Coronagraph Starlight Suppression Model Validation

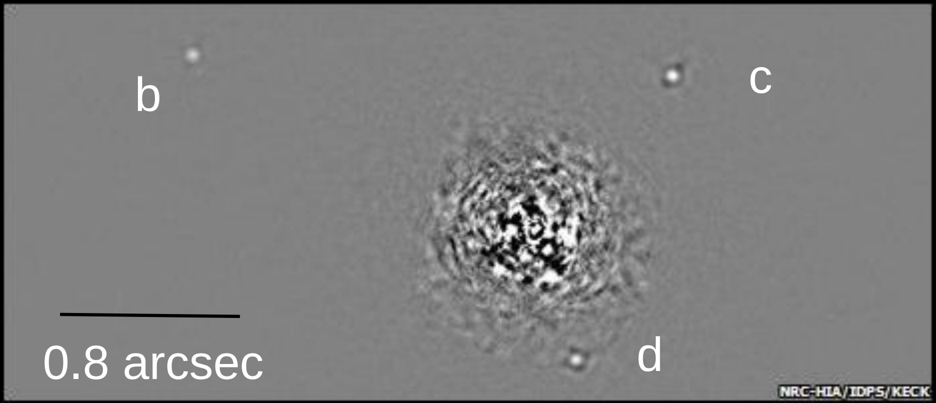
Stuart Shaklan, Erkin Sidick, Eric Cady, Brian Kern, Kunjithapatham Balasubramanian, and John Krist

Mirror Tech Days 2015
Annapolis, MD

11/12/ 2015

Direct Imaging from the Ground

HR 8799



Keck adaptive optics image of 6th magnitude HR 8799 and it's 3 massive Jovian planets.

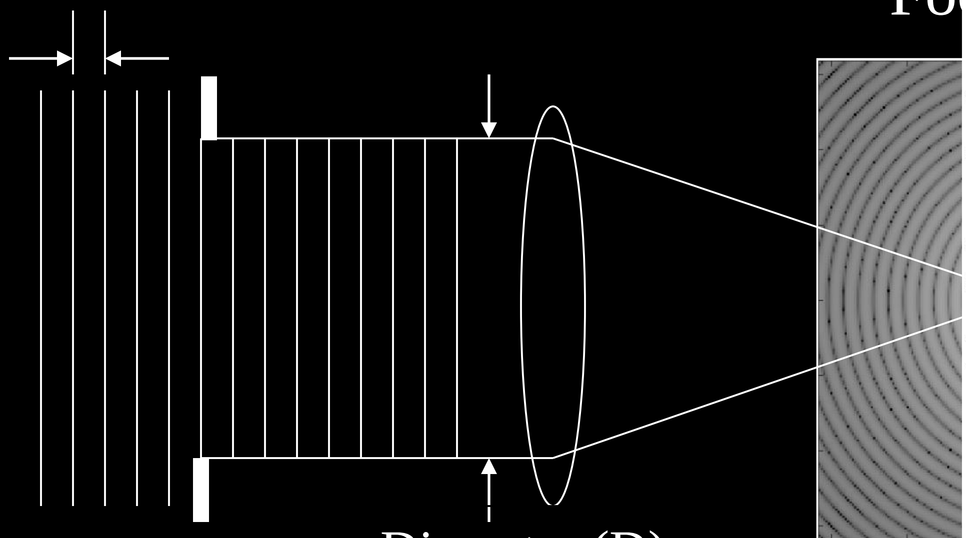
Contrast of planets about 10,000:1

Diffraction

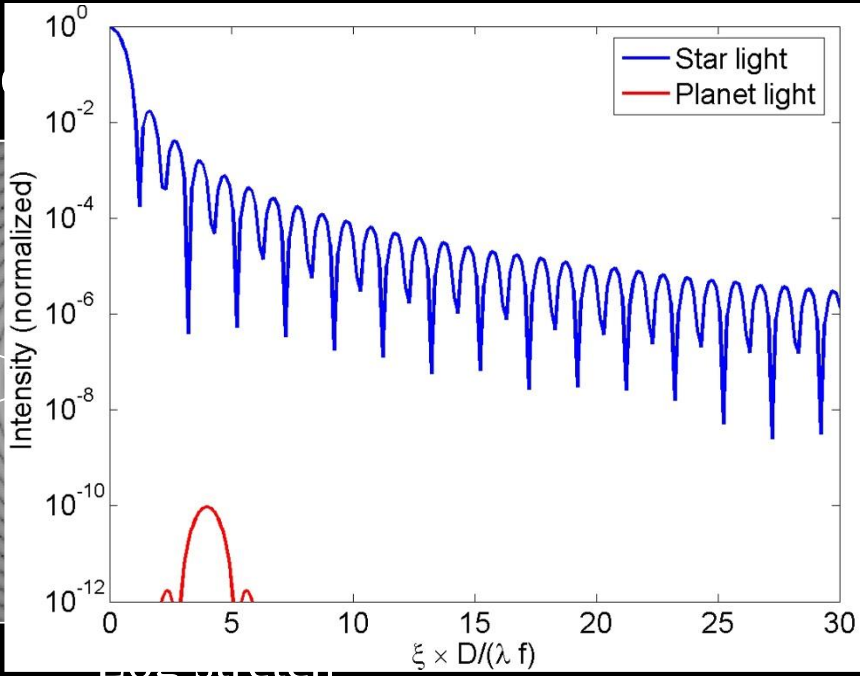
Unfortunately, the planet would be

Wavelength (l)

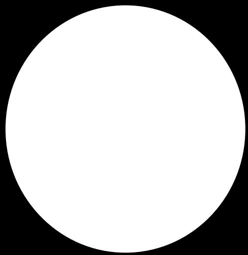
Fo



Diameter (D)



Entrance Pupil



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

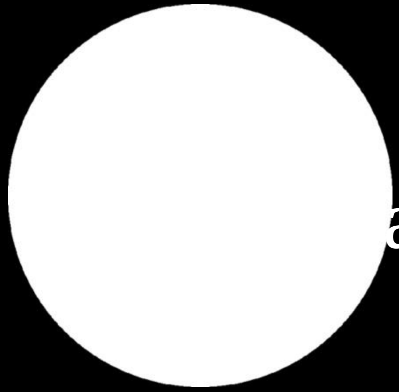
The Lyot Coronagraph

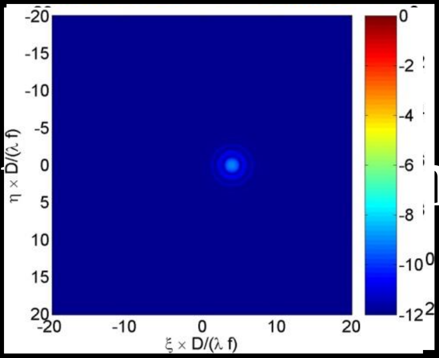
Entrance pupil

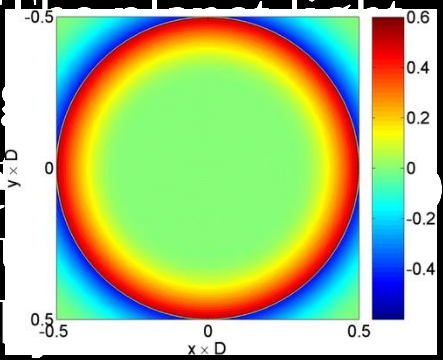
Occulter

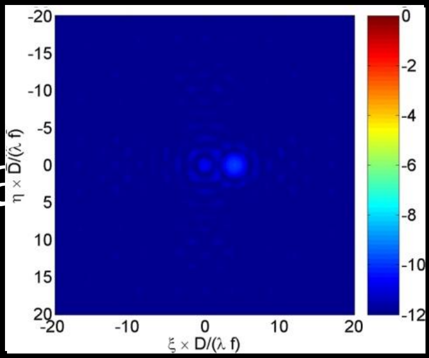
Lyot stop

Image plane

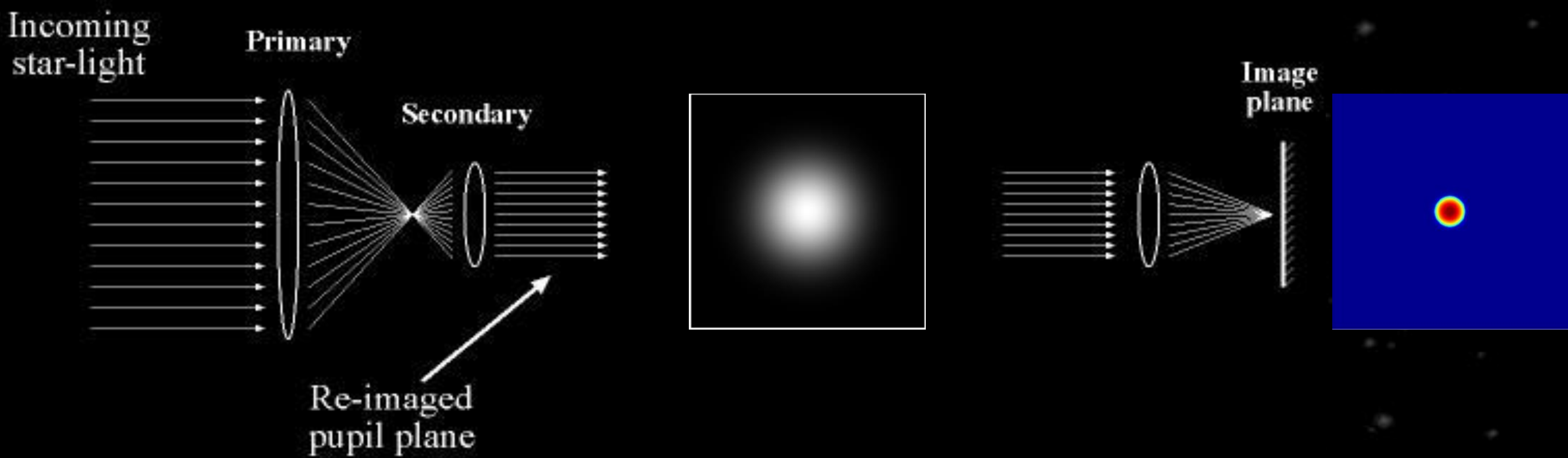






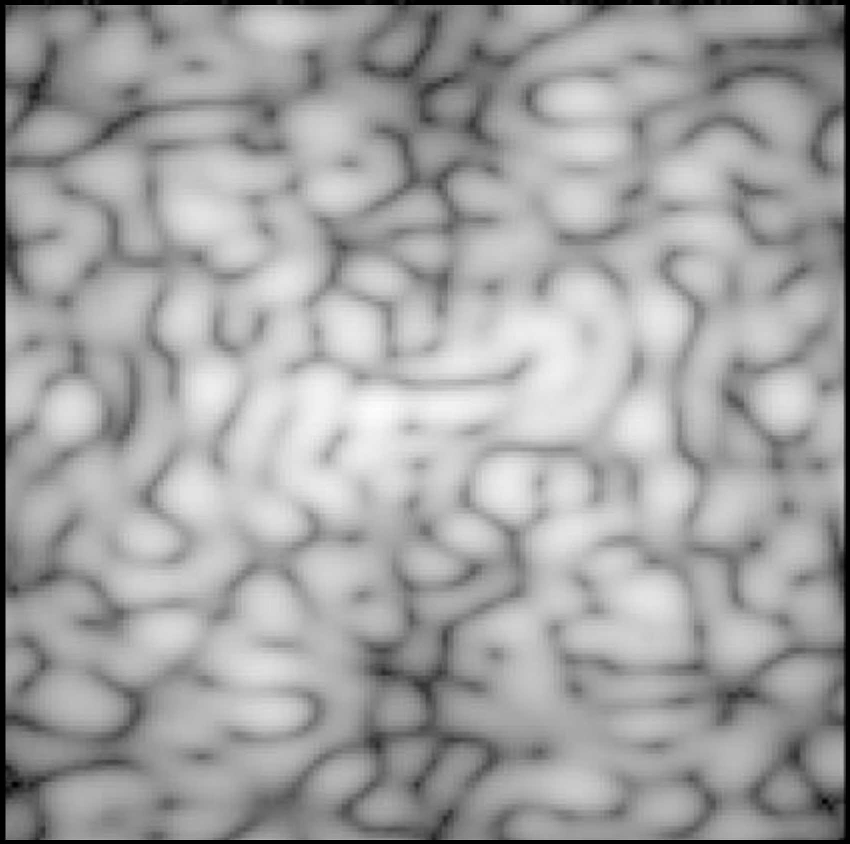


The Apodized Pupil Coronagraph



Digging Deeper

What's left over
After removing diffraction

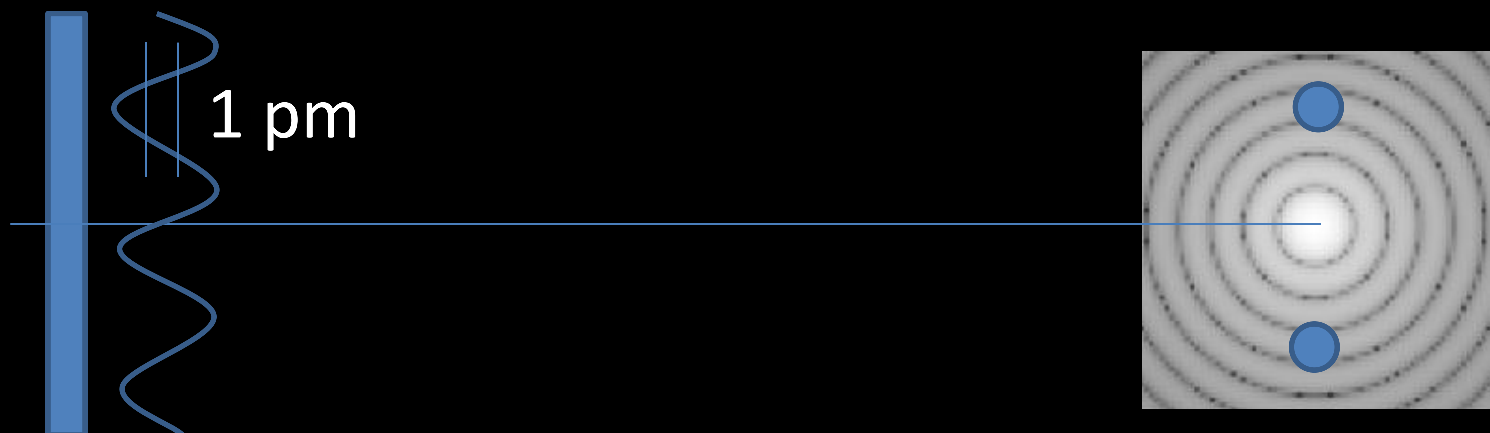


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Deformable Mirror and Wavefront Control

Sine wave, 3 cycles/aperture

Speckles at 3 λ/D



Amplitude

Relative intensity (Contrast)

θ Radians rms Marechal Approximation $C=\theta^2 / 2$

1 picometer

$$\frac{1}{2}\left(\frac{2\pi * 1\ \text{pm}}{1\ \mu\text{m}}\right)^2 = 2*10^{-11}$$

How Challenging is Direct Detection of Terrestrial Planets in Visible Light?

Imagine looking for a bump 1/100 the thickness of a human hair…

…on the slopes of Mt. Everest!!

90 microns / 100 = 9e-7 m

9000 m = 9e3 m

That's a ratio of 1e10, same as Earth to Sun contrast!!

Model Validation Tests

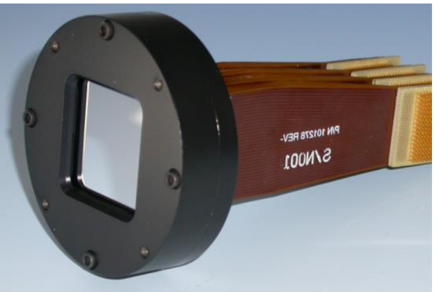
From Milestone #3A Final Report (Draft)

Open Loop Test (DM Static)	Purpose
Source Lateral Focus and Pos'n	Sensitivity to image motion and focus

Closed Loop Tests (Wavefront Control)	Purpose
Occulter Mask Defect	Effect of contamination
Dark Hole Size	Contrast floor vs. Dark Hole size
Control Bands	Contrast vs. λ vs. controlled bands
Pegged Actuators	Sensitivity to failures
Incoherent light estimation	Distinguish planet from instr. scatter

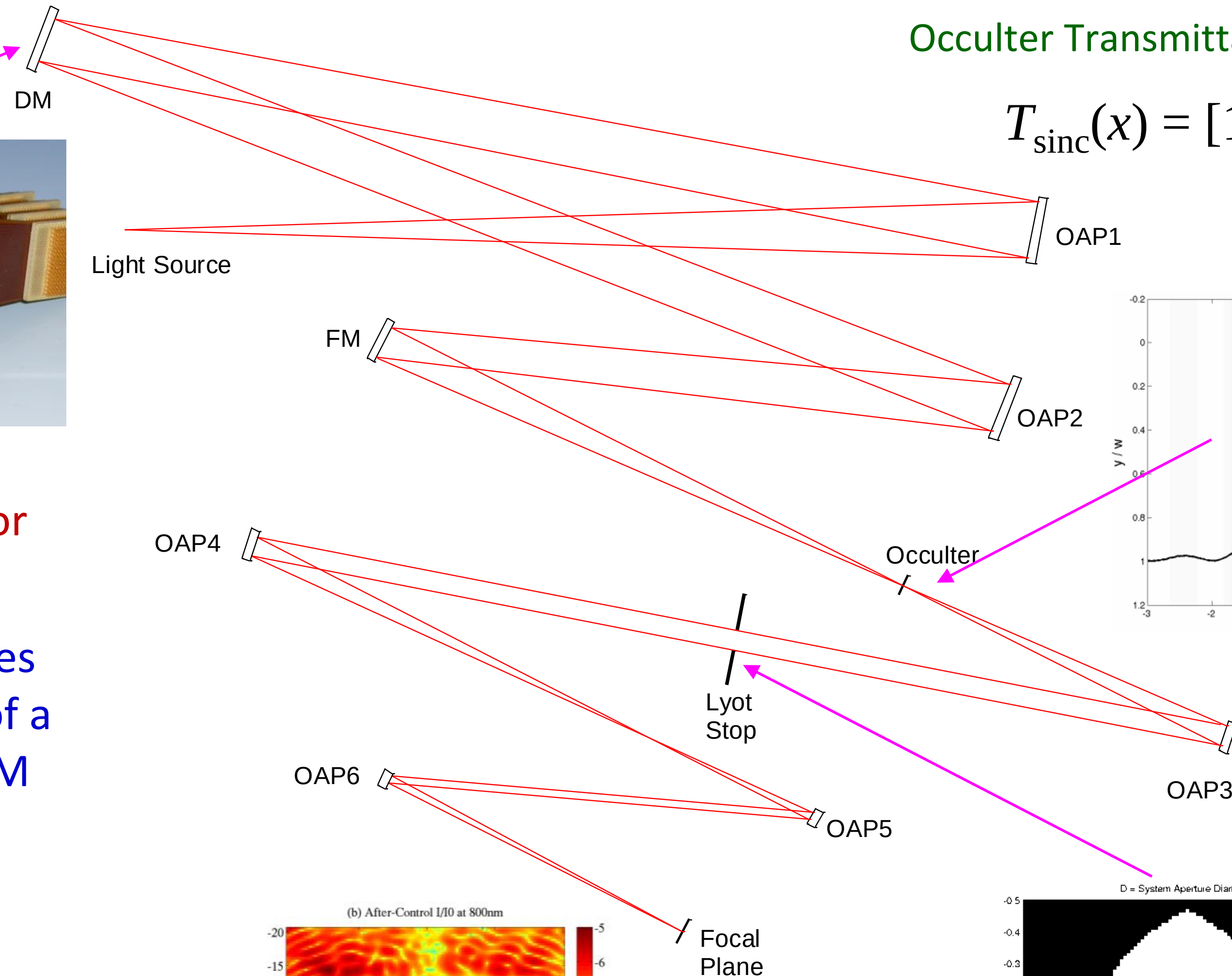
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

High Contrast Imaging Testbed Optical System



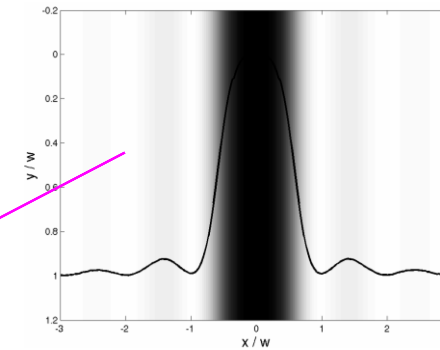
32x32 Actuator Deformable-Mirror

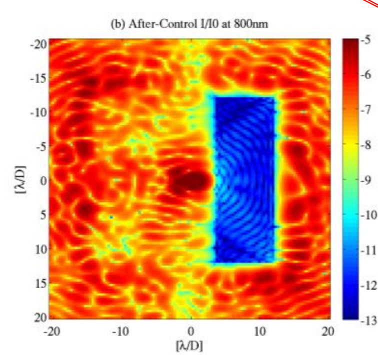
Currently HCIT uses 48x48 actuators of a 64x64 actuator DM

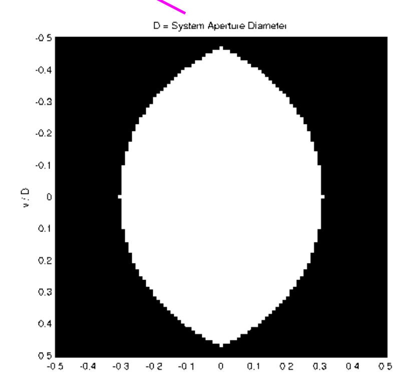


Occulter Transmittance:

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







Occulter OD & Phase Profiles, and Their Dispersion

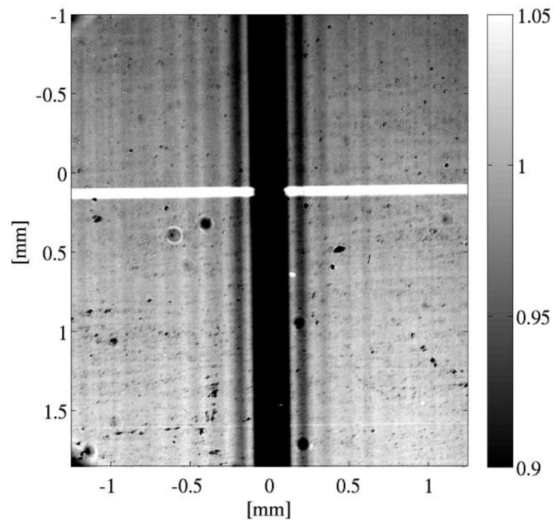
Use a Ni occulter deposited on a fused quartz substrate

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

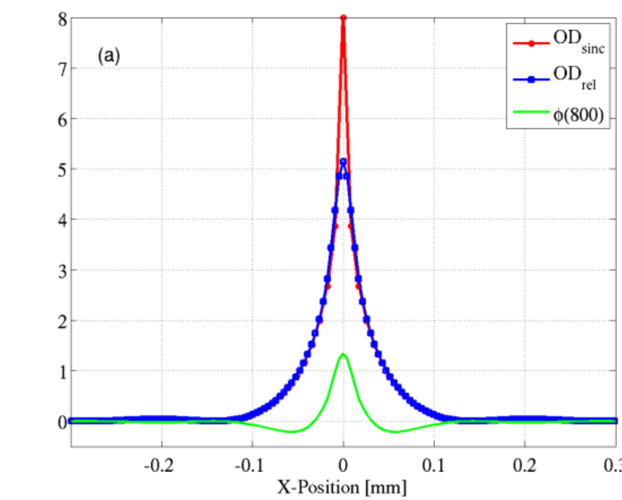
Truncation & Smoothing→ $T_{rel}(x)$

Occulter phase is in radians

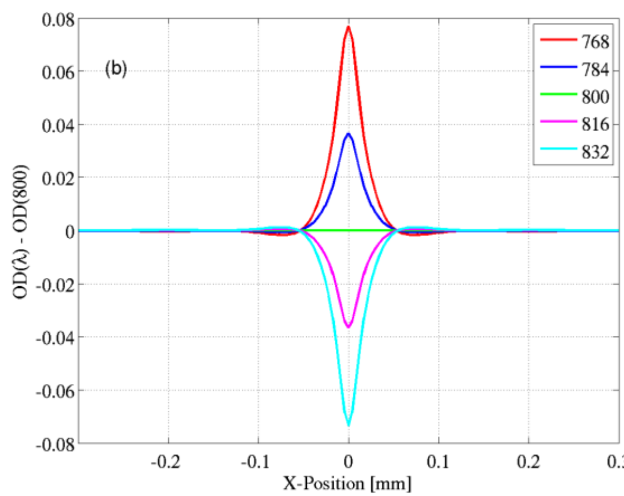
Measured Occulter Transmittance



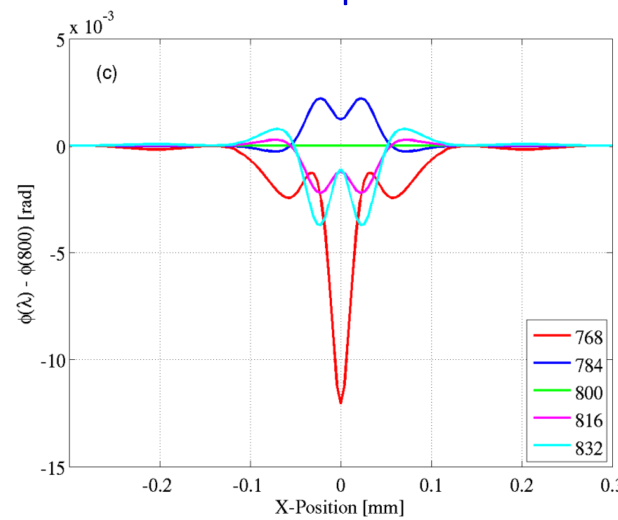
OD & Phase Profile



OD Dispersion



Phase Dispersion



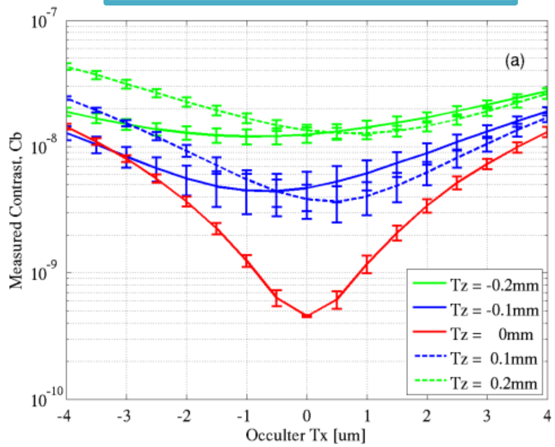
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

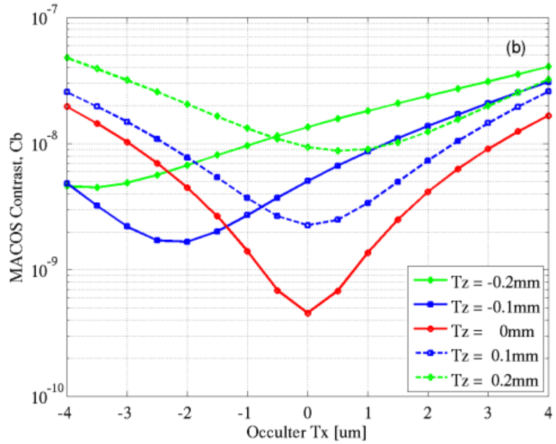
Translation vs. Focus: Measurement versus Simulations

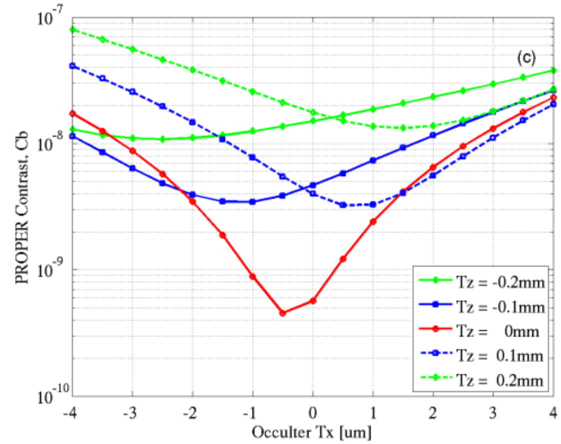
- Simulation does not account for any experimental floor due to incoherent scattered light, so yields much better contrast floor
- Adjusted Cb and Cs values to match with measured ones at Tx = Tz = 0 point
- Measured & simulated curves have similar shapes (red curves are very close to each other)

Measured | **MACOS** | **PROPER**

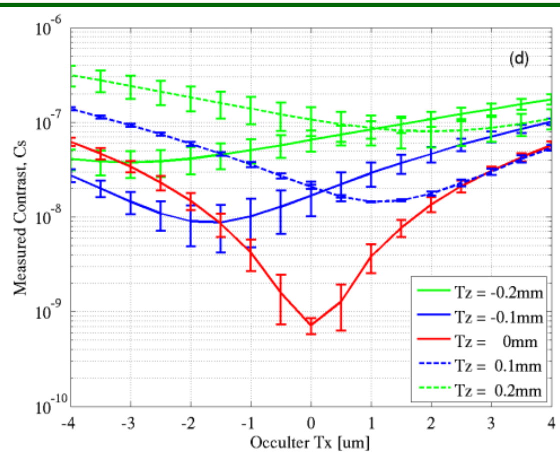
I_b

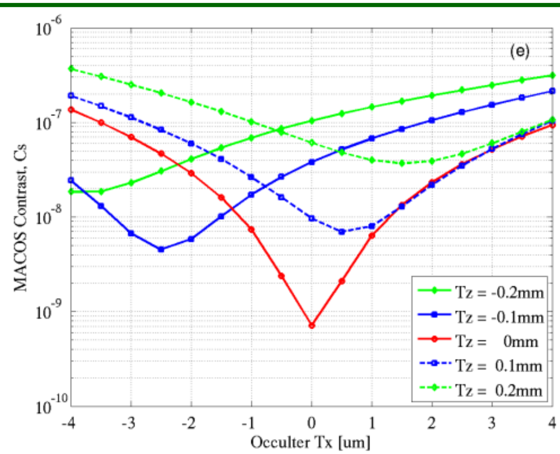


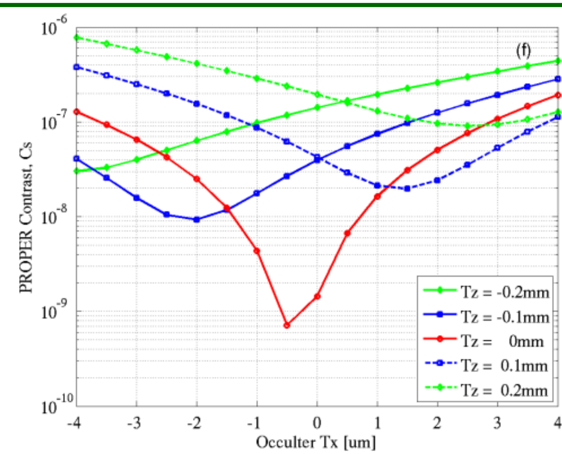




I_s

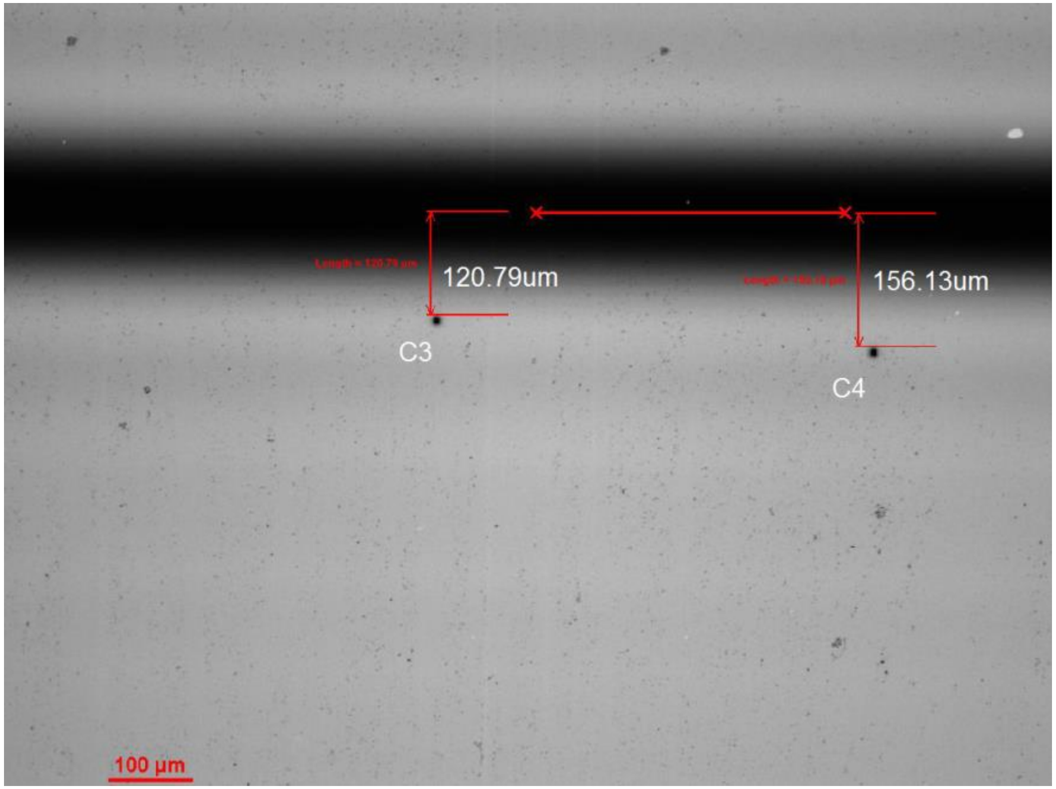


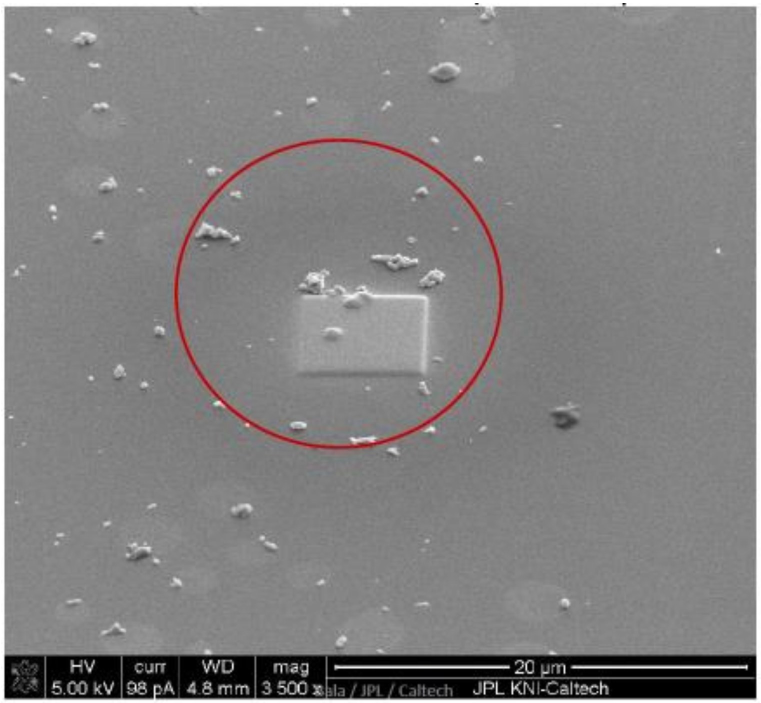




Opaque Spot on Occulter: AFM/SEM Images

- Occulter is fabricated by vacuum deposition of varying thickness Nickel layer on a glass
- Added 6x6 um square shaped marks of Platinum (Pt) to represent dust particle or coating defect
- Left: Optical microscope image of two spots, C3 & C4
- Right: SEM (scanning-electron-microscope) image of C3-spot
- Rectangular shape caused by 52-deg tilted observation of a square mark
- Performance is evaluated one-spot at a time

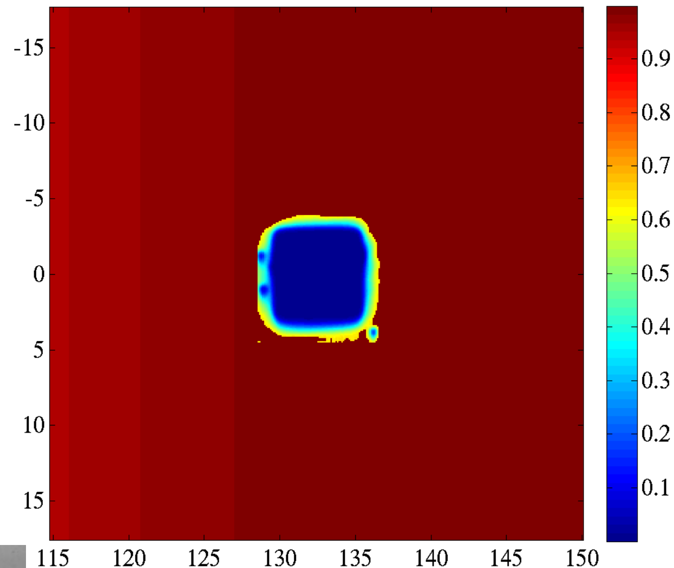




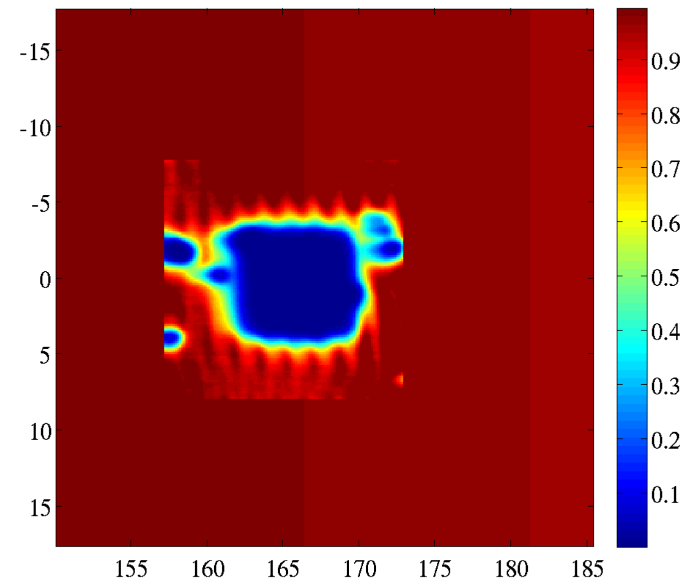
Modeling of an Opaque Spot on Occulter

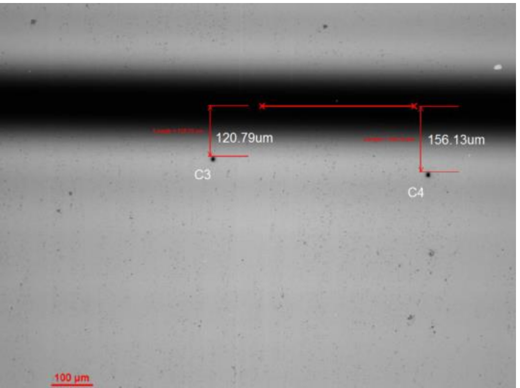
- Up-sampled occulter transmission to match with spot pixel size
- Replaced part of the occulter transmission with actual spot data
- Down-sampled the resultant occulter transmission map to the original occulter transmission sampling ($\Delta x \sim 8.5$um)

C3-spot: w = 6um, $\Delta x = 0.0984$um



C4-spot: w = 6um, $\Delta x = 0.1228$um





Data are AFM (atomic-force microscope) images of two spots

Effects of Occulter C3-Spot

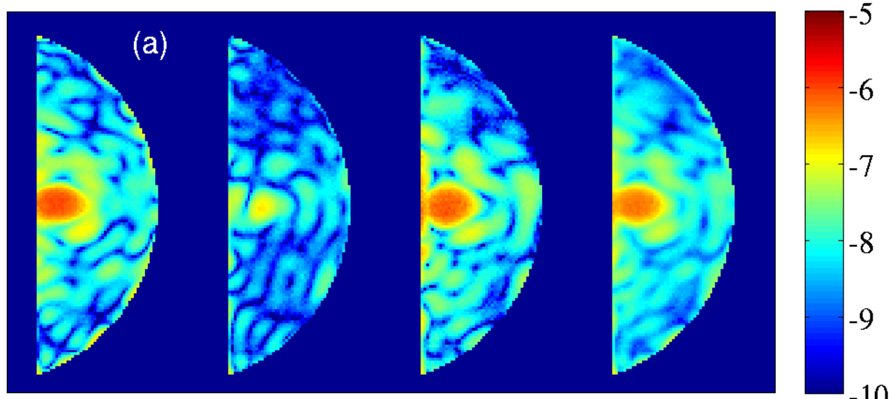
- Measurement and prediction are fairly close, especially the I_b-values

Normalized Intensity Maps

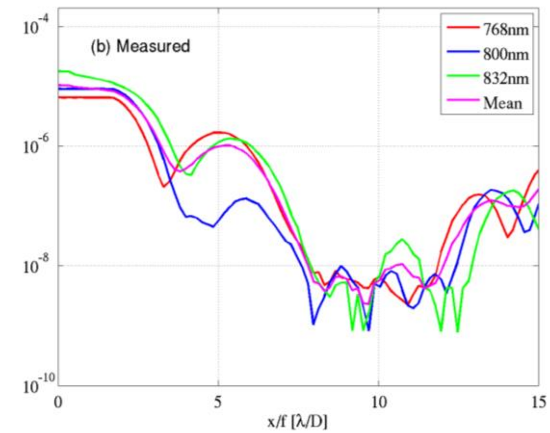
X-Profile at Y = 0

768nm 800nm 832nm Mean

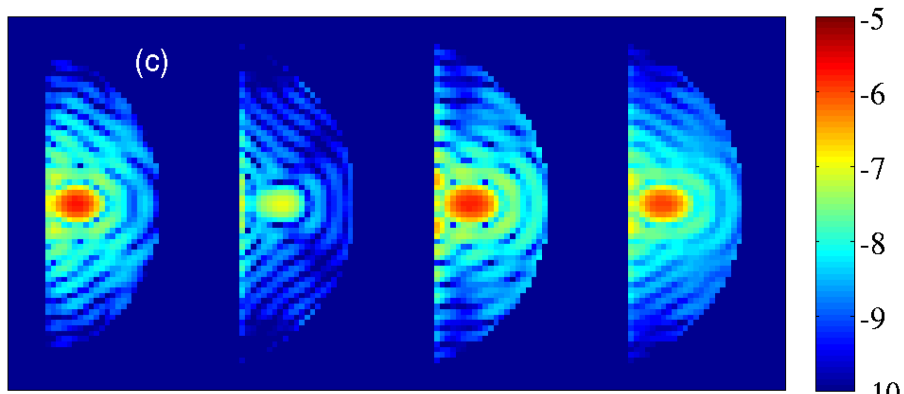
Measured



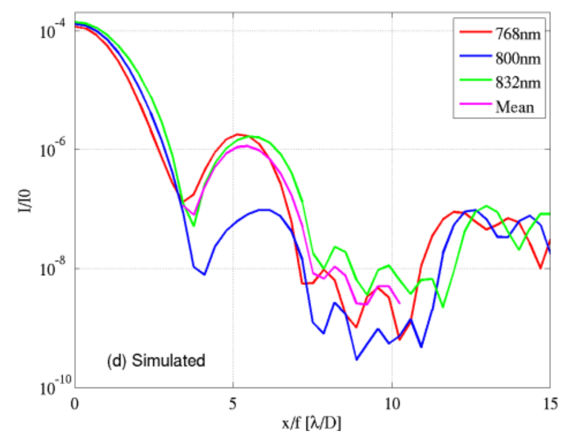
Ib = 2.91e-08



Predicted



Ib = 2.66e-08



National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Effects of Occulter C4-Spot

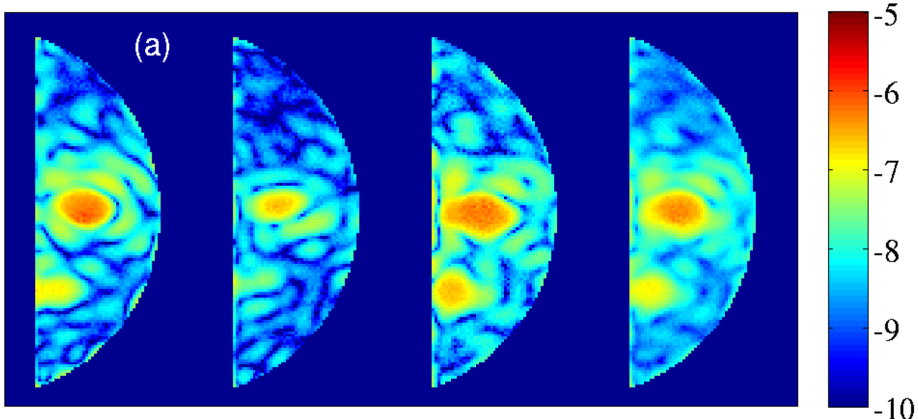
- Again, measurement and prediction are fairly close, especially the I_b-values
- Second spot near C4 is not intentional, and not modeled
- Residual exit-pupil phase-error is not included in simulations

Normalized Intensity Maps

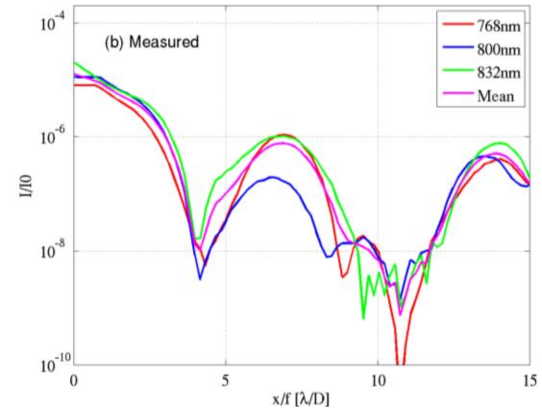
X-Profile at Y = 0

Measured

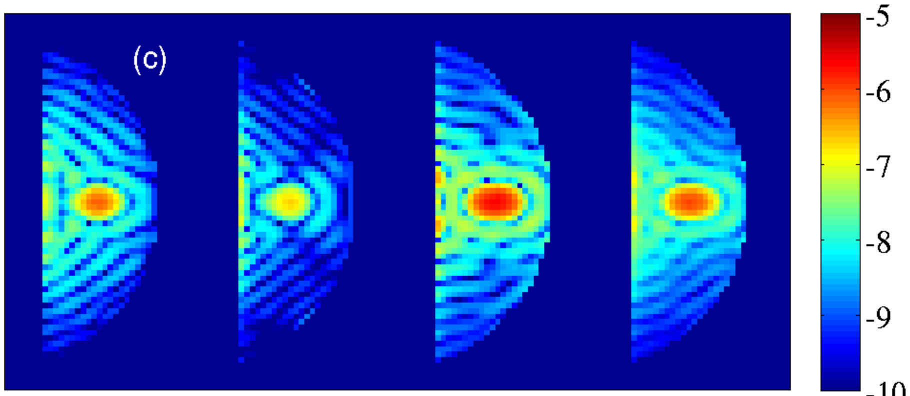
768nm 800nm 832nm Mean



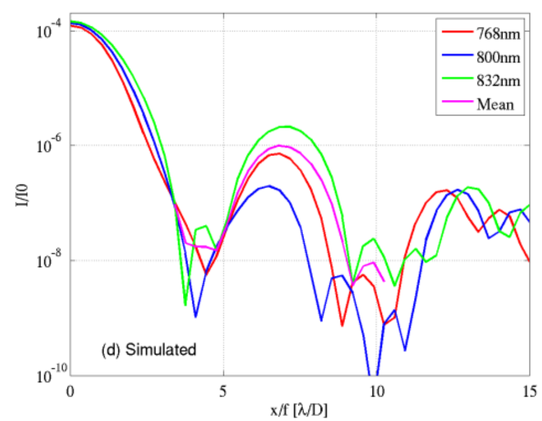
Ib = 2.5e-08



Predicted



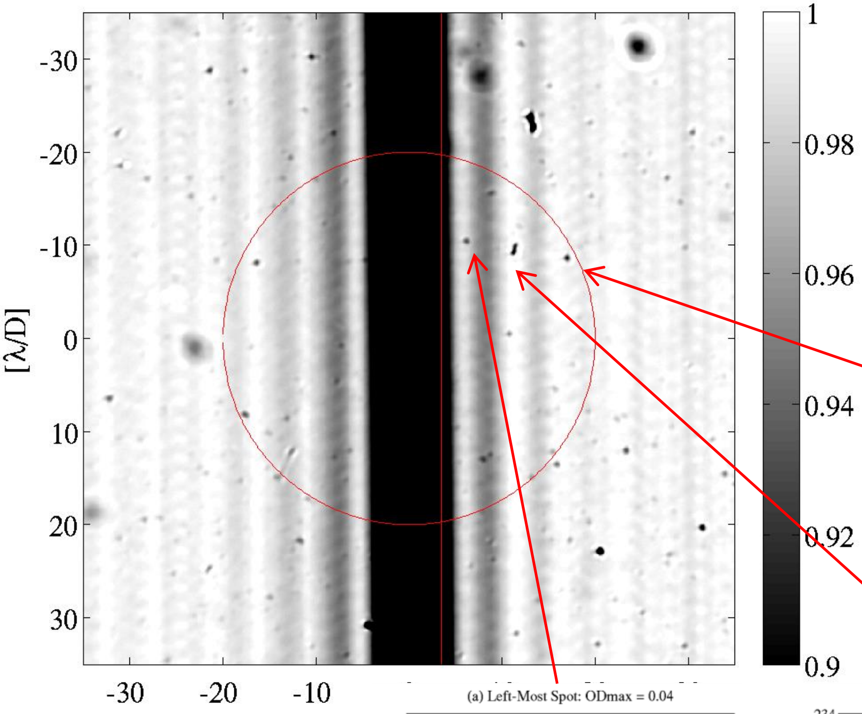
Ib = 2.44e-08

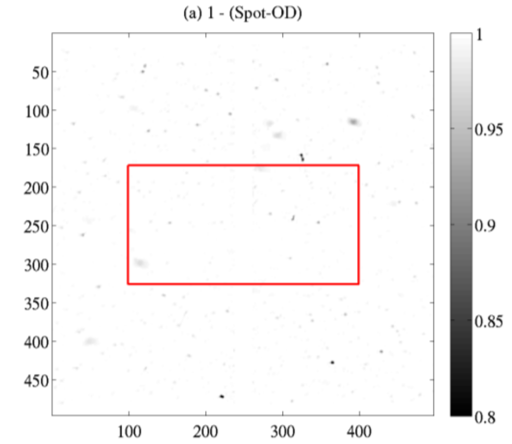


National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

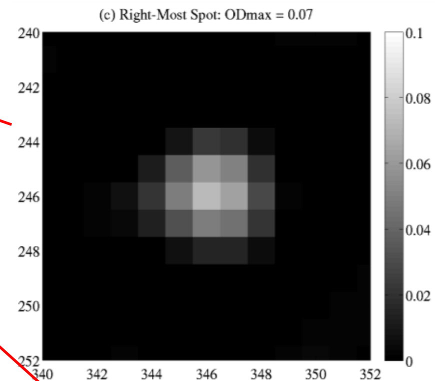
Occulter Used for Dark-Hole Size

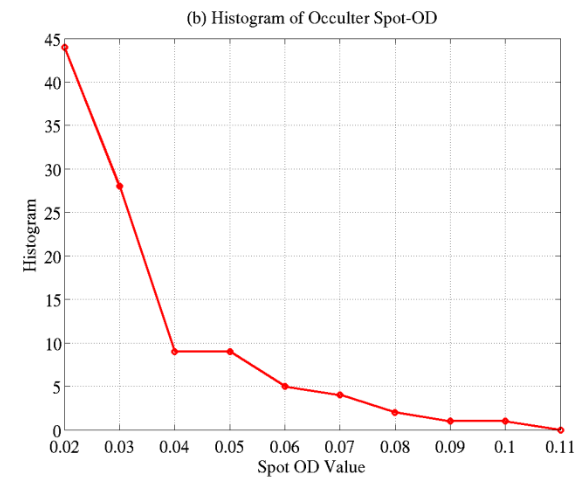
Occulter Transmittance: Circle R = 20λ/D

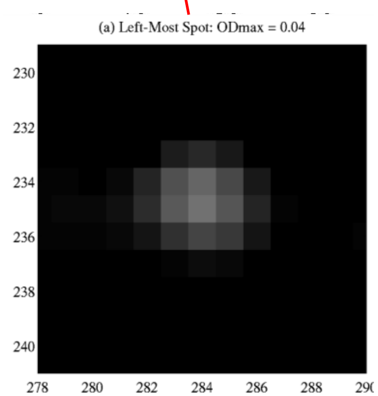


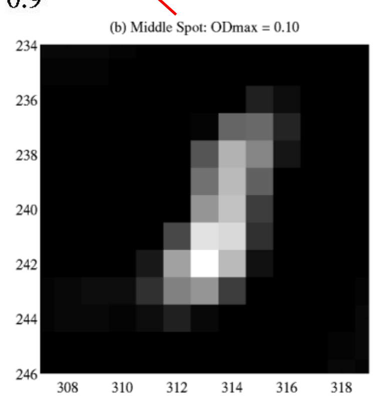


Spot OD







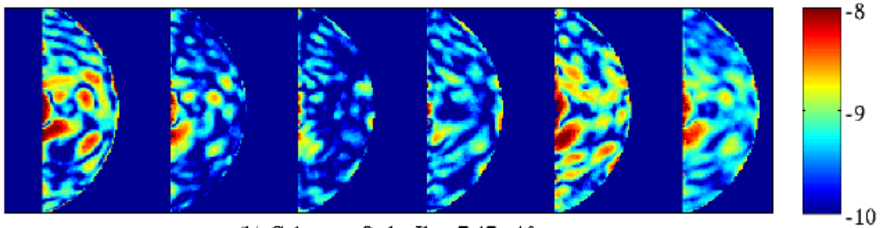


Pix-size = 13/3 um = 4.33 um

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Trying to Match the Model to the Data by Adjusting Particle Phase

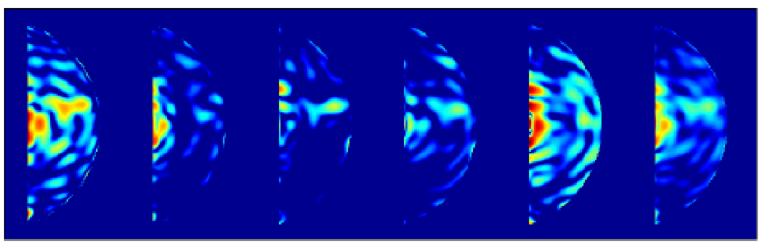
768 784 800 816 832 comp



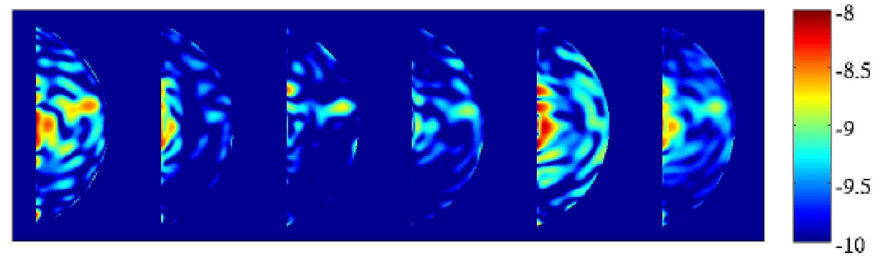
Measured Data

(b) Coherent Only: Ib = 7.47e-10

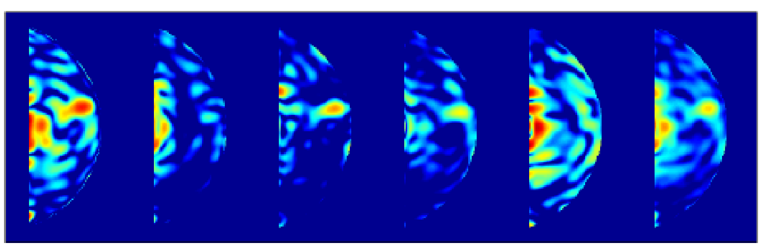
0.0 (a) Focc = 1.5, Fspot = 0: Ib = 3.02e-10



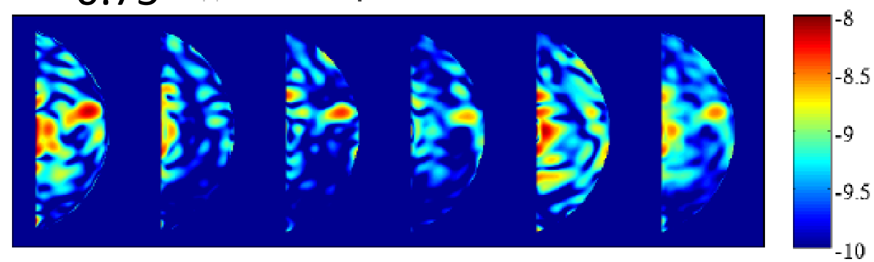
0.25 (b) Focc = 1.5, Fspot = 0.25: Ib = 3.21e-10



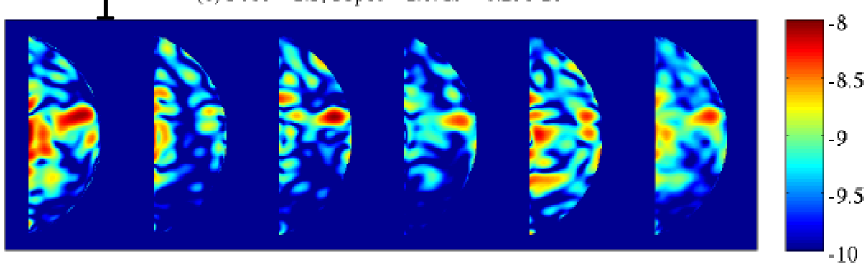
0.5 (c) Focc = 1.5, Fspot = 0.5: Ib = 3.79e-10



0.75 (d) Focc = 1.5, Fspot = 0.75: Ib = 4.75e-10



1 (e) Focc = 1.5, Fspot = 1.0: Ib = 6.23e-10



Phase proportional to OD.
Proportionality from 0 to pi at OD=1.

Dark Hole after Wavefront Control

Particles shifted, then wavefront controlled

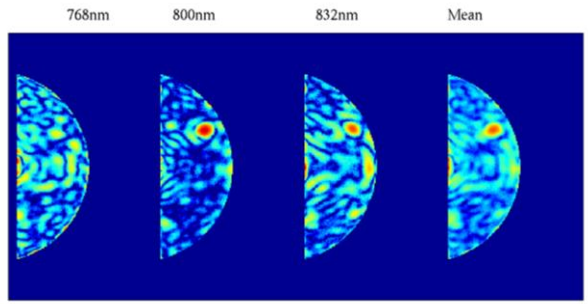
- Video removed, too big

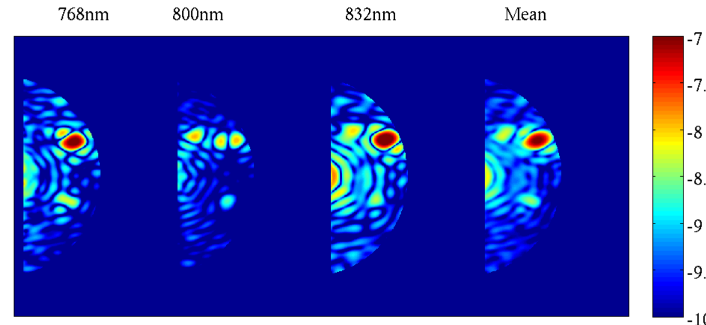
Contrast versus Dark-Hole Size

IntroduceD Occulter Spot Phase: $\Delta\varphi = OD_{spot} \times F_{spot} \times \pi$, $F_{spot} = 1$

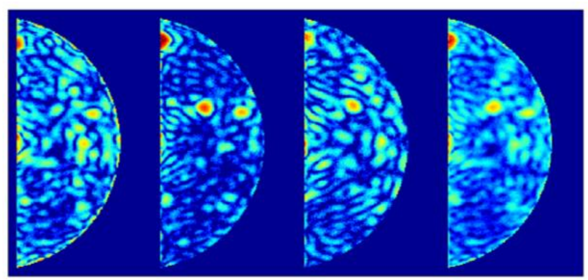
Measured | *Simulated*

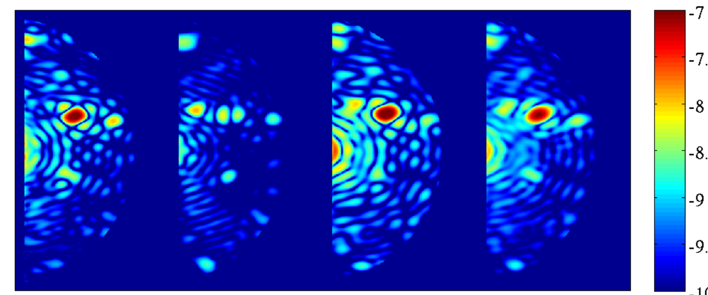
$X_{min} = 3.5,\ R_{max} = 15\ \lambda/D$



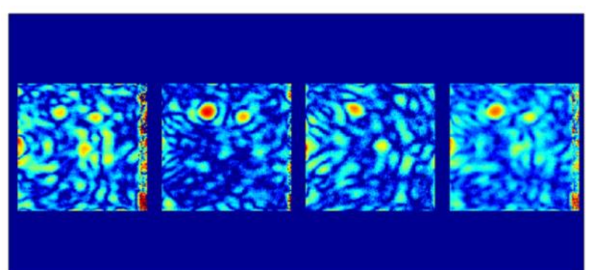


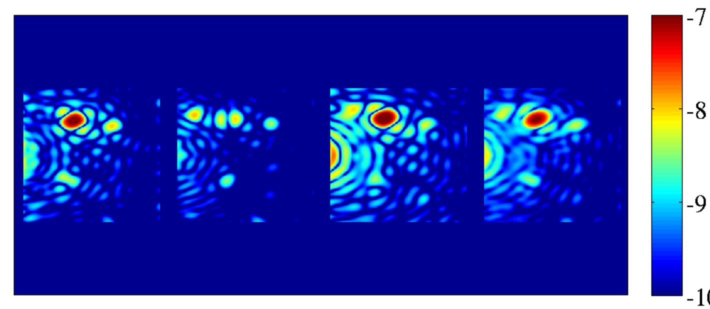
$X_{min} = 3.5,\ R_{max} = 20\ \lambda/D$





$X = 3.5 - 24,\ Y = \pm 10\ \lambda/D$

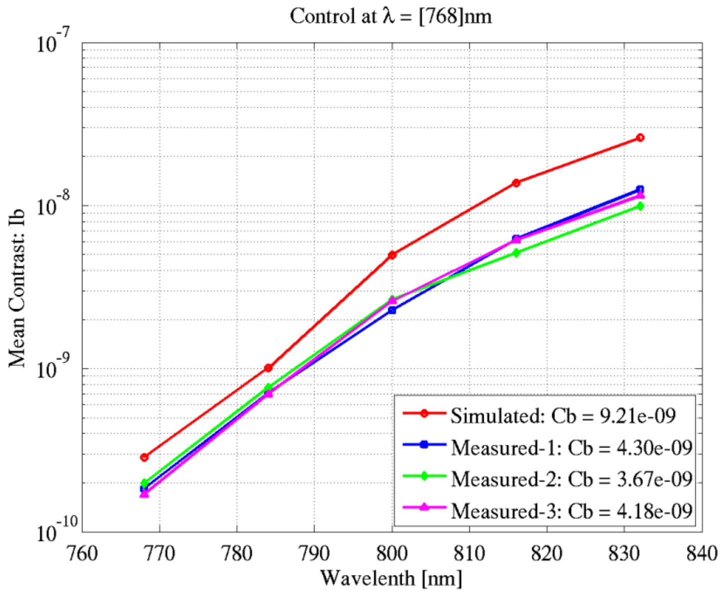


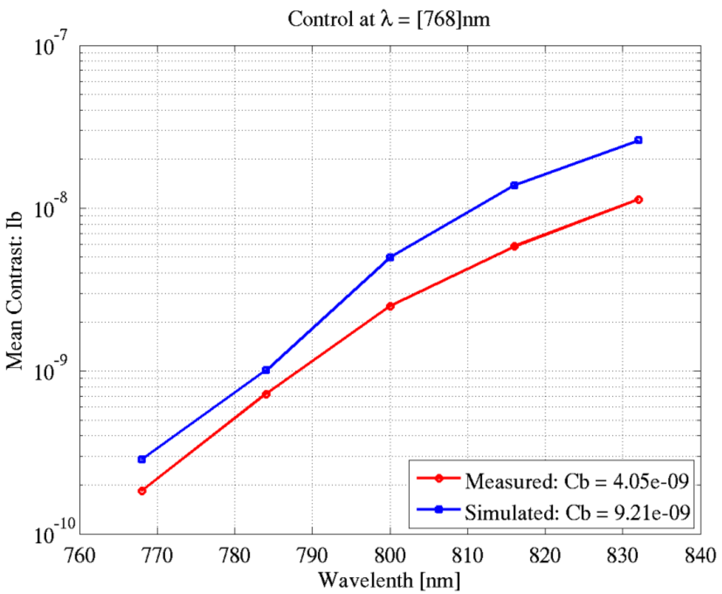


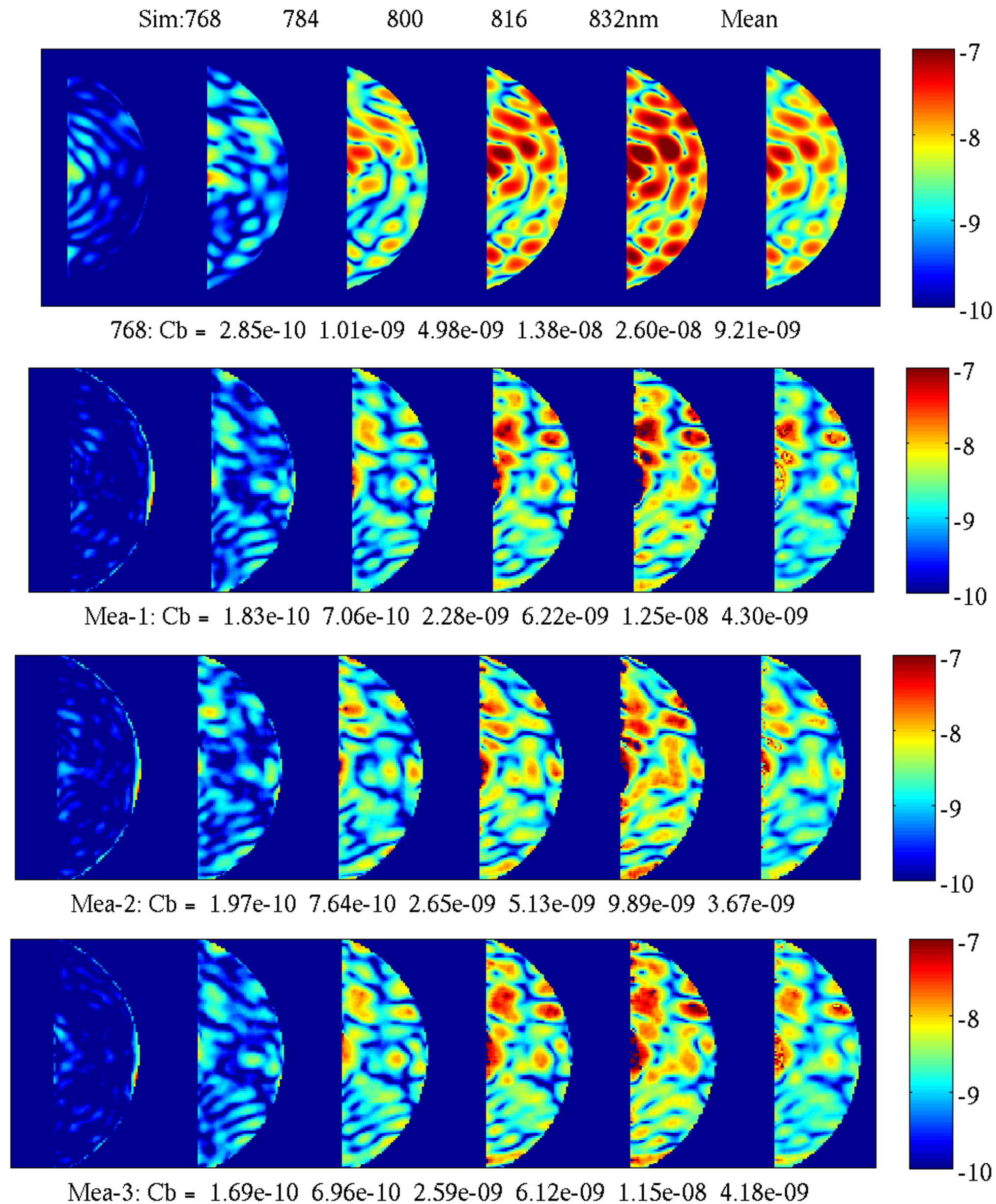
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Control Bandwidth: Control at λ = 768nm

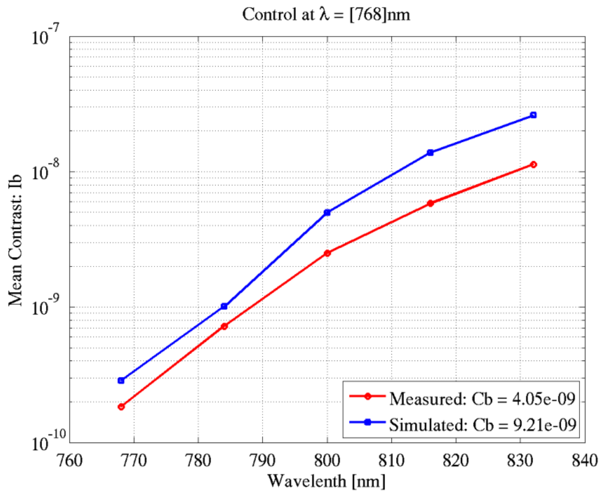
Top: Simulated. Rest: Measured. X_{min} = 3.5, R_{max} = 11 λ/D

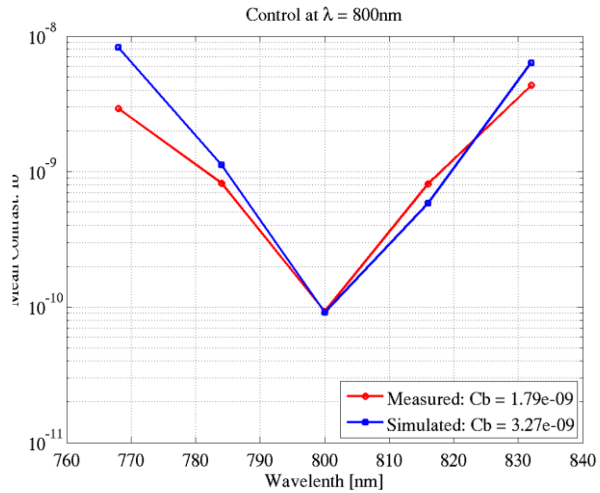


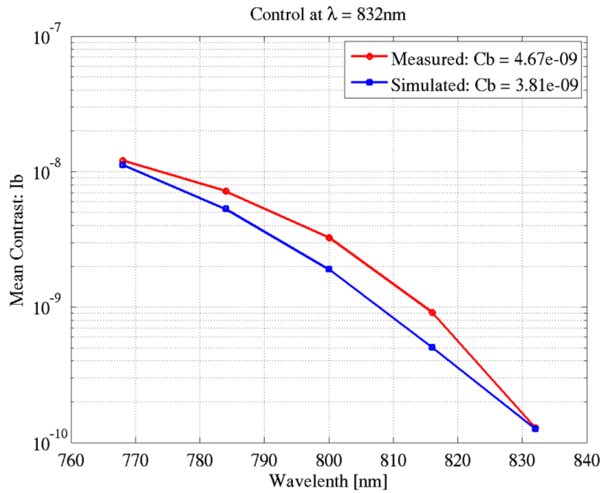


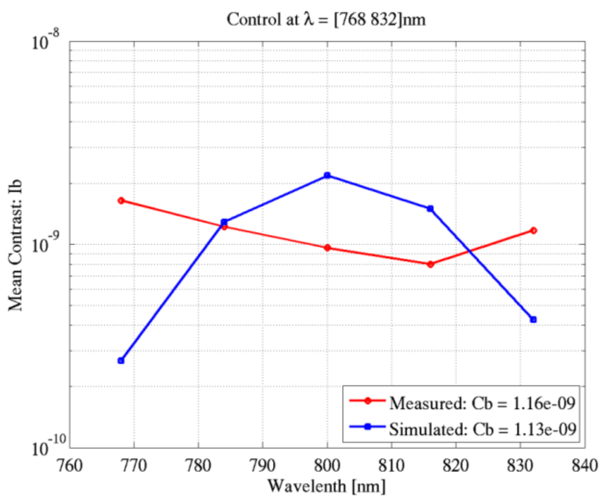


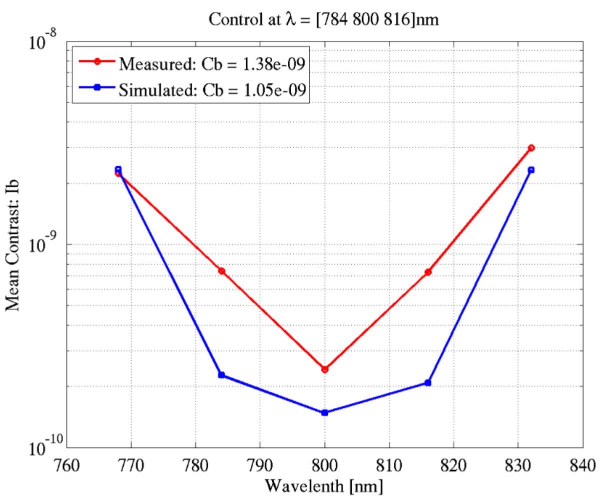
Contrast versus Control Bandwidth

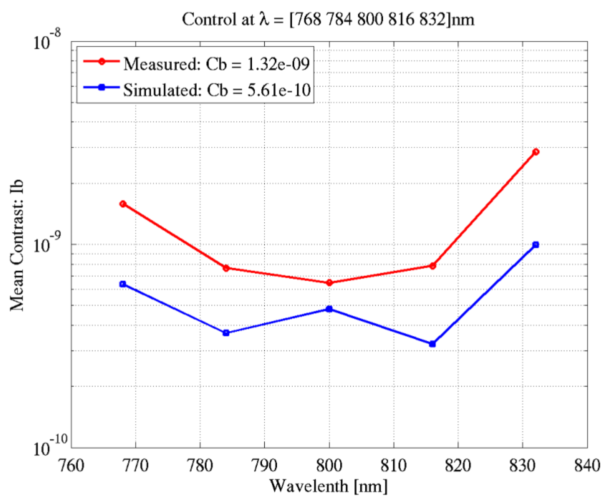








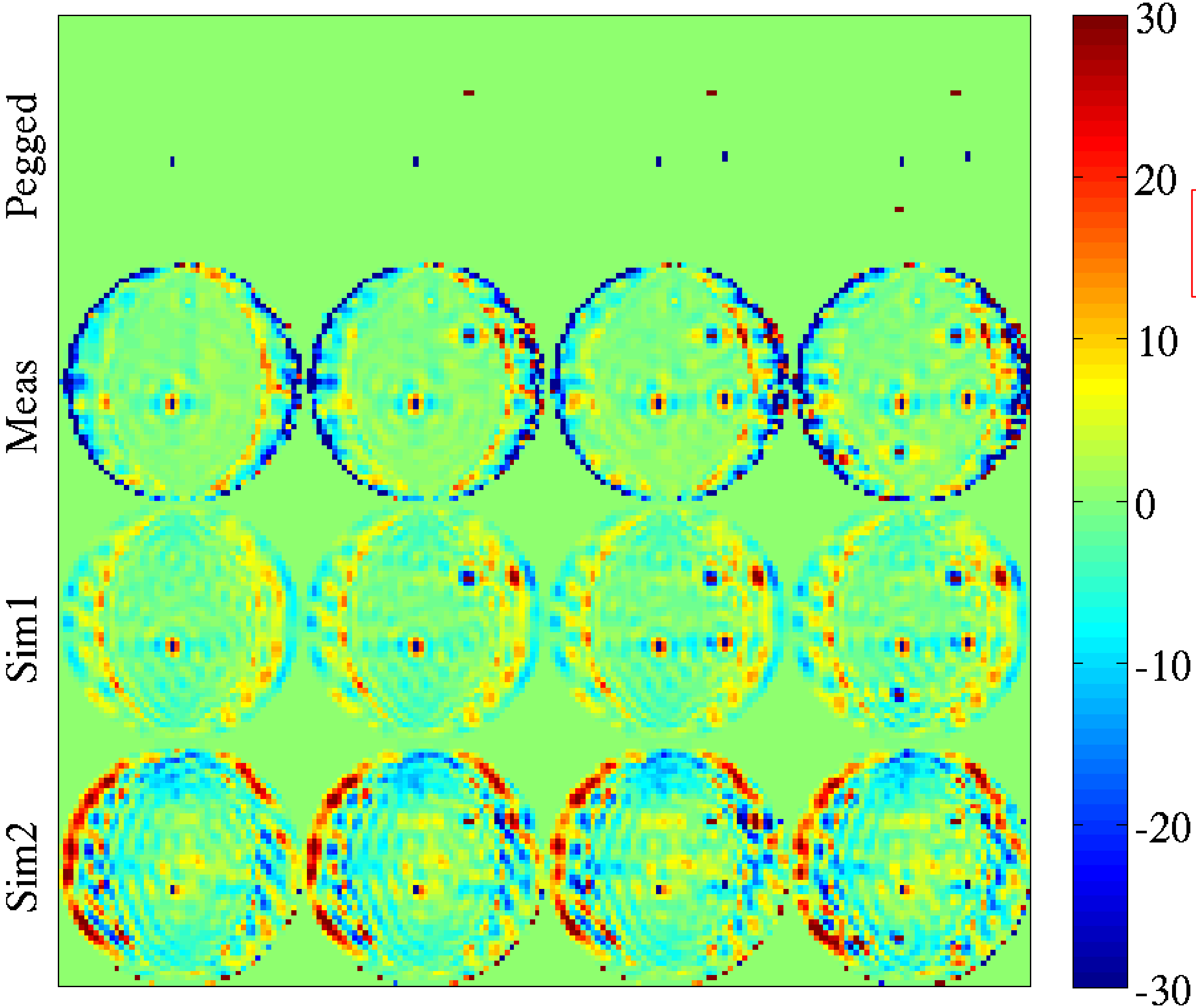




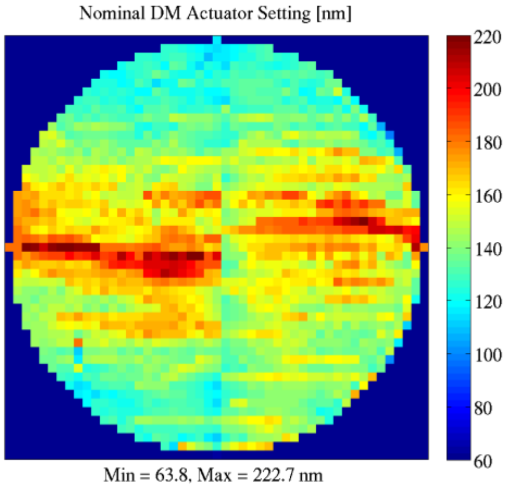
Pegged Actuators: DM Actuator Commands

Sim1: Starting with a Flat-DM. Sim2: Starting with "Meas" actuator state

Pegged actuators cause 125nm change in local WF



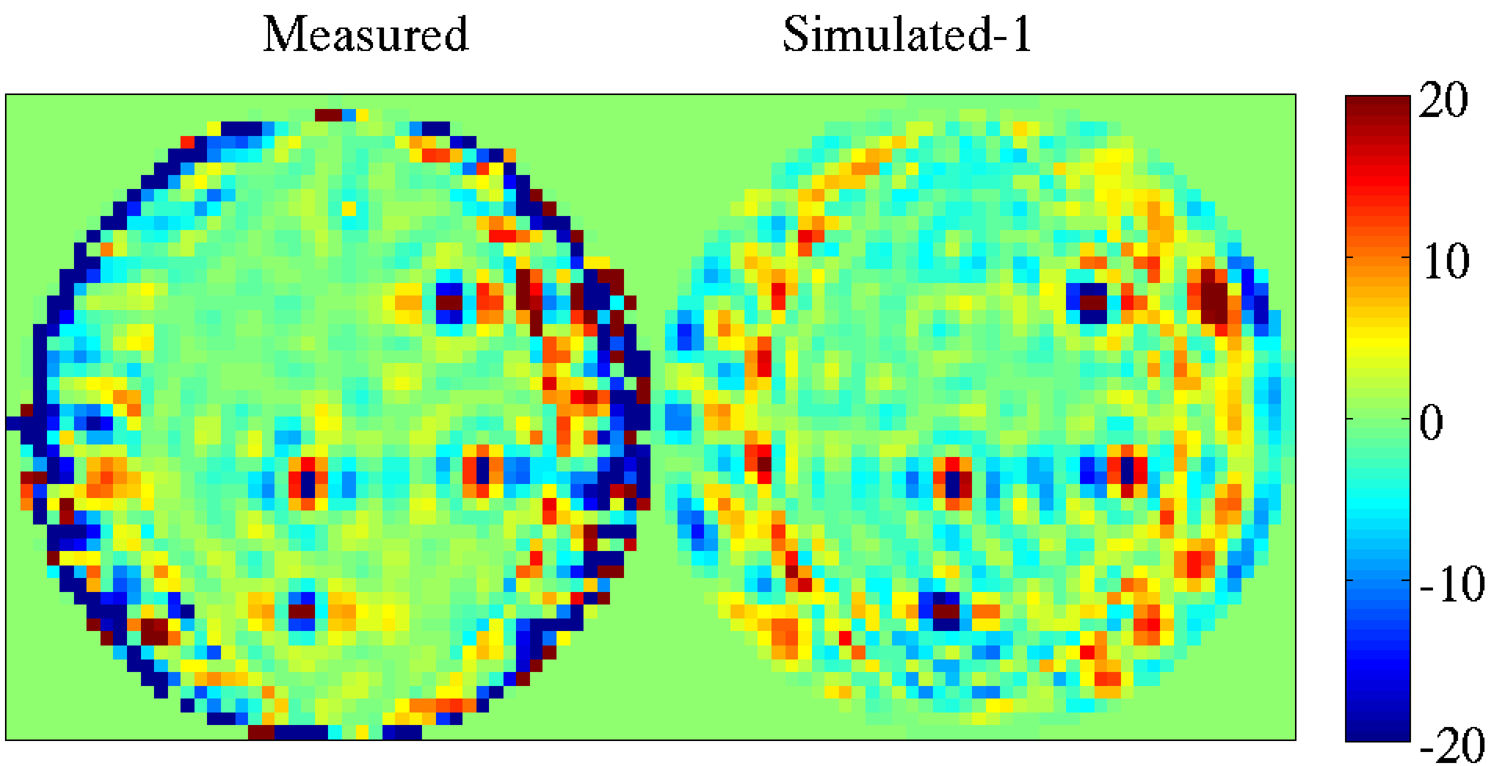
Measured Nominal Act State



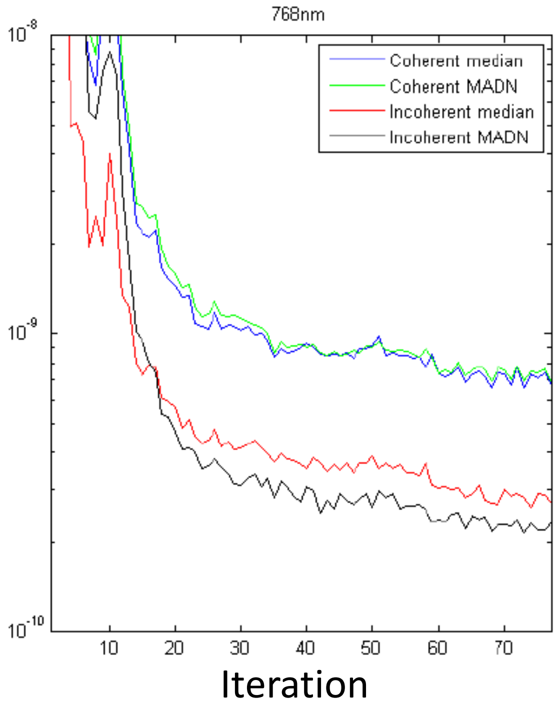
Pegged Actuators: DM Actuator Commands

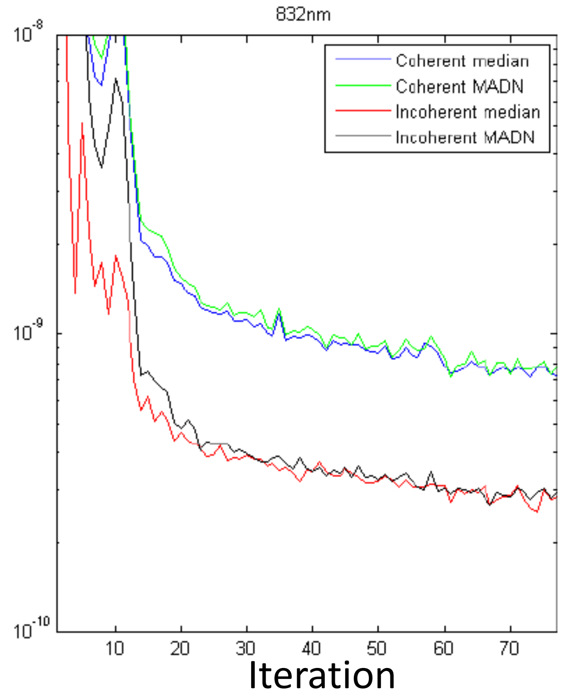
Sim1: Starting with a Flat-DM. Sim2: Starting with "Meas" actuator state

Case of 4-Pairs Act Pegged



Estimation Accuracy

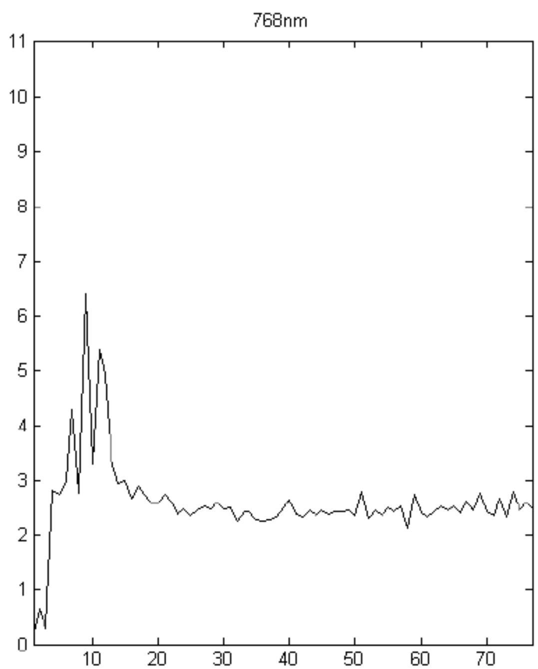


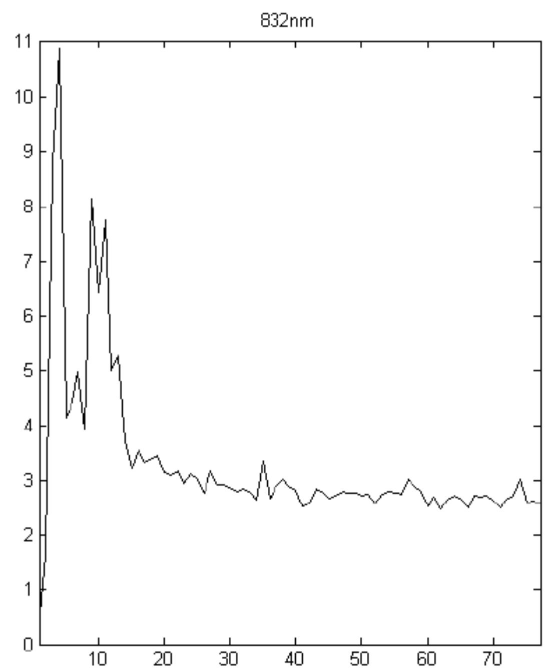


Coherent and Incoherent Measurements

Inc = Total - Coh

Coh comes from wavefront estimation





Looks like Incoherent = 1/3 of Coherent.

We know this is not true: incoherent is much fainter.

More Info can be Found at:

Sidick, E., etal, "Studies of the effects of optical system errors on the HCIT contrast performance," Proc. SPIE 8151, 815106 (ed. S. Shaklan) 2011.

Sidick, E., Shaklan., S., and Balasubramanian, K., "HCIT broadband contrast performance sensitivity studies," Proc. SPIE 8520, 85200M (Ed. J. Dolne, T. Karr, V. Gamiz) 2012.

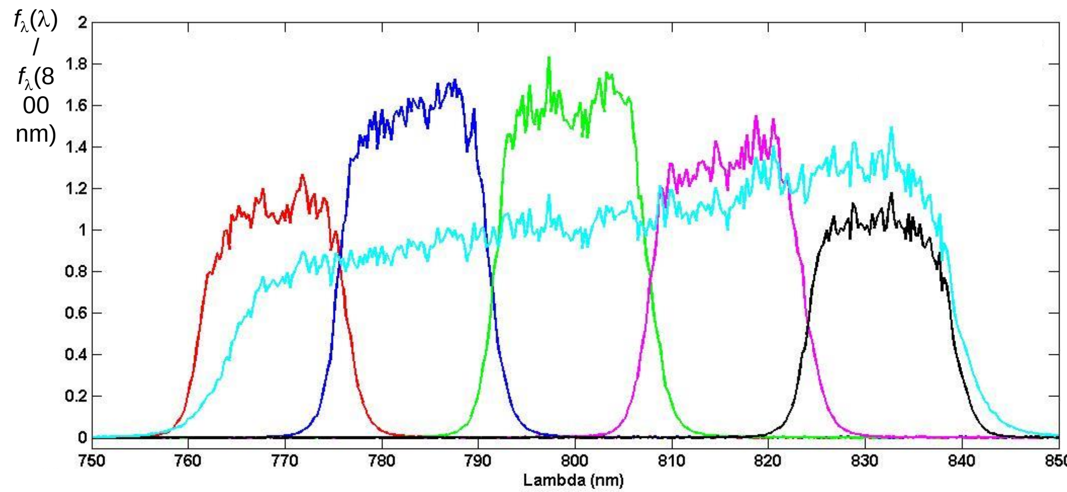
Sidick, E., et al, "HCIT contrast performance sensitivity studies: simulation vs. Experiment," Proc. SPIE 8864, 88640Q (ed. S. Shaklan) 2013.

Sidick, E., et al, "High contrast coronagraph performance in the presence of focal plane mask defects," Proc. SPIE 9143, 914336 (ed. J. Oschmann, M. Clampin, G. Fazio, H. MacEwen) 2014.

Cady, E., and Shaklan, S., "Measurements of incoherent light and background structure at exo_Earth detection levels in the High Contrast Imaging Testbed," Proc. SPIE 9143, 914338 (ed. J. Oschmann, M. Clampin, G. Fazio, H. MacEwen) 2014.

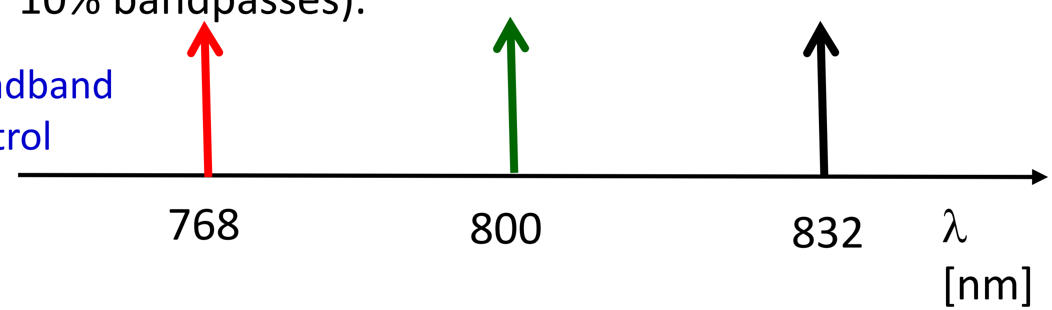
Broadband Control & Contrast: How They are Done

- 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 a 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