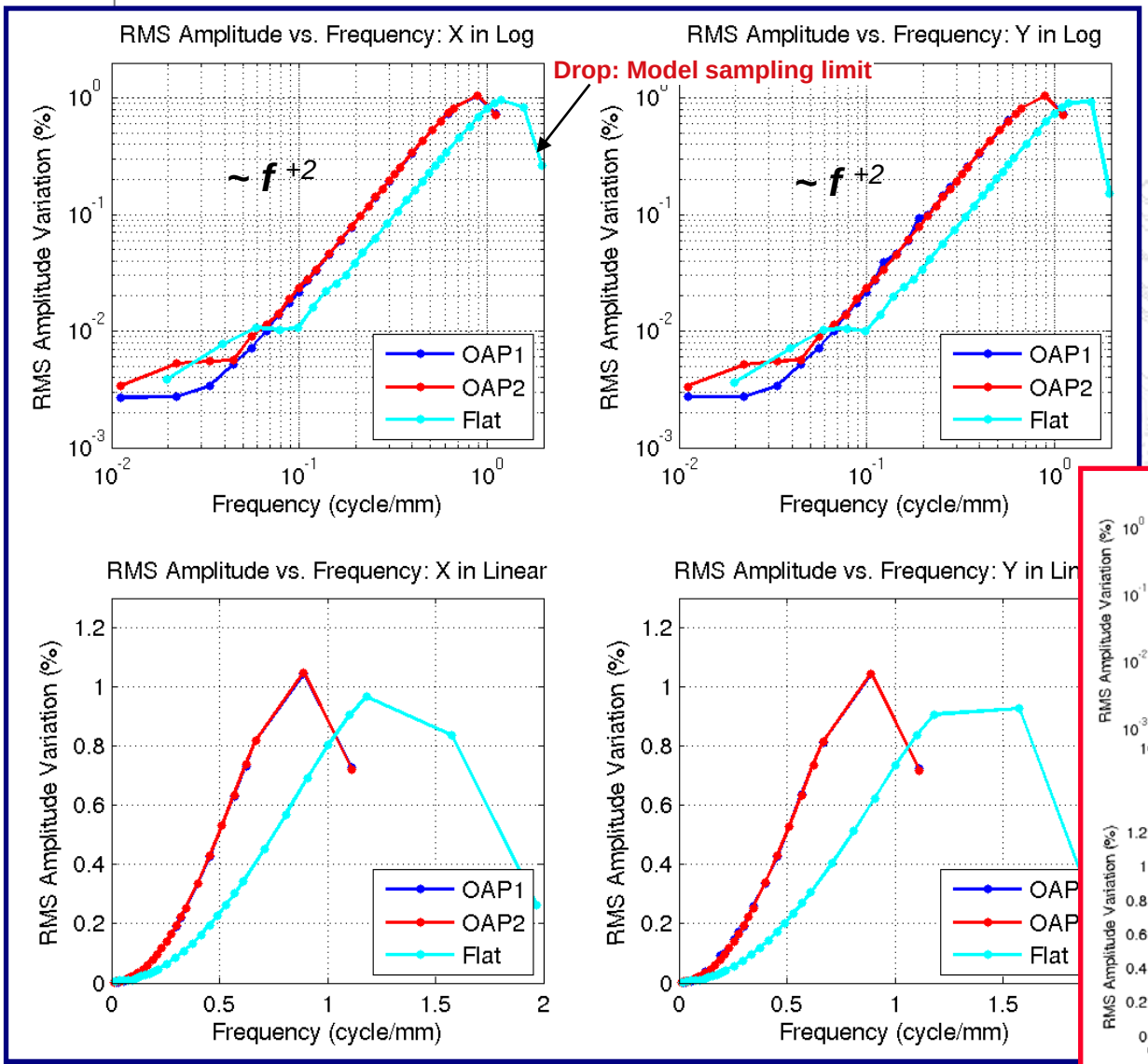
Actual Beam Size





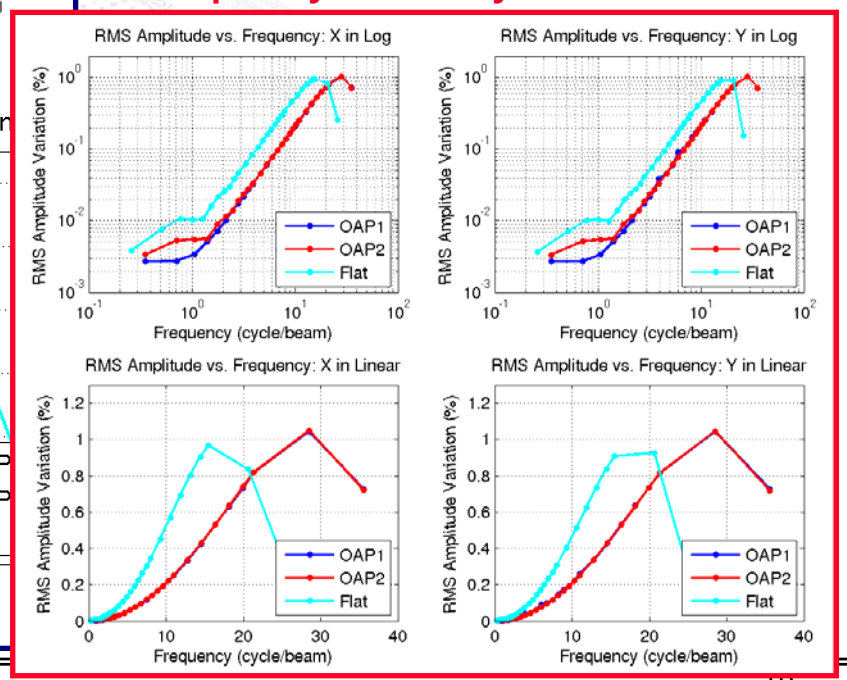
HCIT MACOS Modeling: Spatial Frequency Response

Frequency in Real Physical Dimension



- Plots show amplitude error due to the periodic phase error on HCIT optics
- Amplitude error has a spatial frequency power law of ~2
- High end spatial frequency response drops due to the sampling limitation

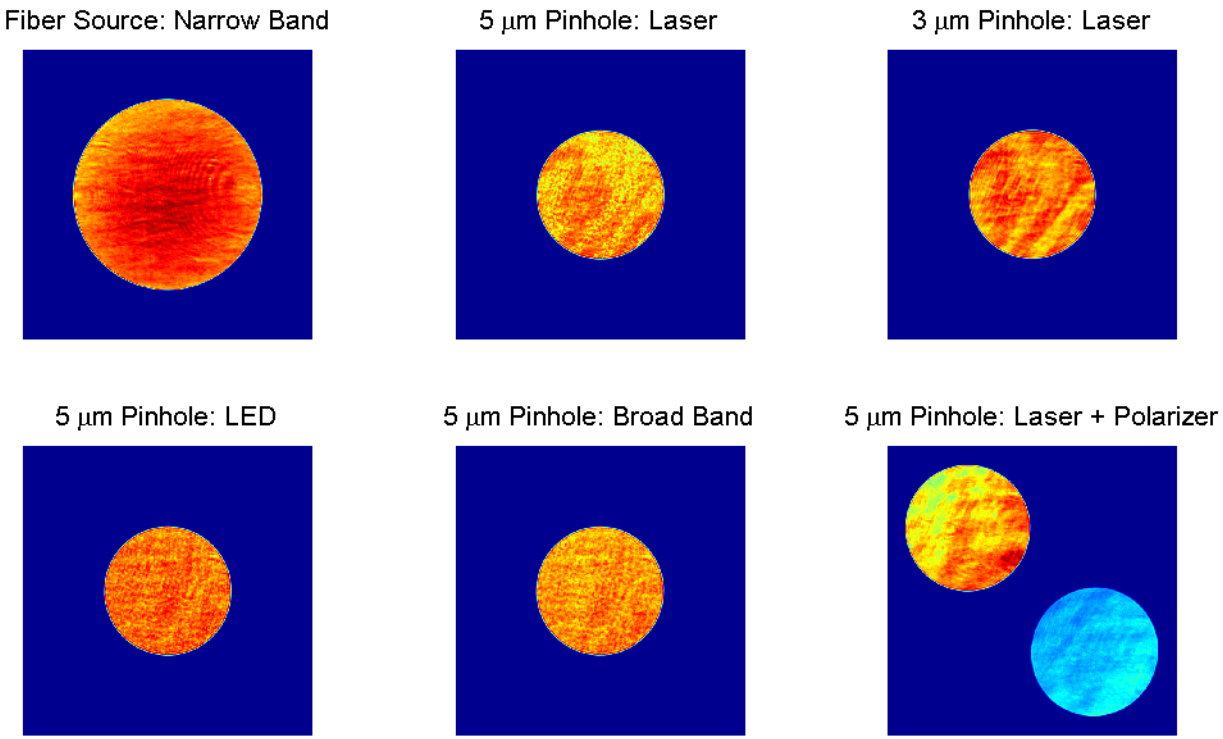
Frequency Scaled by Beam Size



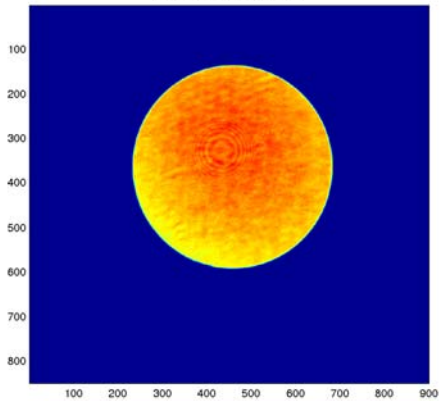
HCIT Experiment: Pupil Imaging

- HCIT is capable of taking front and back end pupil images
  - Designed originally for MGS wavefront sensing
  - Can be used for pupil imaging wavefront sensing together with occultor
- Pupil imaging is used to investigate the HCIT wavefront amplitude
  - Pupil imaging with pupil lens
  - Direct pupil imaging by placing a CCD camera at the Lyot plane

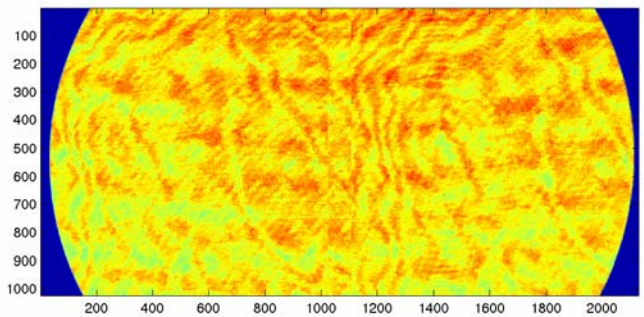
Back-end Pupil Imaging



Front-end Pupil Imaging



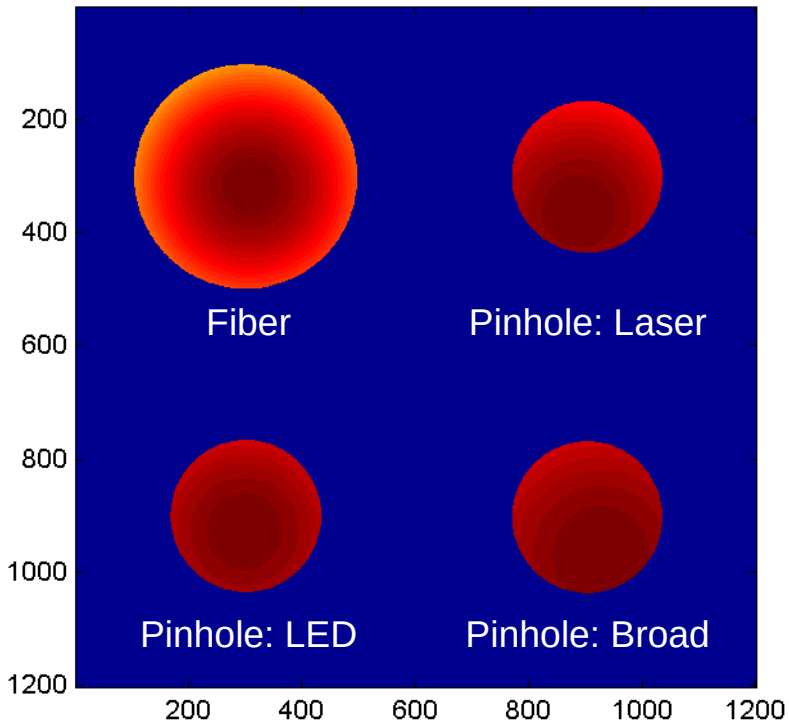
Direct Lyot Imaging



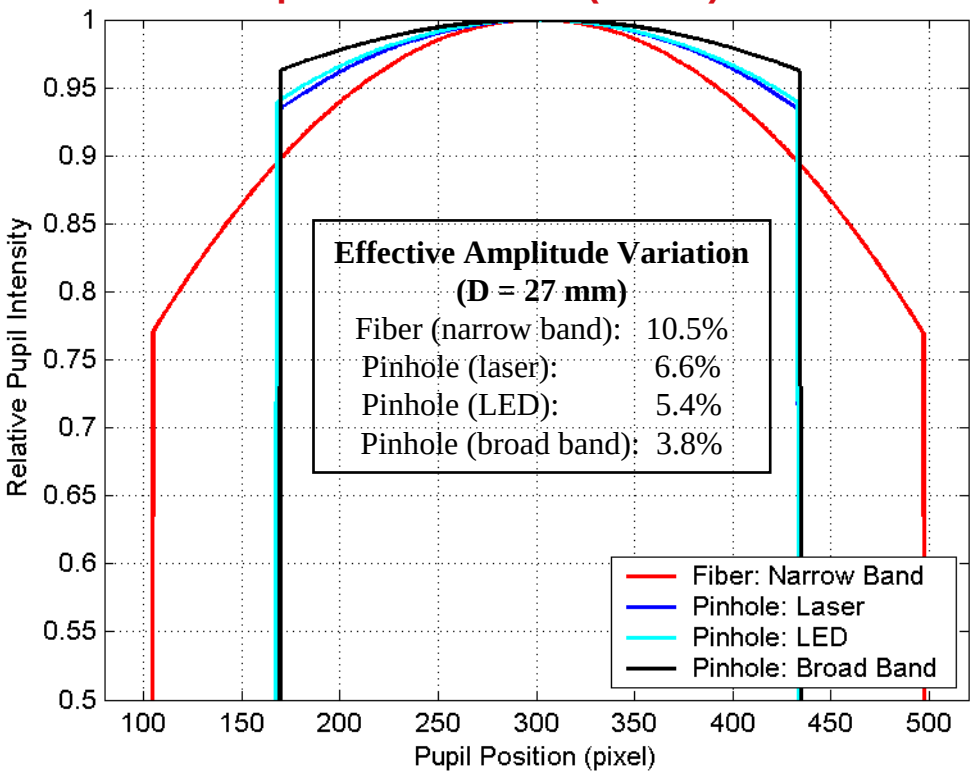
HCIT Experiment: Pupil Illumination

- Overall amplitude changes across the pupil depends on the source
  - Single-mode fiber creates a Gaussian type of illumination
  - Imaging fiber tip to a small pinhole (5 μm) improves illumination
- Low order Zernike fit of pupil image intensity to study the illumination variation caused by source
  - Interference accentuates the effect of the scattering sources such as dusts and ghosts
  - Alignment is critical for uniform illumination

Low Order Fit of Pupil Images



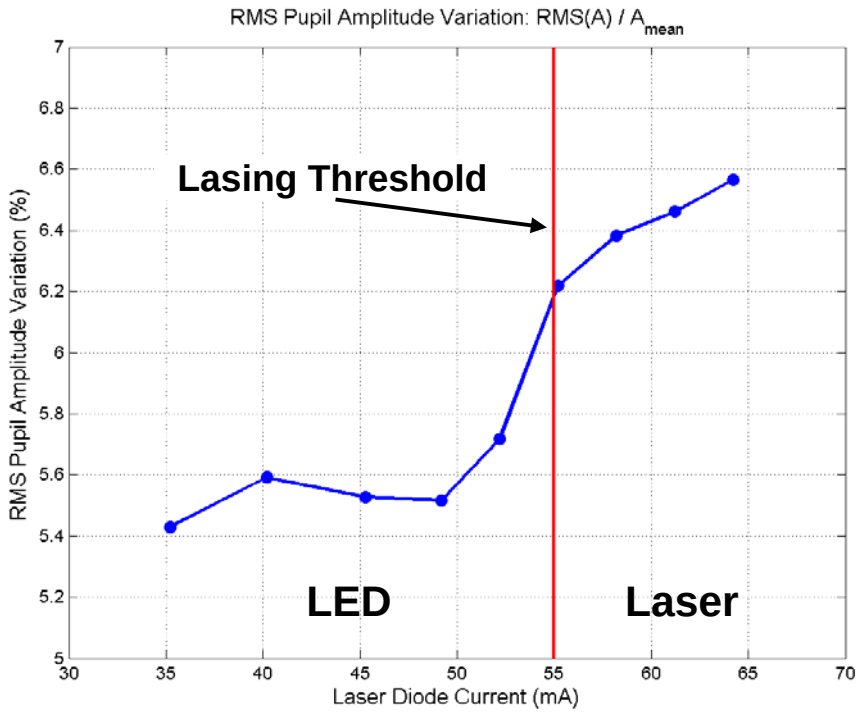
Comparison of the Z4 (Focus) Terms



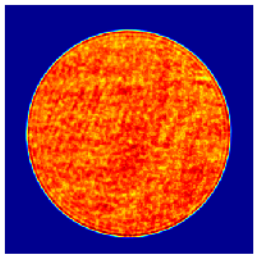
HCIT Experiment: Pupil Imaging and Source Coherence

- Source: a 5 µm pinhole with light from a 785 nm diode laser
- Source coherence can be varied by setting laser diode driving current. When under threshold current the diode laser becomes a LED with FWHM wavelength bandwidth of 20 nm
- As the source coherence increases interference features appears
- RMS variation increases as the the source becomes coherent
  - Occultor substrate
  - Scatter light interference from dusts
  - Pupil lens reflection (ghost)
    - Some features move with the pupil lens

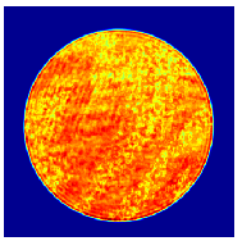
RMS Pupil Amplitude Variation



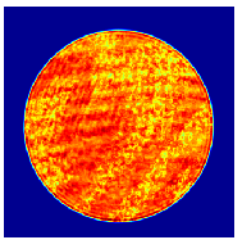
I = 40.20 mA



I = 55.20 mA

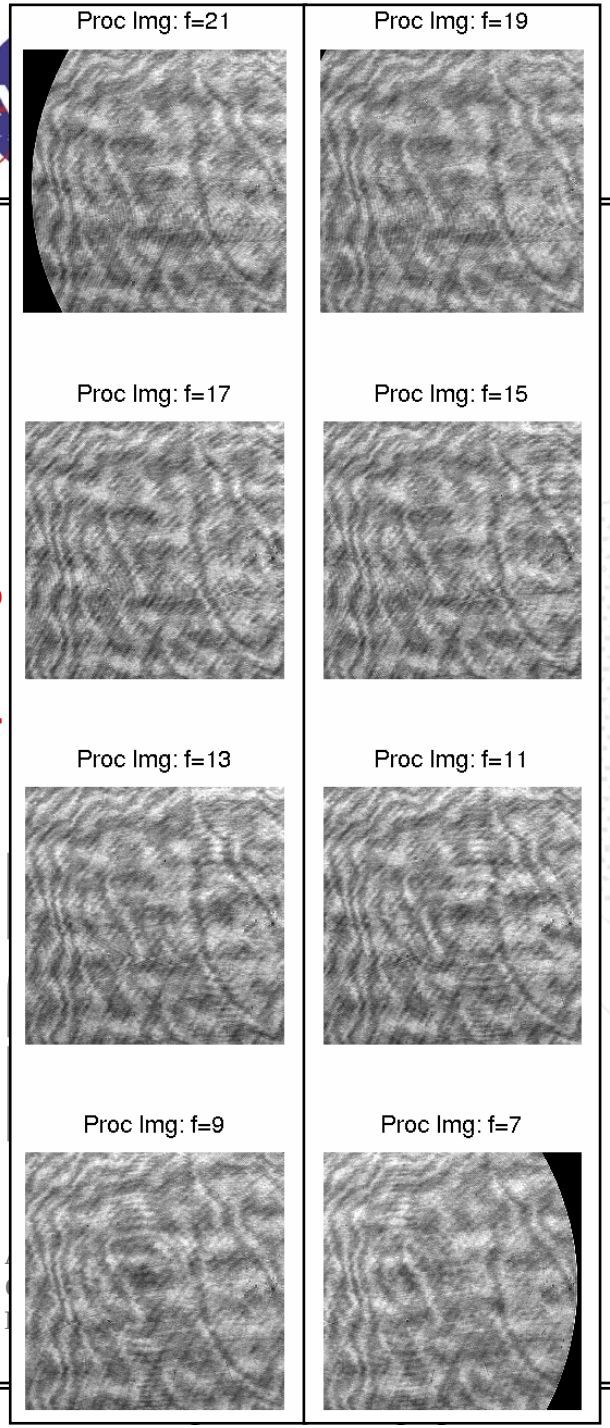


I = 64.22 mA

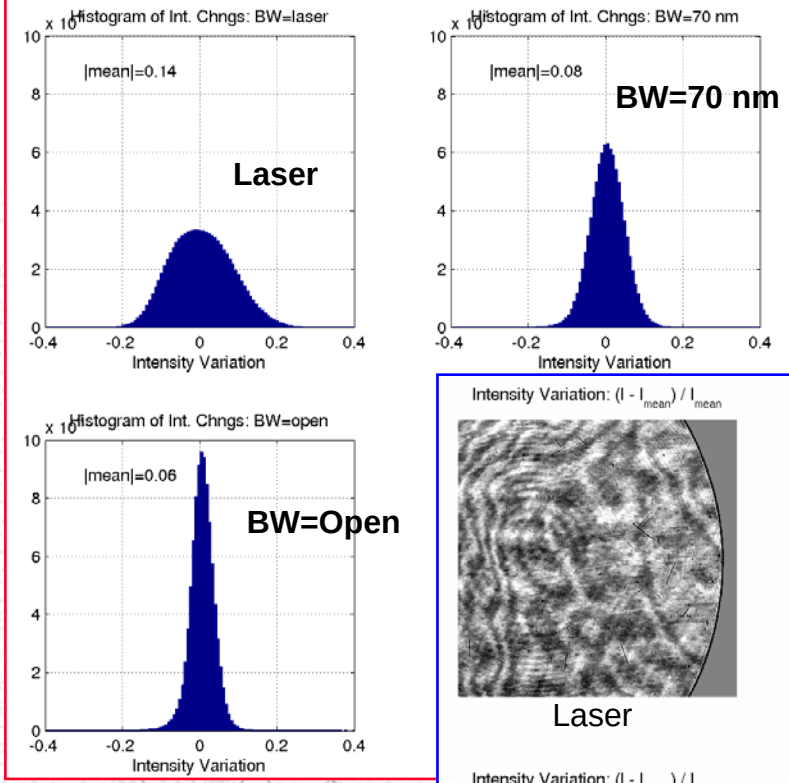


HCIT Experiment: Direct Pupil Imaging

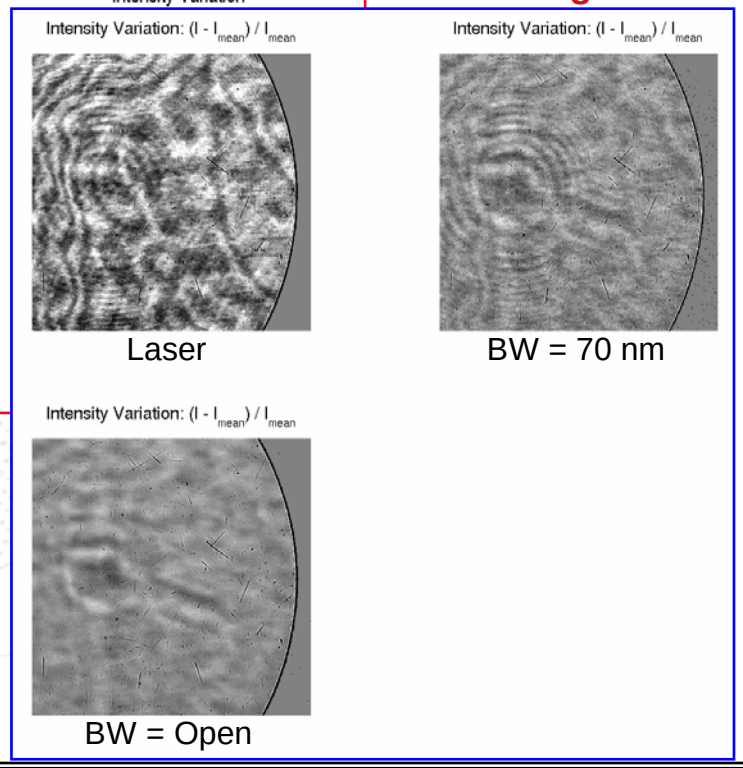
Scanned Pupil Images



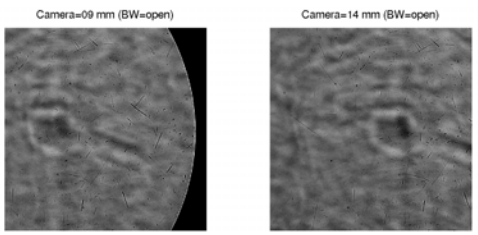
Intensity Variation Distribution



Intensity Variation Image



Common Features



Scanning Pupil Plane with a Optic Fiber: Method and Setup

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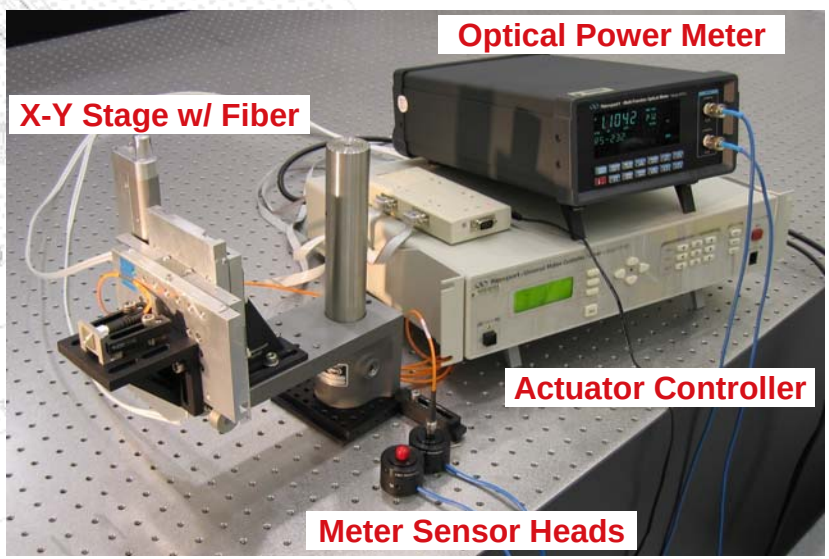
- To avoid interference from pupil imaging system a multi-mode (100 μm core) fiber is used to directly sample the pupil at HCIT's Lyot stop plane
- A 11 mW CW fiber coupled diode laser (λ = 660 nm) is used as source for HCIT
- Power from sampling fiber is measured with a dual-channel low noise optical power meter which provides sub-pWatt sensitivity
- 2D pupil intensity map is measured by mounting the detecting fiber on a motorized X-Y stage with linear actuators which enable the fiber to raster scan the pupil
- While measuring fiber is scanning the pupil another mulit-mode fiber, mounted at the beam dump is monitoring the laser power fluctuation form the back reflection of the occultor and this reference power is used to normalize the scanning measurement
- A computer controls both actuator controller and optical power meter through RS-232 serial ports
- Optical power is constantly read out at ~20Hz with data time stamped for pupil reconstruction
- The optical meter samples input signal at 25KHz
- During the pupil intensity scan the X-Y stage moves in a raster scan pattern with the speed kept constant over the range of pupil diameter
- The stage motion speed (0.1 – 0.5 mm/sec) is set to have a good sampling of the pupil



Scanning Pupil Plane with a Optic Fiber: Data

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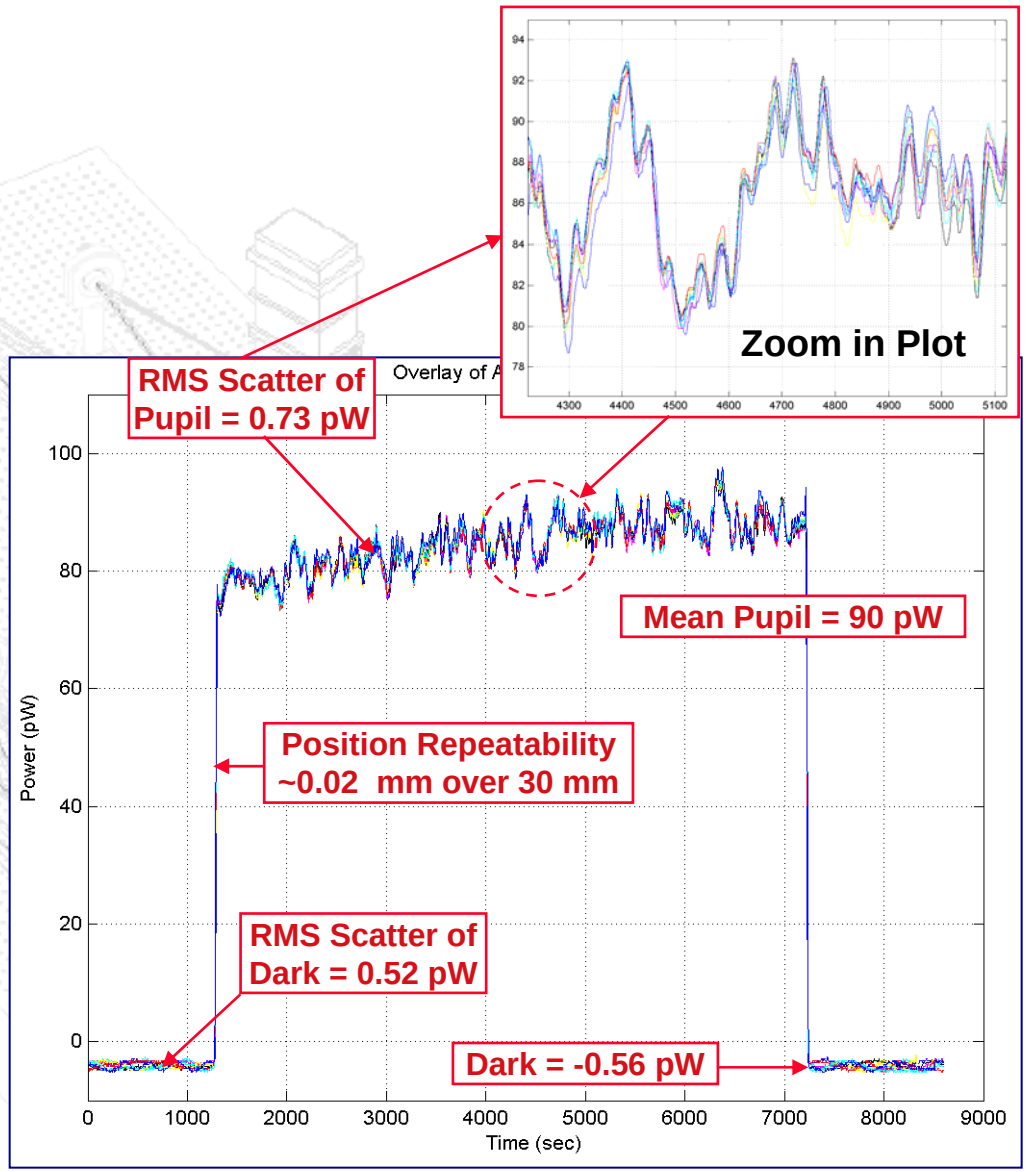
- The measure scan signal is assembled into 2D pupil intensity map using data time stamp as the spatial location guide
- Mean pupil illumination at pupil is measured at I_P ~ 90 pW with RMS measurement noise of 0.2 pW
  - SNR ~ 180
- The RMS X-Y scanning spatial repeatability (after reconstructed with time-stamped data) is 0.02 mm over 30 mm pupil diameter
- The RMS measurement scatter among the 8 repeated back-and-forth scanning is 0.73 pW for the light trace and 0.52 pW for the dark part of trace
- Plots on the left shows overlay of all 8 repeated scan traces and a detail "zoom in" plot on top to show the scatter of the measurement



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Scanning Pupil Plane with a Optic Fiber: Results

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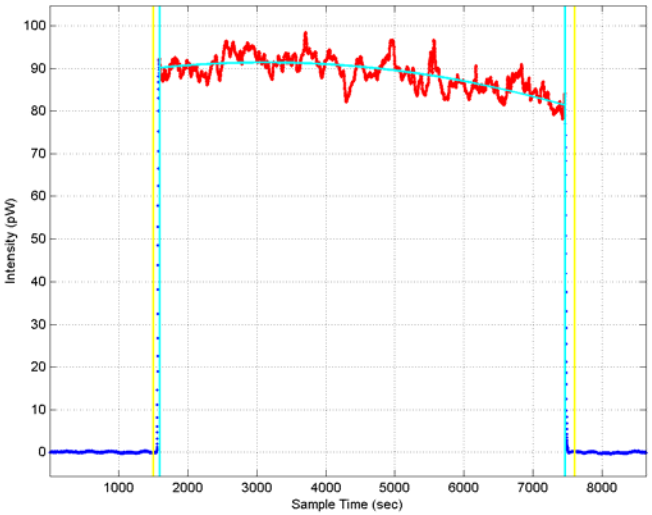
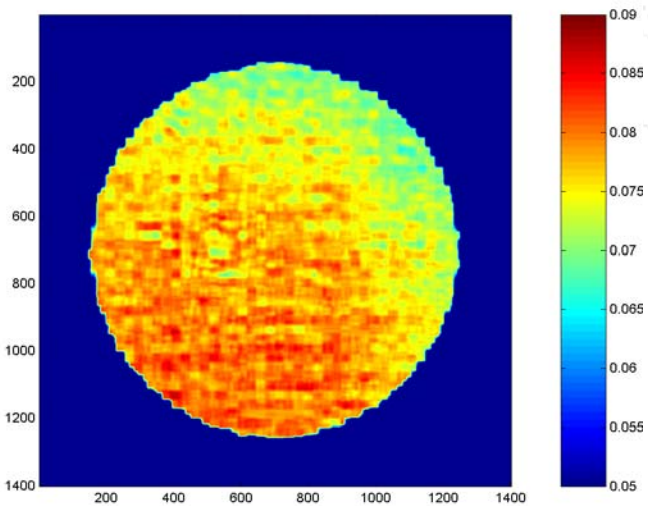
- Composite pupil map is combined from both fine X and Y scanning
  - Intensity variation: *RMS = 4.2 pW (5.5%)*
    - **RMS Amplitude:** ***2.83%***
  - Lower Zernike fit (up to focus) shows the variation from testbed illumination: *RMS = 3.1 pW (4.9%)*
    - **RMS Amplitude:** ***2.03%***
  - With lower terms removed the residual high order intensity variation: *RMS = 2.8 pW (3.7%)*
    - **RMS Amplitude:** ***1.94%***
- Line scanning with finer steps
  - Intensity variation: *RMS = 3.8 pW (4.3%)*
    - **RMS Amplitude:** ***2.44%***
  - Low order (quadratic): *RMS = 2.9 pW (3.2%)*
    - **RMS Amplitude:** ***2.01%***
  - Residual high order: *RMS = 2.6 pW (2.9%)*
    - **RMS Amplitude:** ***1.38%***

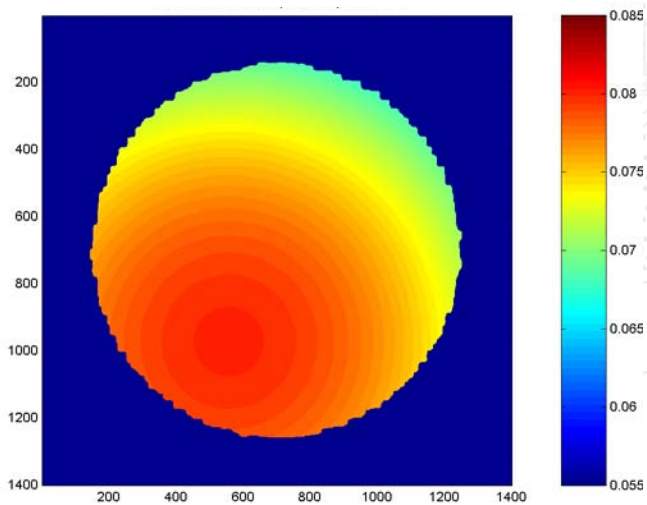
Average of 8 Fine Line Scan Measurement



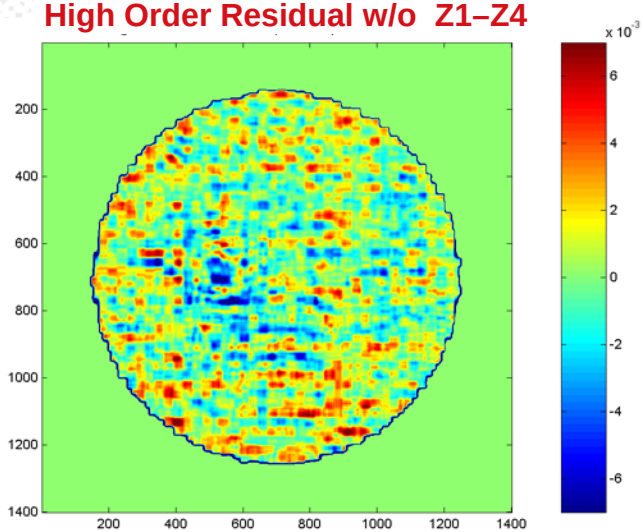
Composite Pupil Intensity Map



Low Order Zernike Fit: Z1–Z4



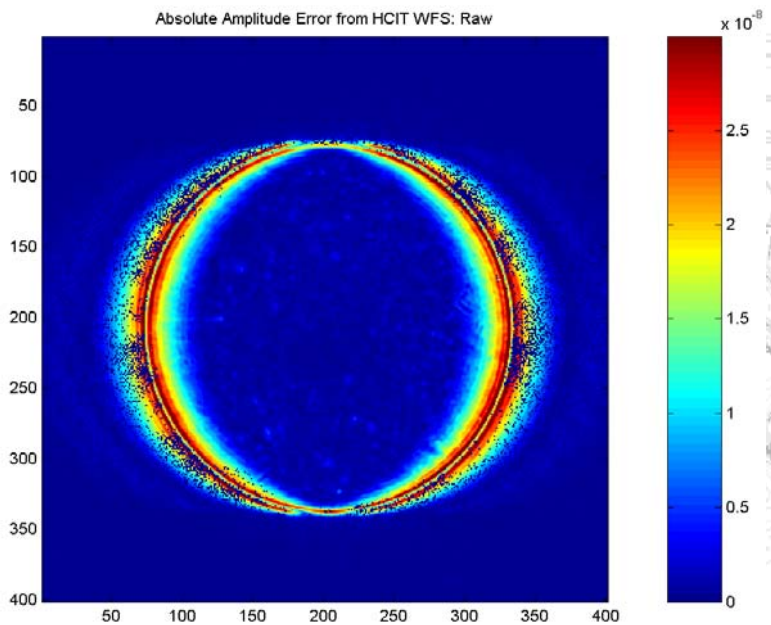
High Order Residual w/o Z1–Z4



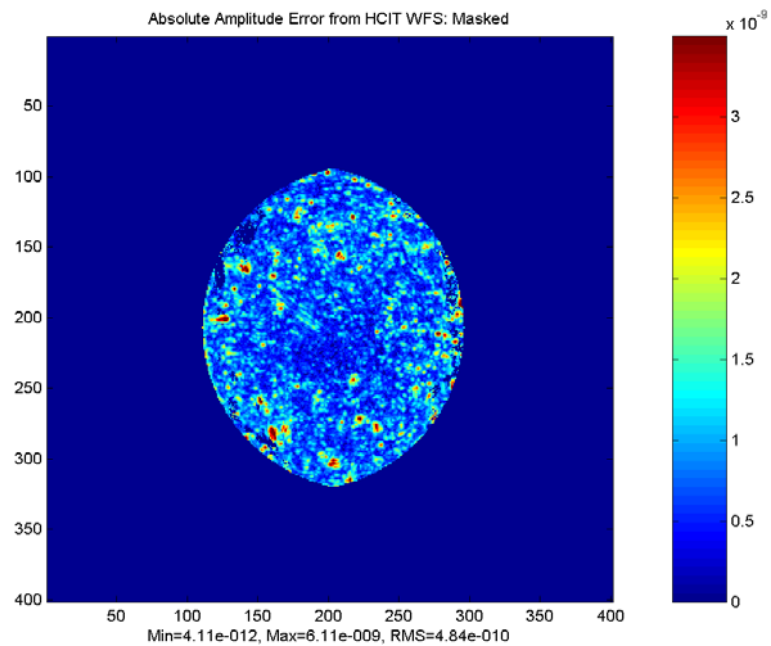
Back-end WFS Using Pupil Lens (D. Moody)

- Data obtained from Dwight Moody (2003?)
- Amplitude detected using back-end camera in pupil imaging mode and occultor in
- The unit of image is in equivalent of wavefront error (meters)
  - Conversion: $k = 2\pi/\lambda$
- The amplitude statistics within the masked area:
  - *RMS = 0.003877*
  - *Mean = 0.007043*
  - *P-V = 0.0890*

Raw Image



Masked Image



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HCIT Amplitude Experiment: Measurement Summary

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- HCIT measurement of amplitude variation
- Measurement of pupil intensity is first covert to amplitude
- Amplitude variation is relative to the mean amplitude
- All Image: amplitude variation is calculated on the image
- Low Order: amplitude variation is calculated on low order Zernike fit (Z1-Z4)
- High Order: amplitude variation is calculated on image with low order removed

Measurement	**Fiber Scanning: Composed 2-D**			**Fiber Scanning: Repeated Line**		
Order	All Image	Low Order	High Order	All Image	Low Order	High Order
RMS Ampl.	2.83%	2.03%	1.94%	2.44%	2.01%	1.38%
Measurement	**Pupil Lens Imaging: Laser**			**Pupil Lens Imaging: LED**		
Order	All Image	Low Order	High Order	All Image	Low Order	High Order
RMS Ampl.	6.57%	1.71%	6.34%	5.43%	1.24%	5.29%
Measurement	**Direct Pupil Imaging: Laser**			**Direct Pupil Imaging: Broadband**		
Order	All Image	Low Order	High Order	All Image	Low Order	High Order
RMS Ampl.	3.55%	0.46%	3.52%	1.60%	0.47%	1.53%

HCIT Amplitude Modeling and Experiment: Summary

Terrestrial Planet Finder Mission

TPF

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- Amplitude error increases with spatial frequency at a power law of 2
- If put the 2nd DM at the Fold Flat #1 position a smaller actuator spacing will be more efficient
- The measured amplitude variation (~2.4 – 2.8% from fiber scanning) is larger than the model prediction (~1.3%) based on the mirror phase error mixing. However,
  - A major part of HCIT amplitude variation (~2%) is due to the non-uniform of illumination
  - With low order illumination part removed the residual amplitude variation is about 1.4 – 1.9 %
  - Besides phase error mixing there are many other factors, such as coating and dust scattering, may also contribute to the amplitude variation
- For pupil imaging measurement the interference from dust and ghost reflection is a major contribution of measured amplitude error
  - For pupil lens: amplitude variation ~6.6% with laser source and ~5.4% with broadband source
  - For direct pupil imaging amplitude variation ~3.6% and ~1.6% with broadband source.
  - Many intensity variations either moves with pupil lens or disappear with bandwidth
  - There is need to measure the amplitude variation with narrow band source
- Fiber scanning method provides a robust approach to measure WF amplitude even under the high coherent source