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

Occulter Transmittance:

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

32x32 Actuator Deformable-Mirror

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

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

\[ w = 142\,\mu m \]

Truncation & Smoothing \(\rightarrow T_{\text{rel}}(x)\)

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

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

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

**WFC over \( \Omega_c \):** \[ 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 \( \Omega_b \): \[ X_1 \ X_2 \ Y_1 \ Y_2 ] = [4 11 -11 11] \lambda / D \)

\( I_s \) and \( C_s \) are mean values averaged over \( \Omega_s \): \( \Delta X = \Delta Y = 1 \lambda / D \)

\( I_m \) and \( C_m \) are maximum values inside \( \Omega_s \)
**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).](image-url)

**Broadband Control**

- 768 nm
- 800 nm
- 832 nm

**Broadband Contrast Evaluation**

- 768 nm
- 784 nm
- 800 nm
- 816 nm
- 832 nm

\[ \frac{f_{\lambda}(\lambda)}{f_{\lambda}(800\text{ nm})} \]
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
• Want to understand how dust particles affect broadband WFC efficiency and contrast

• Placed 1, 3 and 6 square particles with $w = 114 \mu m$ 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
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 $\Delta x = \sim 280\mu m$-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-\(\lambda\) Control

Measured: After 5-\(\lambda\) (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 $N_{\text{dead}} = 0$, 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.
Summary

• Light scattered into the dark-hole by a size \(\sim 100\mu\text{m}\) particle cannot be completely eliminated
• A size \(\sim 100\mu\text{m}\) 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