National Aeronautics and
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Studies of the Effects of Control Bandwidth and Dark-Hole Size on the HCIT Contrast Performance

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Introduction

- In this presentation, we compare model predictions with HCIT experiments. These were done for Coronagraph Milestone 3 model validation.

Goal of HCIT Experiments for Milestone 3 Model Validation

- Demonstrate the ability to predict the performance sensitivities of a high-contrast imaging system at levels consistent with exoplanet detection requirements

High level description of the technology demonstration

- Milestone 3A: Demonstrate that starlight suppression performance predictions from high-fidelity optical models of the HCIT, utilizing measured data on specific testbed components, are consistent with actual measured results on the testbed. Correlation of model predictions with experimental testbed results validates models at a baseline contrast ratio of better than 1×10^{-9} (goal 1×10^{-10}) over a 60-nm bandwidth.

Closed Loop Test Details

CLOSED LOOP TESTS: WFCS TURNED ON DURING/AFTER PERTURBATION IS INTRODUCED

Test	Tolerancing and Sensitivity	Relevance	Experiment	Comment
Bandwidth	What is the best contrast achievable at a given bandwidth?	Tied to the number of separate starlight suppression channels used to meet science requirements.	Use increasing bandwidth (e.g., 2%, 10%, 20%) to perform wavefront control.	This will help to identify efficient means of performing wavefront control, e.g. 3 wide bands vs. 1 narrow band vs. several narrow bands.
Dead Actuators	How severe is degredation due to a dead actuator?	Important for determining manufacturing and reliability requirements.	Drive one or more actuators to their stroke limit and perform wavefront compensation using the active part of the DM. At least 3 sets of 'dead' actuators will be used	Models show that actuators that fail mid-range are tolerable. Actuators that fail at the stroke limit are difficult to compensate.
Occulter Mask Defect	What is the contrast when the occulter has an obscuring spot?	Broadband performance is highly sensitive to local defects.	Introduce an opaque spot on the mask. Measure the effect of bandpass and filter weighting on the dark hole contrast.	Dust and defects were a limiting factor in ASSIC work.Will be an important issue with circular masks. Less important for linear masks because they can be translated to 'clean' position.
Incoherent Light Estimation Accuracy	How accurate is the coherent light estimator?	Tests ability to extract incoherent signals from the data.	Perform coherent light estimation in the presence of an artifical planet signal. Subtract estimated coherent signal from image and measure SNR of planet detection	Compared phase diversity to pinhole estimation in ASSIC TDEM and found contrast agreement better than 5e-10 with nominal contrast = 4e-9.
Number of Actuators or Size of Dark Hole	How does contrast depend on the number of actuators compared to the size of the dark hole?	More elements provide more DoFs to compensate for broad band effects	Adjust dark hole size until broad band contrast control fails to converge.	Important for exo-Jupiter detections, exozodi mapping, and for digging deep around known exo-Earths.

Introduction (cont.)

- Use a MACOS-based algorithm for simulations which
  - Combines a ray trace, diffraction model, and a broadband wavefront control algorithm
  - Is capable of performing full three-dimensional near-field diffraction analysis

HCIT Optical System

DM

32x32 Actuator Deformable-Mirror

Light Source

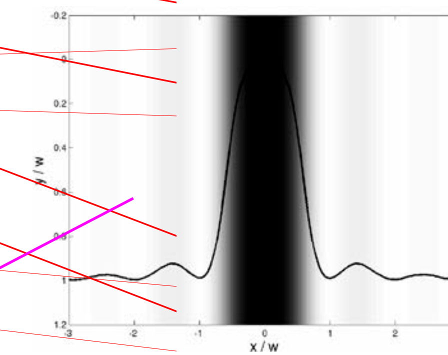
FM

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

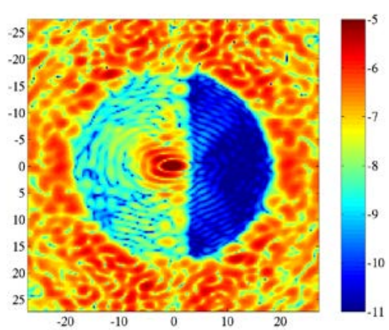
OAP4

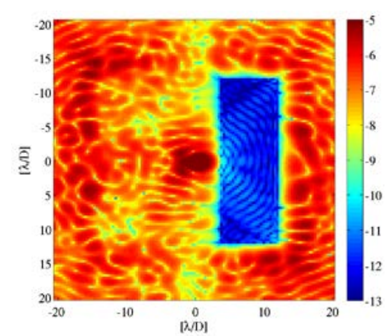
Occulter Transmittance:

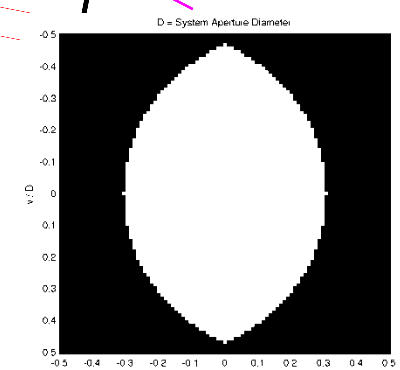
$$T_{\text{sinc}}(x) = [1 - \text{sinc}^2(x/w)]^2$$



Occulter has parasitic phase, and phase & OD dispersion







Definitions: Normalized Intensity & Dark-Hole Area

Normalized Intensity: $I_{\mathrm{n}}(x,y) = I(x,y)/I_0,\quad I(x,y): \text{Occulted},\quad I_0: \text{Un}-\text{Occulted}\ \ \text{Peak Value}$

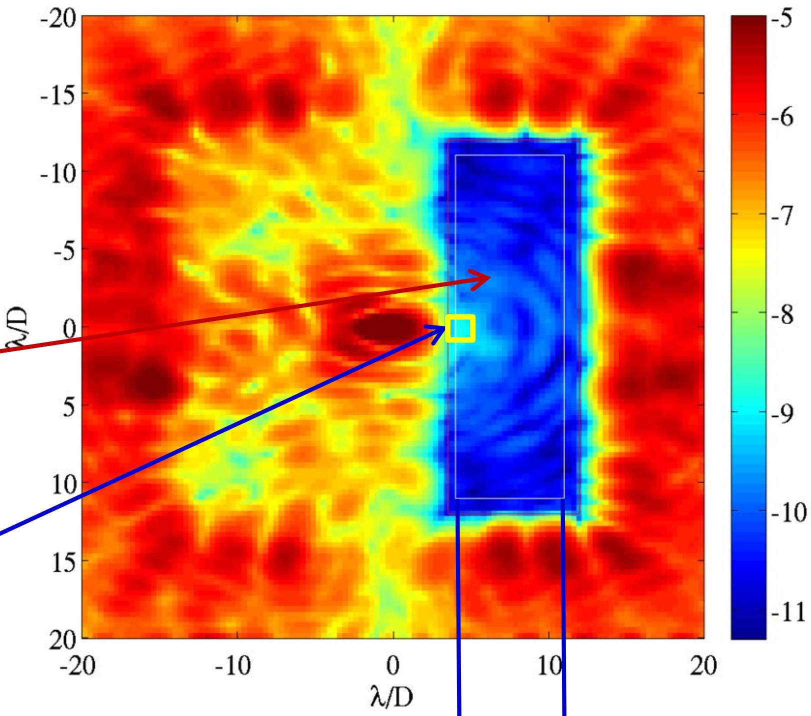
Normalized positions: $X = x/f,\quad Y = y/f,\quad R = \sqrt{X^2+Y^2}$

I_b is mean values averaged over Ω_b :

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

I_s is mean values averaged over Ω_s :

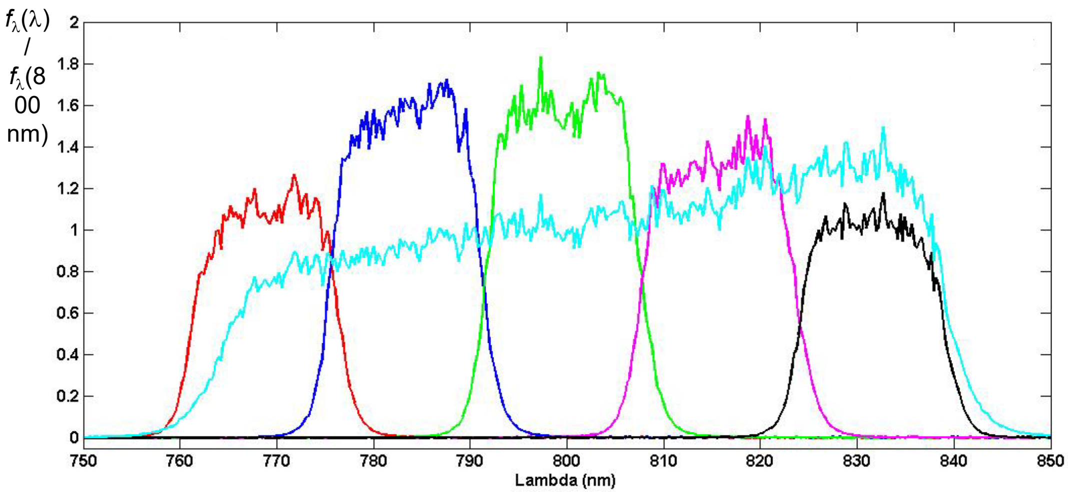
$\Delta X = \Delta Y = 1\lambda/D$



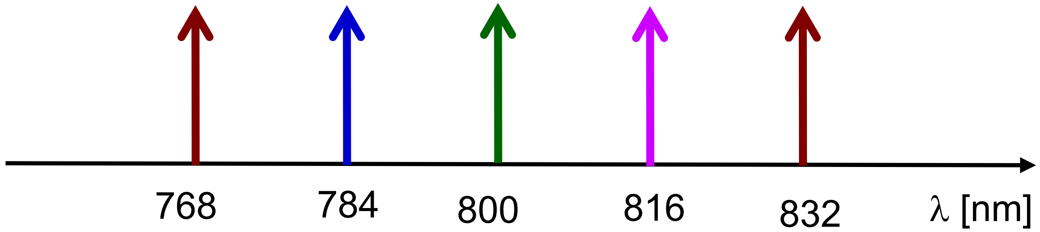
$4\lambda/D$ $\quad 11\lambda/D$

Broadband Control & Contrast: How They are Done

- A super-continuum source (shown on the right) is used for nulling
- For dark-hole size, WFC is carried out at 3 bands, each 2%, centered at 768, 800, 832nm
- For contrast dependence on control bands, WFC is carried out at different number of bands, each 2%
- On testbed, broadband contrast is obtained by evaluating a single set of DM solutions at 3 or five 2%-bands (shown on the right), and averaging the resulted intensity maps
- In simulations, it is done with 3 or 5 monochromatic wavelengths



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

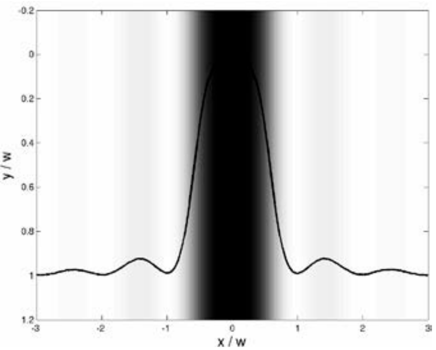


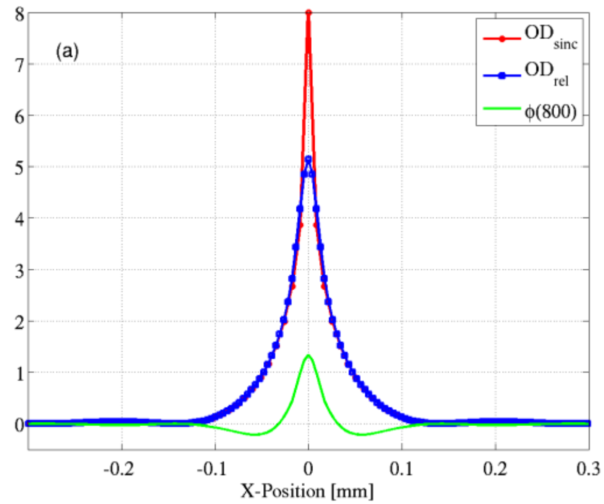
Broadband Field Control and Contrast Evaluation Bands

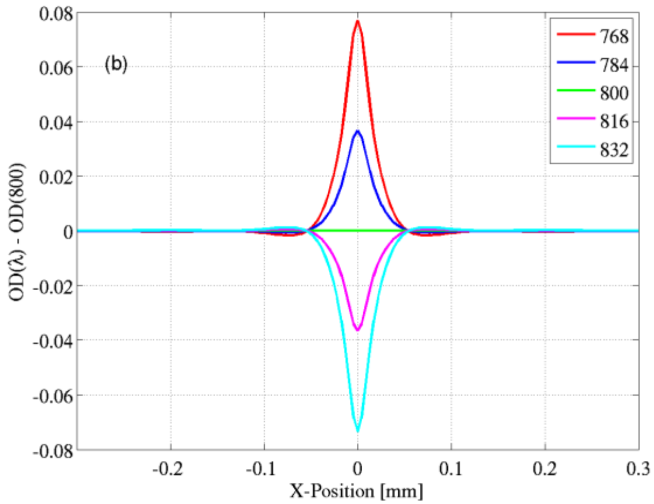
OD and Phase Profiles of Occulting Mask

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

Thin-film Nickel (Ni) occulter deposited on a fused quartz

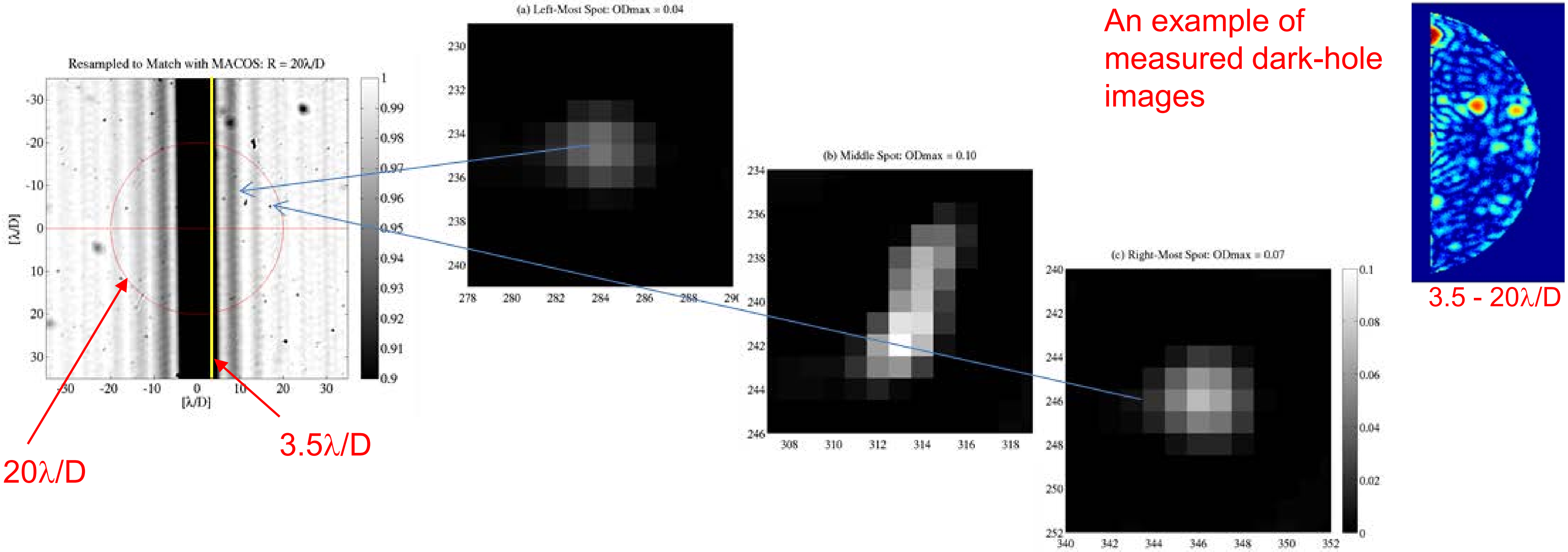






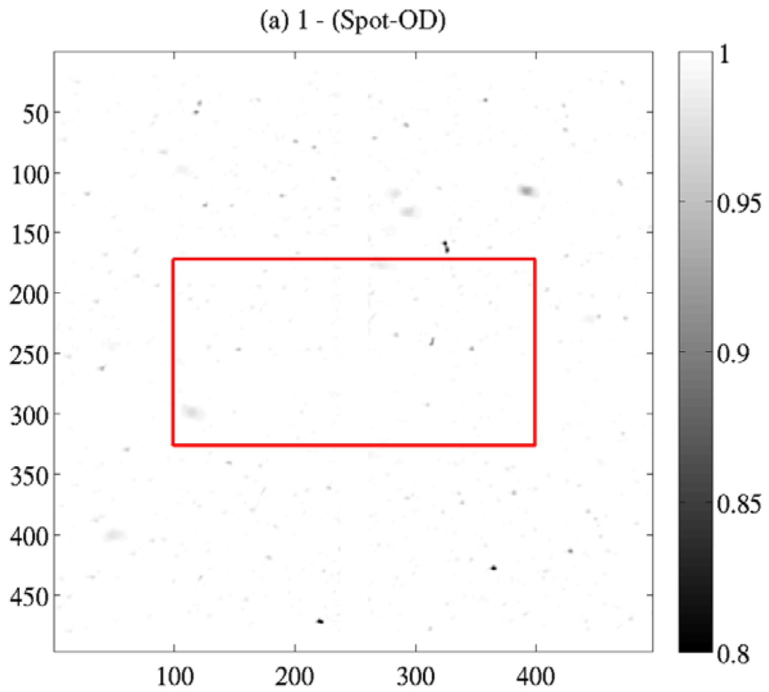
- HCIT uses a modified 1-D band-limited occulter whose OD profile at λ = 800nm is truncated and smoothed by convolution with a Gaussian function
- Occulter is fabricated by vacuum deposition of varying thickness Nickel layer on a fused quartz
- “Model Occulter” uses the above “clean” (free of partially-transmitting spots) OD and phase profiles
- “Measured Occulter” uses the measured transmission coefficient with partially-transmitting spots (including spot phases), and the above phase profile

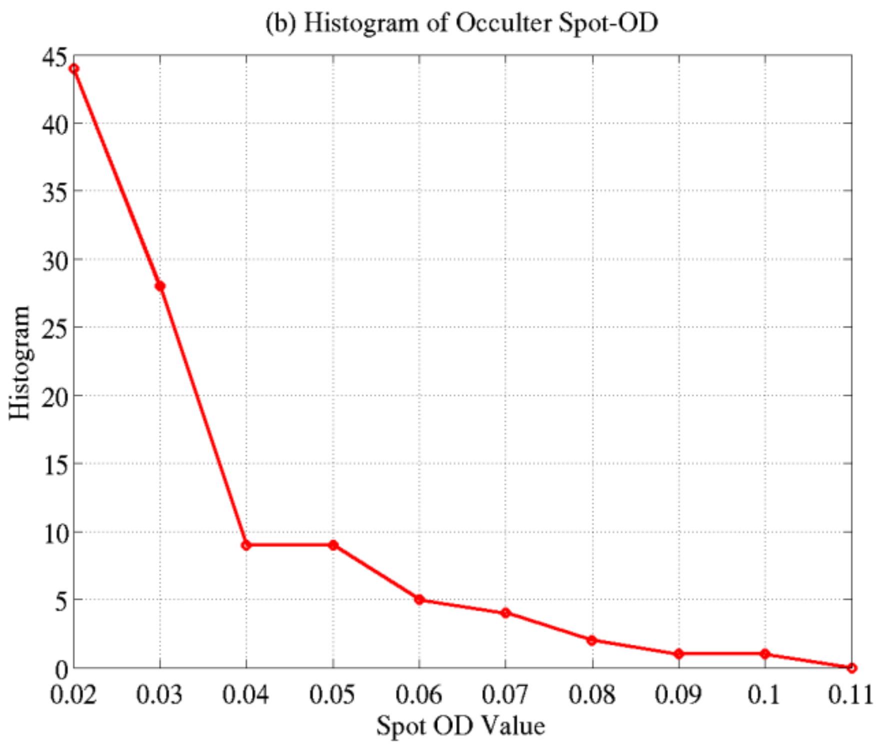
Occulter: Measured Transmission Image with Occulter Spots



- Localized mask errors are the likely cause of the contrast floor
- Measured the transmission (amplitude only, not phase) of the occulter using high resolution microscope images
- Registration of the dark-hole with the mask was confirmed by the presence of 3 spots roughly horizontally aligned within the upper half of the red circle

Distribution of Occulter Spot OD Values



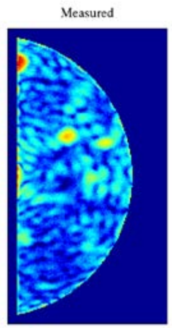


- The red-box (left) has a dimension of X = ±24, Y = ± 14 λ/D, and corresponds to measured dark-hole area

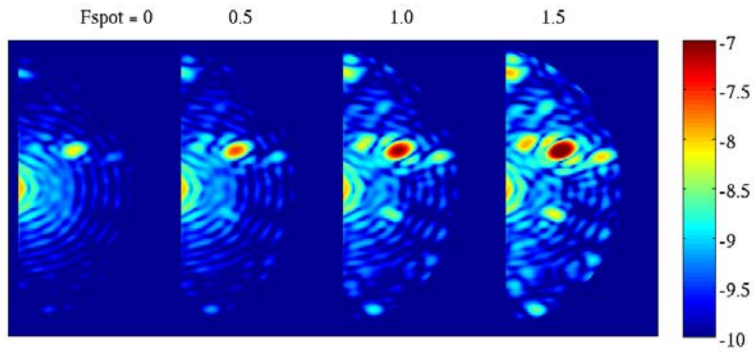
- Right: Histogram of Spot-OD values having OD > 0.02 and are located inside the red-box

Contrast Dependence on Occulter Spot Phase (Simulated)

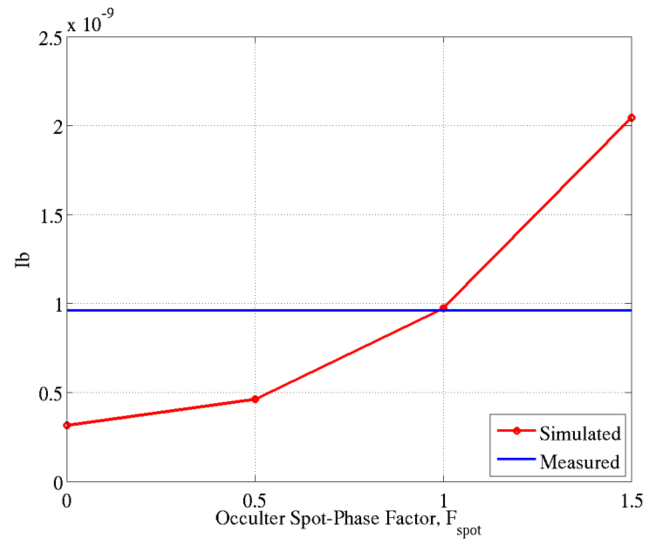
Measured



Simulated



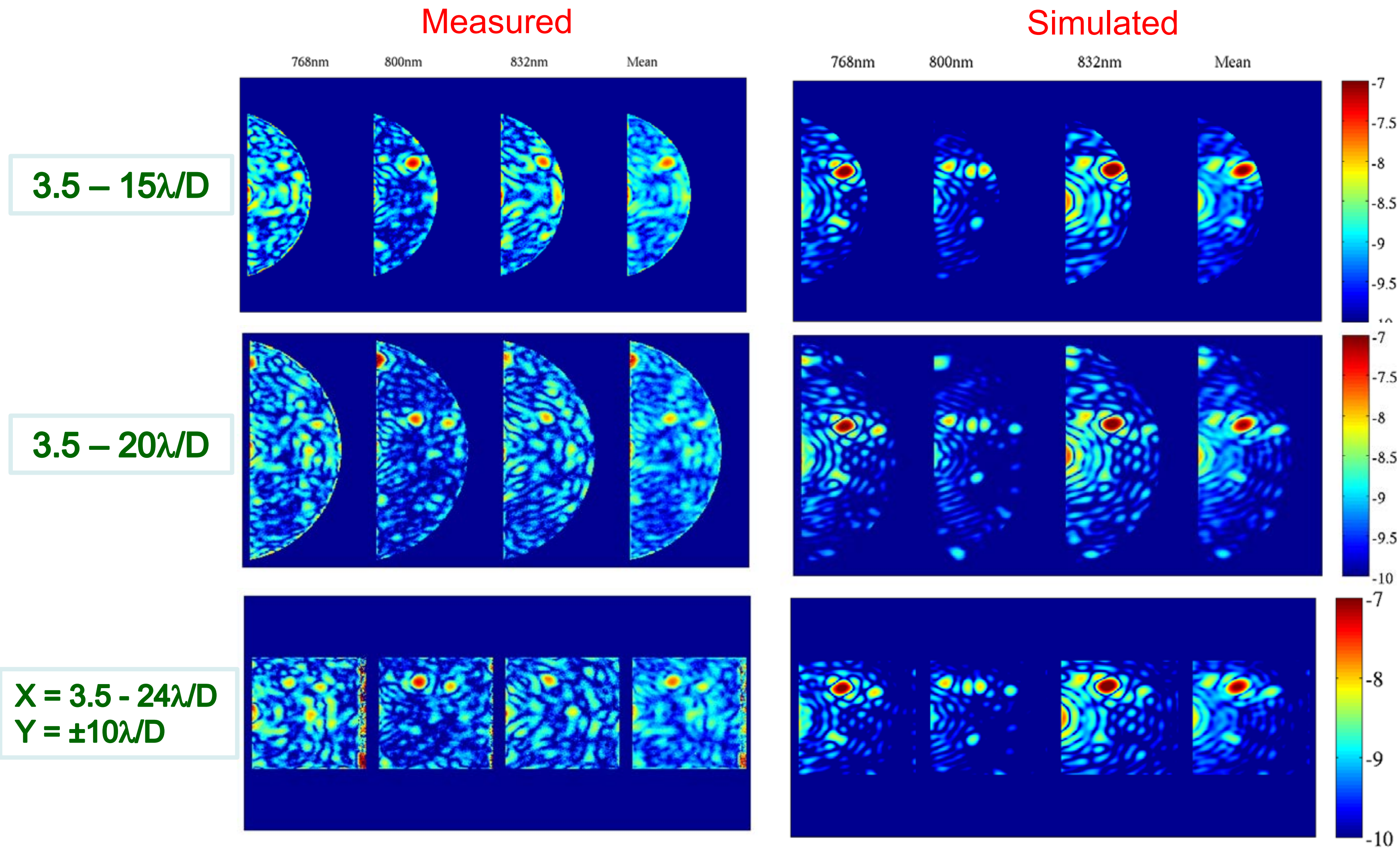
$[X_{min}, R_{max}] = 3.5 - 20\lambda/D$



10% mean contrast vs $_{Fspot}$

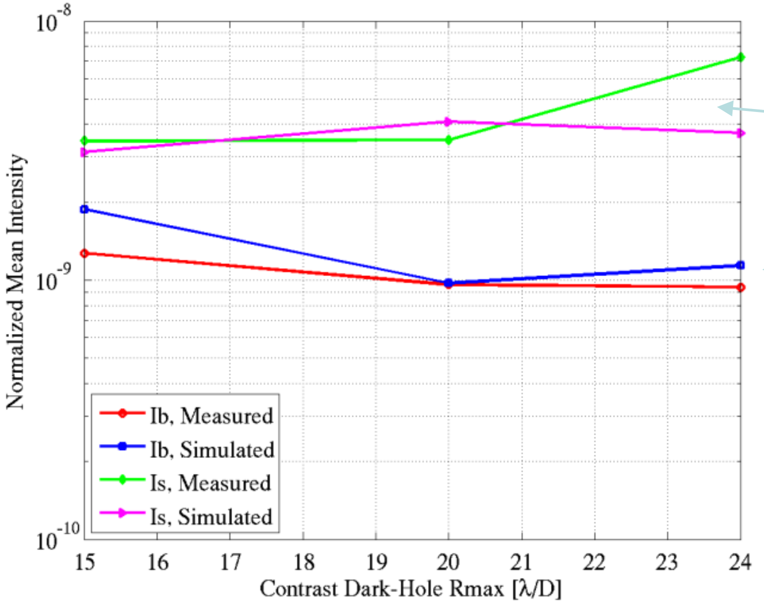
- Introduced Occulter Spot Phase = $F_{spot} \times (\pi / OD_{spot})$
- Found a best match in terms of I_b: $F_{spot} = 1$
- Will use $F_{spot} = 1$ in all simulations

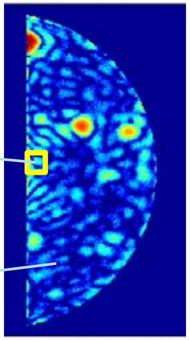
Results: Contrast vs Dark-Hole Size



- Experiments were carried out with the 768, 800, and 832 nm 2%-passband filters, with the resulting images combined to form a composite broad-band image.

Results: Contrast vs Dark-Hole Size (cont.)





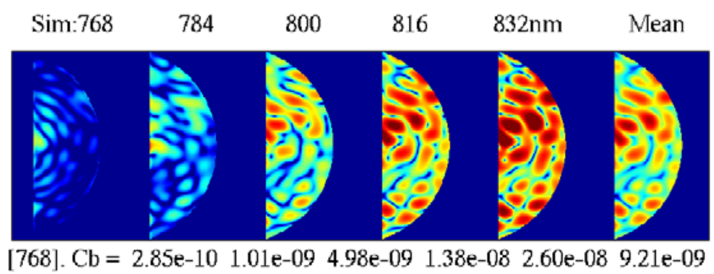
- Average dark-hole contrast is essentially independent of dark-hole size up to the Nyquist-limit of the DM used (24 λ/D for 48x48 actuators).

- For I_b, the worst case model agreement is 32%; for I_s, prediction is off by up to a factor of 2

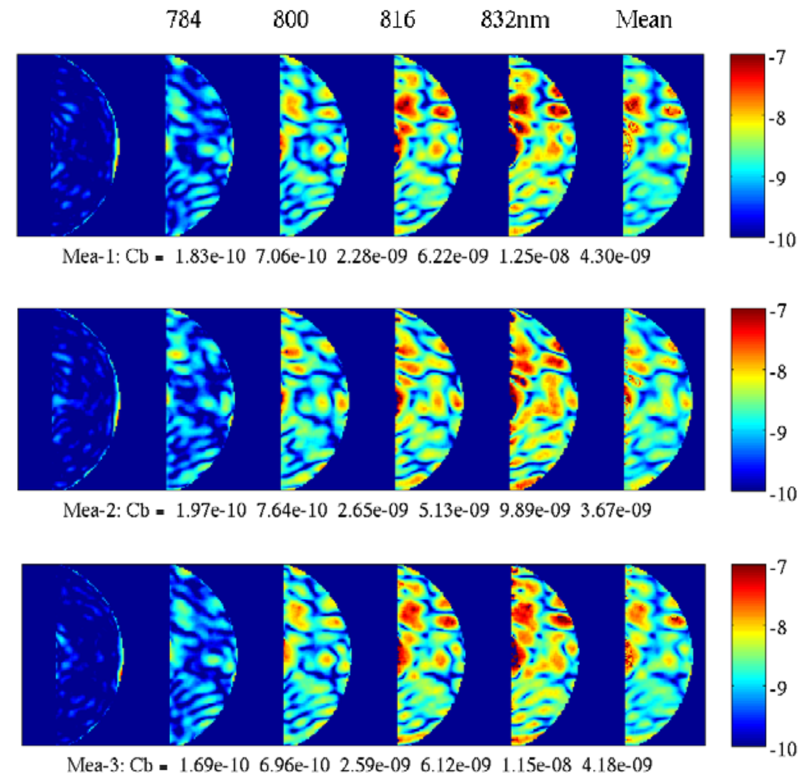
- I_b, and I_s values are provided in a table in the paper

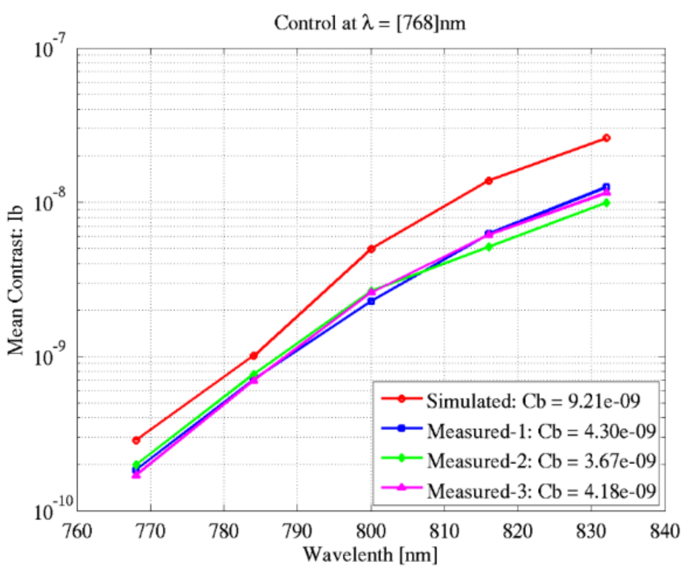
Results: Contrast vs Control Bands

Simulated



Measured





- An example: Single simulation, multiple tests, control at λ = 768nm, evaluation with 5-λ's
- Different tests were done on different days
- Occulter area used in these tests/simulations is different from dark-hole size mask—The 3 big spots do not exist, but there are many other smaller spots on this occulter surface

Results: Contrast vs Control Bands (cont.)

Control Bands | Simulated | Measured

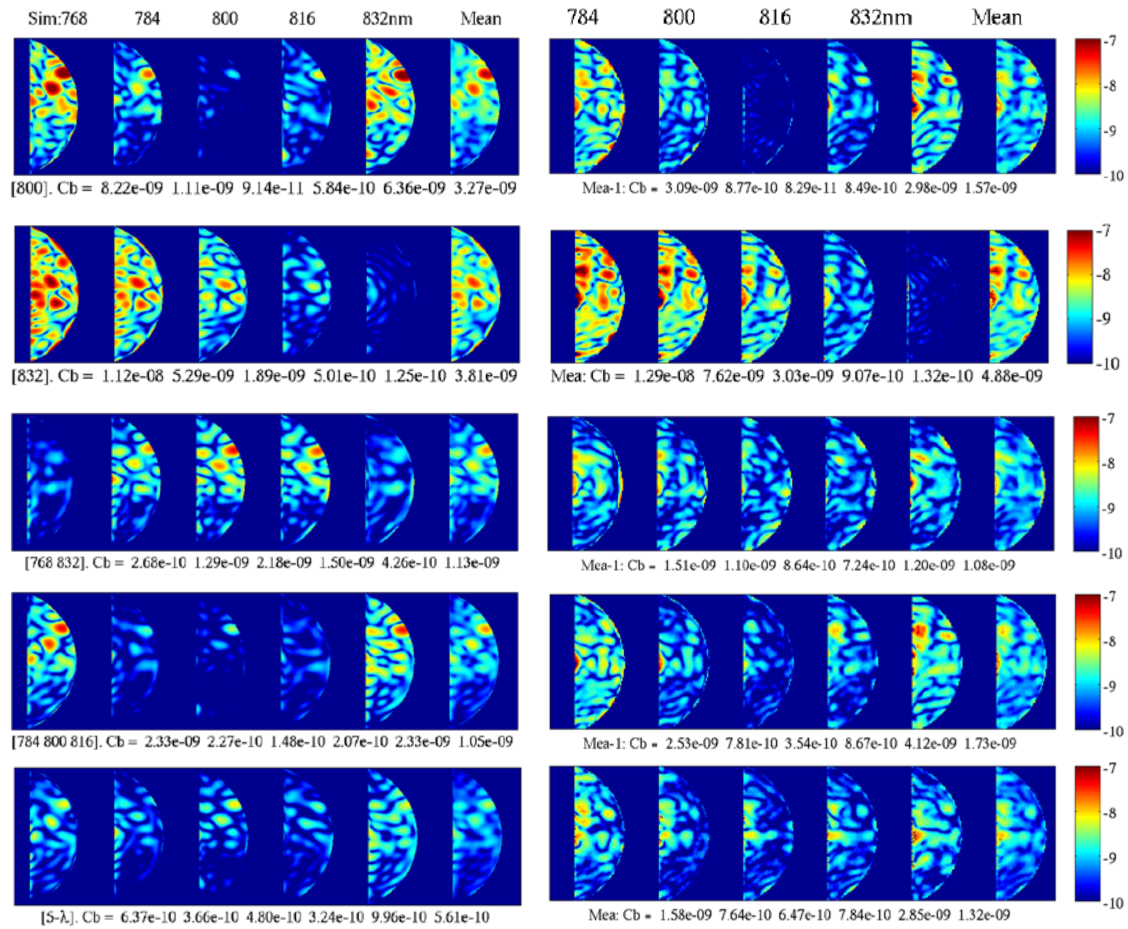
800nm

832nm

768, 832nm

784, 800, 816nm

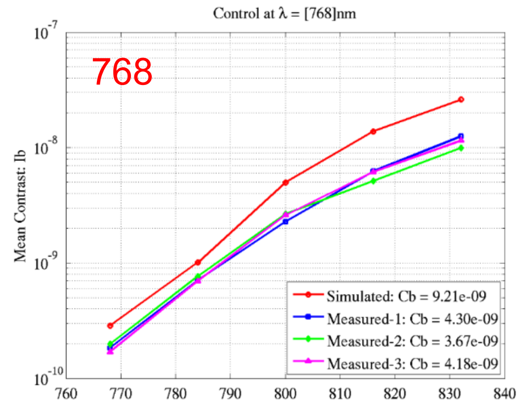
All 5 bands

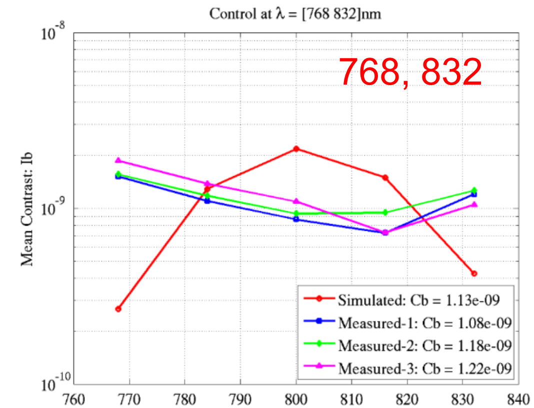


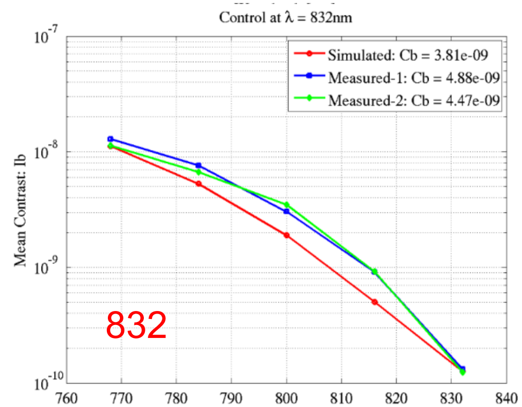
- Only one example is shown for each measured case

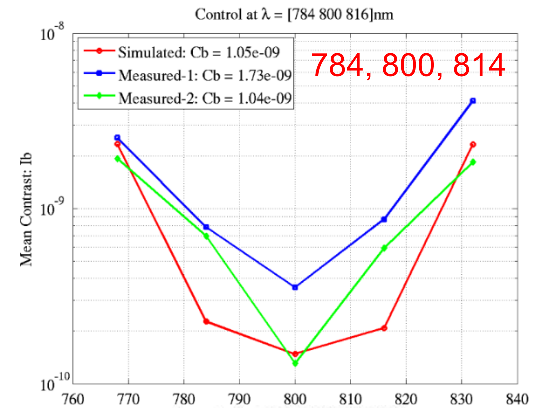
Results: Contrast vs Control Bands (cont.)

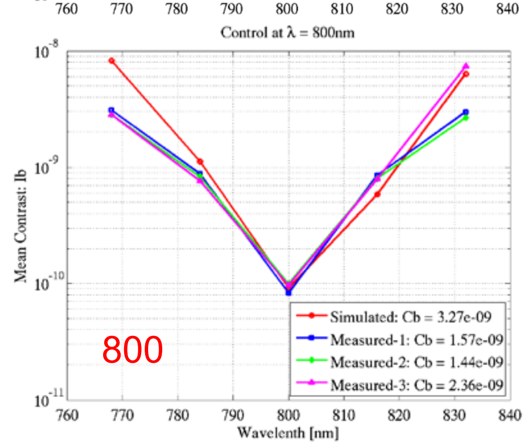
- Multiple tests in all cases except one with 5-λ's
- The prediction for 768, 832nm control is intuitive. But the testbed did not behave this way. We do not understand why this happened.
- Another significant difference is seen in 784, 800, 816nm control. Here, the model predicts what looks like a quadratic increase in contrast from the central band outward, but the experiment shows that the contrast increases linearly (in log space).
- Measured (mean) and simulated I_b values are provided in a table in the paper

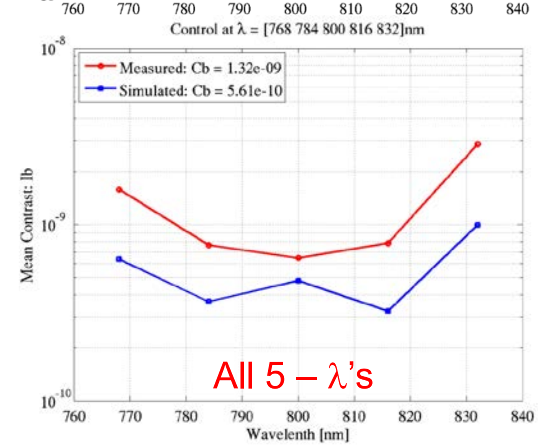












Summary

- We have found in *Sidick et al, SPIE 9143 (2014)* that the average value, general nature, and chromatic behavior of the dark hole floor is explained by a model based on the measured occulter transmittance image after introducing additional phase values to all major occulter spots: Spot-Phase = π x (Spot-OD)
- Results of the current studies reinforce those findings:
  - Mask contaminants or defects, such as partially-transmitting spots with large parasitic phases, were the performance-limiting factor
- Presented results on our theoretical and experimental studies of the sensitivity of dark-hole contrast to the control bandwidth and dark-hole dimensions in our HCIT testbed
- Showed good agreement between measurement and simulations, with one major and unexplained difference that the experiment and model diverged when we controlled only at the two end points in wavelength. This result remains unexplained
- These experimental validations of key coronagraph sensitivity factors will additionally contribute to the confidence in performance prediction models for future flight systems