National Aeronautics and Space Administration

Studies of the Effects of Optical System Errors on the HCIT Contrast Performance

Erkin Sidick, Stuart Shaklan, Amir Give'on and Brian Kern

Jet Propulsion Laboratory
California Institute of Technology

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

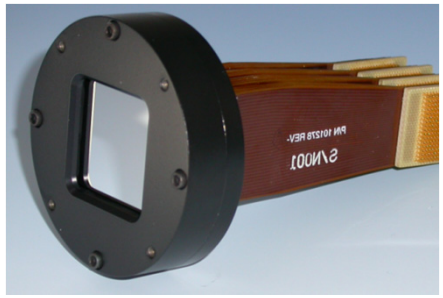
- Specifically, want to understand the effects of some common errors on the estimation and the EFC-based control of e-field over a half dark-hole region

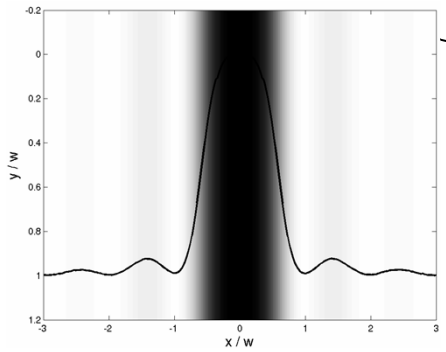
- Investigated errors include:
  - Two or 3 dead actuators (broadband)
  - Lateral and longitudinal movement of the occulting mask (narrowband)
  - Lateral movement of a flat optical surface (narrowband)

- 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

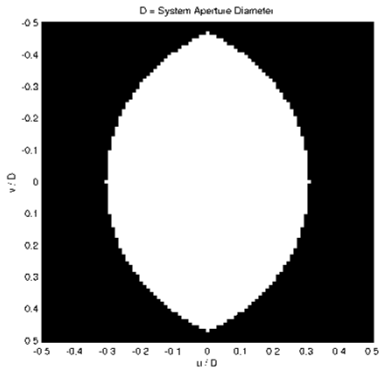
HCIT Optical System

Deformable-Mirror
(32x32 actuators)





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



DM

Light
Source

OAP1

FM1

OAP2

Occulter

OAP3

FM2

Lyot Stop

OAP5

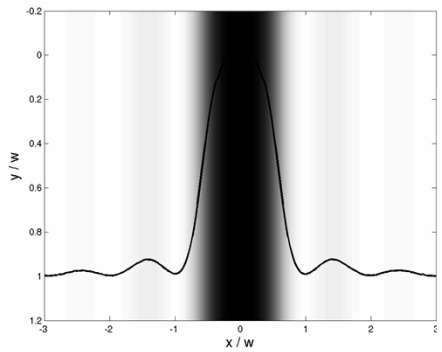
OAP4

Back Focus

OAP6

OD and Phase Profiles of 2 Occulting Masks

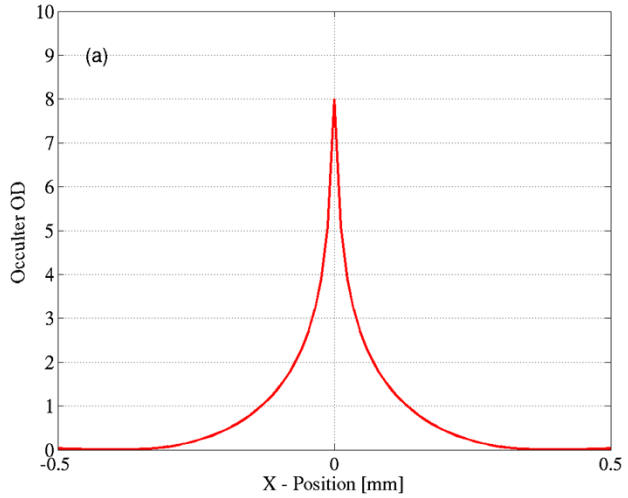
$$T(x) = [1 - \mathrm{sinc}^2(x/w)]^2$$

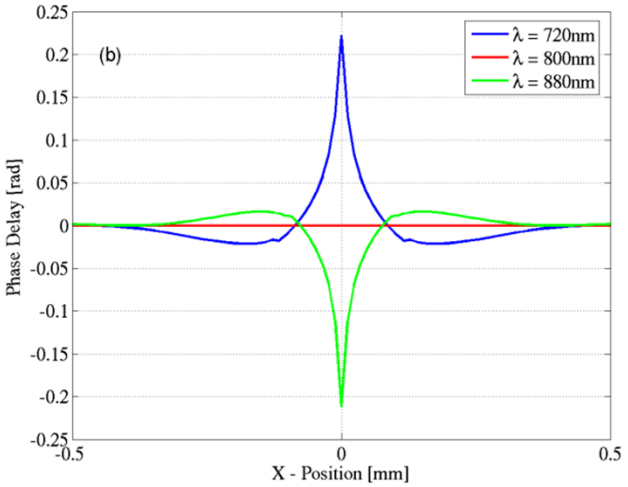


Pt-occulter is used in "dead-actuator" and FM1 x-translation

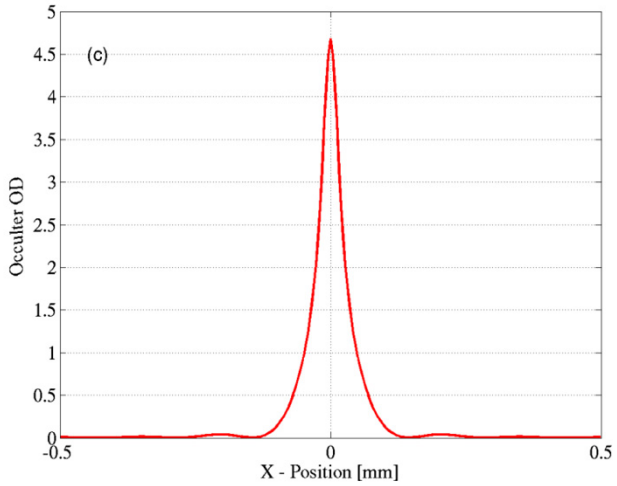
Ni-occulter is used in occulter x- & z-translation

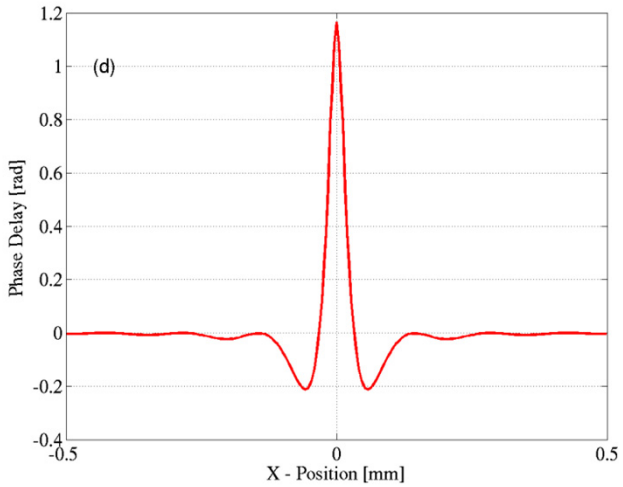
Platinum (Pt) deposited on a fused-silica and compensated with spatially profiled PM





Thin-film Nickel (Ni) occulter deposited on a glass

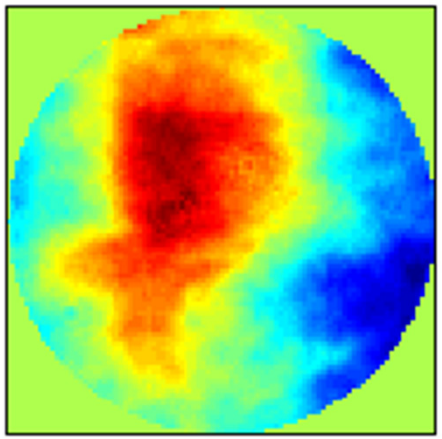


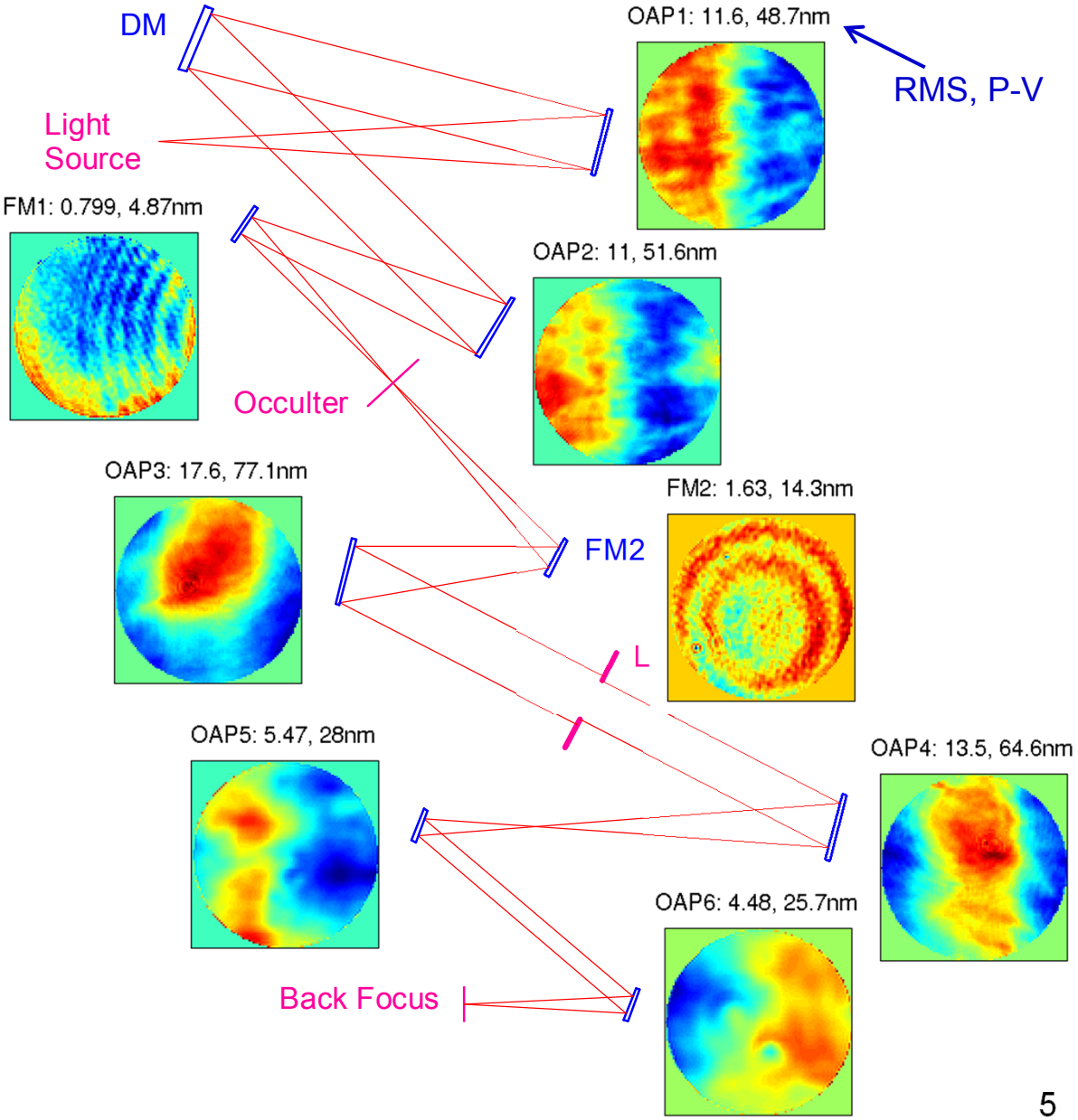


Surface Errors Used in Simulations

- 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 8 surface error maps in simulations

All: 35.9, 163nm





Definitions: Normalized Intensity & Contrast

Normalized Intensity: $I(x,y) = I_o(x,y) / I_{uo\max}, \quad I_o(x,y)$: Occulted, $\quad I_{uo\max}$: Un – Occulted

Contrasnt: $C(x,y) = \left[\frac{I_o(x,y)}{I_{uo\max}}\right]\left[\frac{Max\{T(x,y)\}}{T(x,y)}\right] = I(x,y)\left[\frac{T_0}{T(x,y)}\right], \quad T(x,y) = \text{Occulter Transmittance}$

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

WFC over Ω_c: $[X,R] = [4,11]\lambda / D$

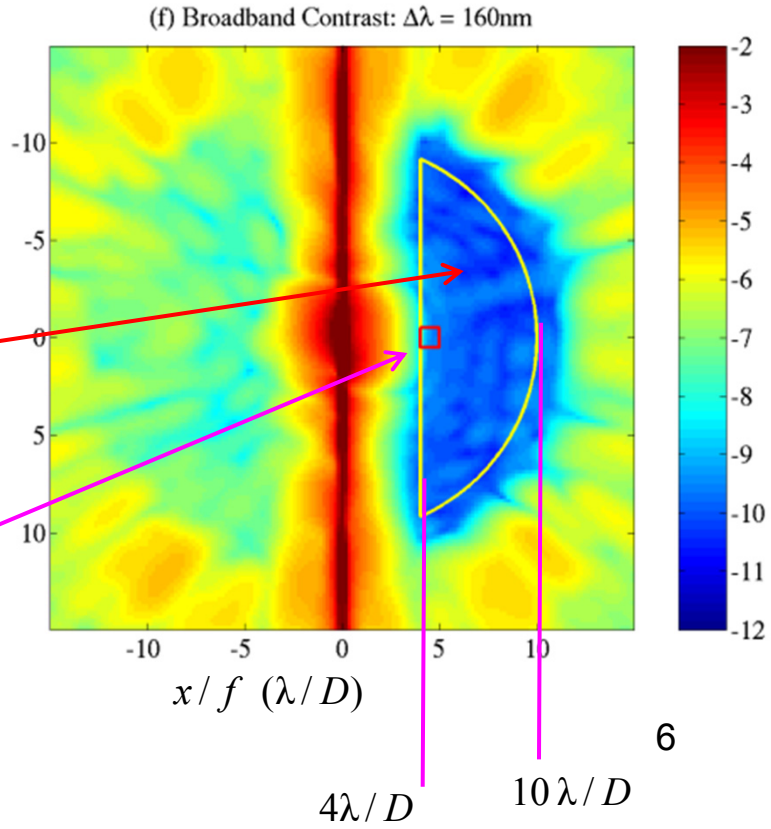
I_b and C_b are mean values averaged over Ω_b :

$[X,R] = [4,10]\lambda / D$

I_s and C_s are mean values averaged over Ω_s :

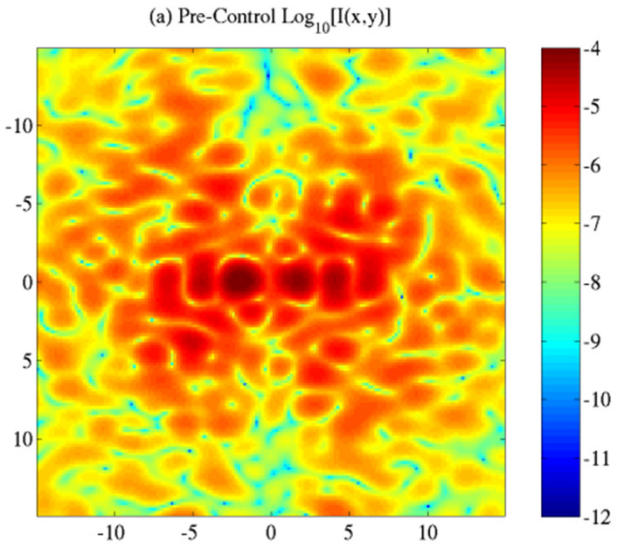
$\Delta X = \Delta Y = 1\lambda / D$

I_m and C_m are maximum values inside Ω_s

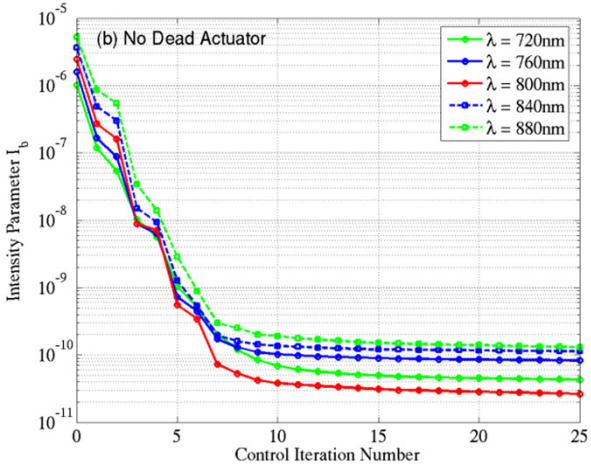


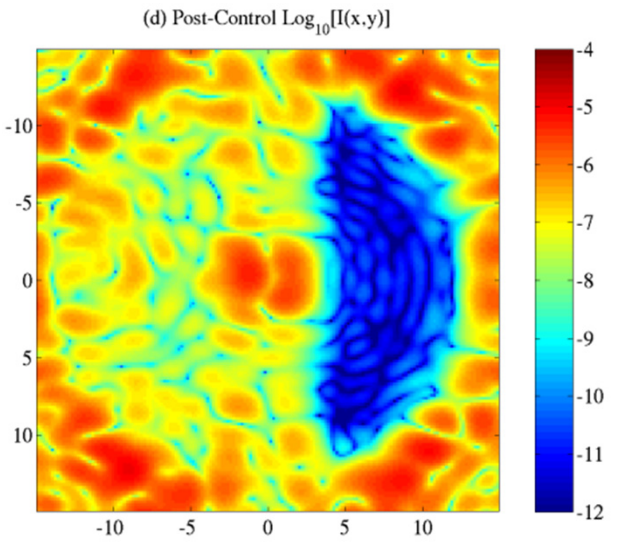
Nominal Case as a Baseline: Normalized Intensity

Including only optical surface errors and occulter phase

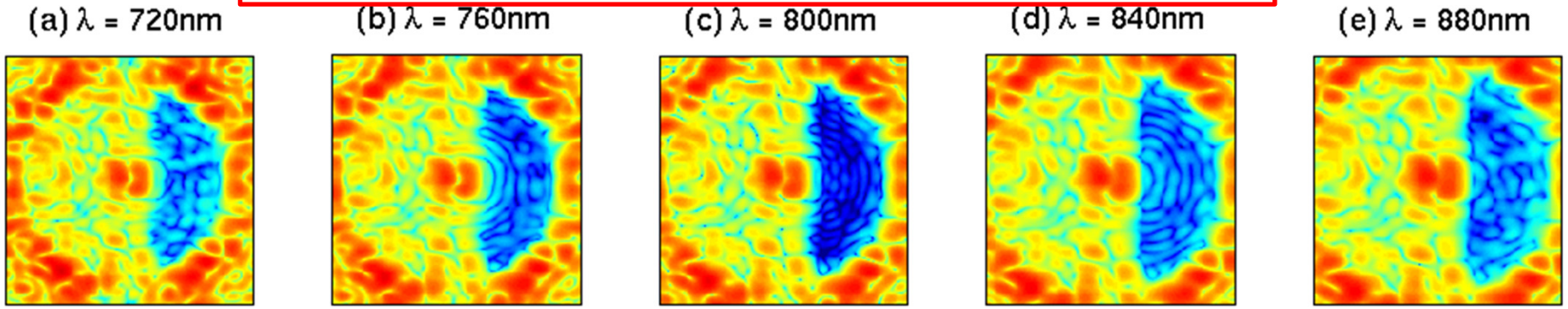


I_b versus control iterations



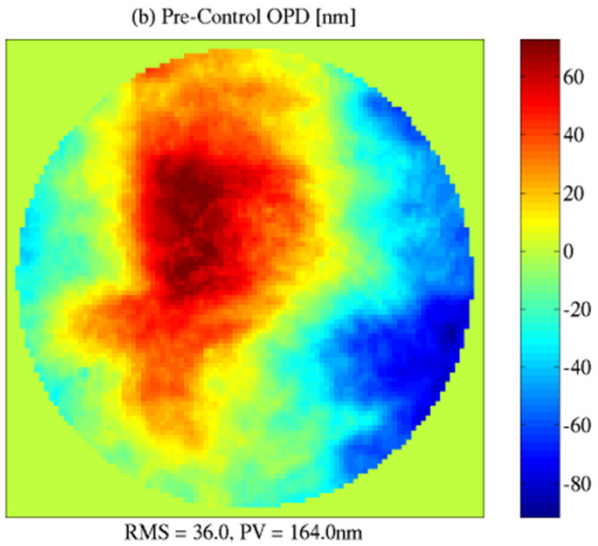


Post-Control $I(x,y)$ in Log-Scale

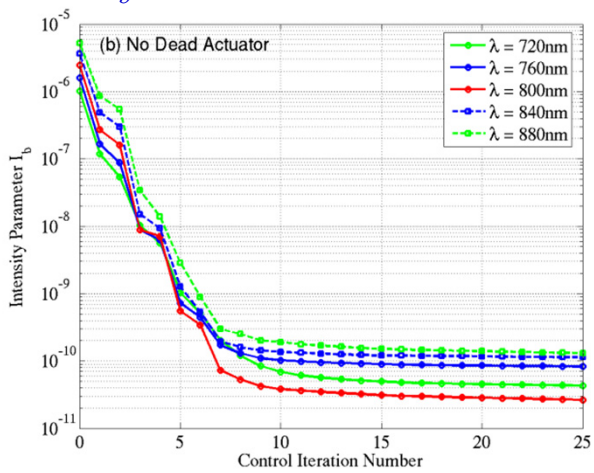


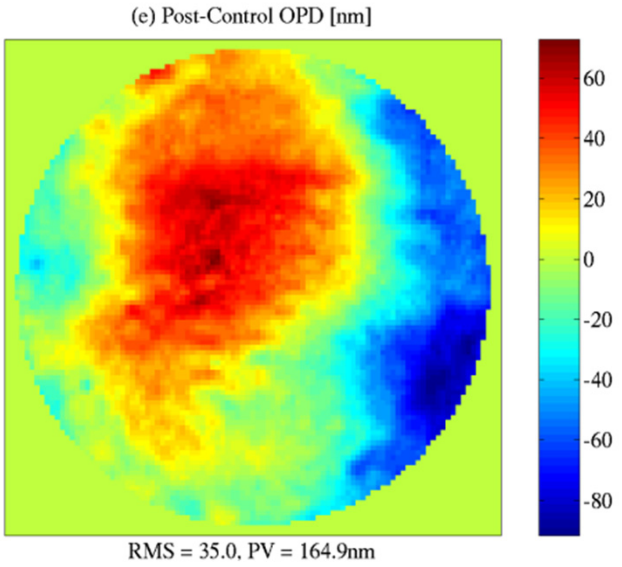
Nominal Case: OPD, DM Commands & Broadband Contrast

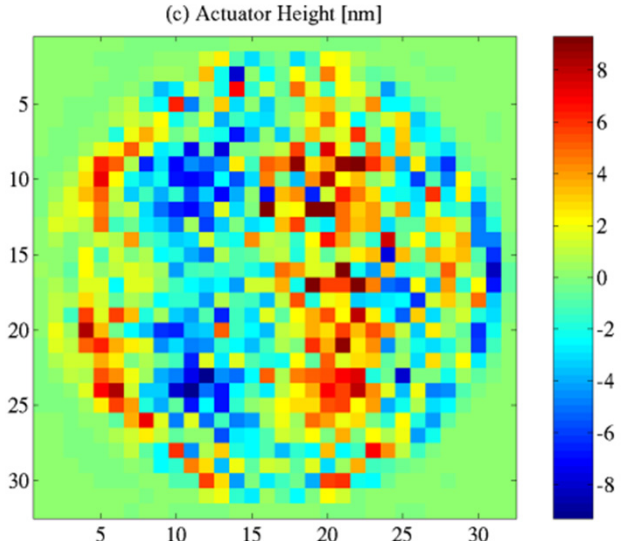
Including only optical surface errors and occulter phase

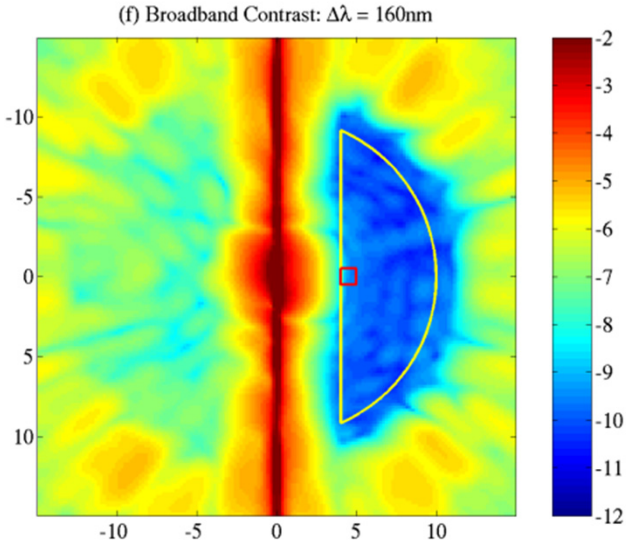


I_b versus control iterations





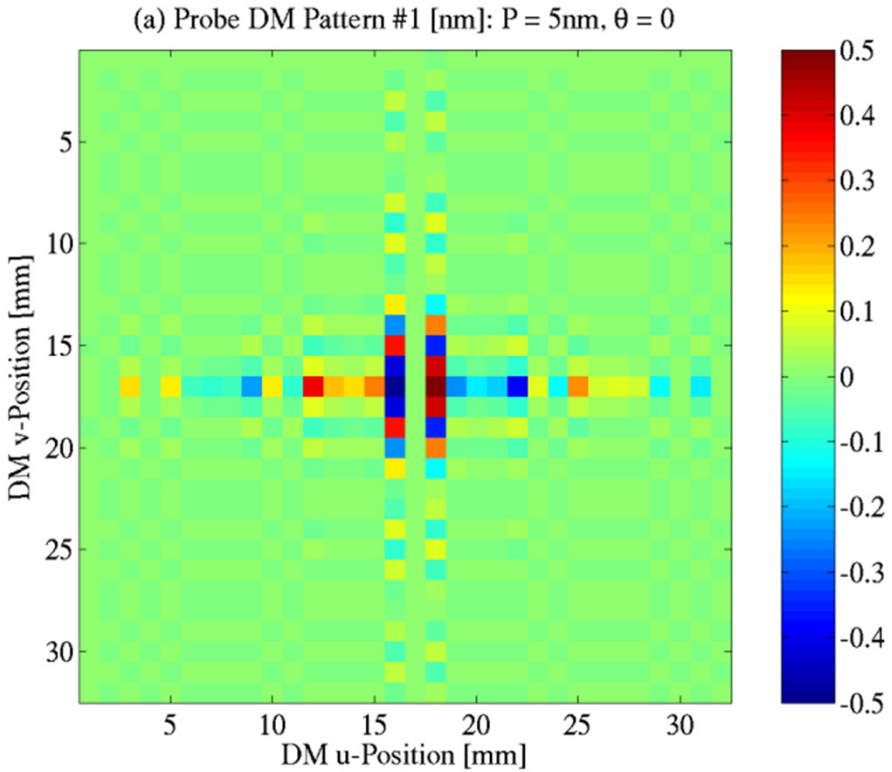


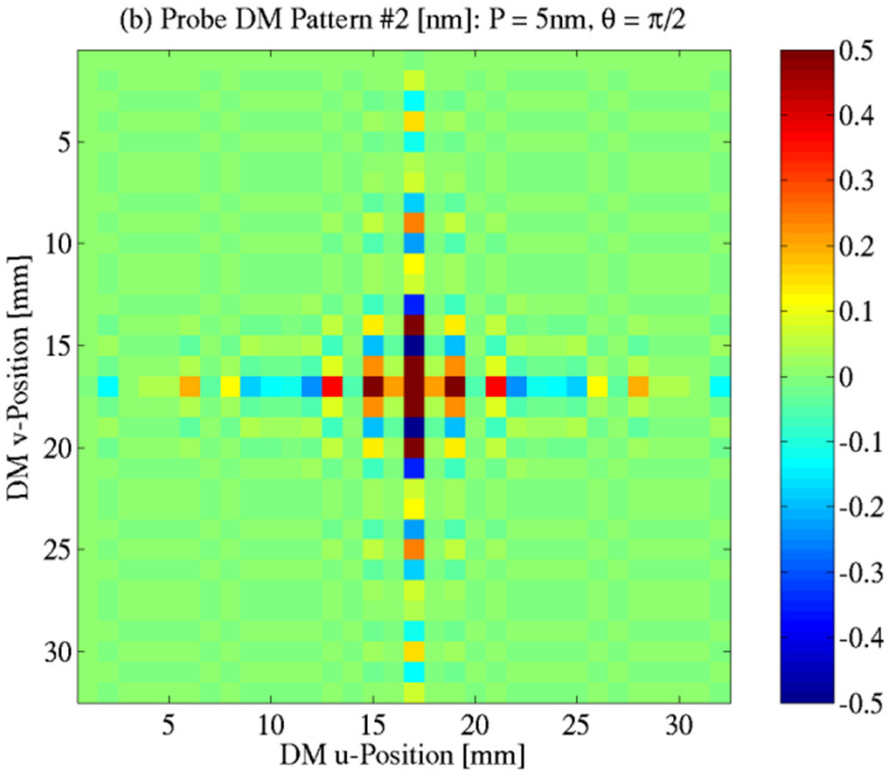


DM Settings Used in 4-Probes E-Field Estimation

Probe DM Settings: $\psi(u,v;\theta) = P\,\mathrm{sinc}(\Delta\xi\,u)\,\mathrm{sinc}(\Delta\eta\,v)\sin(\xi_c\,u+\theta)$

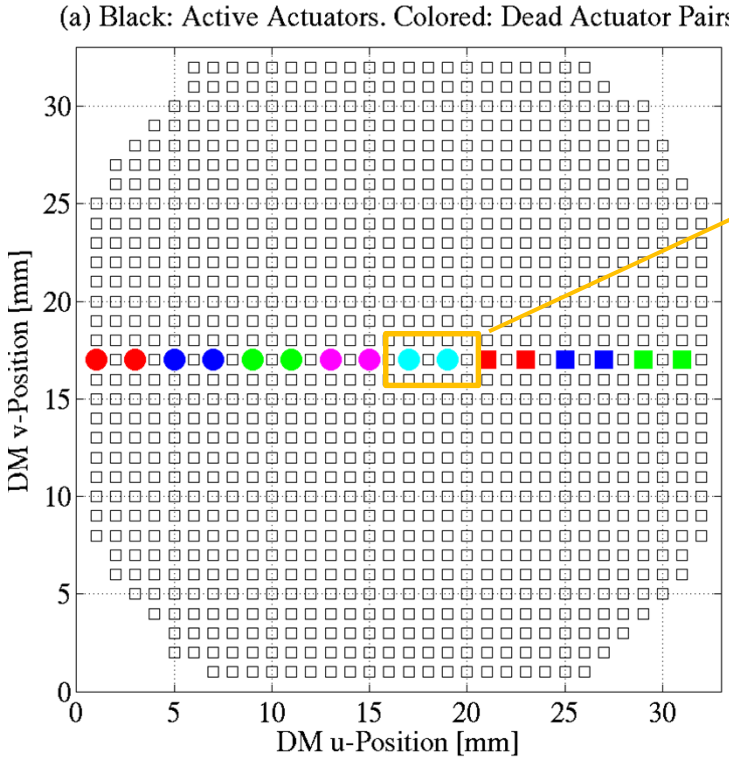
$$\theta = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$$

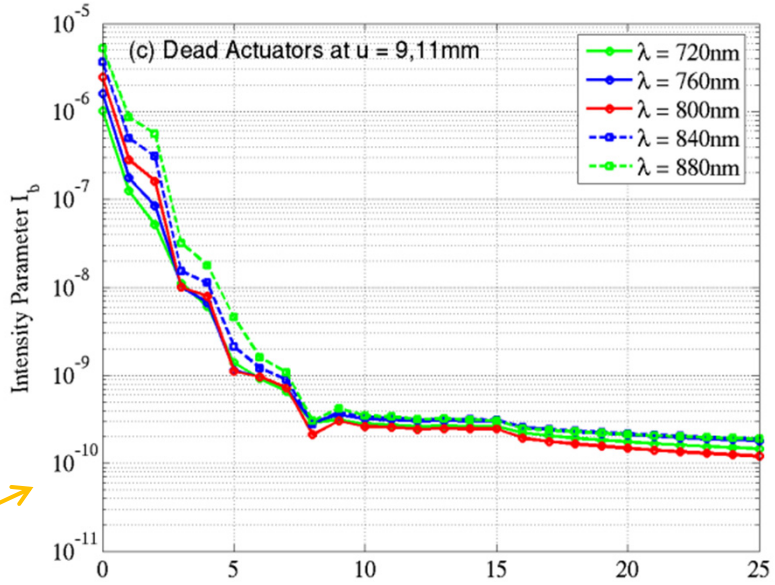


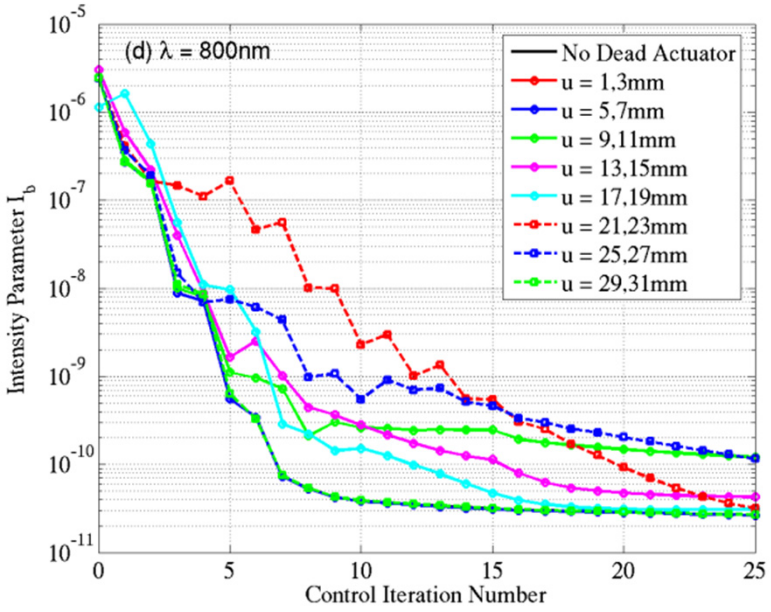


Dead Actuators: 2 Actuators Interleaved by One Actuator

- DM actuator spacing = 1mm
- E-field estimation & control are most sensitive to actuators on row v = 17mm
- Different colors/shapes represent different dead actuators
- Less WFC efficiency in some cases, but all work

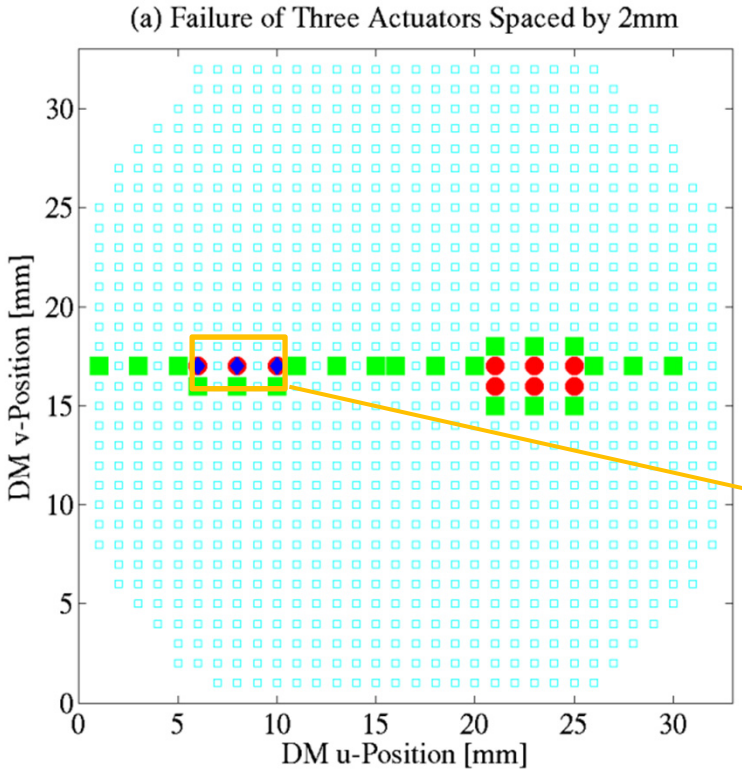


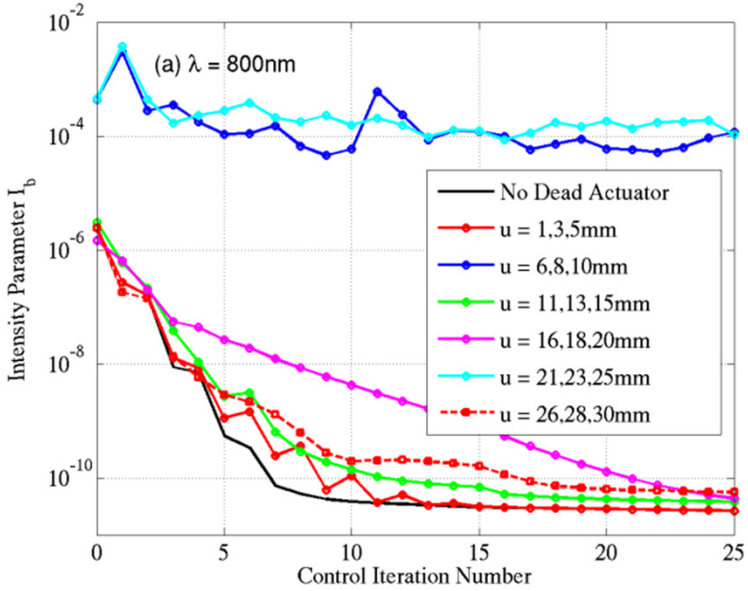


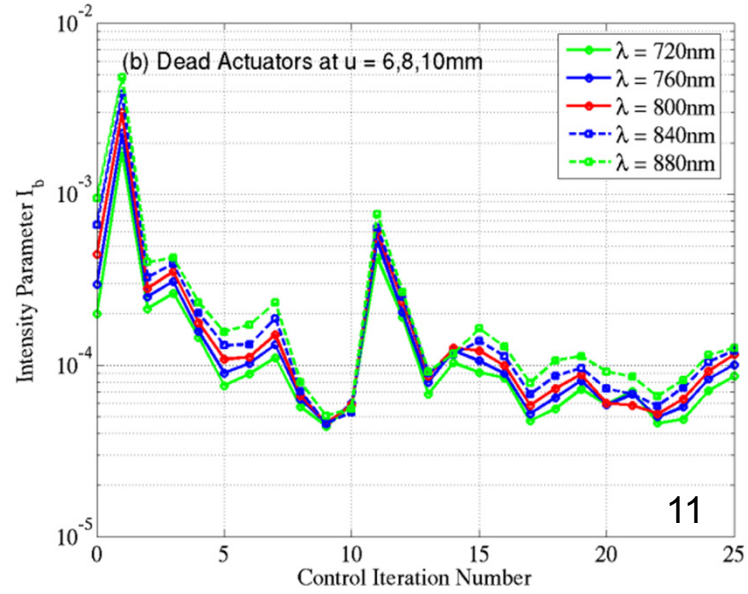


Dead Actuators: 3 Actuators Interleaved by One Actuator

- DM actuator spacing = 1mm
- E-field estimation & control are most sensitive to actuators on row v = 17mm
- Green groups: Work
- Red groups: Fail
- Blue on top of the red: Fail with e-field estimation, but work without it

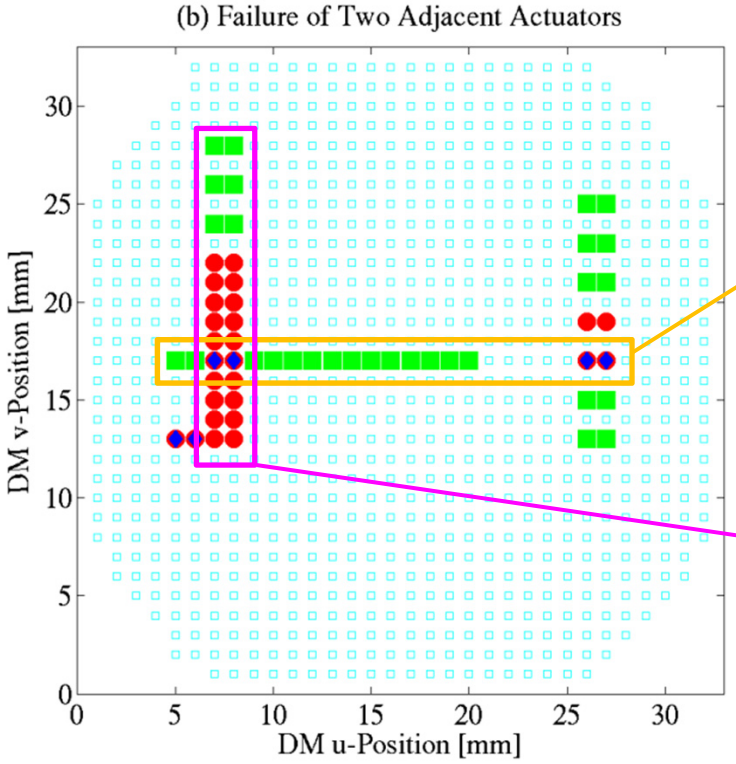


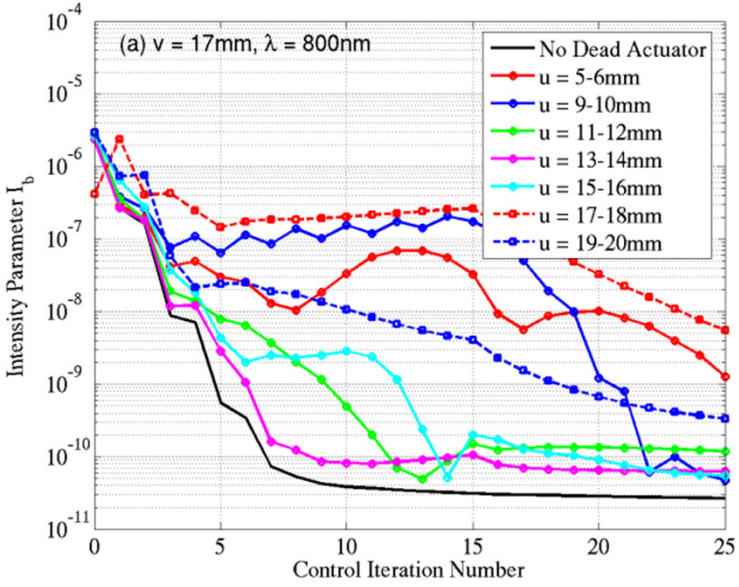


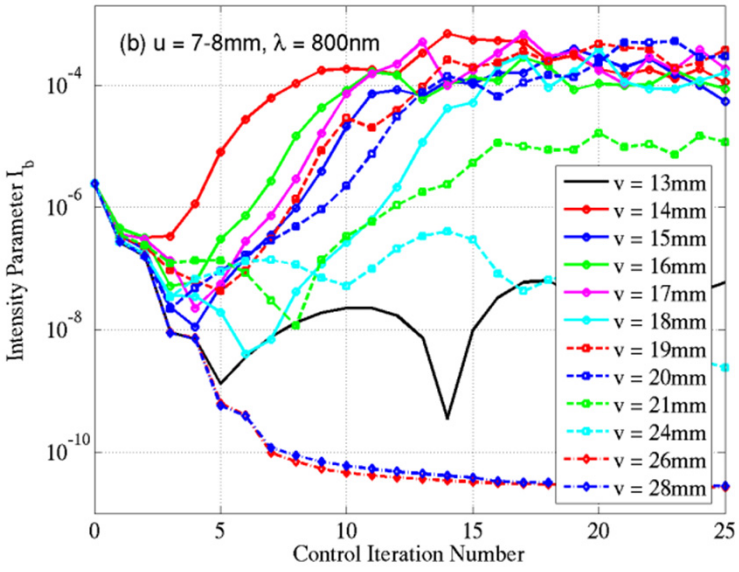


Case of 2 Adjacent Actuators Dead

- DM actuator spacing = 1mm
- E-field estimation & control are most sensitive to actuators on row v = 17mm
- Green groups: Work
- Red groups: Fail
- Blue on top of the red: Fail with e-field estimation, but work without it







X-Translation (T_x) of FM1—Case of Sine-Wave Phase

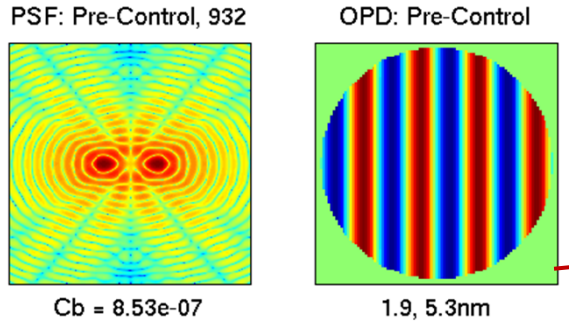
$$\text{True}: \Delta I(x,y) = \left|E(x-T_x,y) - E(x,y)\right|^2 / I_{uo\max}$$

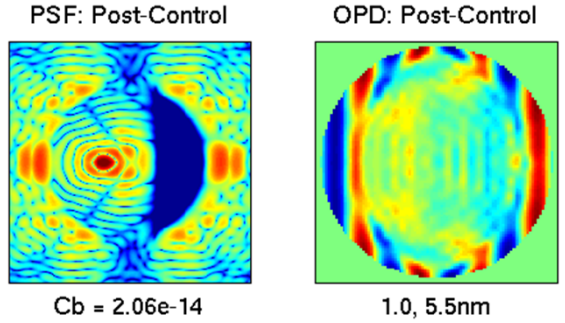
$$\text{Predicted}: \Delta I(x,y) = (\pi/\lambda)^2 [PV(\Delta OPD)/2]^2 \left|M(x - N_x \lambda f / D, y) E(x',y')\right|^2 / I_{uo\max}$$

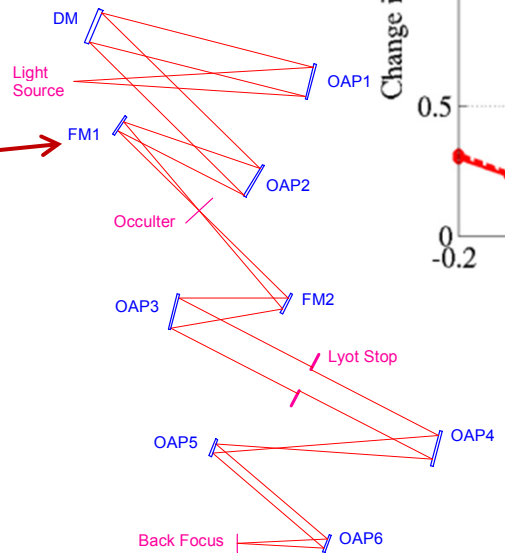
Origin of $[x',y'] = [0,0]$; Origin of $[x,y] = [N_x \lambda f / D, 0]$

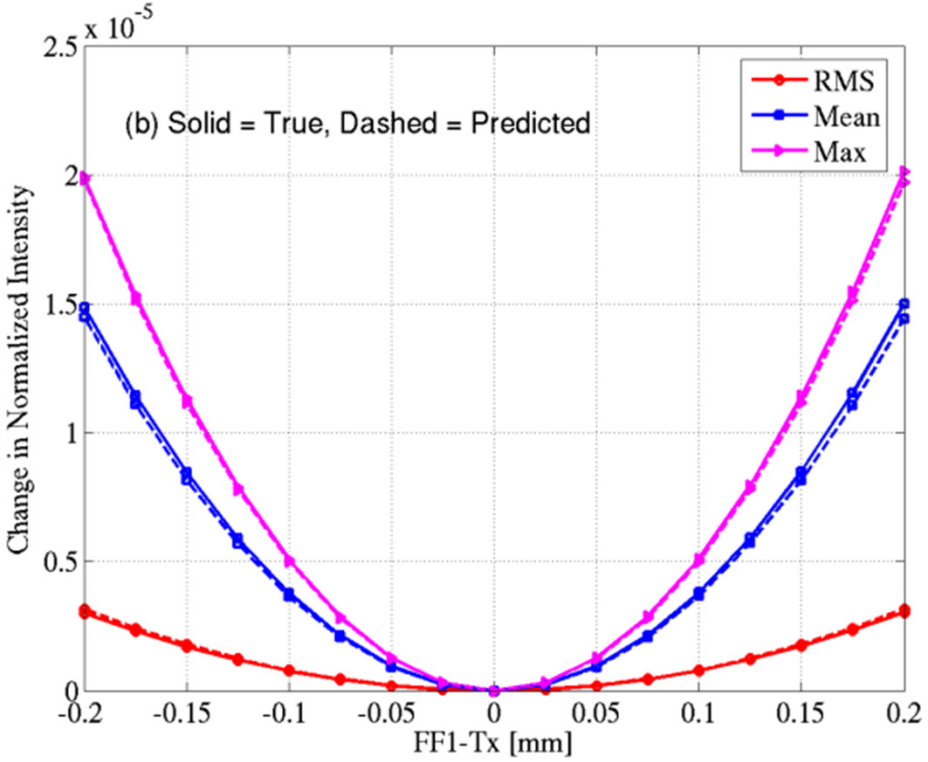
N_x = Spatial – Frequency

- "True" and "Predicted" agree well

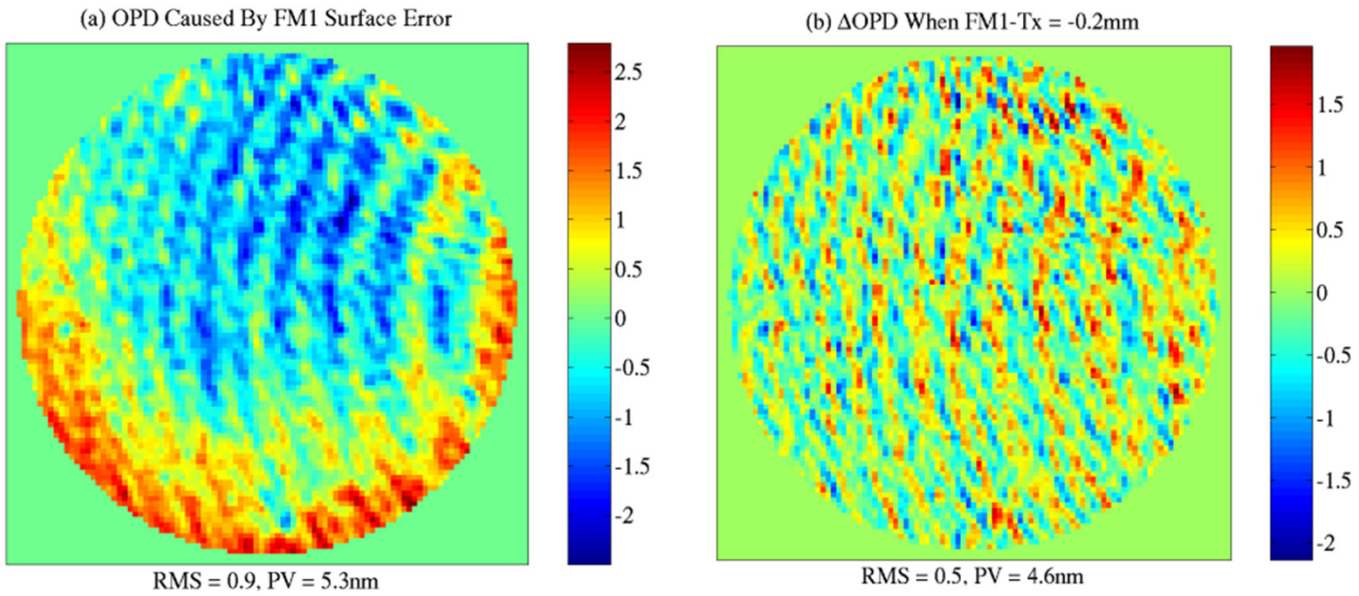






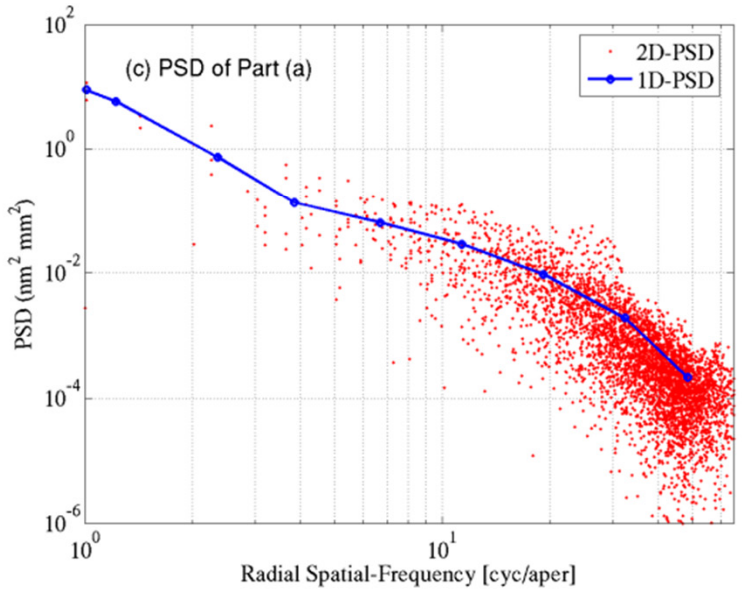


X-Translation (T_x) of FM1—Case of All 8 True Phase Errors



Change in OPD at exit-pupil:

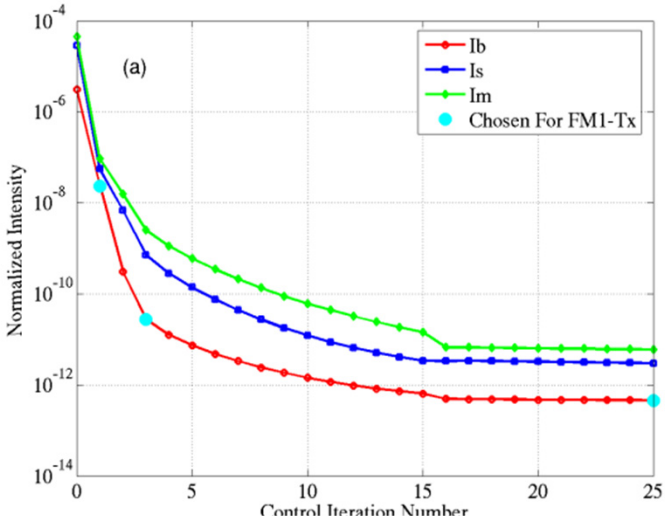
$$\Delta OPD = OPD(T_x) - OPD(0)$$

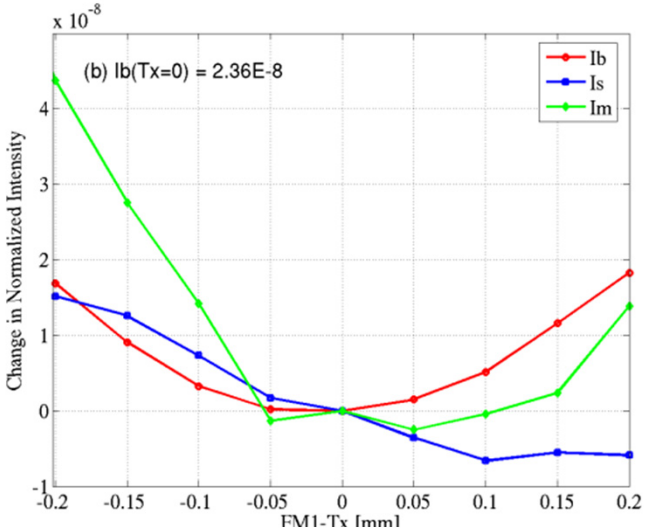


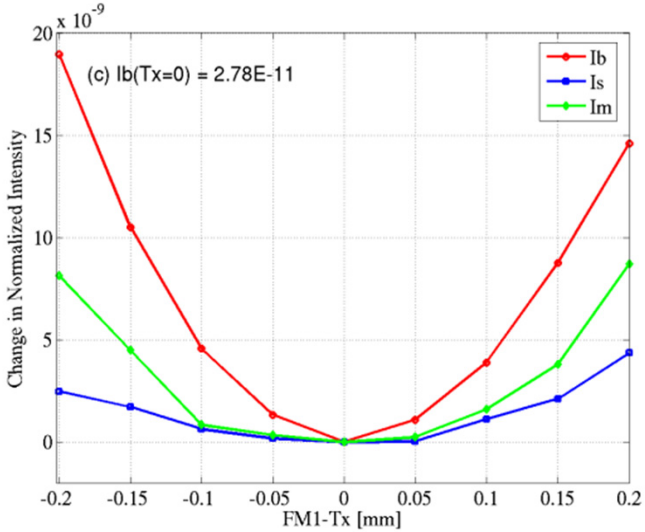
FM1- T_x—Case of All 8 True Phase Errors (cont)

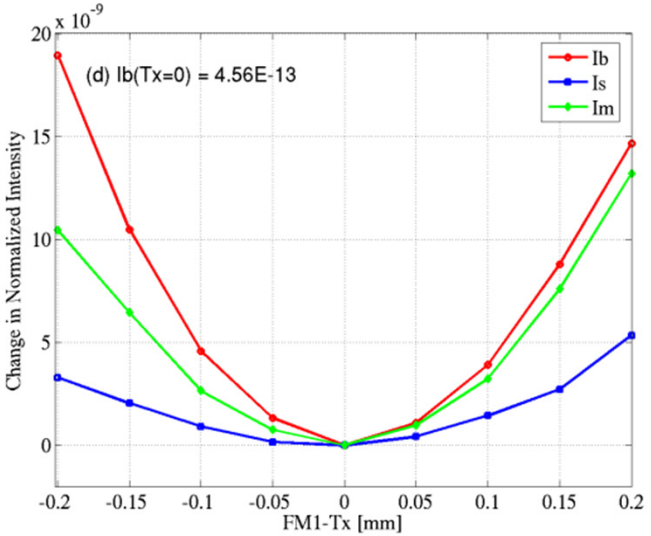
- Change in $I(x,y)$: $\Delta I(x,y;\ T_x) = I(x,y\ ;\ T_x) - \Delta I(x,y;0)$
- $\Delta I(x,y\ ;\ T_x)$ is evaluated at 3 different contrast levels

- $\Delta I(x,y;\text{Tx})$ is not symmetric with respect to FM1-T_x
- $I(x,y)$ sensitivity to FM1-T_x depends on the darkness of the dark-hole achieved







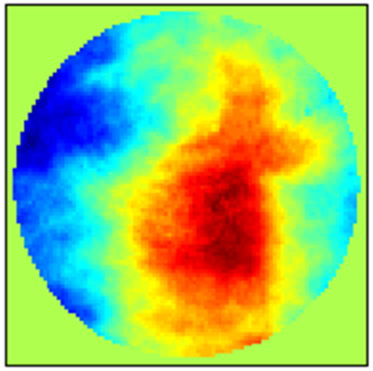


Occulter T_x and T_z Translations: 2-Step WFC

- Before x- and y-translations of the occulter, 2-step WFC was conducted a generate a dark-hole
- All surface errors are included in the simulation

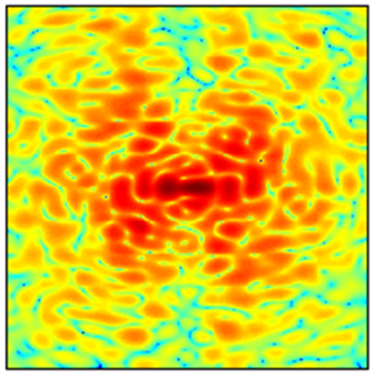
Before Control

OPD: Pre-Control



RMS, PV = 36.0, 164.0nm

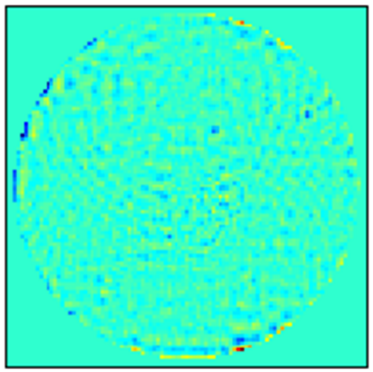
PSF: Pre-Control, 715



Cb = 1.95e-06

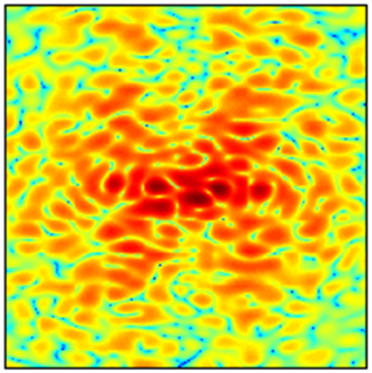
After OPD-Based WFC

OPD: Post-Control



2.4, 56.5nm

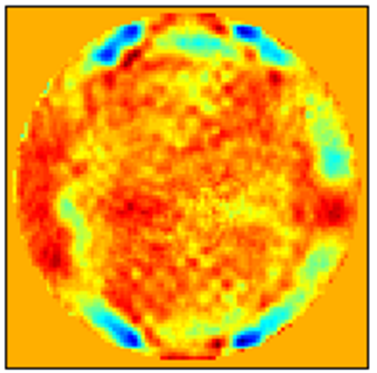
PSF: Pre-Control, 890



Cb = 1.12e-06

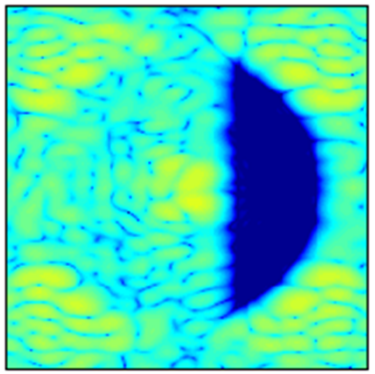
After EFC

OPD: Post-Control



10.3, 87.3nm

PSF: Post-Control



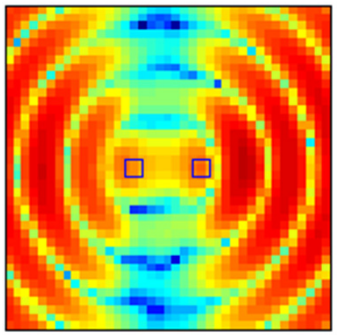
Cb = 4.94e-13

Occulter T_x & T_z : Finding the Symmetric Point in T_x

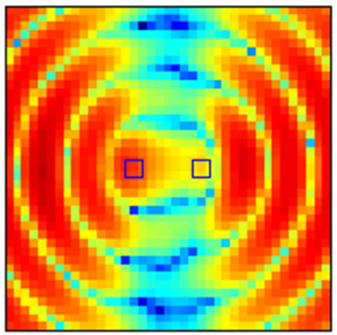
- Remove the Lyot Stop
- Move the Occulter by T_z
- Move (scan) the Occulter along the x-axis to find the symmetric point T_{x0} where PSF side-lobes have the same peak value

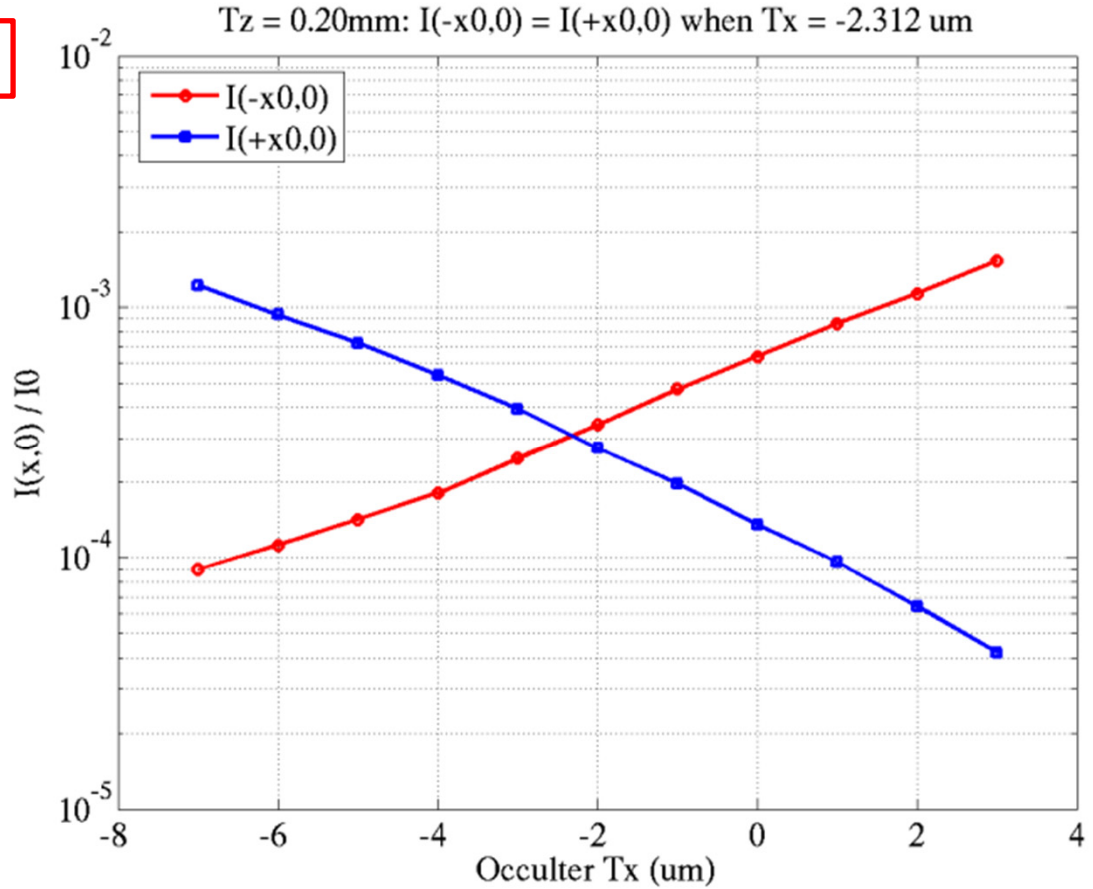
PSF when Occulter is out

Δx = -3um



Δx = 1um





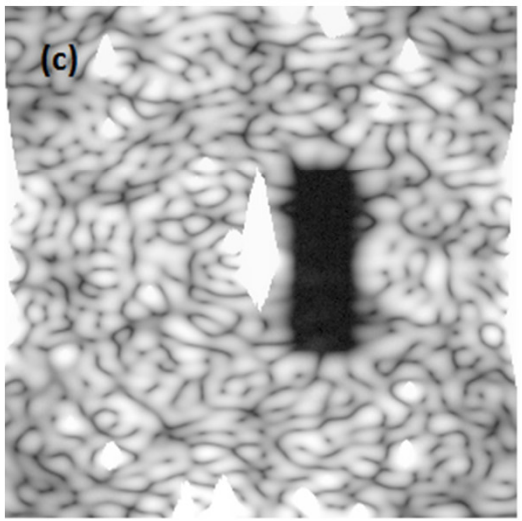
Occulter T_x & T_z : Contrast Sensitivity

- Change in $I(x,y)$ as a function of T_x with T_z as a parameter

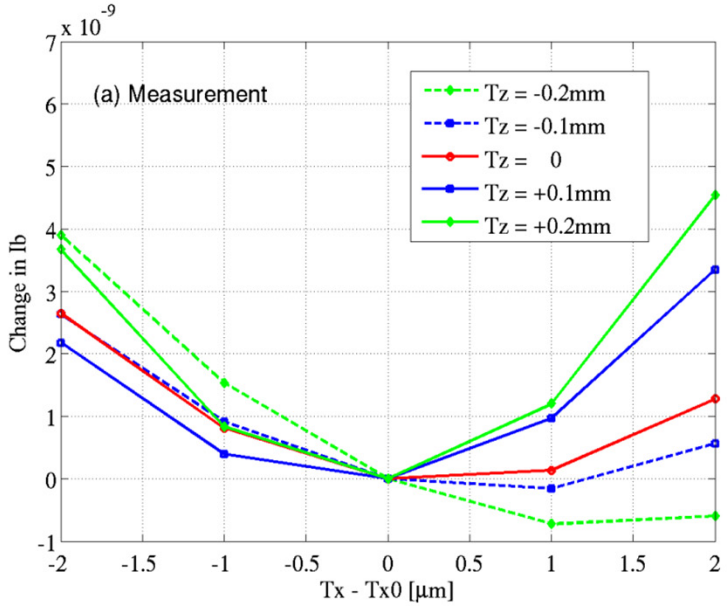
- Difference between measurement & simulation:
  1. λ: 808nm vs 800nm
  2. Surface error maps: Magnitude and registration
  3. Occulter: Actual vs design
  4. WFC region: Rectangle vs D-shape
  5. Darkness of the dark-hole achieved

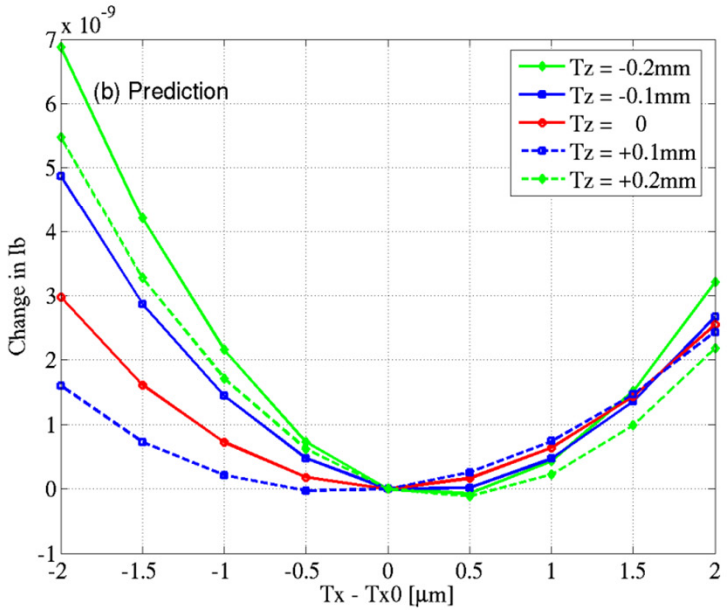
- $\Delta I(x,y)$ is not symmetric with respect to T_x
- Values of $\Delta I(x,y;\ T_x)$ depend on the darkness of the dark-hole achieved
- Measured & simulated $\Delta I(x,y;\ T_x)$ are comparable

Measured $I(x,y)$



I_b = 2.91E-9





Summary

- One to 3 dead actuators can be tolerated
  - When 1-3 crucial actuators are dead, we can still make the e-field estimation & control work by rotating or moving the DM, or by moving the probe DM pattern

- When a flat-optic moves towards and away from the dark-hole, the change in contrast exhibits an asymmetric behavior
  - Sensitivity of contrast on such motion depends on the darkness of the dark-hole achieved
  - $\Delta I_b < 2E\text{-}9$ when FM1- $T_x = \pm 50\mu m$

- When occulter moves towards and away from the dark-hole, the change in contrast exhibits an asymmetric behavior for a given T_z-value—Same as in the case of FM1- T_x
  - Sensitivity of contrast on such motion depends on the darkness of the dark-hole achieved
  - $\Delta I_b < 2E\text{-}9$ when Occulter- $T_x = \pm 1\mu m$ for all T_z–values considered (-0.2 to +0.2mm)
  - Measured and simulated dependencies of contrast sensitivity on the occulter motion are comparable