Experimental Progress and Limitations of Optimal Wavefront Correction in Polychromatic Light

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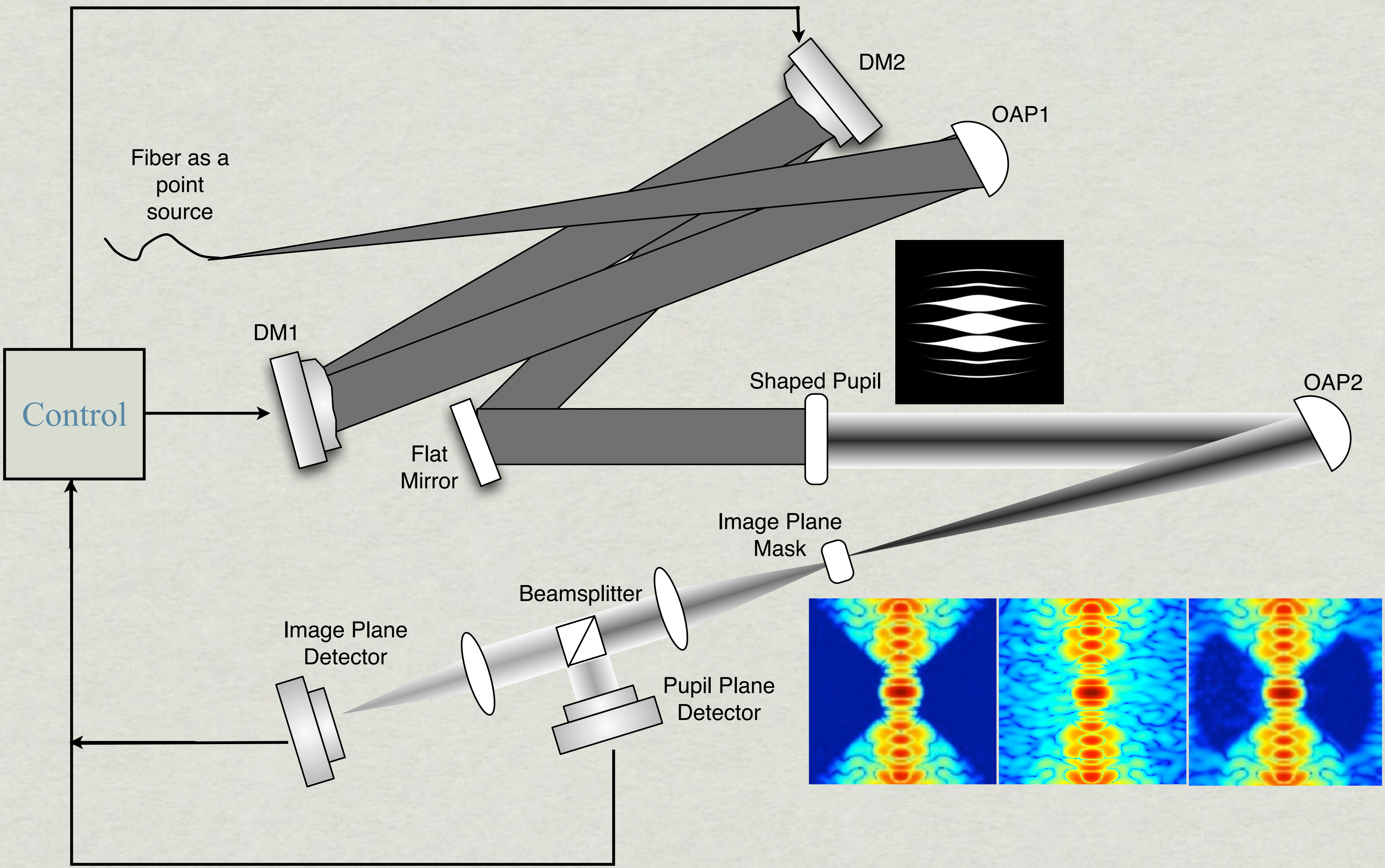
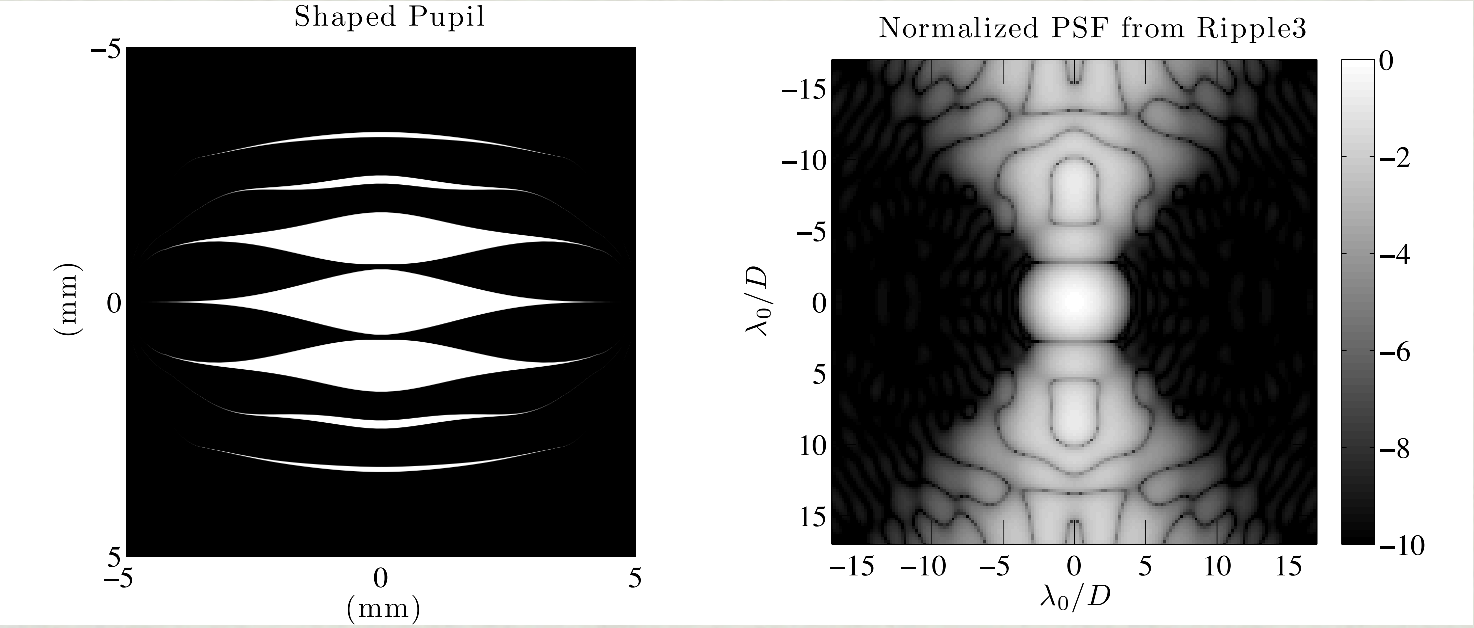
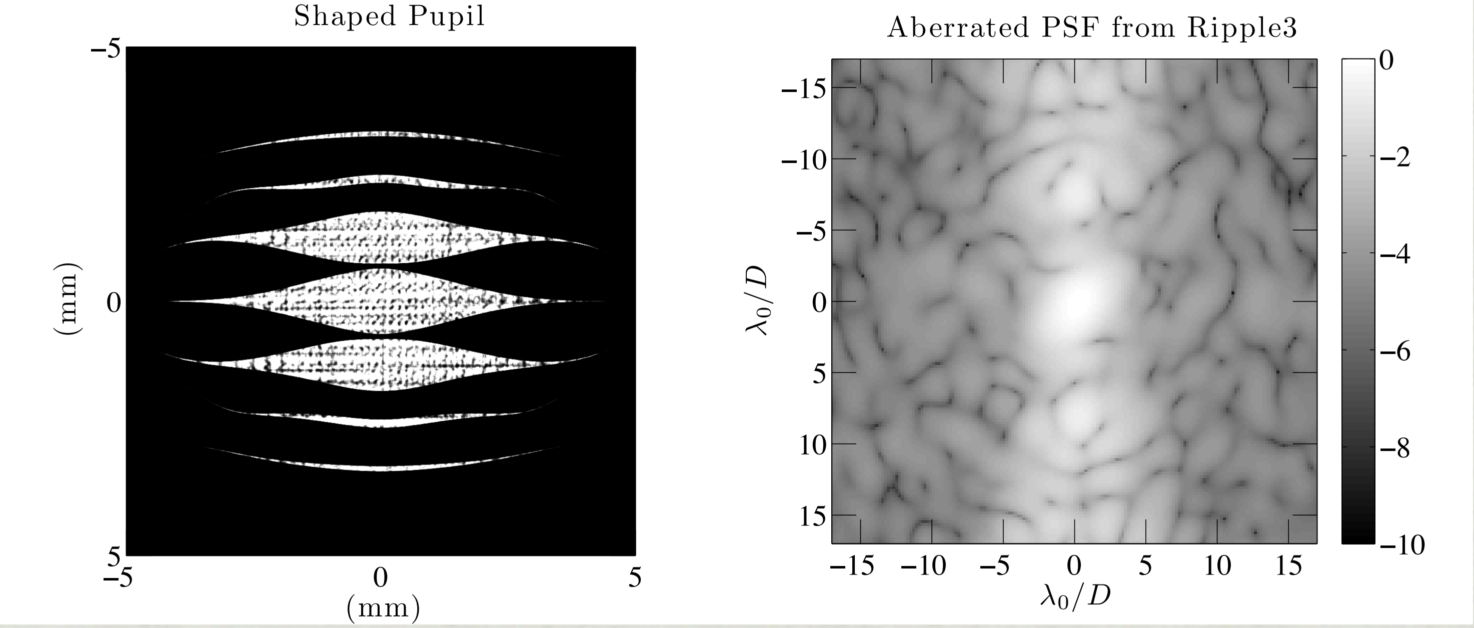
Princeton High Contrast Imaging Lab



Shaped Pupil Coronagraph



Ripple3 Shaped Pupil
and its PSF with 10^{-10} contrast



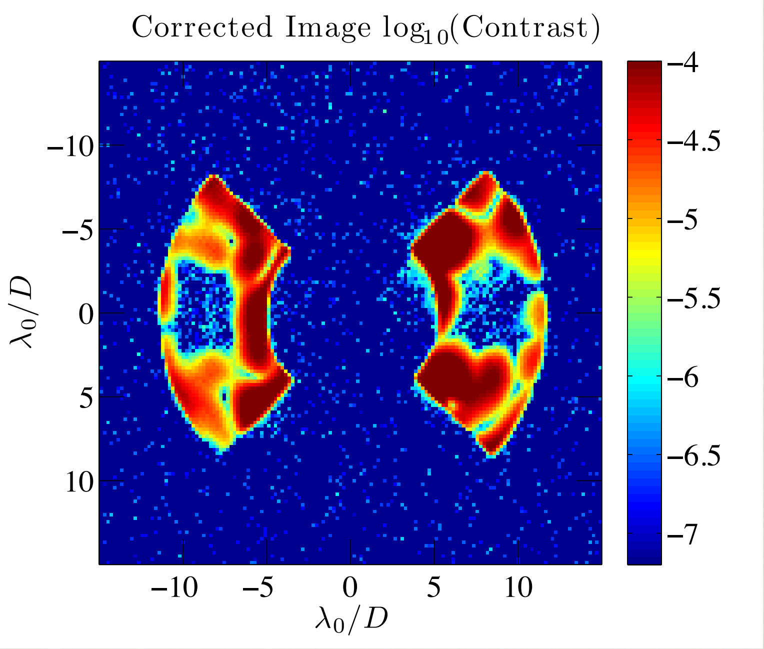
Ripple3 Shaped Pupil
and its PSF with 10^{-5} contrast

After Fresnel Propagating the
DM zero-volt surfaces

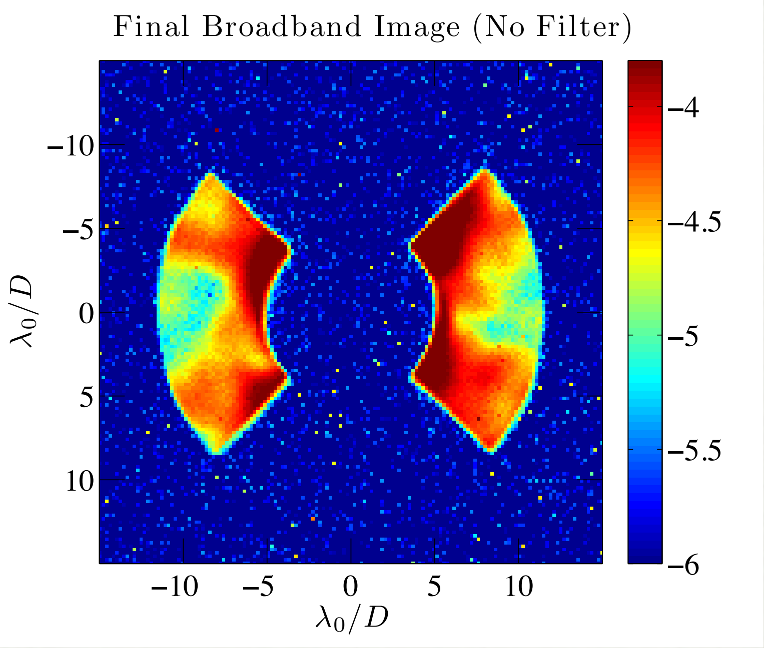
Kasdin et. al 2003
Kasdin et. al 2005
Belikov et. al 2007

Introduction (Results)

- Monochromatic Results
  - 2.34×10^{-7} Contrast in Symmetric Dark Holes



- Broadband Suppression with Monochromatic Estimation
  - 5.36×10^{-6} Contrast in Symmetric Dark Holes in 10% Band



Correction Algorithm: Stroke Minimization

Dark Zone Intensity:

$$I_{DZ} = \left(\frac{2\pi}{\lambda}\right)^2 XMX^T + \frac{4\pi}{\lambda} X \Im\{b^T\} + d$$

Optimization problem:

$$\begin{aligned} &\text{minimize} && \textstyle\sum_{k=1}^{N} a_k^2 = XX^T \\ &\text{subject to} && I_{DZ} \leq 10^{-C} \end{aligned}$$

Cost Function:

$$J = X\left(\mathcal{I} + \mu\left(\frac{2\pi}{\lambda}\right)^2 M\right)X^T + \mu\frac{4\pi}{\lambda}X\Im(b^T) + \mu(d - 10^{-C})$$

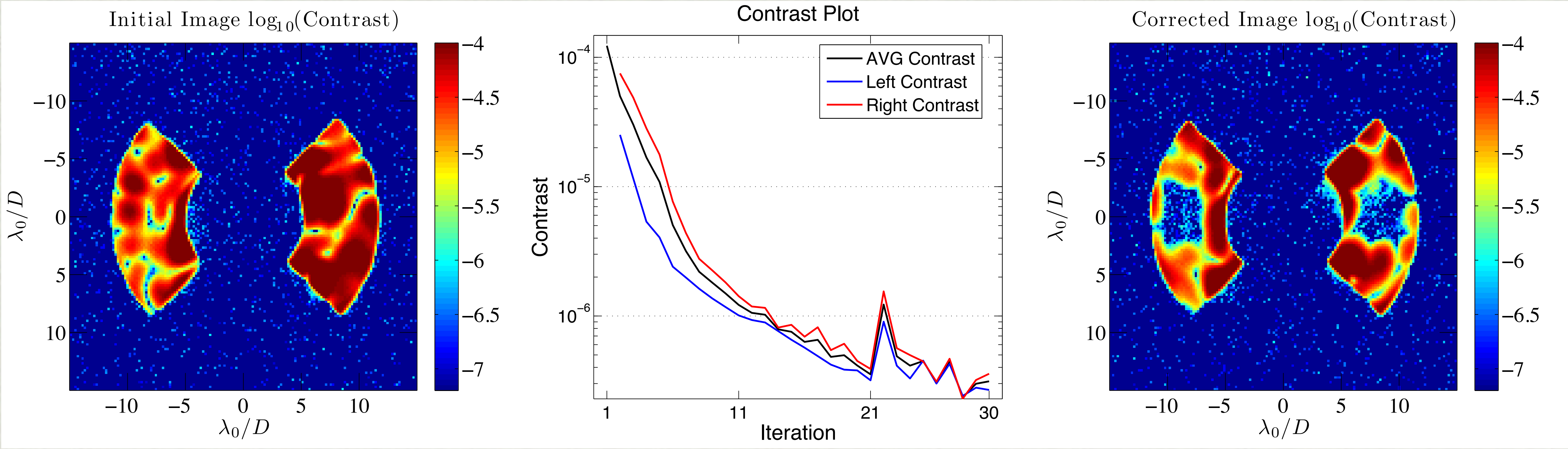
Optimal DM command:

$$X_{opt} = -\mu\Im(b)\left(\frac{\lambda}{2\pi}\mathcal{I} + \mu\frac{2\pi}{\lambda}M\right)^{-1}$$

X	$=$	$[a_1, a_2, ..., a_n]$	Basis function coefficients
M	$=$	$\langle\mathcal{F}\{Af\}, \mathcal{F}\{Af\}\rangle$	Dark Zone influence of basis functions
b	$=$	$\langle\mathcal{F}\{A(1+g)\}, \mathcal{F}\{Af\}\rangle$	Dark Zone effect of basis functions with aberrations
d	$=$	$\langle\mathcal{F}\{Ag\}, \mathcal{F}\{Ag\}\rangle$	Dark Zone effect of aberrations

Pueyo et. al 2009, Applied Optics Vol. 48 Number 32

Monochromatic Performance



- Initial Contrast = 1.23 x 10^{-4}
- Final Average Contrast = 2.34 x 10^{-7}
  - Left Dark Hole = 2.41 x 10^{-7}
  - Right Dark Hole = 2.28 x 10^{-7}

Best monochromatic correction to-date on both sides of the image plane

- Improvements in DM model
- Improved stability in the experiment

Current Limitations

- DM model error
- Laser power stability
- Camera noise
- Air Experiment - Computation Time

Broadband Correction

- Correct polychromatically with single wavelength estimate
- Optimal solution for multiple wavelengths
- Estimation is the most costly component of an iteration
  - Pairwise Estimation requires at least 6 exposures
  - Simultaneous estimation means non-common Path
  - Common path means temporal ambiguity

Requires an expression for wavefront error as a function of wavelength

Scaling a Single Estimate with Wavelength

Pupil Electric Field:

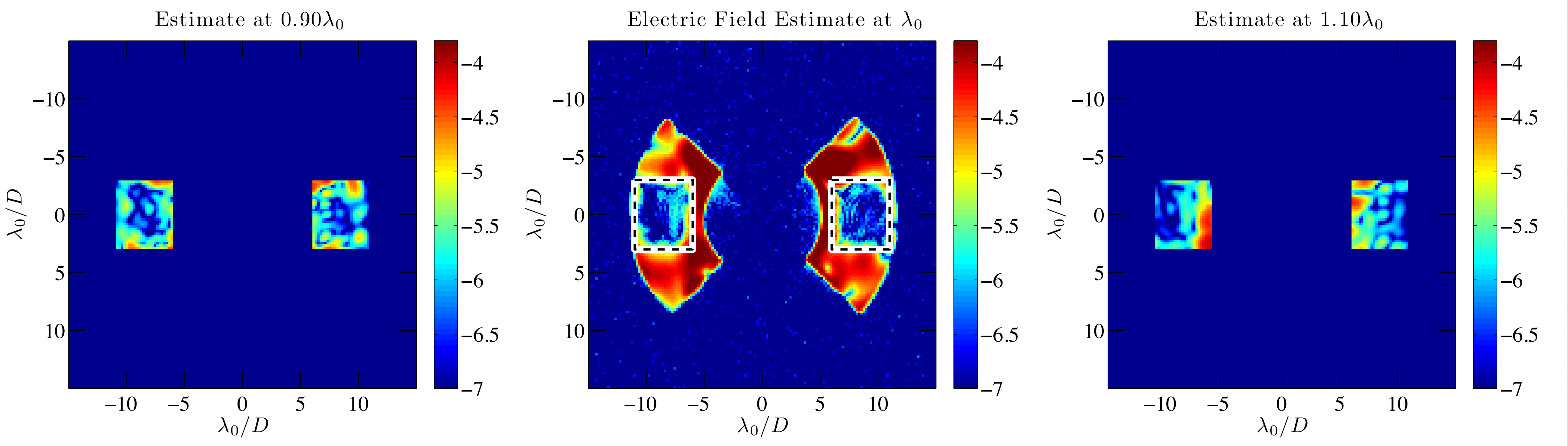
- Amplitude errors are wavelength independent
- Phase errors scale linearly in wavelength

$$g(u,v,\lambda) = \alpha(u,v)\, e^{i\frac{\lambda_0}{\lambda}\beta_0}$$

Functional relationship:

$$\frac{g(u,v,\lambda_0)^{\frac{\lambda_0}{\lambda}}}{|g(u,v,\lambda_0)|^{\frac{\lambda_0}{\lambda}-1}}$$

$$E_{est}(\lambda) = \mathcal{C}_\lambda \left\{ \frac{\mathcal{C}_{\lambda_0}^{-1}\{E_{est}(\lambda_0)\}^{\frac{\lambda_0}{\lambda}}}{|\mathcal{C}_{\lambda_0}^{-1}\{E_{est}(\lambda_0)\}|^{\frac{\lambda_0}{\lambda}-1}} \right\}$$



Limitations: 1) Bounds of estimation area limit accuracy of shift

2) Assume wavelength independence of amplitude errors

Windowed Stroke Minimization

Wavelength Dependent Dark Zone Intensity:

$$I_{DZ}(\lambda) = w(\lambda)\left(\frac{2\pi}{\lambda}\right)^2 X M_\lambda X^T + w(\lambda)\frac{4\pi}{\lambda}\Im\{b_\lambda\}X^T + w(\lambda)d_\lambda$$

Optimization problem:

λ_0 is the Estimated Wavelength

$$\begin{aligned}
\text{minimize} \quad & \sum_{k=1}^{N} a_k^2 = XX^T \\
\text{subject to:} \quad & I_{DZ}(\lambda_0) \leq 10^{-C_{\lambda_0}}, \\
& I_{DZ}(\lambda_1) \leq 10^{-C_{\lambda_1}}, \\
& I_{DZ}(\lambda_2) \leq 10^{-C_{\lambda_2}} \\
\text{where} \quad & \lambda_1 = \gamma_1 \lambda_0 \\
& \lambda_2 = \gamma_2 \lambda_0
\end{aligned}$$

$$\begin{aligned}
M_\lambda &= \; < C_\lambda\{A_o f\}, C_\lambda\{A_o f\} > \\
b_\lambda &= \; < C_\lambda\{A_o(1+g_\lambda)\}, C_\lambda\{A_o f\} > \\
d_\lambda &= \; < C_\lambda\{A_o g_\lambda\}, C_\lambda\{A_o g_\lambda\} > \\
w(\lambda) &= \text{Intensity Normalization Function}
\end{aligned}$$

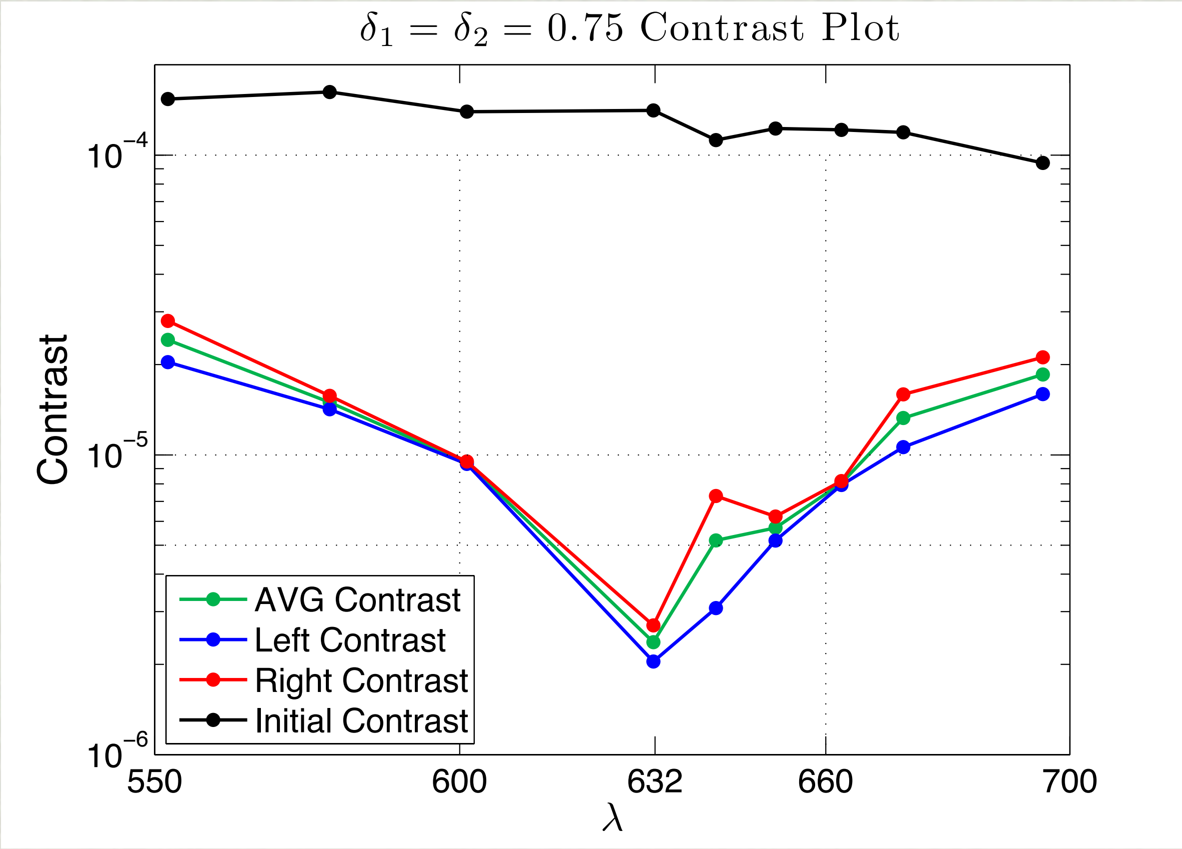
These are the same matrices, but the aberrations and transfer function, C, are wavelength dependent

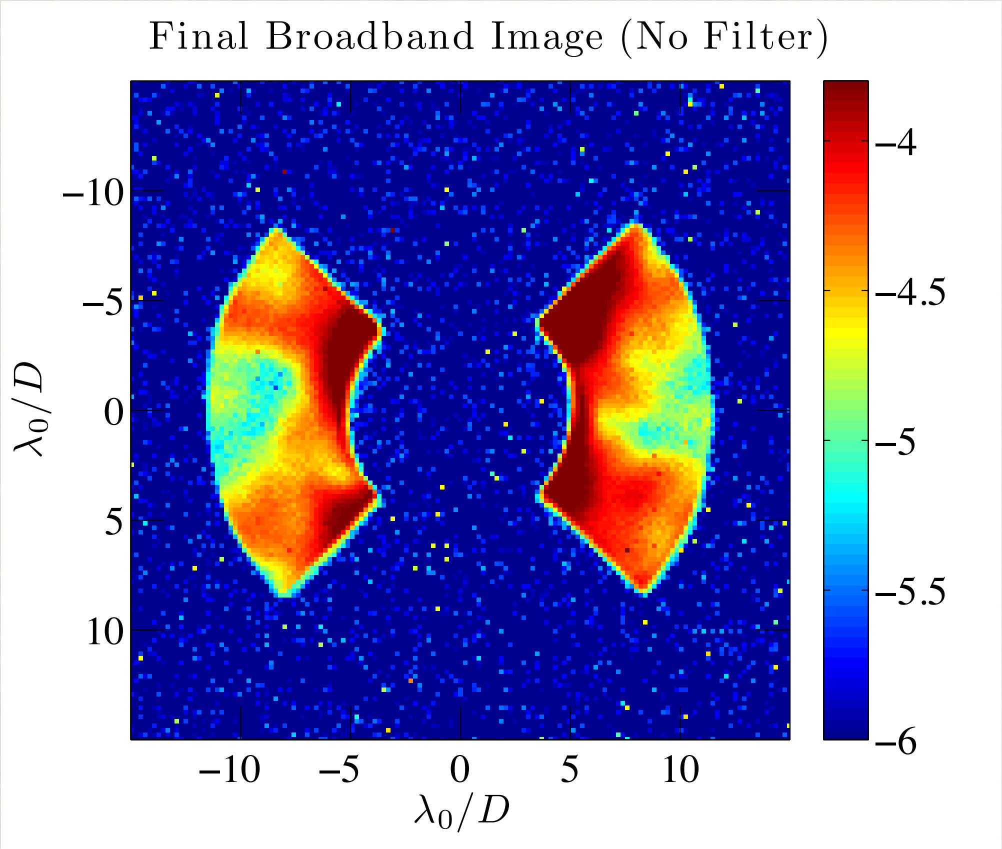
Correction Procedure

- Take an initial data set with each filter
- Estimate and Correct at the central wavelength (632nm)
  - Calculating bounding wavelength estimates (10-20%)
  - Windowed Stroke Minimization algorithm
- After the dark hole is generated, take another filter set

Experimental Results

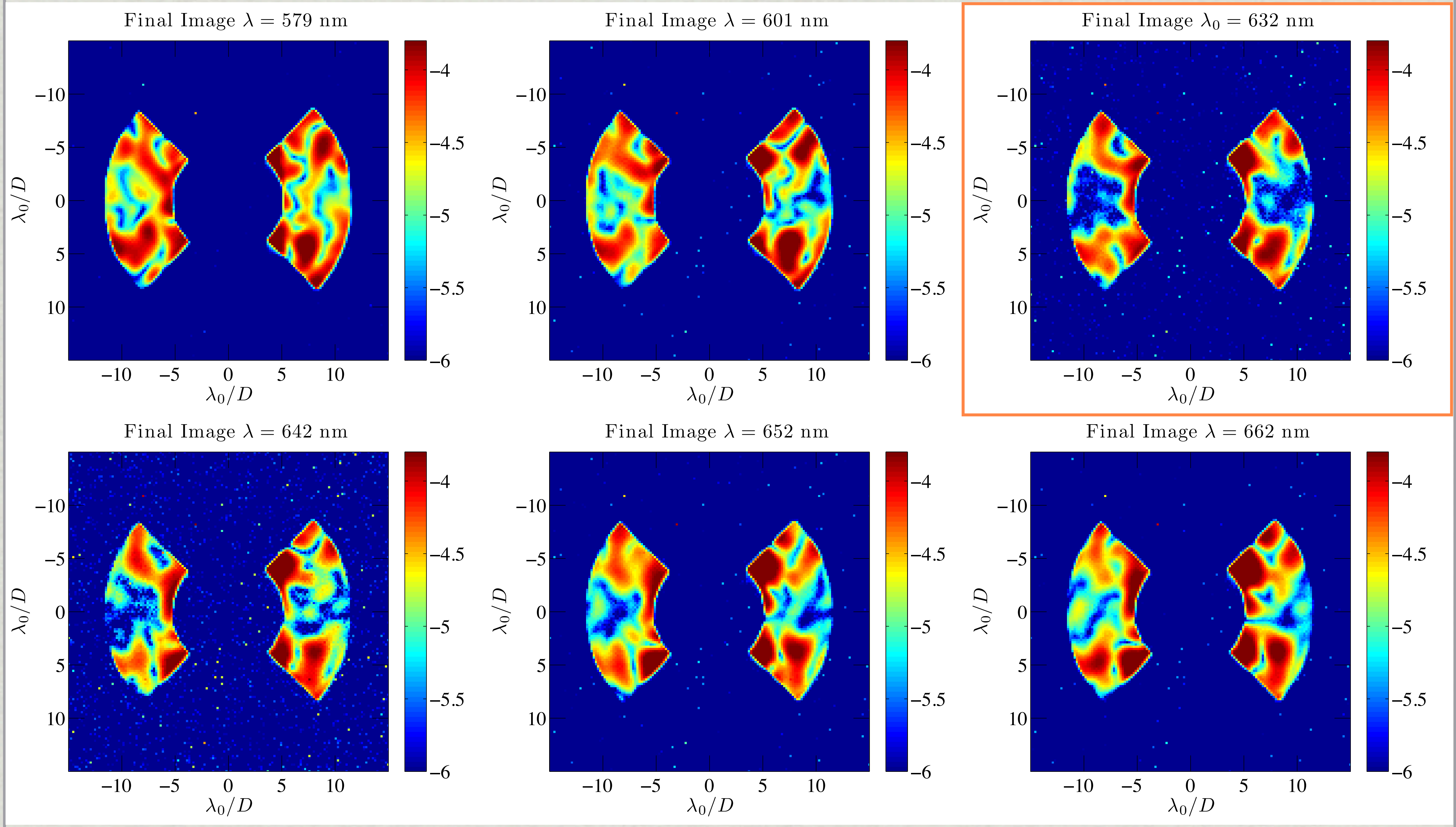
- 10% mean contrast = 5.67 x 10^{-6}
- No Filter (~400-900 nm detector response)



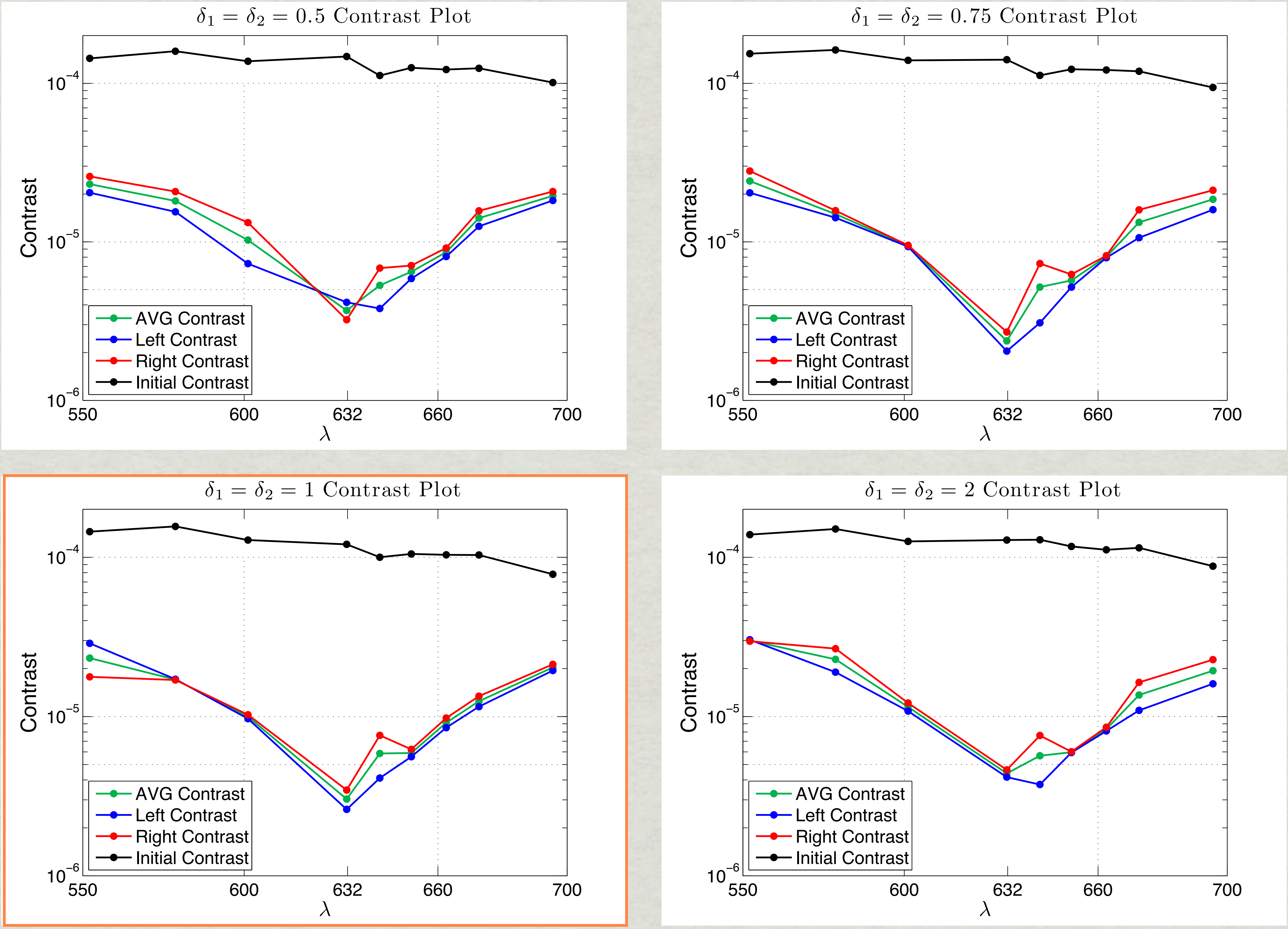


- Full Band Contrast = 1.84 x 10^{-5}
- Approximately 10-17 Volts actuation P-V (~30 nm)

Dark Hole Degradation with Wavelength



Varying Delta to Measure Contrast Performance



Conclusions

Current Performance

- Optimal Broadband Suppression in symmetric dark holes
- Estimating at a single wavelength
- 5.67×10^{-6} Average contrast in symmetric dark holes
  10% band with ~30 nm P-V actuation
- 1.84×10^{-5} Average contrast in symmetric dark holes
  22% band

Limitations:

- Narrow, assymetric band of single mode fiber output
- Finite extent of the electric field estimate
- Assumption of wavelength independent amplitude aberrations
- Input of the shifted estimates amplifies the original estimate error in the control algorithm

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Future Work

Experimental:

- Minimize errors from wavelength shifting
    - Increase Estimation area beyond control area
    - Establish a characteristic wavelength relationship for amplitude errors (design specific, e.g. 2 DMs in series)
- Improve DM model
- Broadband photonic crystal single-mode fiber

Theoretical:

- Establish a tradeoff between bandwidth and dark hole size, single vs. two sided dark holes, and lowest achievable contrast
- Proof of estimation error propagation