National Aeronautics and
Space Administration

HCIT Broadband Contrast Performance Sensitivity Studies

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Beginning Remarks

- One of the important milestones of the TPF Coronagraph project is to demonstrate the ability to predict the performance sensitivities of the system at levels consistent with exo-planet detection requirement.

- Want to gain some general understanding about the potentials and the limitations of the current single-DM HCIT system through modeling and simulations

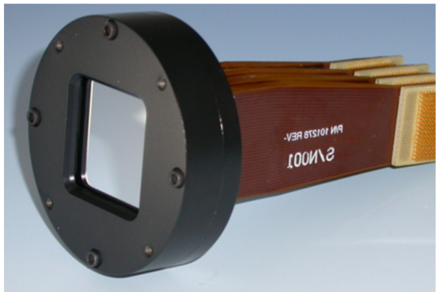
- Specifically, want to understand the effects of some common errors on the EFC-based control of e-field over a half dark-hole region and broadband contrast

- Investigated errors include:
    - Absorbing particles on a flat-mirror
    - Defects on the Occulter surface
    - Dead actuators on the DM

- Also investigated the effects of control bandwidth on the broadband contrast

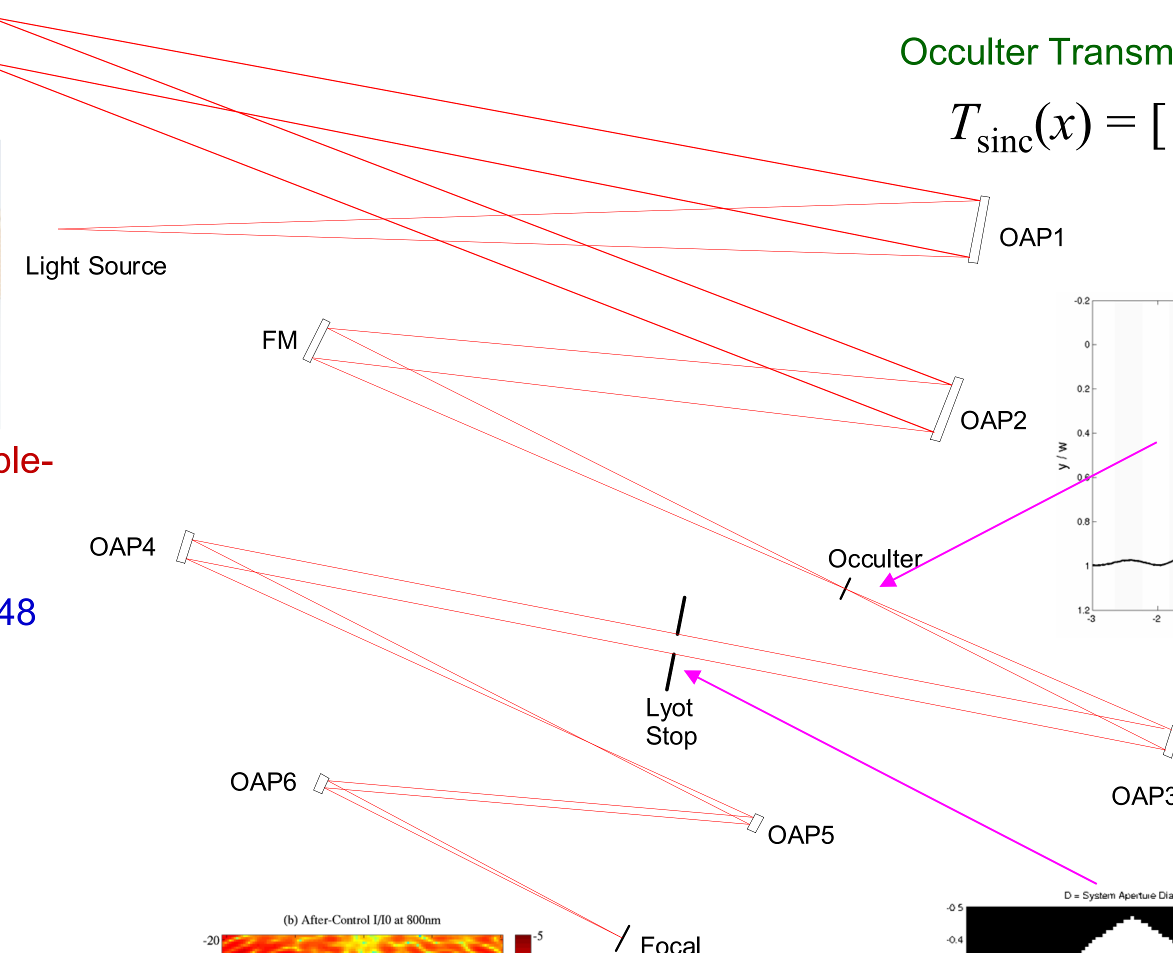
- Use a MACOS-based simulation algorithm which
    - combines a ray trace, diffraction model, & a broadband wavefront control algorithm
    - is capable of performing full three-dimensional near-field diffraction analysis

HCIT Optical System



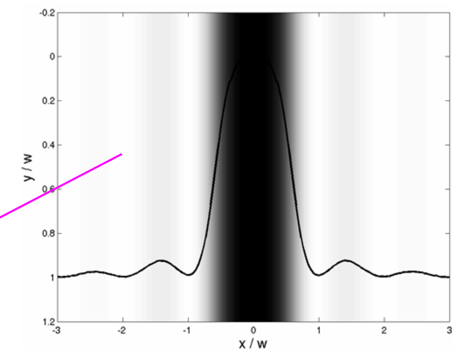
32x32 Actuator Deformable-Mirror

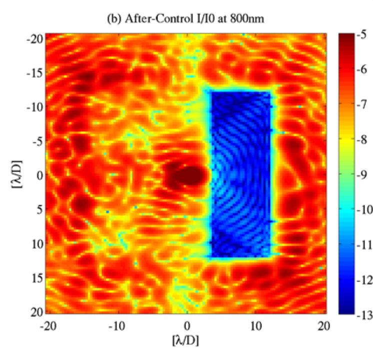
Currently HCIT uses 48x48 actuators of a 64x64 actuator DM

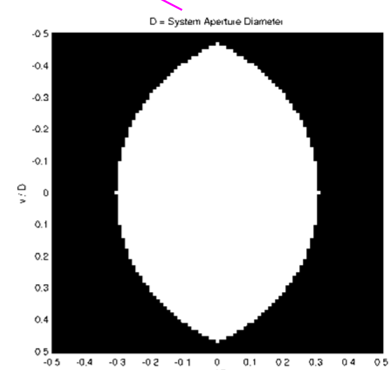


Occulter Transmittance:

$$T_{\text{sinc}}(x) = [1 - \text{sinc}^2(x/w)]^2$$







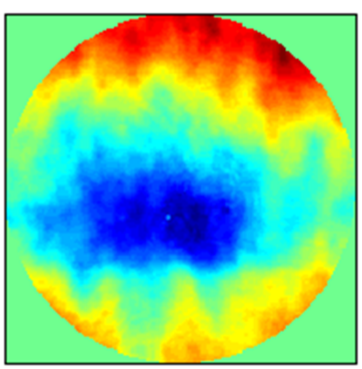
Will Include 2 Types of Errors for Nominal System

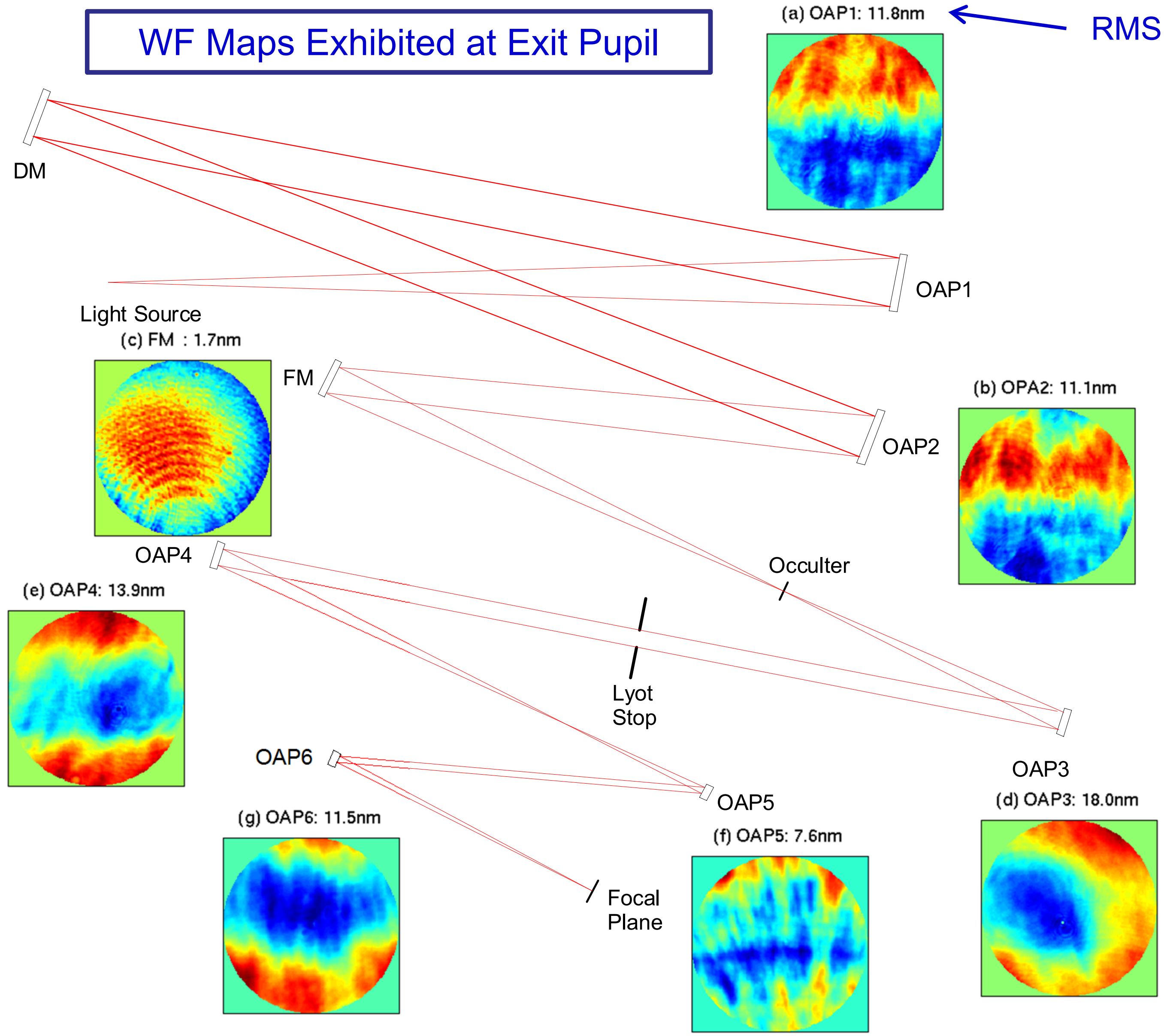
1. Optical Surface Height Errors
2. Occulter phase, occulter phase dispersion and occulter OD dispersion

Surface Errors Used in Simulations

- The phase maps were measured independently with a Zygo interferometer
- Each WF map was obtained by including the phase map of one optic at a time in the optical model
- "All" was obtained by "turning-on" all surface errors
- Will include these 7 surface error maps in simulations

(h) ALL : 42.3nm





Occulter OD & Phase Profiles, and Their Dispersion

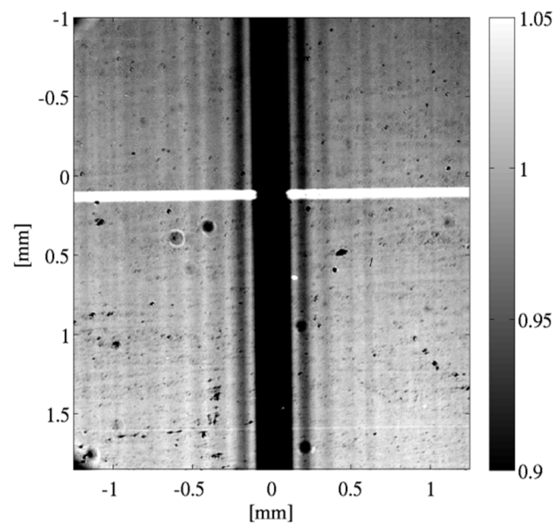
Use a Ni occulter deposited on a fused quartz substrate

$T_{sinc}(x) = [1 - \text{sinc}^2(x/w)]^2$
$w = 142\mu m$

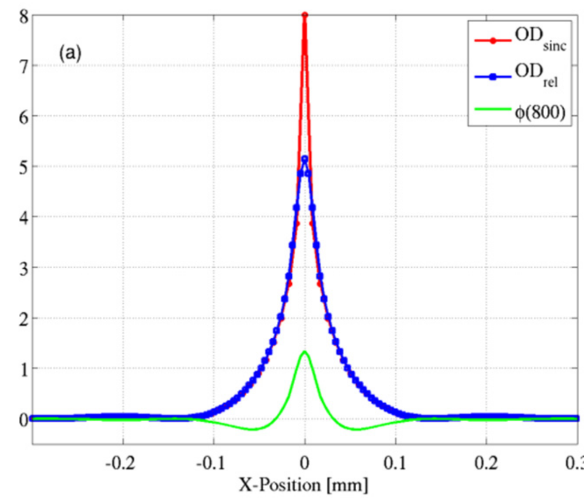
Truncation & Smoothing→ $T_{rel}(x)$

Occulter phase is in radians

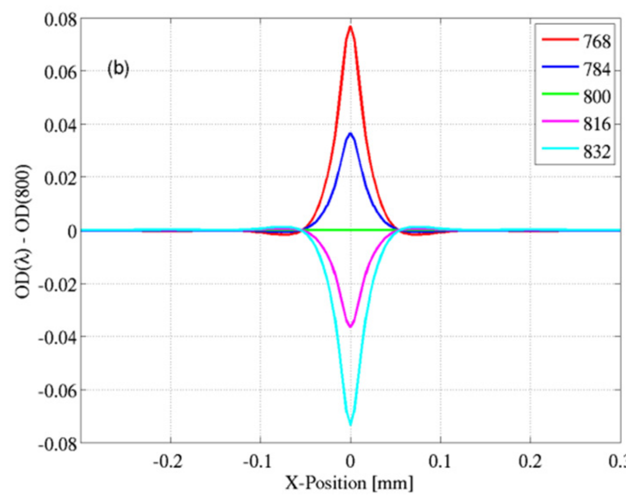
Measured Occulter Transmittance



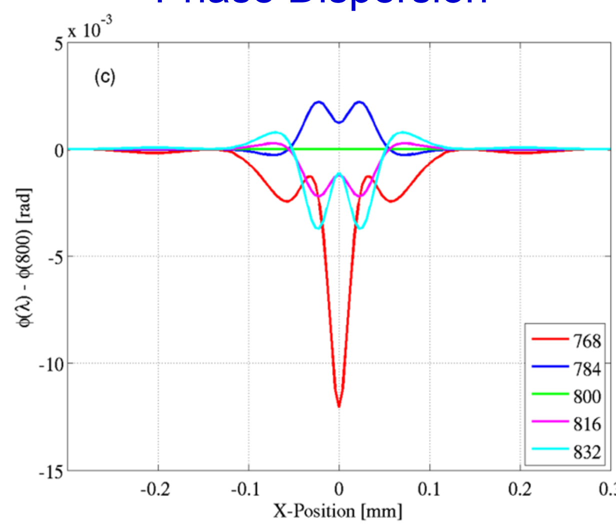
OD & Phase Profile



OD Dispersion



Phase Dispersion



Definitions: Normalized Intensity & Contrast

Normalized Intensity: $I_n(x,y) = I(x,y)/I_0$, $I(x,y)$: Occulted, I_0 : Un – Occulted Peak Value

Contrasnt: $C(x,y) = \left[\frac{I(x,y)}{I_0}\right]\left[\frac{Max\{T(x,y)\}}{T(x,y)}\right] = I_n(x,y)\left[\frac{T_0}{T_{rel}(x,y)}\right]$, $T_{rel}(x,y)$ = Occulter Transmittance

Normalized positions: $X = x/f$, $Y = y/f$, $R = \sqrt{X^2 + Y^2}$

WFC over Ω_c: $[X_1\ X_2\ Y_1\ Y_2] = [3.5\ 12\ \ -12\ 12]\lambda/D$

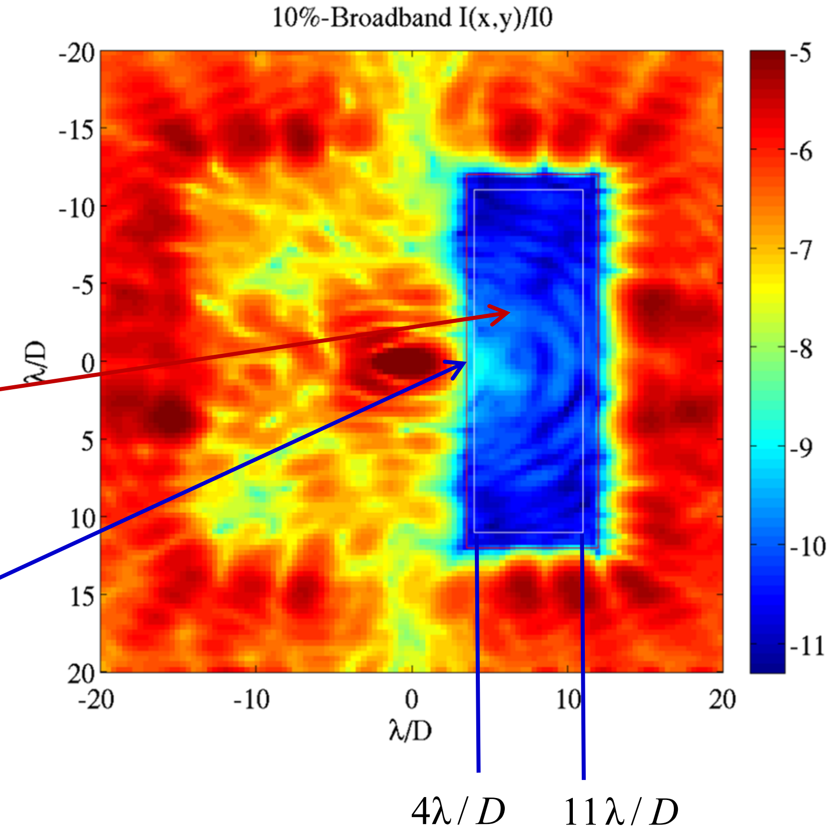
I_b and C_b are mean values averaged over Ω_b :

$[X_1\ X_2\ Y_1\ Y_2] = [4\ 11\ \ -11\ 11]\lambda/D$

I_s and C_s are mean values averaged over Ω_s :

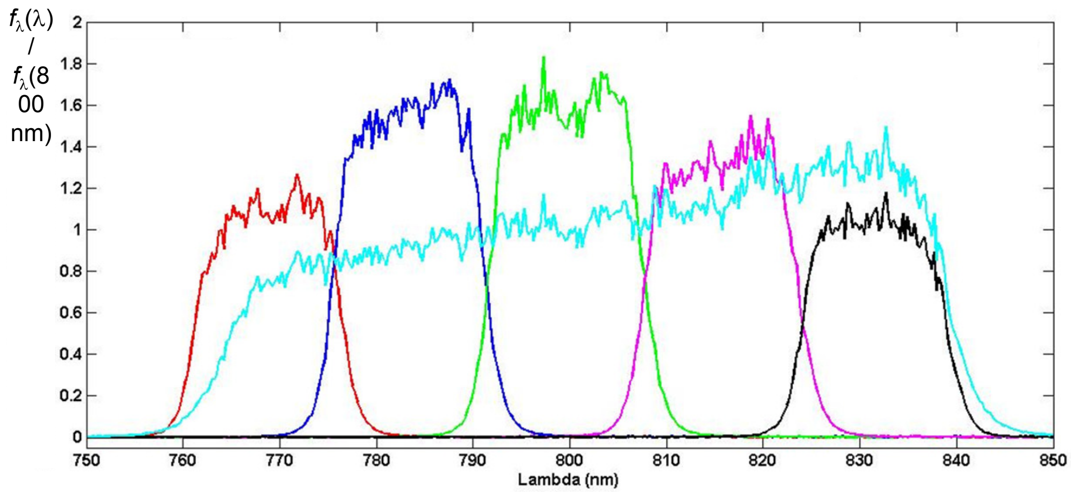
$\Delta X = \Delta Y = 1\lambda/D$

I_m and C_m are maximum values inside Ω_s



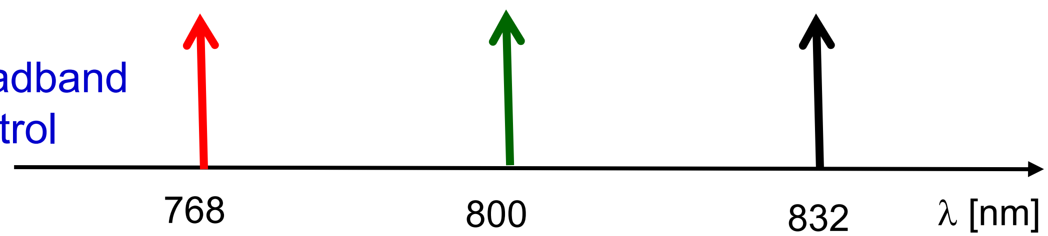
Broadband Control & Contrast: How They are Done

- A super-continuum source (shown on the right) is used for nulling
- WFC is carried out at 3 bands, each 2%, centered at 768, 800, 832nm
- In simulations, WFC is carried out at 3 monochromatic wavelengths: 768, 800, 832nm
- Broadband contrast is obtained by evaluating a single set of DM solutions at 5 monochromatic wavelengths, 768, 784, 800, 816, 832nm, and averaging the resulted intensity maps
- In some cases, will use more than 5 wavelengths to obtain a broadband intensity map

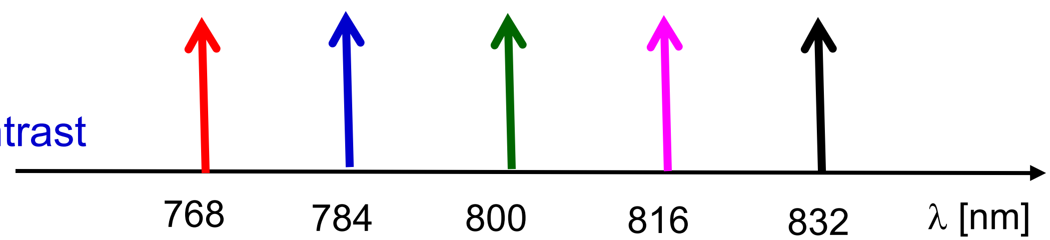


Measured net spectra of supercontinuum source, through each of six bandpass filters (Five 2% and one 10% bandpasses).

Broadband Control



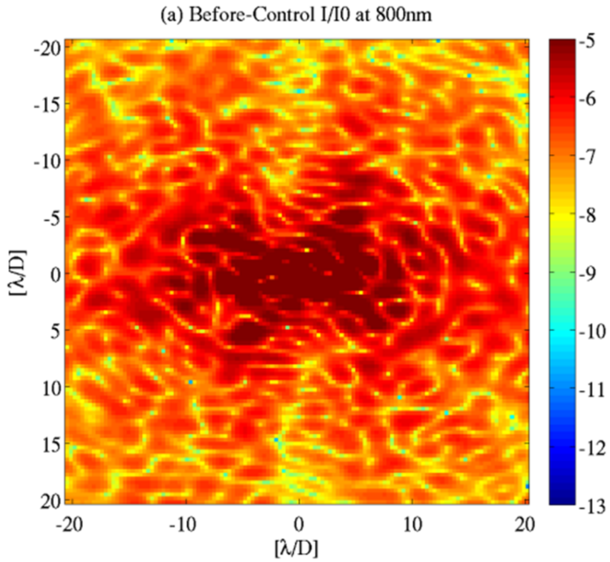
Broadband Contrast Evaluation

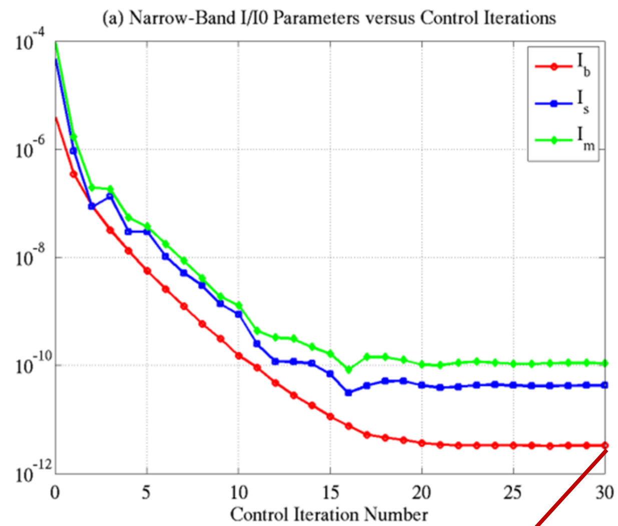


Nominal Case as a Baseline: Monochromatic

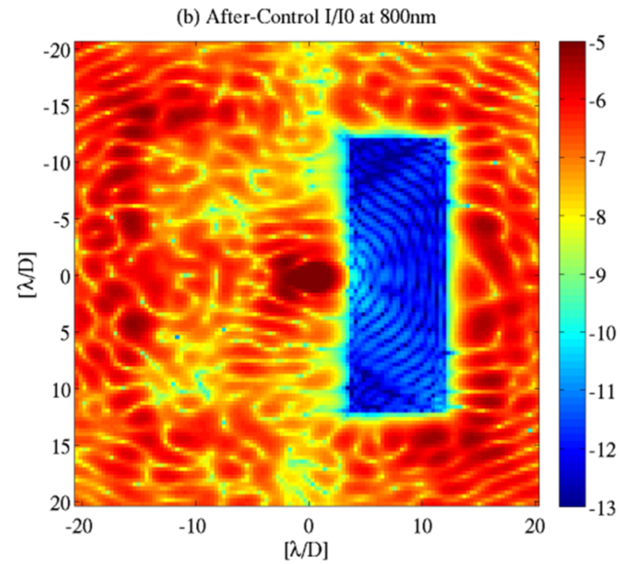
Including only optical surface errors and occulter phase

Log-Scale, Before Control, at 800nm

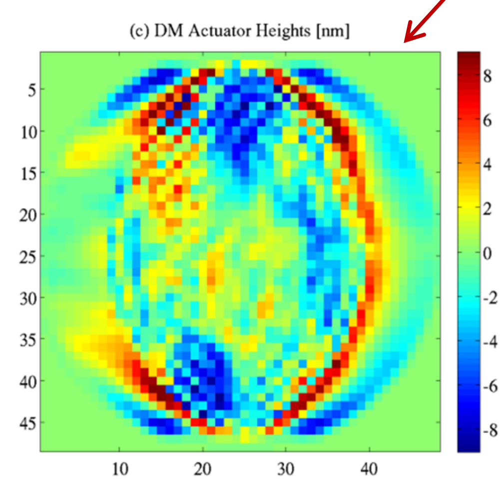




Log-Scale, After Control, at 800nm



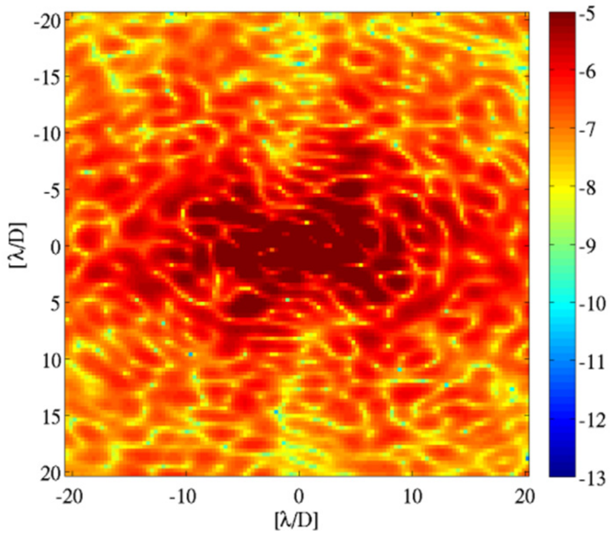
DM Actuator Heights



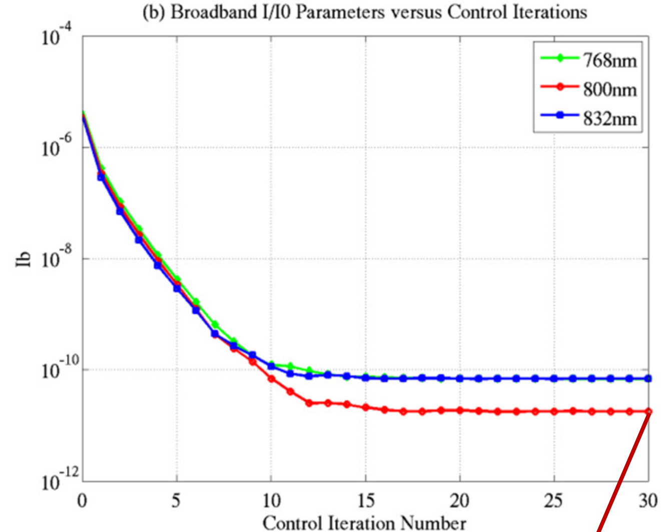
Nominal Case as a Baseline: 8%-Broadband Control

Including only optical surface errors and occulter phase. 768, 800, 832nm are center wavelengths of 2%-bandpass filters

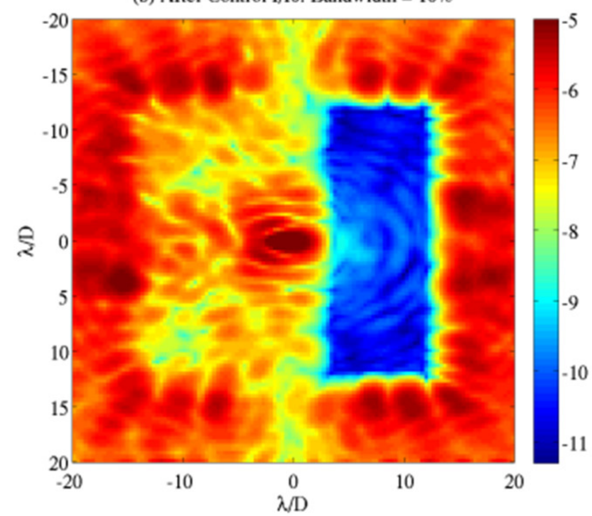
(a) Before-Control I/I0 at 800nm



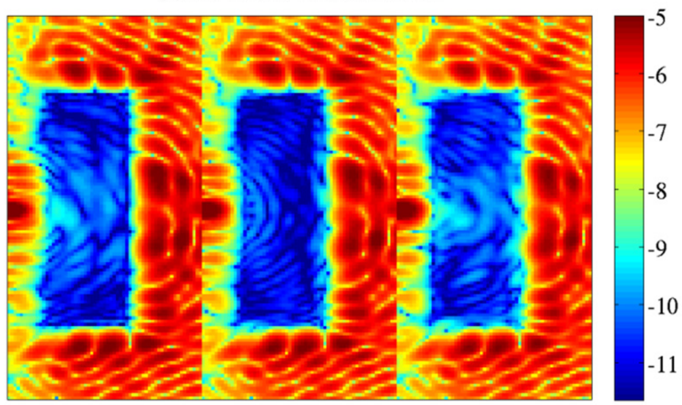
(b) Broadband I/I0 Parameters versus Control Iterations



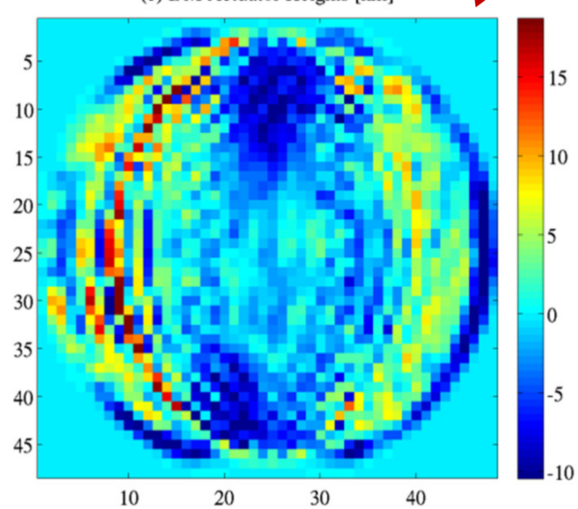
(b) After Control I/I0: Bandwidth = 10%



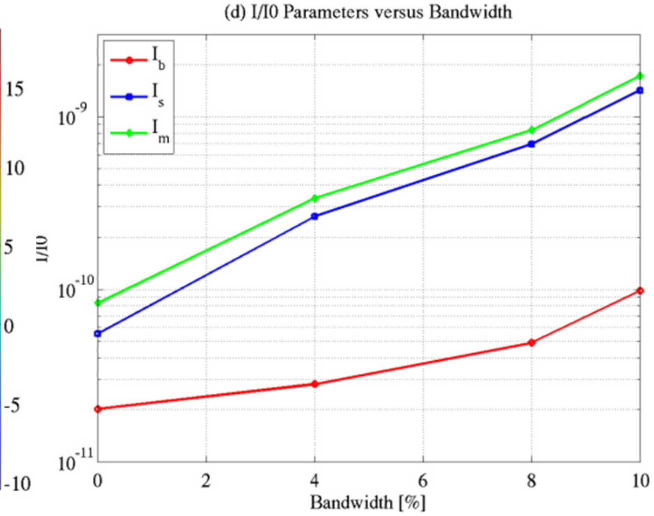
(a) I/I0 at 768, 800 and 832nm



(c) DM Actuator Heights [nm]

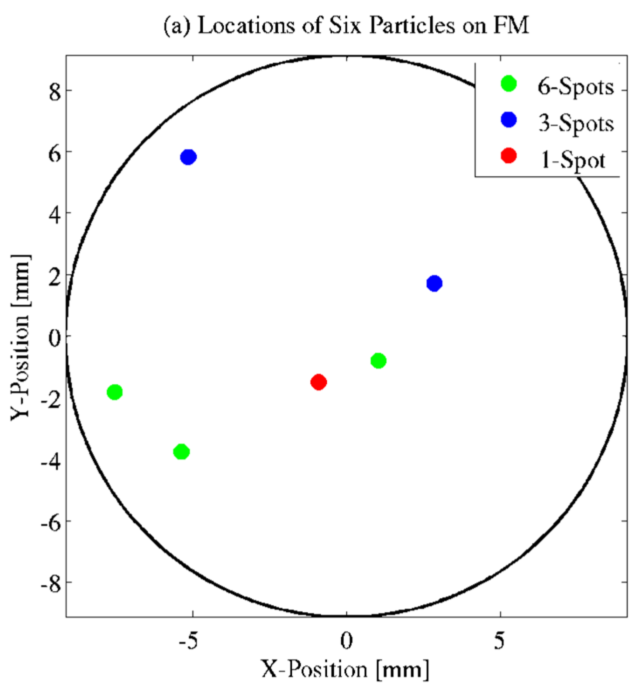


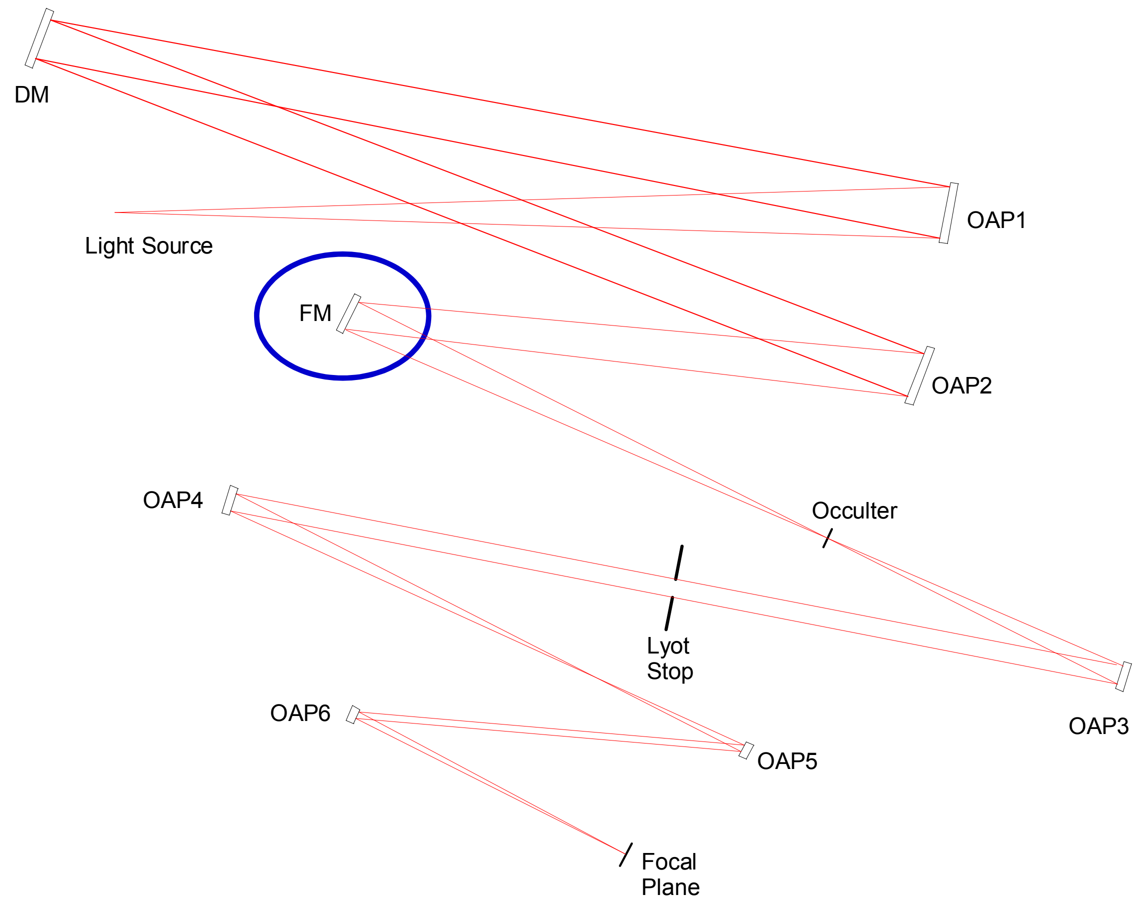
(d) I/I0 Parameters versus Bandwidth



Particles on Fold-Mirror

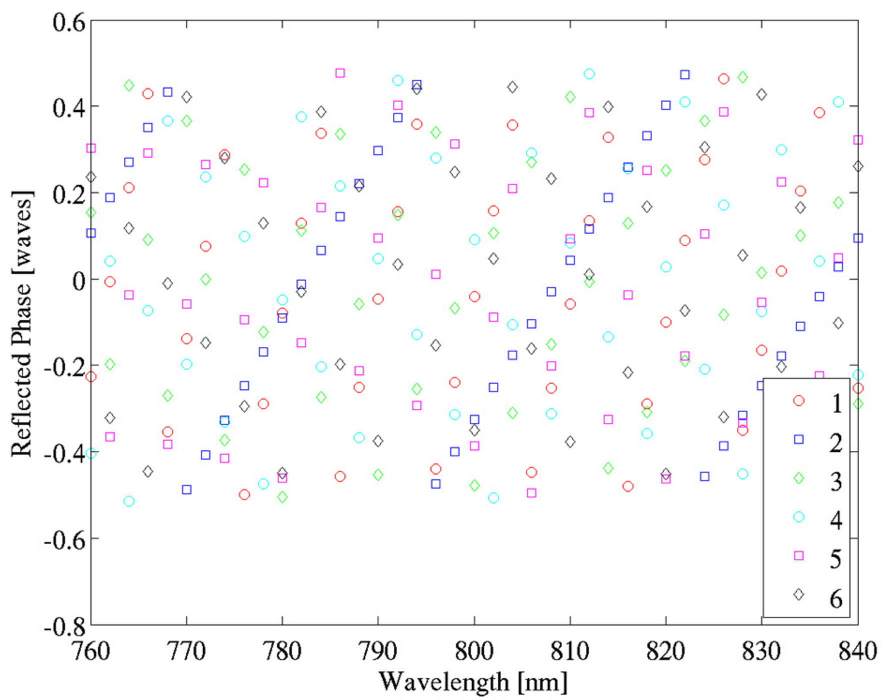
- Want to understand how dust particles affect broadband WFC efficiency and contrast
- Placed 1, 3 and 6 square particles with w = 114µm on FM
- (MACOS size, 512x512 pix, determines the FM pixel size)
- Particles' heights and locations are randomly chosen

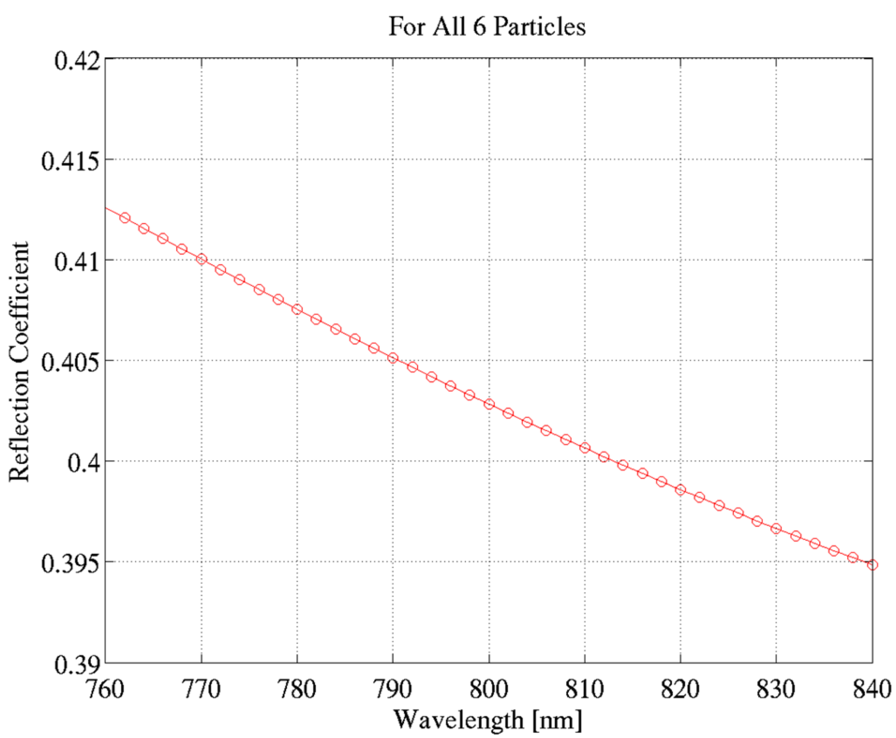




Particles on Fold-Mirror—Reflected Phase & Amplitude

- Particle heights vary in the 10 – 100μm range
- Reflected phase is different for different particles & different wavelengths
- Reflected amplitude is different for different wavelengths, but the same for different particles

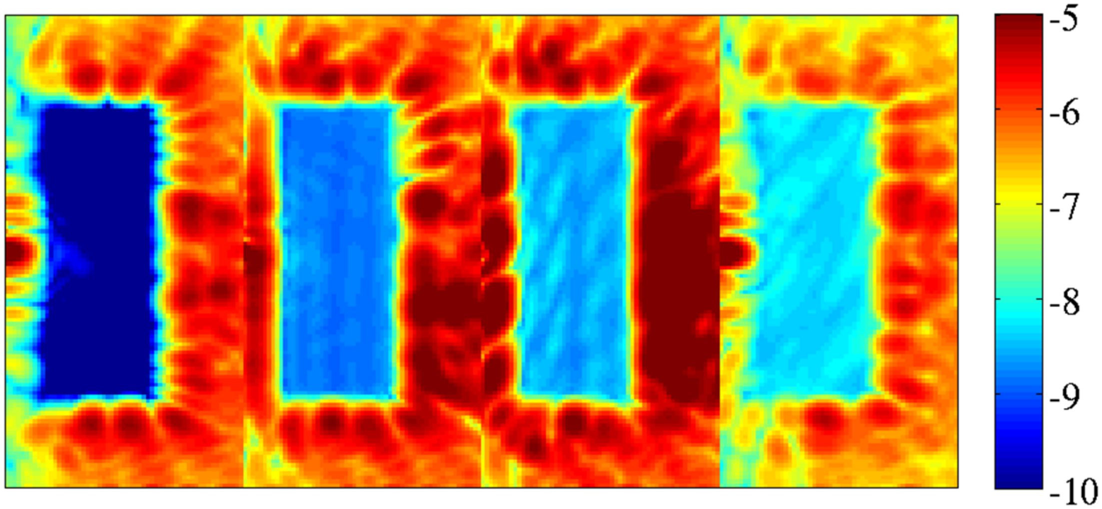




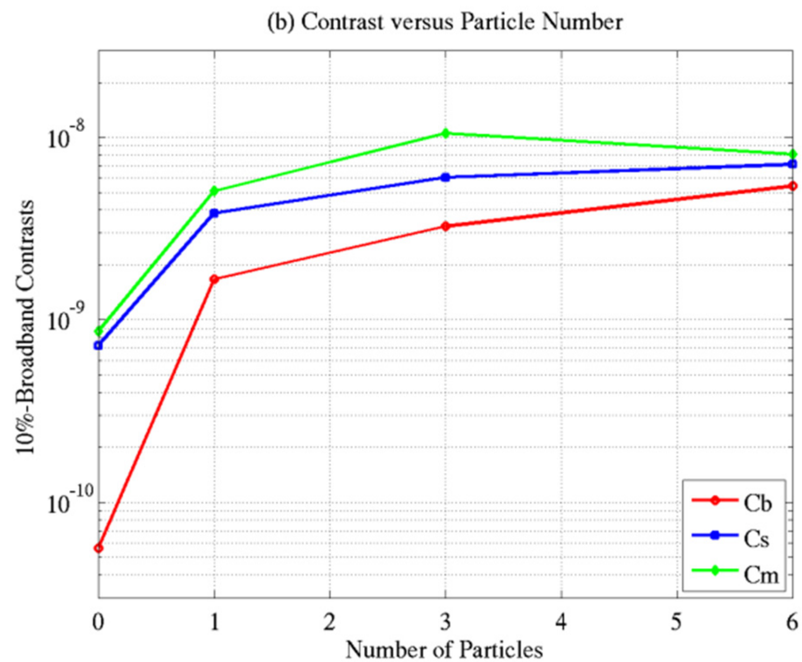
Particles on Fold-Mirror— Contrast

- Results after 30-iterations of 8%-BB WFC
- Placing one particle makes big difference on the 10%-broadband contrast
- Increasing the particle # from 1 to 6 degrades the contrast slightly

Log-Scale 10%-Broadband Normalized Intensities



Part. #= 0 1 3 6

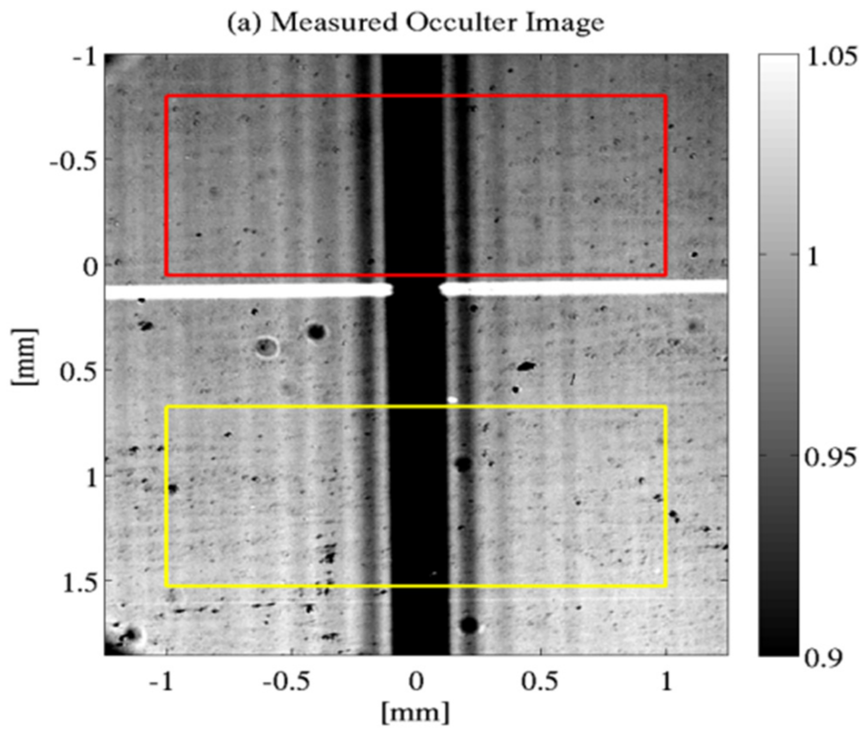


Defects on Occulter Surface

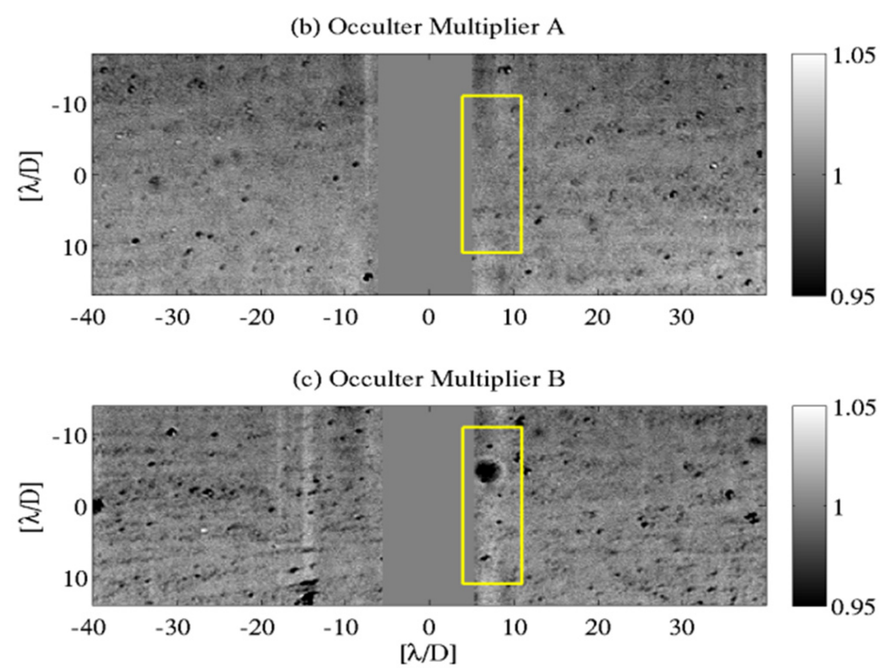
- Steps to obtain occulter transmittance multipliers:
  1. Select a "good" area from the transmittance map→ Call it "sub-area"
  2. Average the sub-area vertically to obtain an occulter transmittance profile
  3. Divide the each row of the transmittance map by this profile
  4. Replace the central Δx = ~280μm-wide region by 1

- Occulter transmittance multiplier changes only the transmitted amplitude, not the phase

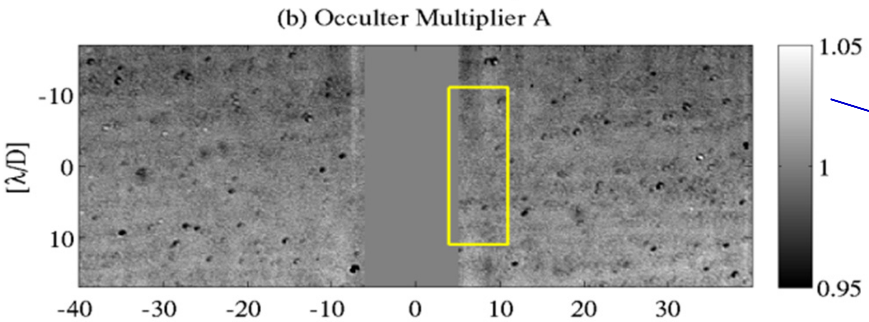
Measured Occulter Transmittance



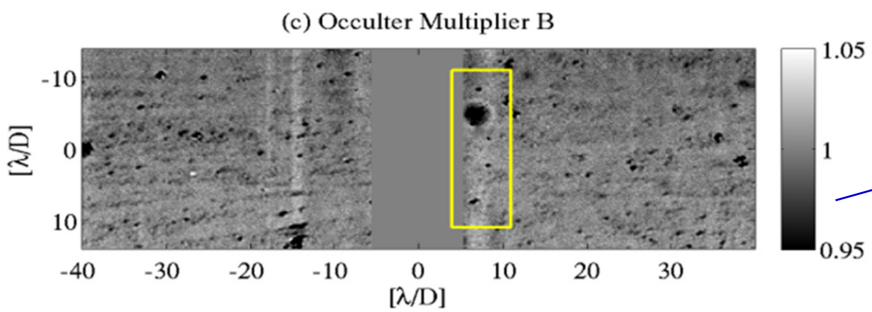
Occulter Transmittance Multipliers

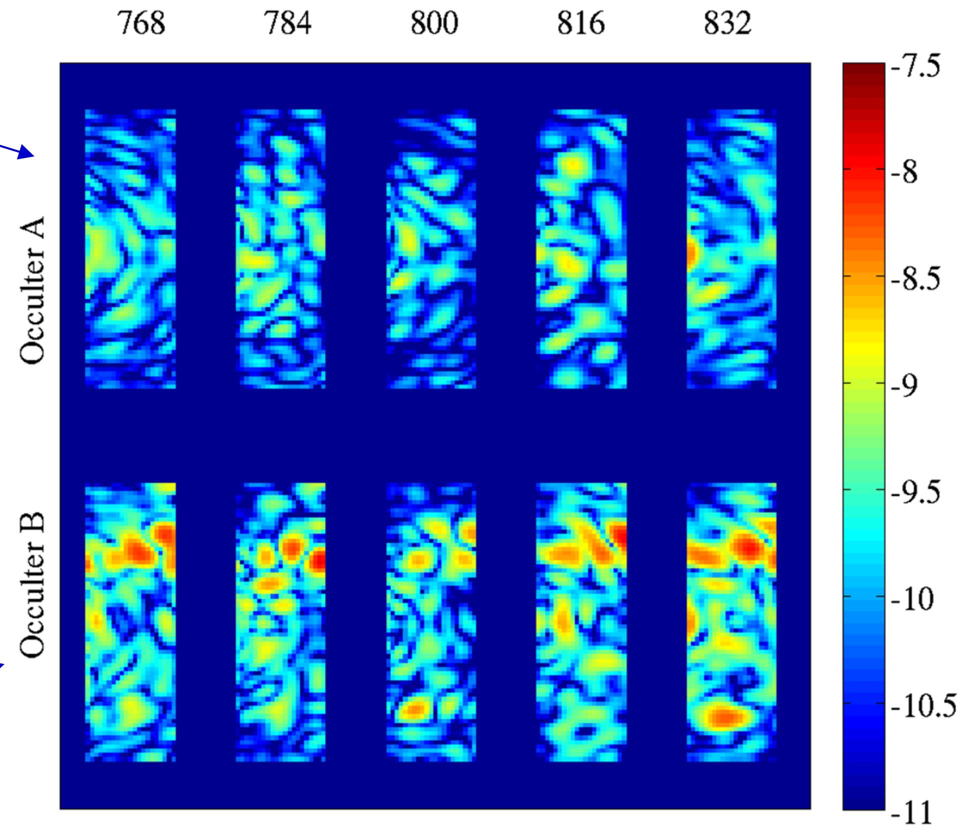


Effects of Occulter Defects on Contrast

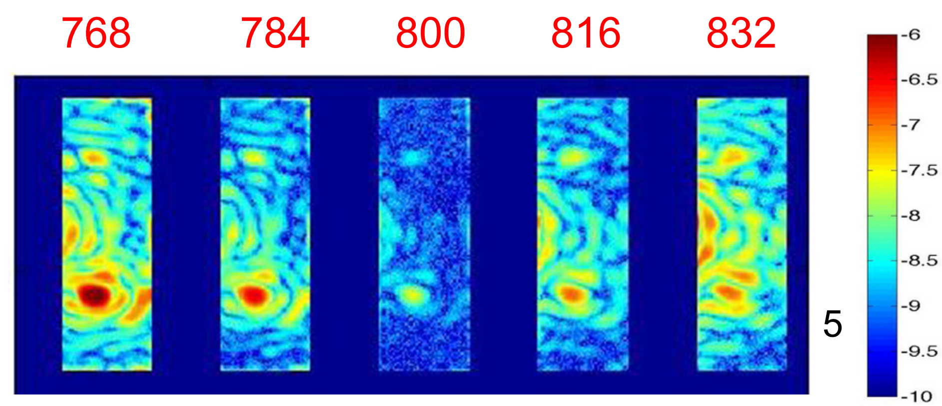


Simulated: After 3-λ Control

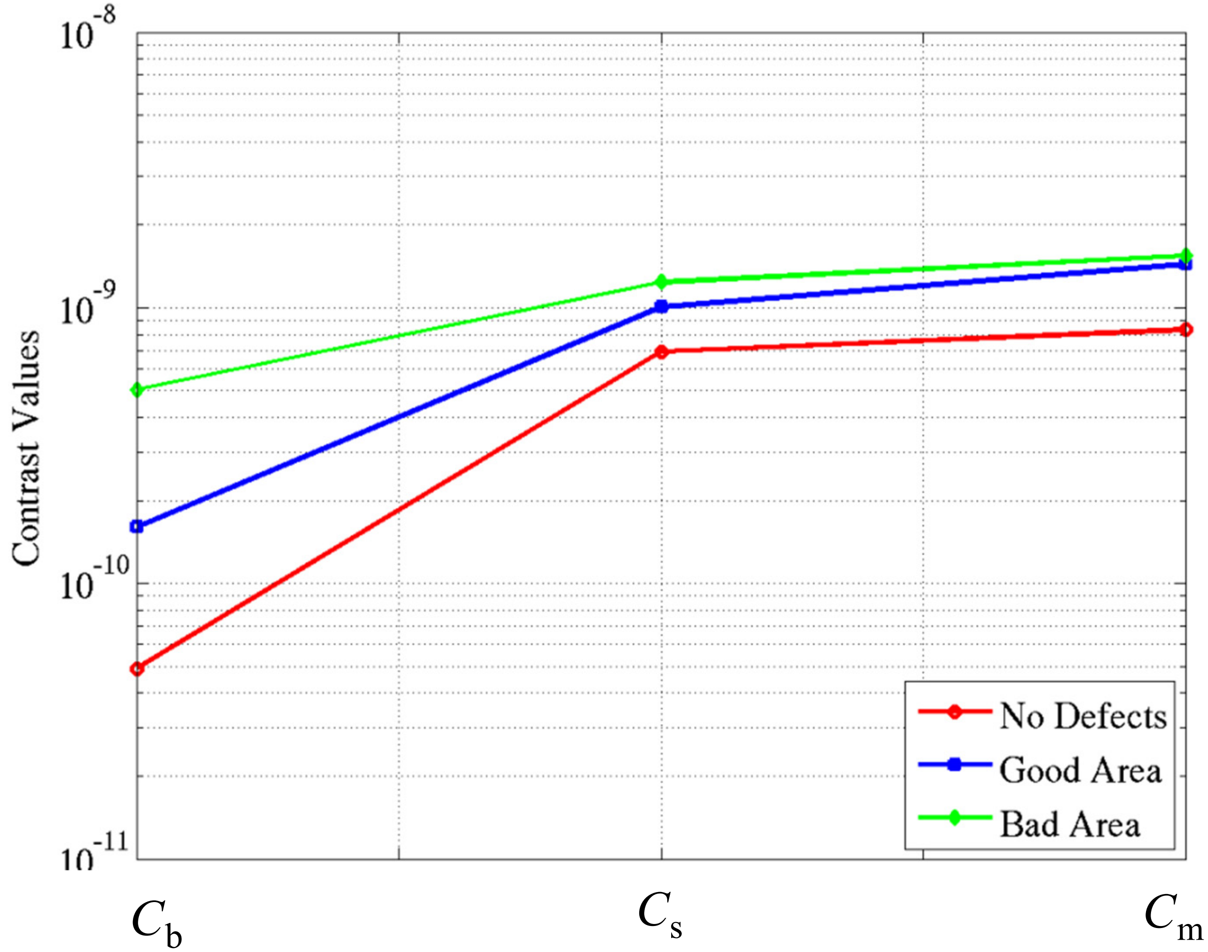




Measured: After 5-λ (5-Filters) Control



Defects on Occulter Surface – Contrast Comparison

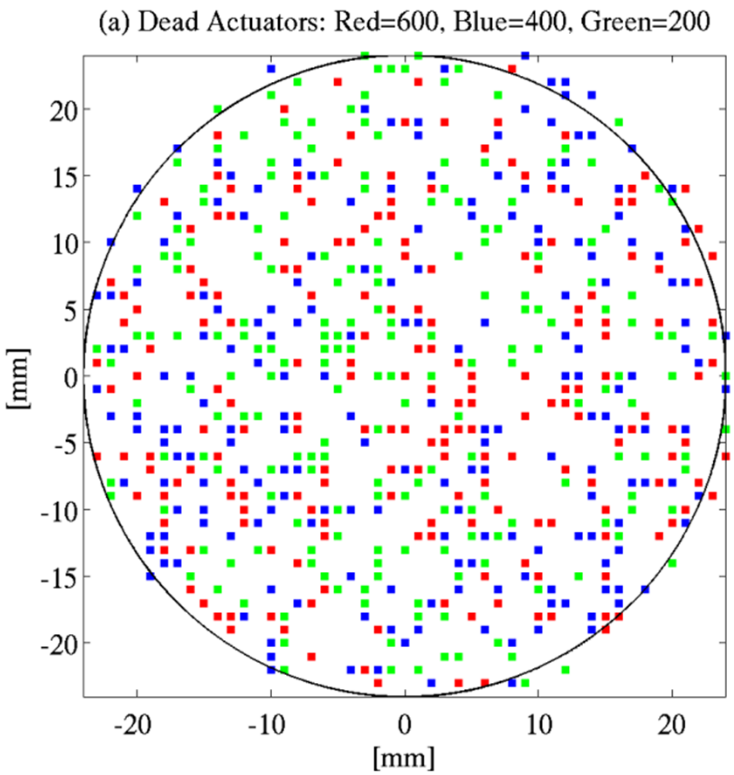


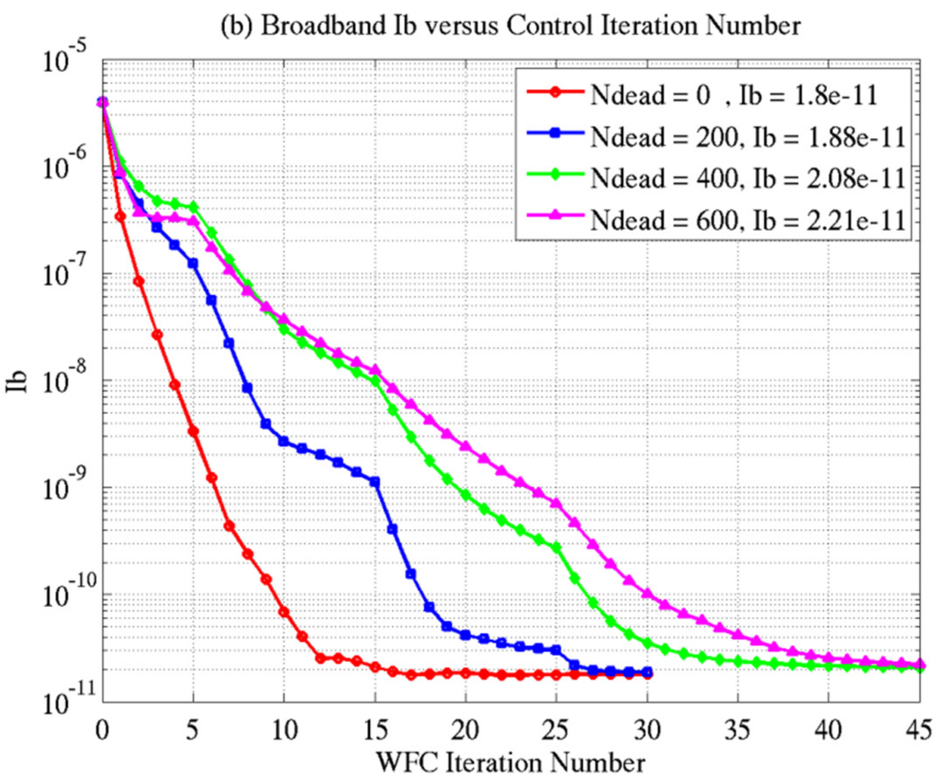
Blue-Cb is x3.3 worth than Red-Cb

Green-Cb is x10.3 worth than Red-Cb

Dead Actuators

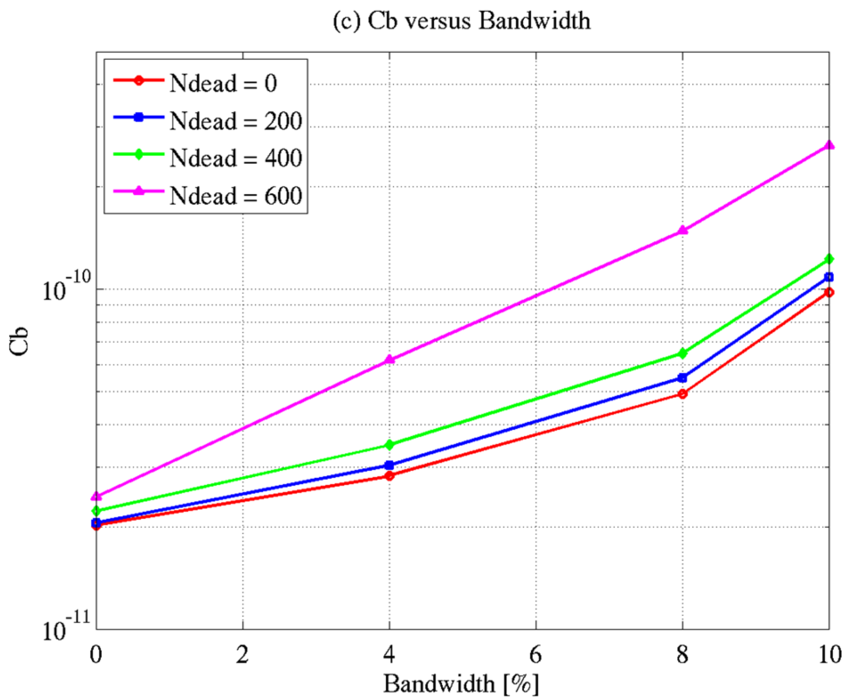
- Dead actuators: Height remains fixed at the mid-point of its control range (-200 → +200nm)
- Represents one of the actuator failure modes
- Affects both e-field estimation & control , but here consider the effects on the control only
- Left plot: Different colors represent different groups of dead actuators, they are randomly chosen
- Right plot: Normalized intensity versus Ndead (# of dead actuators)
- Larger Ndead leads to lower control efficiency, but the final Ib values are comparable

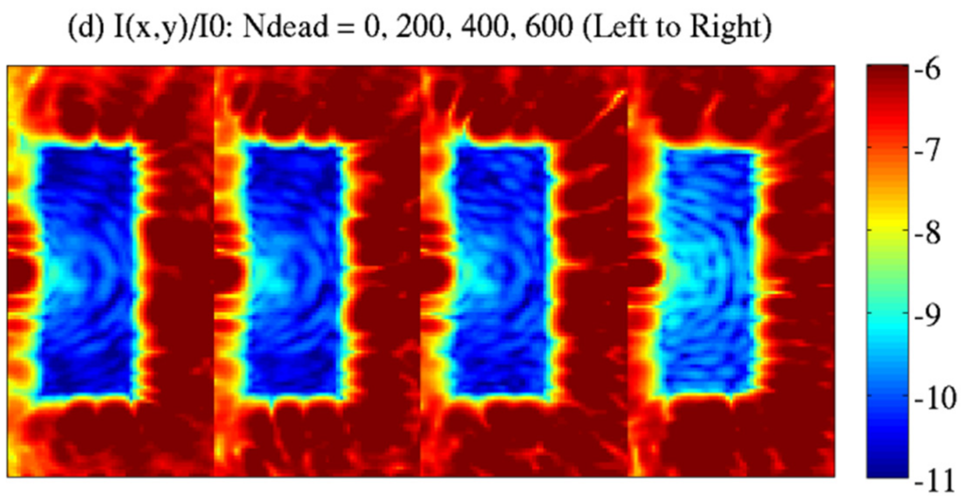




Effects of Dead Actuators on Broadband Contrast

- Results of N_{dead} = 0, 200 and 400 are comparable

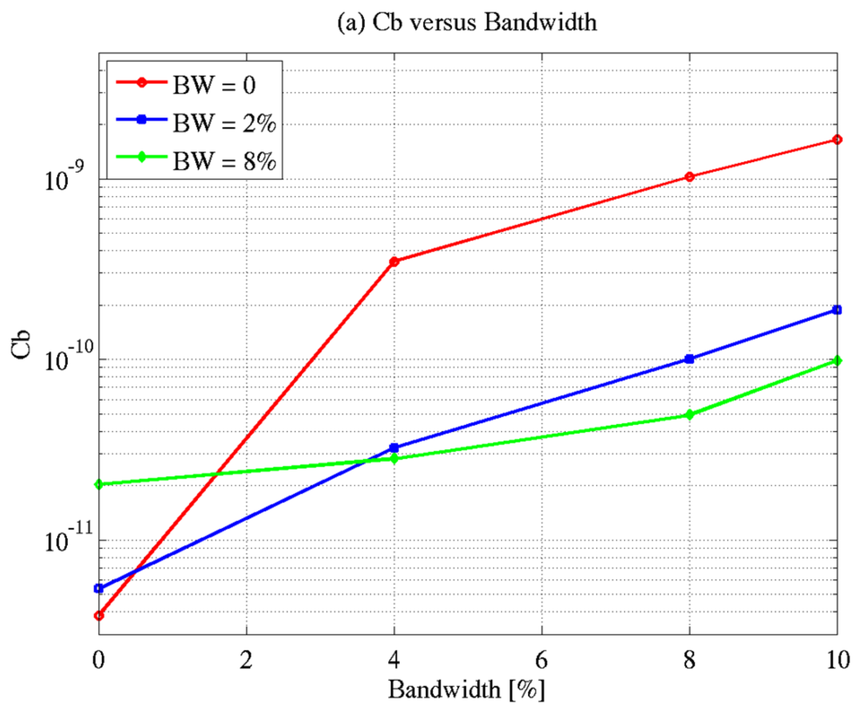


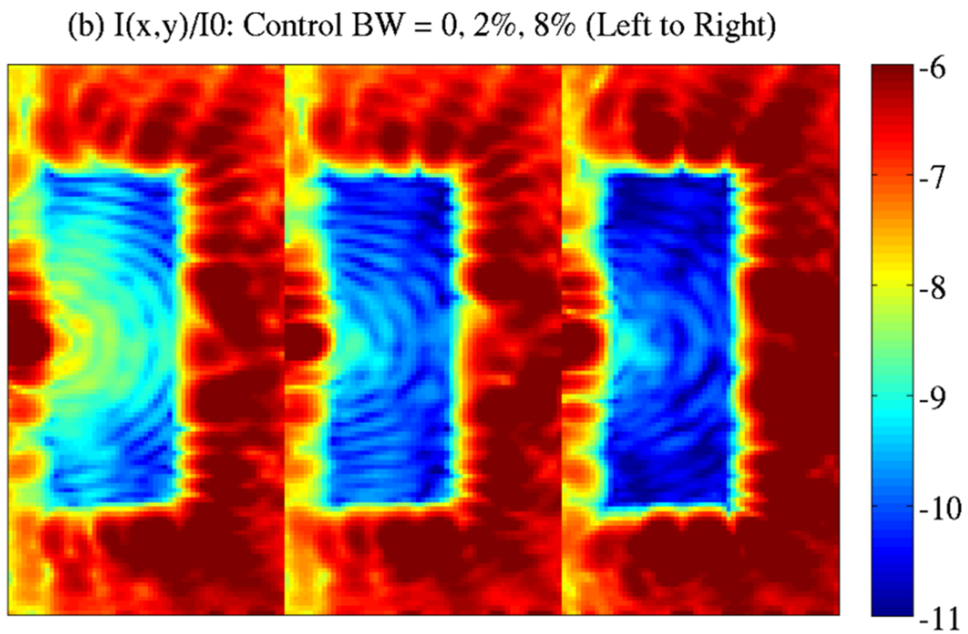


Log-Scale 10%-Broadband Normalized Intensities

Effects of Control Bandwidth on Broadband Contrast

- 8%-control (3 filters) yields 10%-C_b about x2 better than 2%-control, but requires at least x3 time





Log-Scale 10%-Broadband Normalized Intensities

Summary

- Light scattered into the dark-hole by a size ~100μm particle cannot be completely eliminated
- A size ~100μm particle can worsen the 10%-broadband contrast by >10 times

- Some commonly found defects on occulter surface can degrade the broadband contrast by >10 times
  - Simulated contrast maps showed features very similar to measured ones
  - Use “good area” on occulter surface whenever possible

- WFC can tolerate up to 400 dead actuators
- Will investigate other actuator failure modes:
  - Actuators that are stuck at one end of their range
  - Actuators that fail in local groups

- 8%-control yields contrast about x2 better than the 2%-control, but requires at least x3 time