

End-to-End Modeling of Coronagraphs

John Krist (JPL)

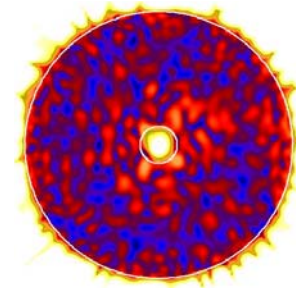
Outline

- The need for end-to-end modeling
- The optical system model and aberrations
- Propagation between optics
- Representing particular coronagraphs
- Wavefront control
- Wavefront changes

Note: I'm concentrating here on propagation in generally static systems (in space); other talks in this series will provide details on modeling ground-based systems (SPHERE: Mouillet, 27 Feb; GPI: Poyneer, 17 Feb) and wavefront sensing and control (Pueyo, 6 Feb)

Goal: Create a realistic coronagraphic speckle field

- Speckles are noise against which a planet must be measured
- They have wavelength-dependent behavior
 - Phase vs. amplitude speckles
 - Effects of wavefront control
- Speckles vary in size and shape
- They will vary over time
 - Changes due to pointing errors, changes in wavefront due to thermal and mechanical stresses, atmosphere
- Realistic speckle fields require end-to-end modeling; they cannot be directly computed for realistically complex systems

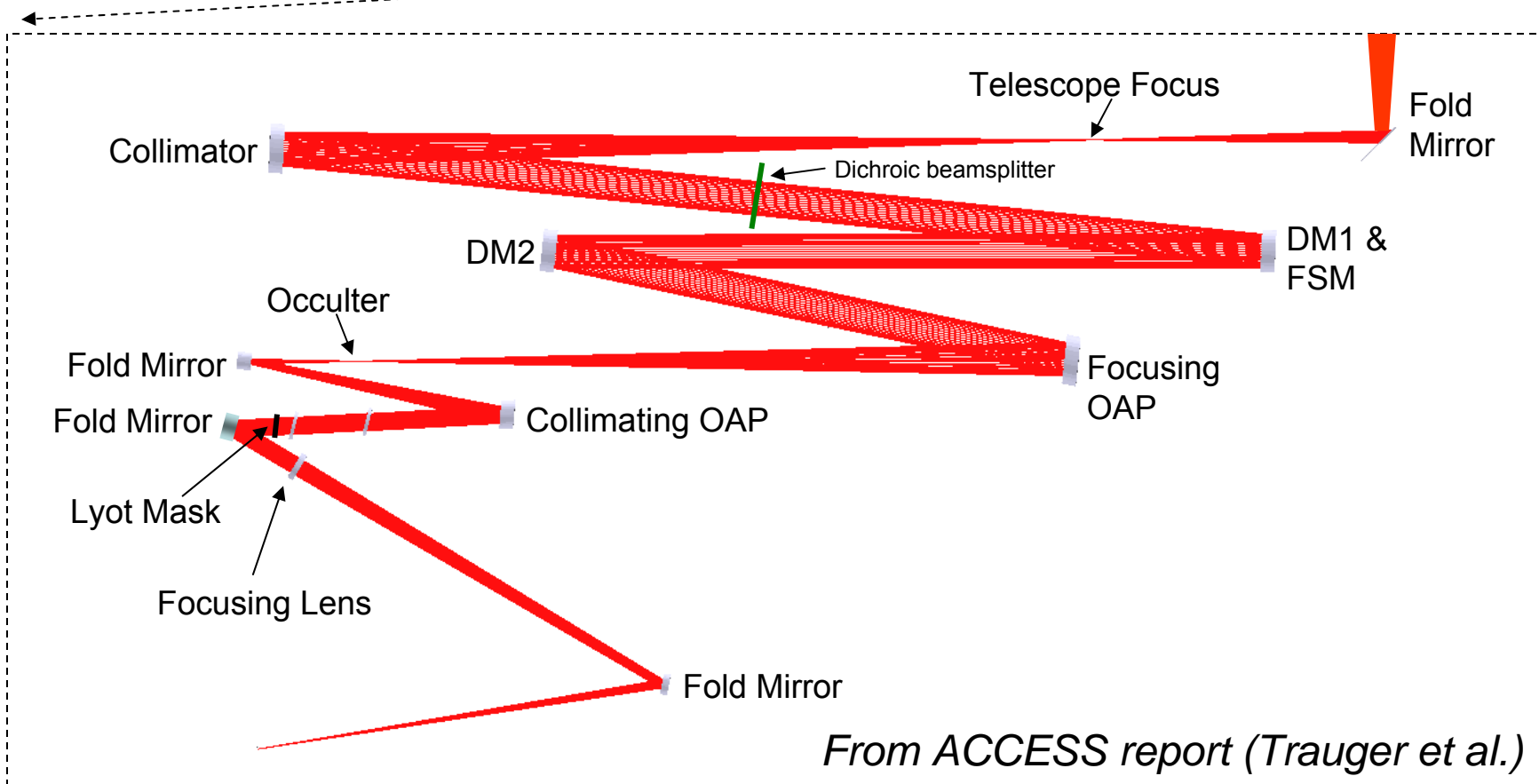
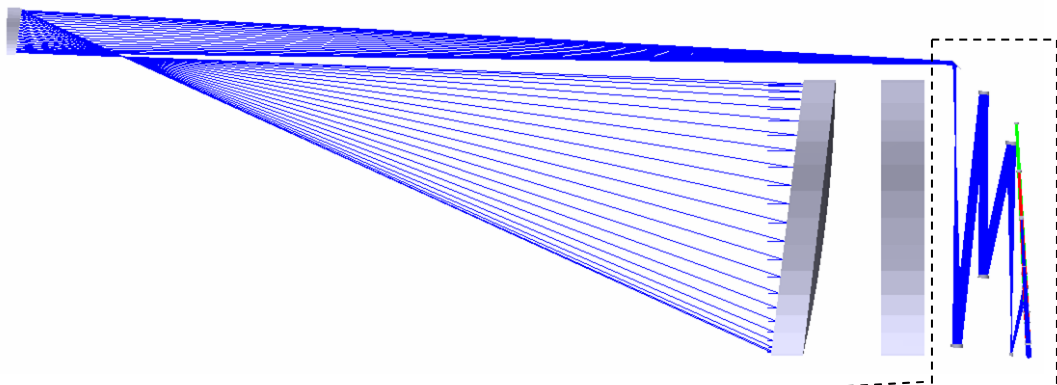


End-to-end modeling to create realistic speckle fields: Requirements

- Model of a telescope+coronagraph with realistic aberrations and deformable mirrors
- Method of propagating a wavefront between optical surfaces
- Method for sensing of wavefront errors (if not directly obtained from computed field)
- Method for determining DM settings to minimize speckles in the image plane

System layout

- Realistic system layout with all necessary optics
 - For numerical wavefront propagation, system is usually unfolded into a linear layout and mirrors replaced by thin lenses (except for unusual optics)
 - Optics have realistic fabrication errors
- Deformable mirrors with realistic actuator influence functions
 - 2 DMs in series can provide phase & amplitude control
- Coronagraph

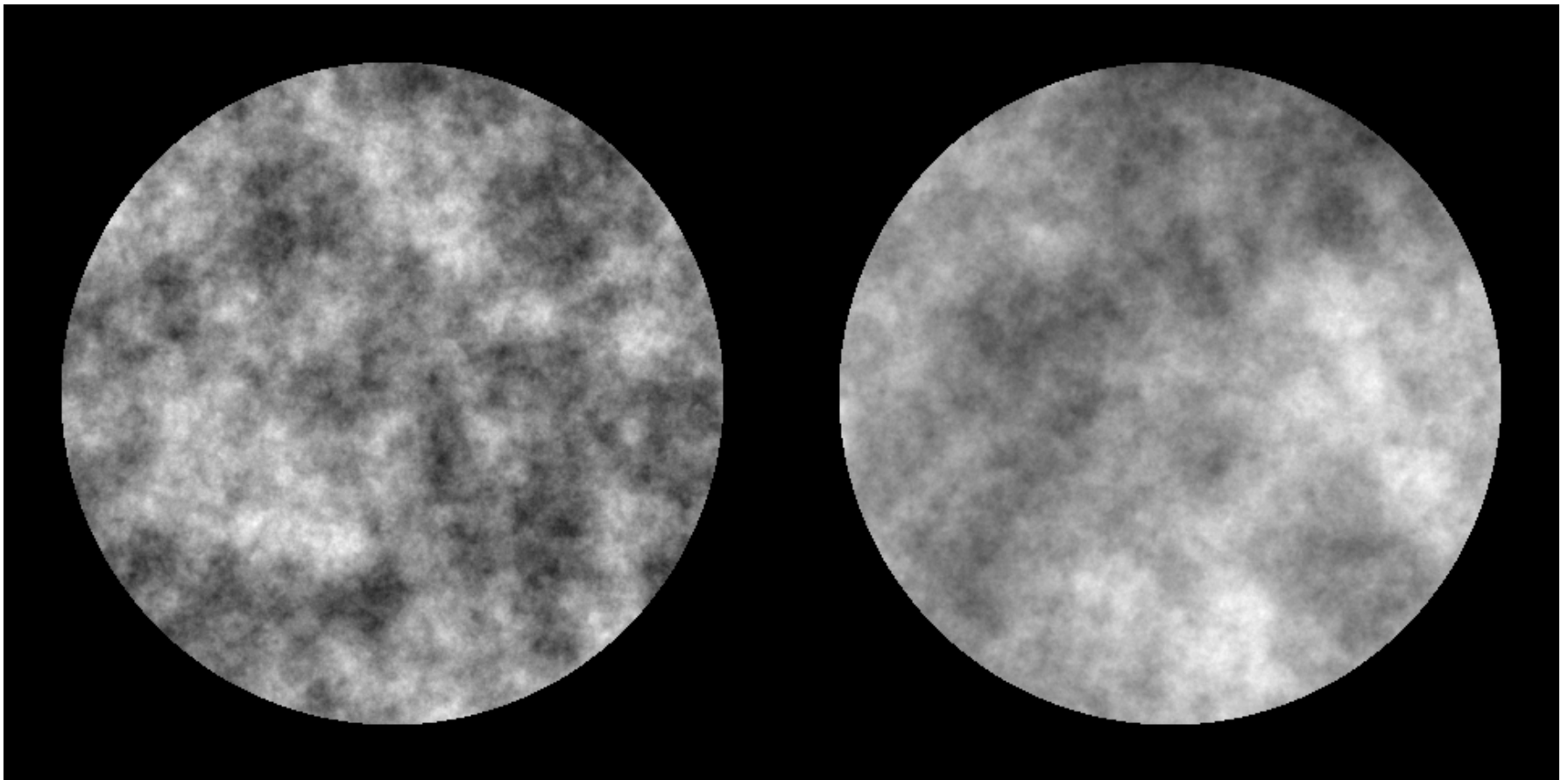


Errors on Optics

Simulated Error Maps

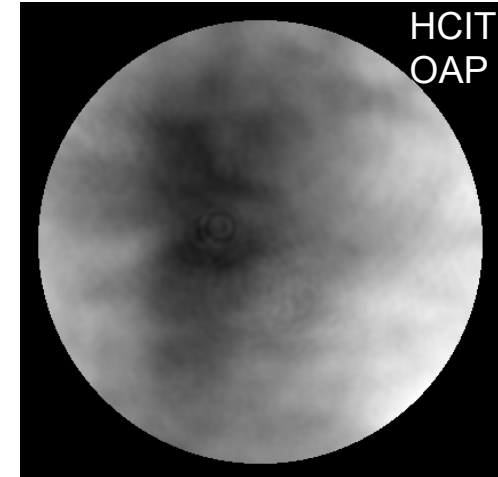
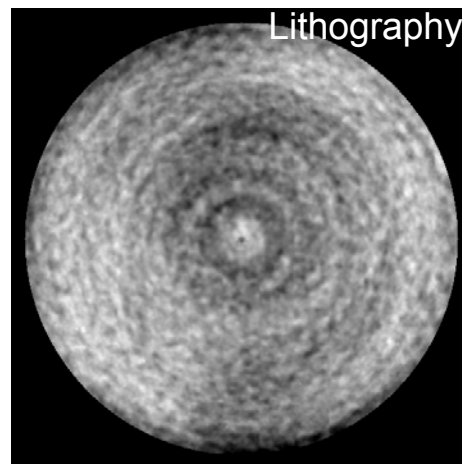
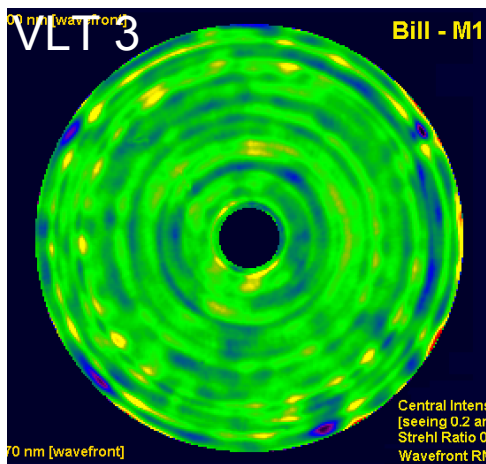
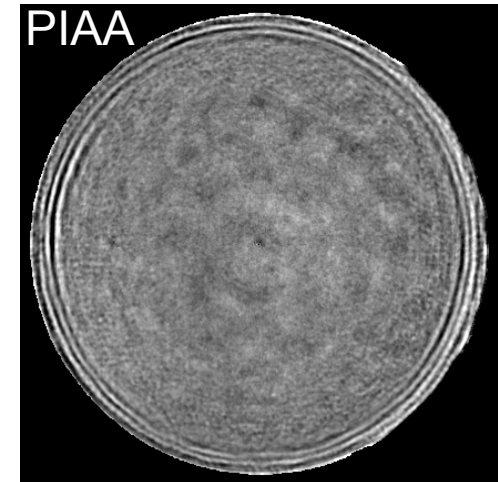
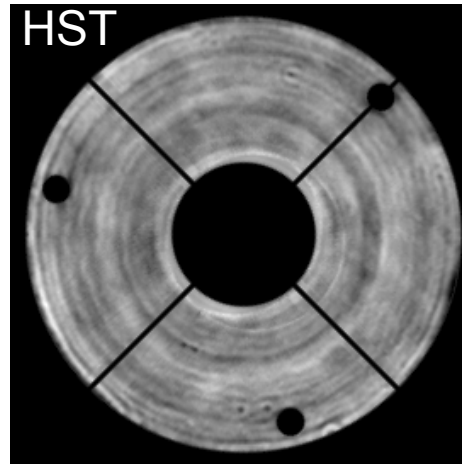
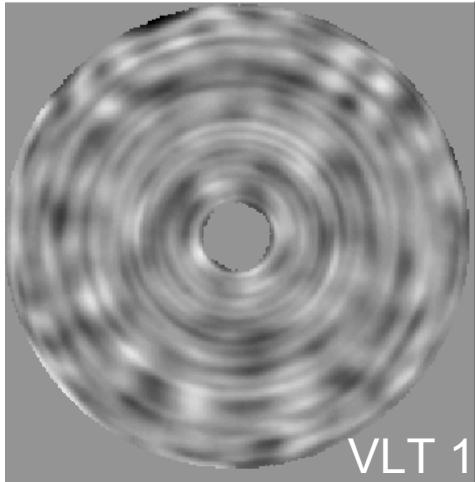
Phase Errors
(Figuring, polishing)

Amplitude Errors
(Coating)

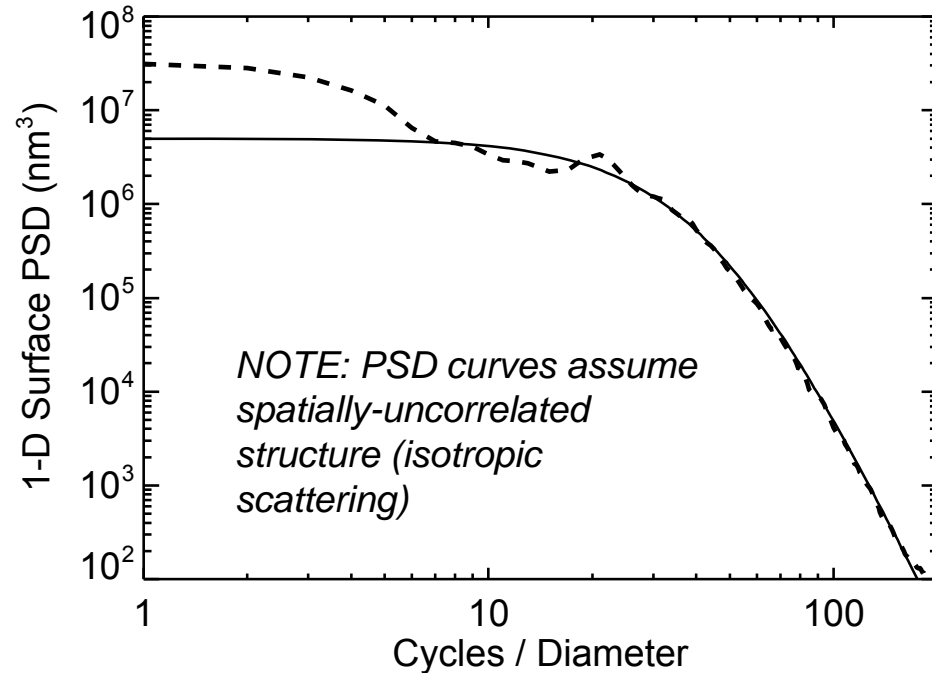
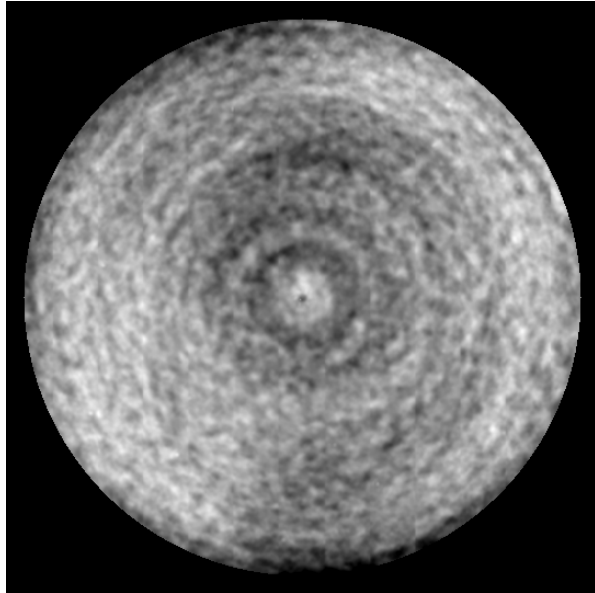


Other errors include dust, scratches, residue

Measured Surface Height Errors



Surface Error Maps & Power Spectral Density (PSD) Curves



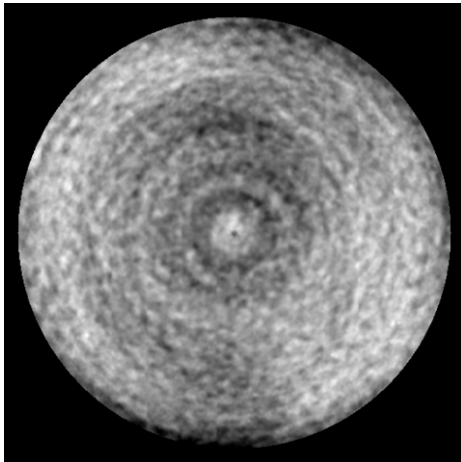
$$PSD_{2D}(k) = \frac{a}{\left[1 + \left(\frac{k}{b}\right)^2\right]^{\frac{c+1}{2}}}$$

(a variety of PSD curve descriptors exist)

Church et al., Proc. SPIE, v1165, p136 (1989)
Dittman, Proc. SPIE, v6291, p62910R (2006)

Surface Error Map & Low Order Aberrations

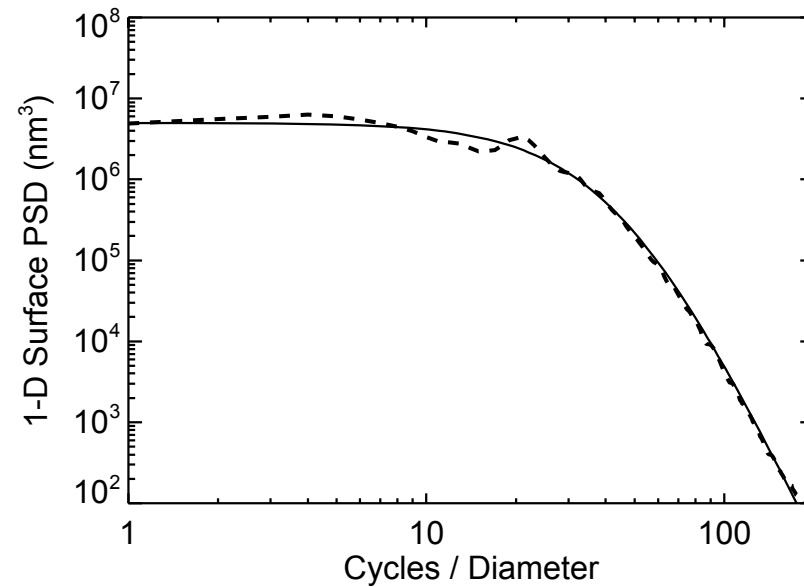
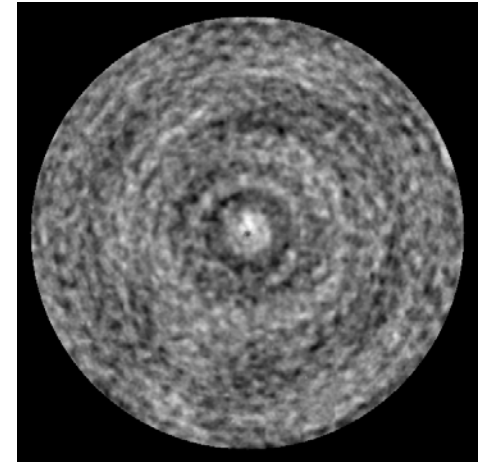
Original Map



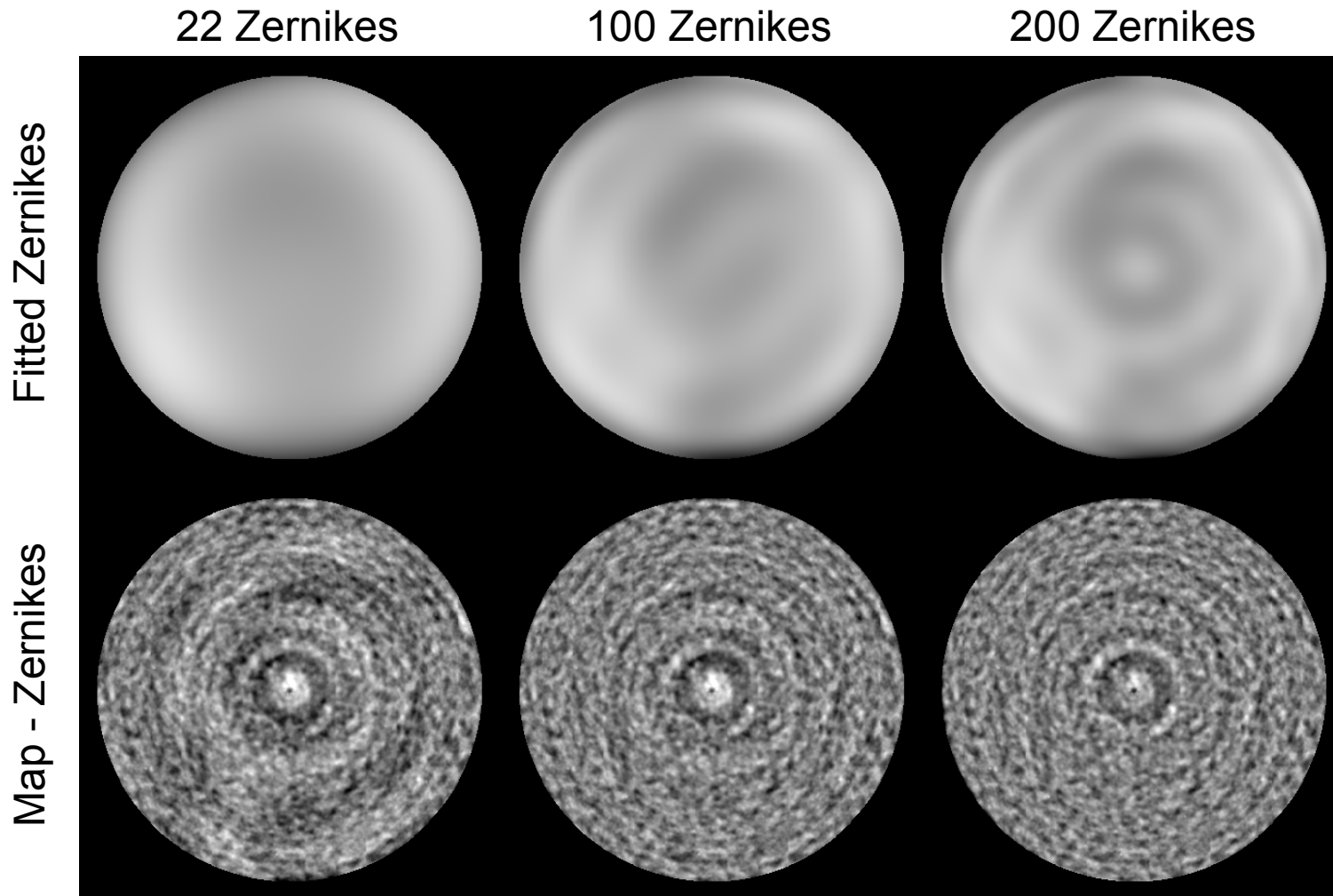
Fitted Zernikes



Map - Zernikes



Surface Error Map & Zernike Fits

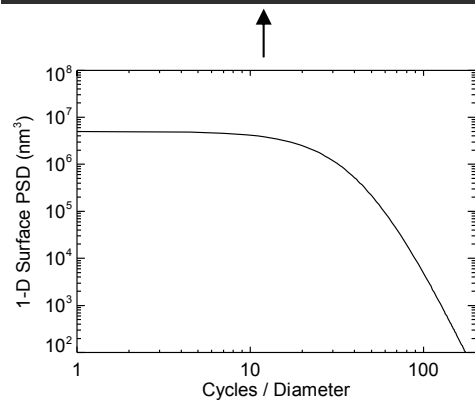


Creating Simulated Error Maps

Create mid-freq
from PSD

Create low-freq
from Zernikes or PSD

Add

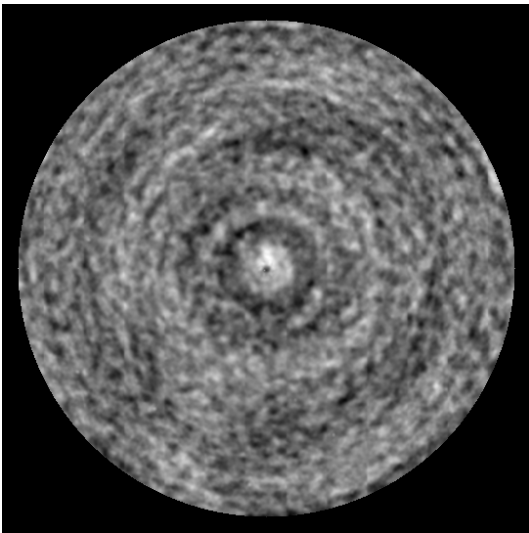


Both phase and amplitude error maps can be created in this manner; wavelength-dependence may also be introduced

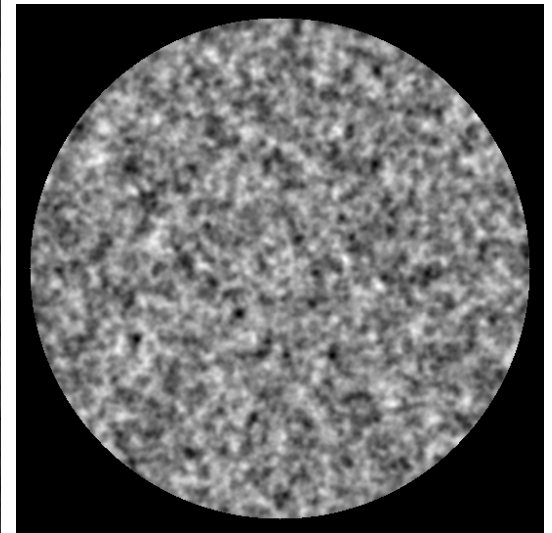
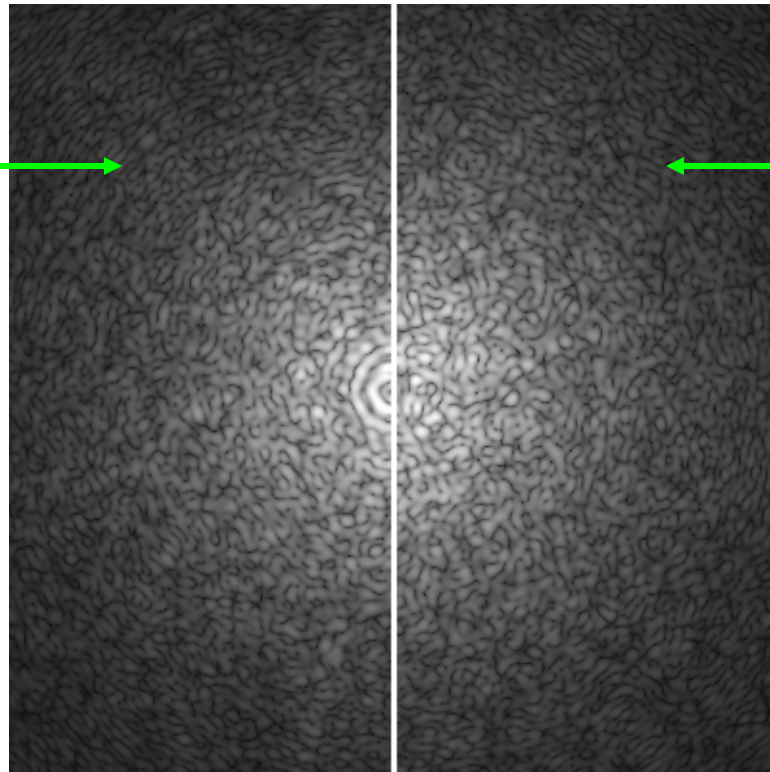
$\text{Sqrt(PSD)} + \text{random phases}$

Image Plane
(after coronagraph)

Real Error Map
(non-isotropic)



PSD-defined
Error Map
(isotropic)



Also see: Tamkin & Milster, "Effects of structured mid-spatial frequency surface errors on image performance," Applied Optics, v.49, p.6522 (2010)

Folding Frequency Speckles

Speckles from two phase ripples on primary
(40 & 50 cycles/D, P-V = 1/80 wave)

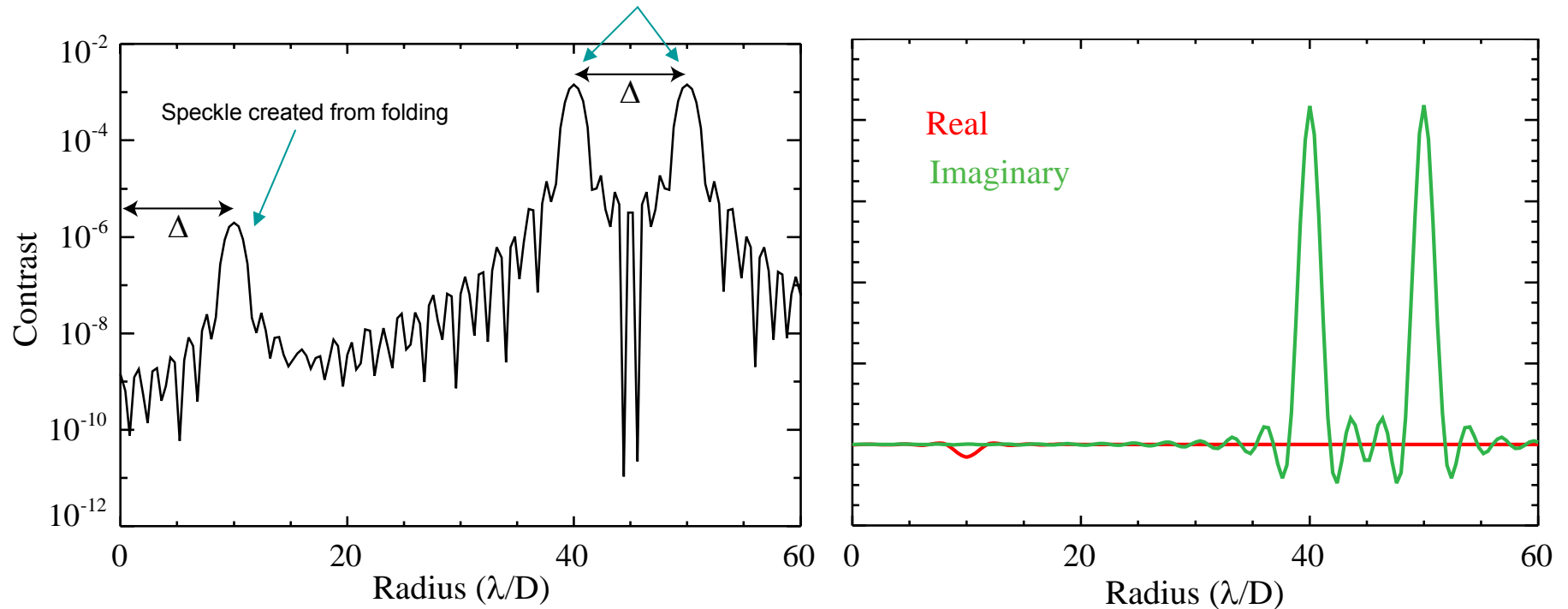


Image plane after coronagraph

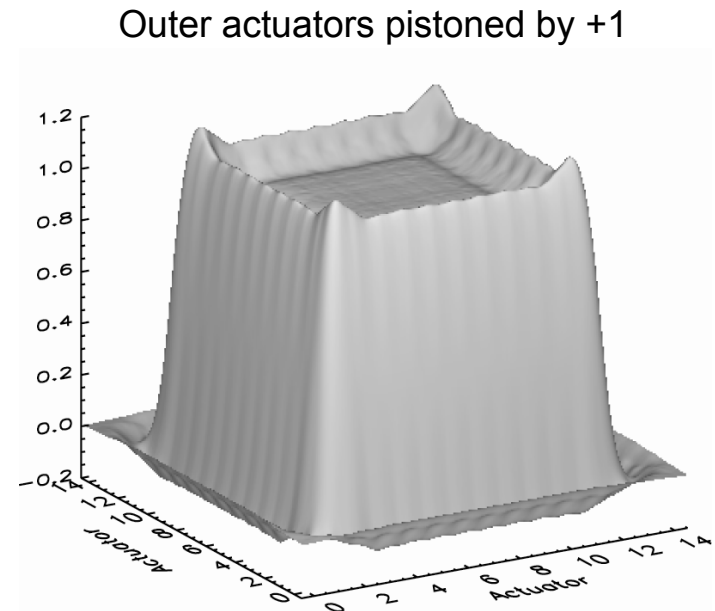
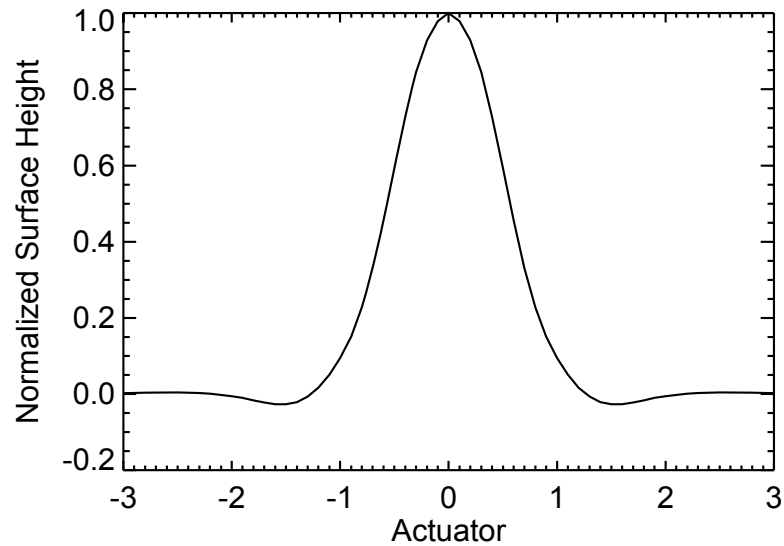
$$I_{fold} \propto ripple^4$$

Give'on et al., "Amplitude and phase correction for high-contrast imaging using Fourier decomposition", Proc. SPIE, v. 5905 (2005)

Error Maps

- Error maps can be created for both phase and amplitude errors
- Both types of errors may be wavelength dependent (reflectivity, transmission coatings, etc)
 - Wavelength dependent errors at a focus are especially problematic
- Polarization may also be a factor

Deformable Mirror Model



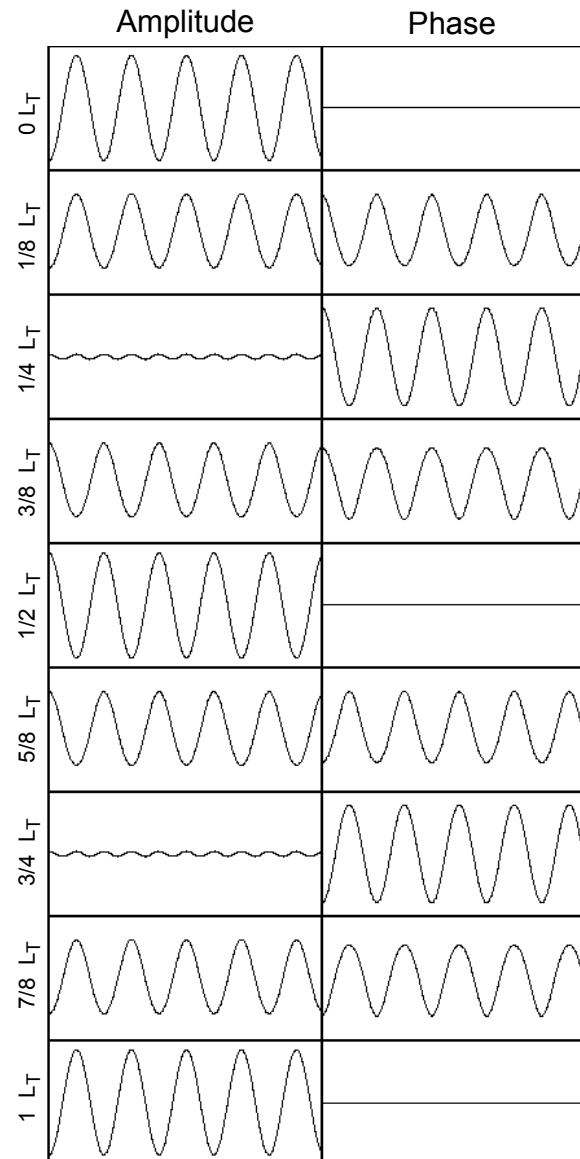
PROPER DM model uses measured influence function from Xinetics DM

Propagation

- Simple Fraunhofer diffraction (Fourier transform between pupil and image planes) is not sufficient to account for aberrations introduced by intermediate optics in high contrast simulations
- Surface-to-surface propagation required
- Fourier-based angular spectrum & Fresnel algorithms are the most efficient for end-to-end modeling
- Highly aspheric optics require other propagators
- Highly segmented systems may need modified propagators, depending on contrast requirements

Non-Pupil Optics & the Talbot Effect

*Talbot length in
a collimated beam:
 $L_T = 2 P^2 / \lambda$
where $P = \text{period}$*



*A phase error on an
optic not at a pupil can
create a mix of phase and
amplitude errors at the
image plane with
different wavelength
dependencies*

For more info: Zhou & Burge, "Analysis of wavefront propagation using the Talbot effect", Applied Optics, v. 49 (2010)

Fourier-based Wavefront Propagation

$a(k, l)$ = wavefront array (complex) of dimension (M, N) points

$$-\frac{M}{2} < k < \frac{M}{2}, \quad -\frac{N}{2} < l < \frac{N}{2}$$

$$a(k\Delta x_2, l\Delta y_2, z_2) = \frac{1}{j\lambda\Delta z} q(r_2, \Delta z) FF^s [a(k\Delta x_1, l\Delta y_1, z_1) q(r_1, \Delta z)]$$

$$\Delta x_2 = \frac{\lambda|\Delta z|}{M\Delta x_1}, \quad \Delta y_2 = \frac{\lambda|\Delta z|}{N\Delta y_1}$$

M, N = number of array elements in x, y ($M = N$, usually)

$$r^2 = (k\Delta x)^2 + (l\Delta y)^2$$

$$s = \text{sign}(\Delta z)$$

$$q(r, \Delta z) = e^{j\pi r^2 / \lambda\Delta z}$$

Fresnel (far field) propagation
(diverging or converging
beam; scale changes)

$$a(k\Delta x, l\Delta y, z_2) = FF^{-1} [T(\Delta z) FF^+ [a(k\Delta x, l\Delta y, z_1)]]$$

$$T(\Delta z) = e^{-j\pi\lambda\Delta z\rho^2}$$

$$\rho^2 = \xi^2 + \eta^2, \quad \xi = \frac{k}{M\Delta x}, \quad \eta = \frac{l}{N\Delta y}$$

Angular spectrum (near field)
propagation (collimated, or
nearly so, beam; scale constant)

Other Propagators

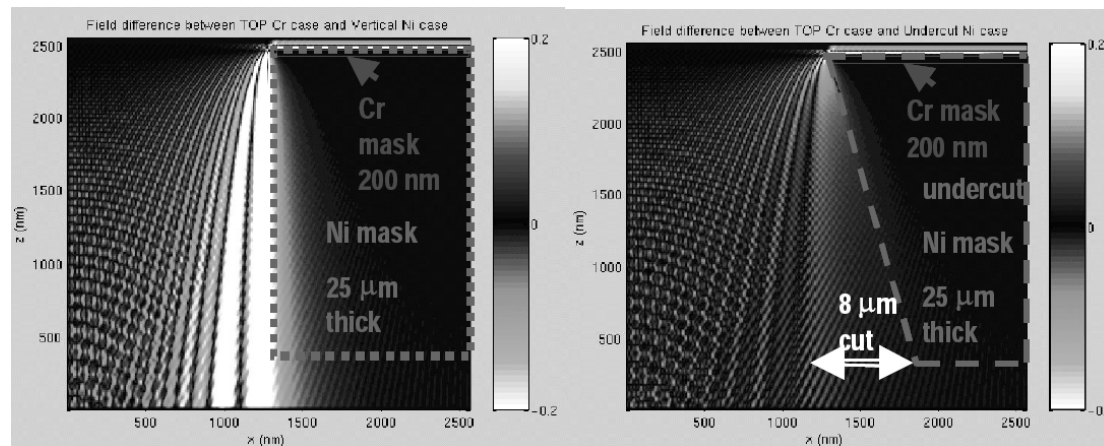
- Beam Propagation Method (Gaussian Beam Decomposition)
 - *Wave Optics in ASAP*
(www.breault.com/resources/kbasePDF/brotg0919_wave.pdf)
 - *Practical considerations for simulating beam propagation: A comparison of three approaches* (Stone & Bruegge, Proc. SPIE, v. 4832 [2002])
 - *Comparing geometrical and wave-optical algorithms of a novel propagation code applied to VLT1* (Wilhelm, Proc. SPIE, v. 4436 [2001])
- S-Huygens (Belikov et al., *Astrophys. J.*, v. 652 [2006]; Vanderbei, *Astrophys. J.*, v. 636 [2006])
- Angular Spectrum for PIAA (Pueyo et al., *JOSAA*, v. 28 [2011])
- Fast Lyot-coronagraph propagation (Soummer et al., *Optics Express*, v. 15 [2007])

Vector Propagation

- Propagators discussed so far are scalar and ignore the coupling of E-M fields with materials
 - important when E-M effects of finite-thickness materials (occulter, wavelength-scale pupil mask openings) can impact required contrast
- Vector propagation includes these effects
 - Very computationally demanding, to be used only at particular surfaces

Lieber et al., “Vector wavefront propagation modeling for the TPF coronagraph”, Proc. SPIE, v. 5487 (2004)

Shiri et al., “A vector diffraction model of wave propagation in coronagraphic Terrestrial Planet Finder”, Proc. SPIE, v. 5487 (2004)



From Lieber et al.

Propagation Tools

- Commercial: Code V, Zemax, GLAD, APART, etc.
 - Expensive, complex, not well suited for end-to-end modeling
- Proprietary: BeamWarrior, MACOS, etc.
- Free: Arroyo, PROPER, etc.

Propagation with PROPER

- A freely-available, well-documented propagation library for IDL at www.openchannelsoftware.com (be sure to get manual from the download section, not the front page document link, which has the old one)
- Fresnel & angular spectrum propagators
 - Automatic selection of propagator based on analytic propagation of a Gaussian reference beam (works on with well-behaved systems)
- Deformable mirror models with influence functions
- Complex apertures
- Generates aberration maps from PSD specs
- Also used by Gemini/GPI, VLT/Sphere, Palomar, JWST/NIRCam, JWST/NIRSpec
- PROPER does not do wavefront sensing or wavefront optimization
- PROPER does not perform ray tracing (does not account for tilted optics, propagation through lenses, etc.)

PROPER: an optical propagation library for IDL (Krist, Proc. SPIE, v. 6675 [2007])

PROPER-like Propagation Algorithm References

- PROPER manual
- GLAD software theory manual
 - www.aor.com/anonymous/pub/theory.pdf
- *Computational Fourier Optics: A MATLAB Tutorial* (Voelz; SPIE Press)
- *Numerical Simulation of Optical Wave Propagation* (Schmidt; SPIE Press)
- *Introduction to Fourier Optics* (Goodman)
- *Optalix Reference Manual*
 - www.optenso.com/download/optalix_reference.pdf

Some Models using PROPER

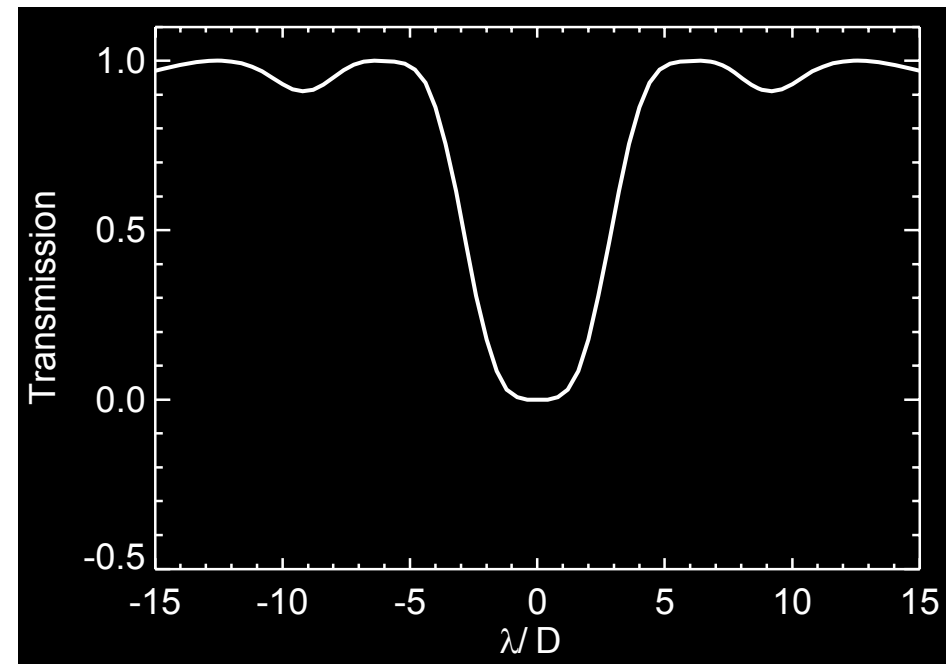
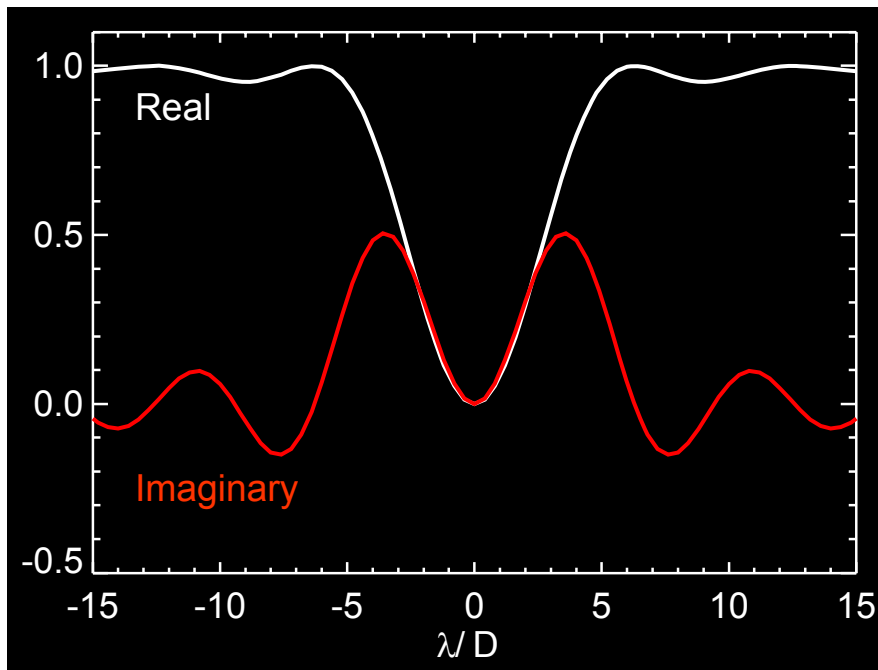
- *Simulation of planet detection with the SPHERE integral field spectrograph* (Mesa et al., *Astronomy & Astrophysics*, v. 529 [2011])
- *FFREE: a Fresnel-Free Experiment for EPICs, the EELT planets imager* (Antichi et al., *Proc. SPIE*, v. 7736 [2010])
- *FOROS: Fresnel optical propagation code for SPHERE* (Yaitskova et al., *Proc. SPIE*, v. 7735 [2010])
- *An end-to-end polychromatic Fresnel propagation model of GPI* (Marois et al., *Proc. SPIE*, v. 7015 [2008])
- *Extraction of extrasolar planet spectra from realistically-simulated wavefront-corrected coronagraphic fields* (Krist et al., *Proc. SPIE*, v. 7010 [2008])
- *Assessing the performance limits of internal coronagraphs through end-to-end modeling: a NASA TDEM study* (Krist et al., *Proc. SPIE*, v. 8151 [2011])
- *End-to-end simulations of different coronagraphic techniques* (Krist et al., *Proc. SPIE*, v. 7440 [2009])
- *Hunting planets and observing disks with the JWST NIRCам coronagraph* (Krist et al., *Proc. SPIE*, v. 6693 [2007])

Is PROPER State of the Art?

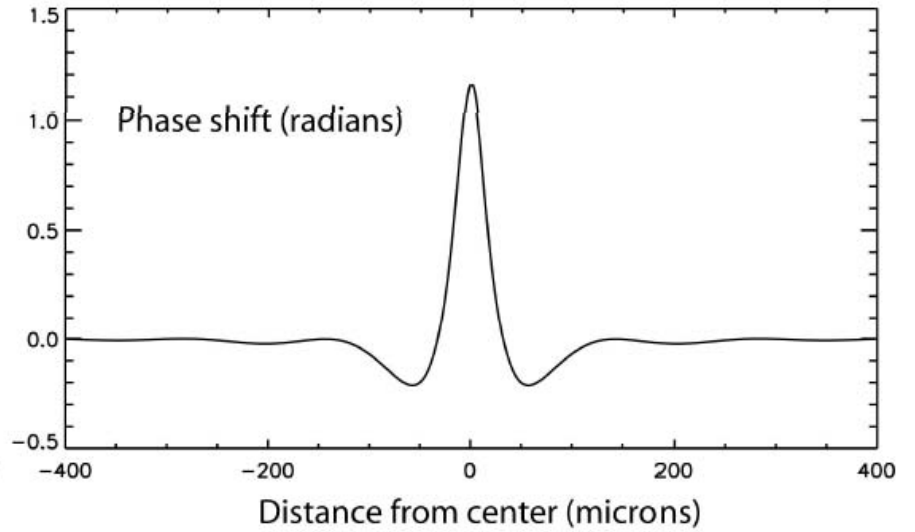
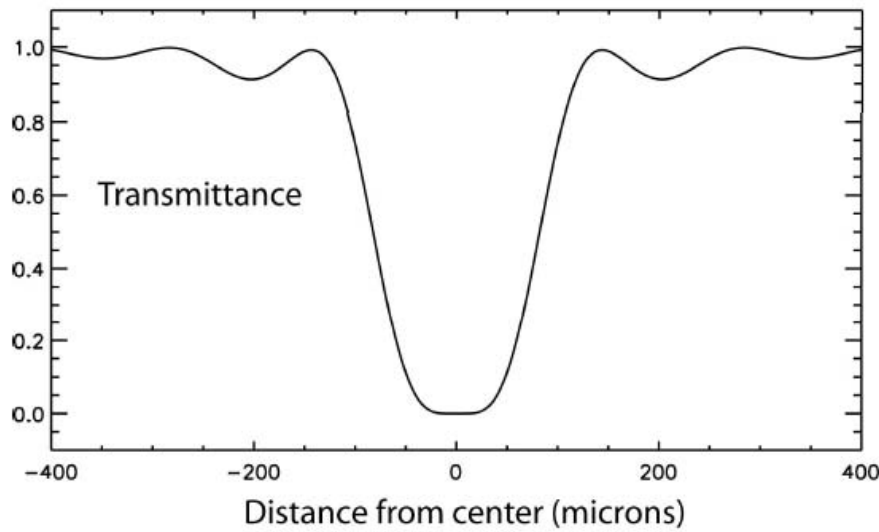
- Yes
 - Results verified against more rigorous propagators for a simple coronagraphic system to 0.6% RMS accuracy for 10^{-10} contrast fields
 - Automatically selects propagator
 - Fast (<35 sec/wavelength for ACCESS layout [see slide 6] using 2K x 2K arrays and FFTW on a current workstation)
 - Relatively easy to use
- No
 - Does not propagate through refractive optics (all lenses approximated as parabolic phase modifiers)
 - Handles only “simple” optics accurately (parabolas)
 - Does not account for propagation between tilted components
 - Does not use ray tracing to determine best propagator (needed if system is highly aberrated)
 - No polarization
 - No vector propagation
- Maybe
 - No package does everything
 - More complex packages are usually slow, very complex, and expensive/proprietary
 - PROPER is free and distributed as IDL source code

Complex BLC Occulter

*Inner working angle (50% transmission) at $3 \lambda/D$ @ $\lambda = 550 \text{ nm}$
4th order aberration response*

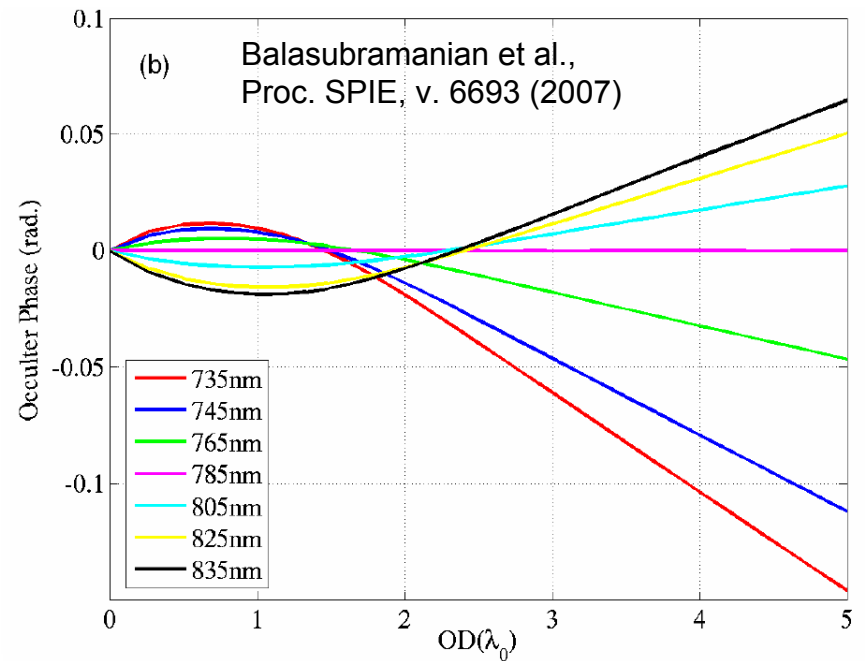


Complex-valued transmission achieved using amplitude-attenuating metal (e.g. nickel) and patterned dielectric coatings (Moody & Trauger)

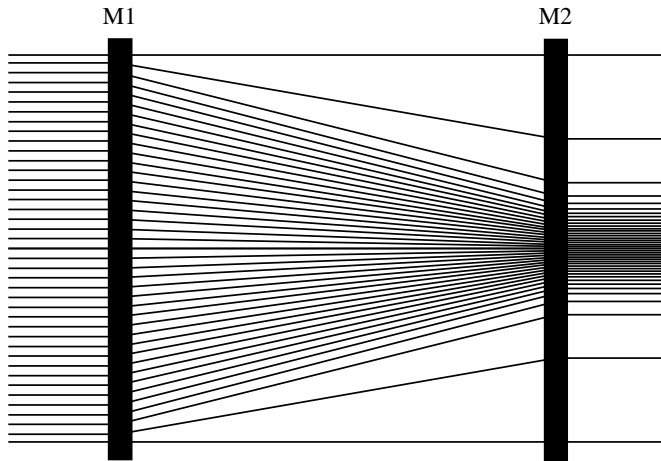


For a nickel-only mask; from Moody et al., Proc. SPIE, v. 7010 (2008)

An amplitude-modifying transmission mask will introduce an optical-density-dependent phase shift that is also wavelength dependent.

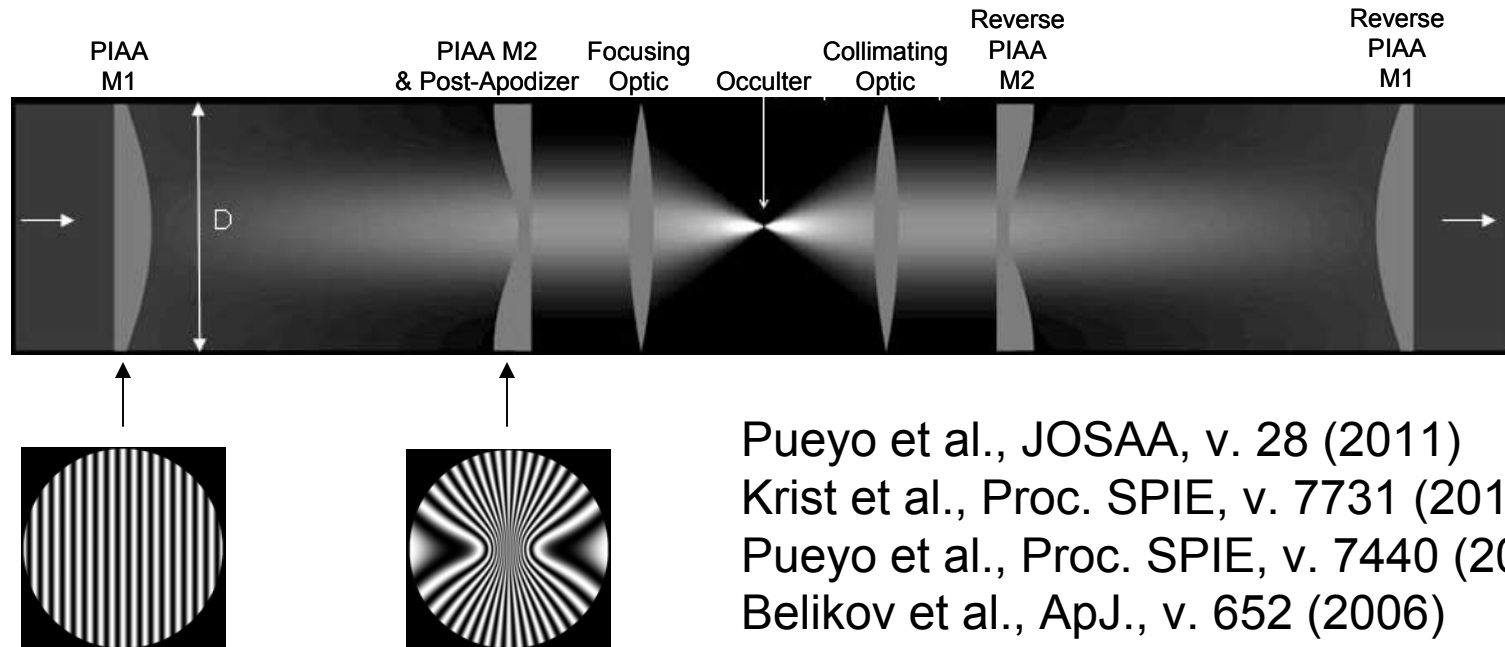


Propagating Through PIAA



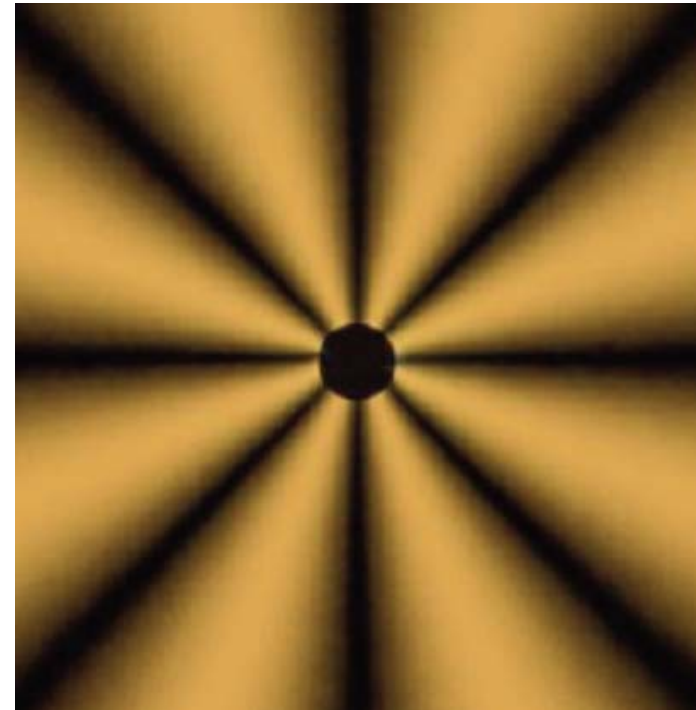
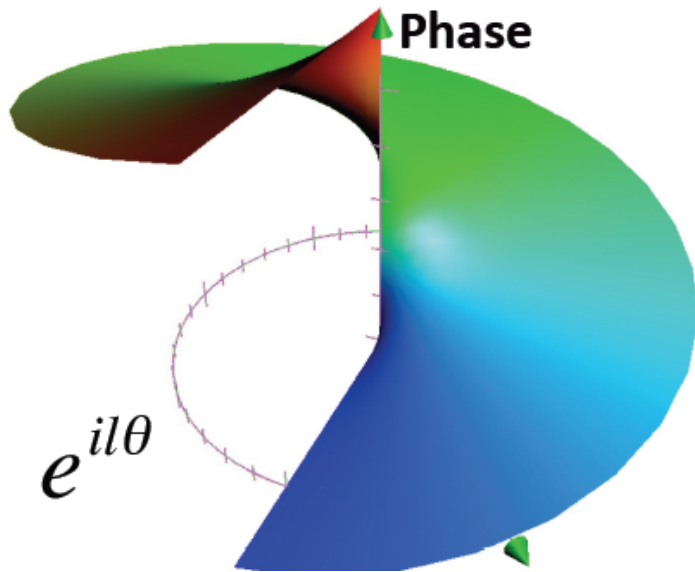
Phase-Induced Amplitude Apodization: use highly aspherical remapping optics to create an apodized beam rather than a throughput-reducing transmission mask

Large curvature changes and non-uniform ray sampling during propagation prevents use of usual Fourier-based propagators; practical variants are described in references given below



- Pueyo et al., JOSAA, v. 28 (2011)
- Krist et al., Proc. SPIE, v. 7731 (2010)
- Pueyo et al., Proc. SPIE, v. 7440 (2009)
- Belikov et al., ApJ., v. 652 (2006)

Propagating through a Vector Vortex Mask



Vector vortex mask viewed between cross polarizers; central opaque spot masks confused region caused by misalignments of coating layers

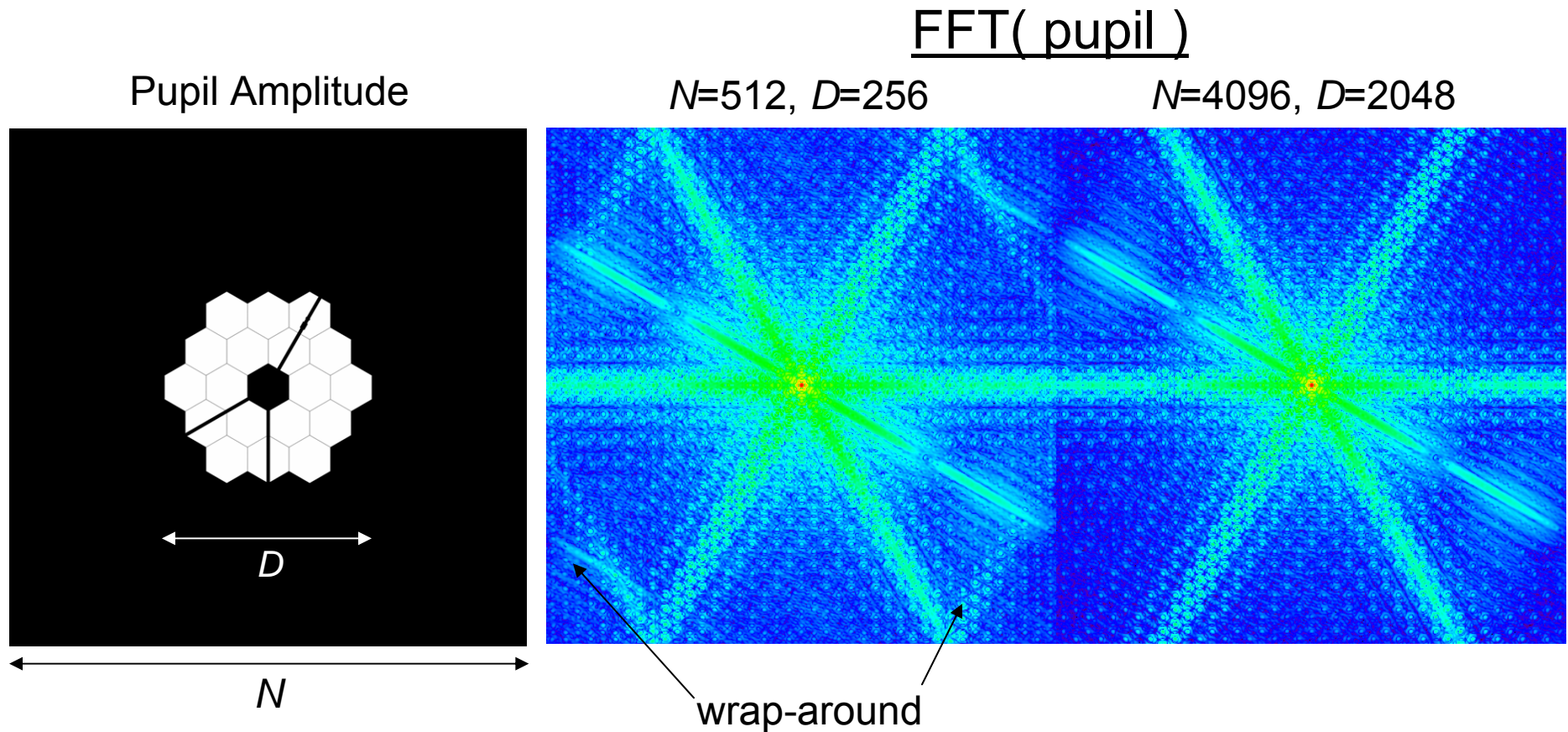
Figures from papers by Mawet et al.

Computational Aspects

- Array sizes must be chosen to adequately sample obscurations and errors, provide sufficient sampling at focus, and prevent numerical errors (wrap-around, aliasing)
- Use optimized FFT (FFTW is 10x faster than IDL FFT for 4K x 4K arrays)
- Propagation is easily made parallel when computing multiple wavelengths to produce polychromatic field (e.g., broadband observation)
- Graphics processing units (GPUs) may provide >1 magnitude improvement for some propagation methods

Numerical Artifacts, Not Speckles

Example: Fourier transform wrap-around



Also be careful of wavefront aliasing ($>1/2$ wave difference between grid points)

Creating the Speckle Field

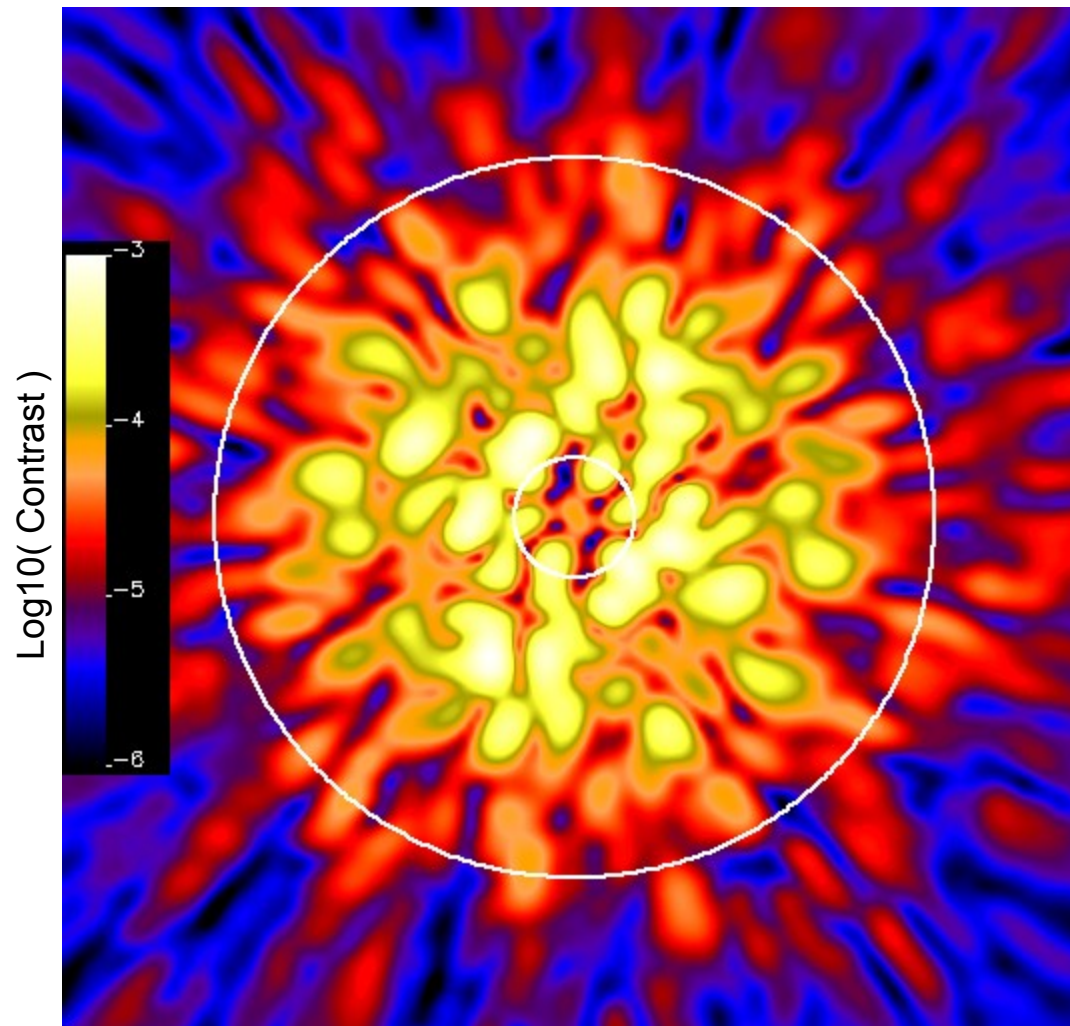
- Propagate monochromatic wavefronts through the entire system at $(\lambda_1 \dots \lambda_n)$ and record field at each λ
- To create polychromatic image, add field intensities with appropriate weighting
- Determine wavefront amplitude & phase
- Determine DM settings to reduce scatter
- Propagate through system with new DM settings, repeat

Model Setup

- ACCESS layout
- band-limited coronagraph (4th order, amplitude-only occulter, 50% transmission at $2.5 \lambda_c/D$)
- $\lambda = 500 - 600$ nm
- Control region $r = 2.5 - 18 \lambda_c/D$
- dual sequential 48 x 48 DMs
- wavefront “sensed” at 5 wavelengths

Contrast before wavefront correction

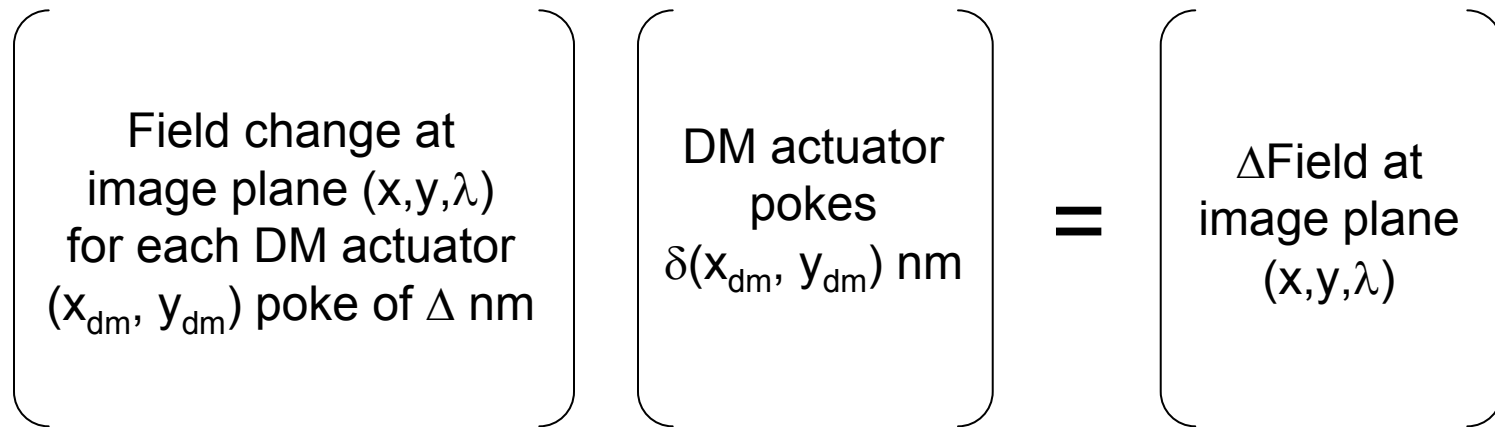
$$\lambda = 500 - 600 \text{ nm}$$



Circles are
 2.5 & $18 \lambda/D$

Wavefront control: Electric field conjugation

Linear approximation to a non-linear system

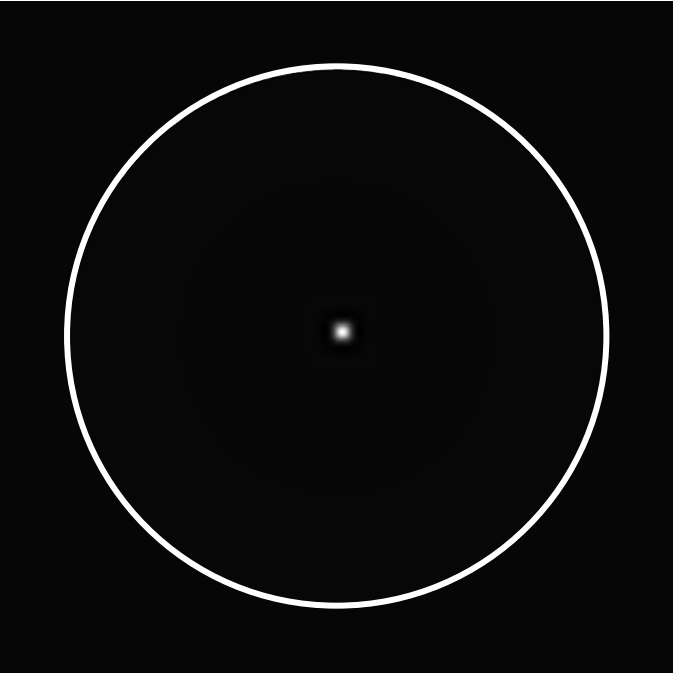


*Determined by numerically propagating
DM actuator pokes through a model system*

λ = a few wavelengths that sample the bandpass

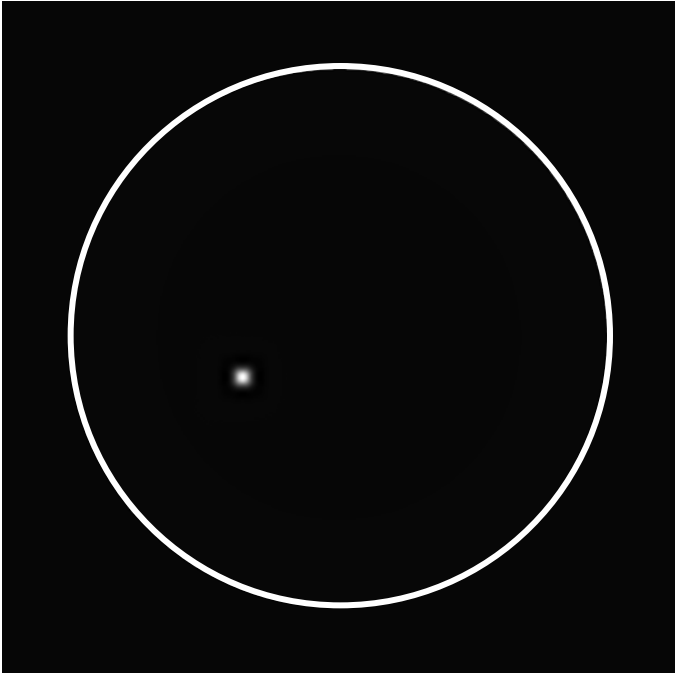
See papers by Give'on and Bordé & Traub

Field changes at final image due to DM actuator piston



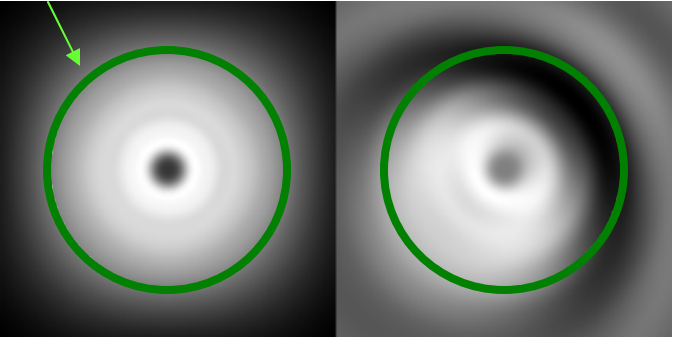
(24,24)

$\delta\text{Phase at DM \#1}$



(15,20)

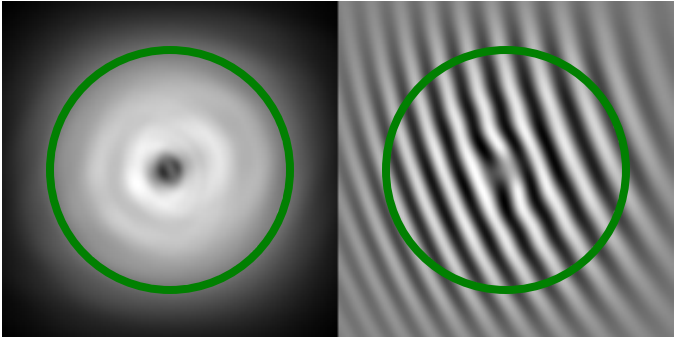
$20 \lambda/D$



Amplitude

Phase

$\Delta\text{Field at final image}$

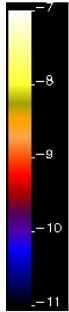


Amplitude

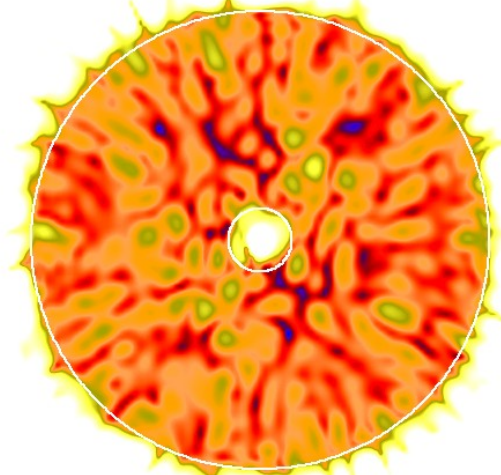
Phase

Iterative wavefront optimization

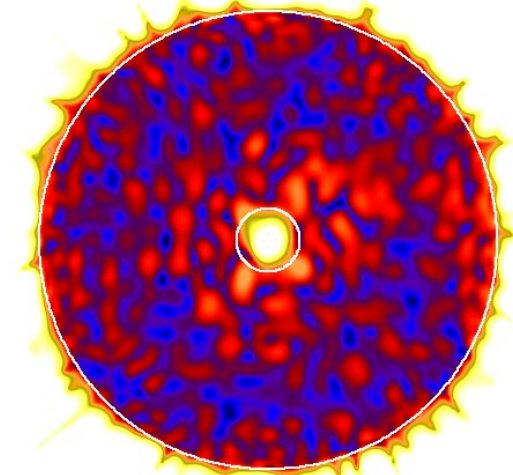
iter = 0



1



2

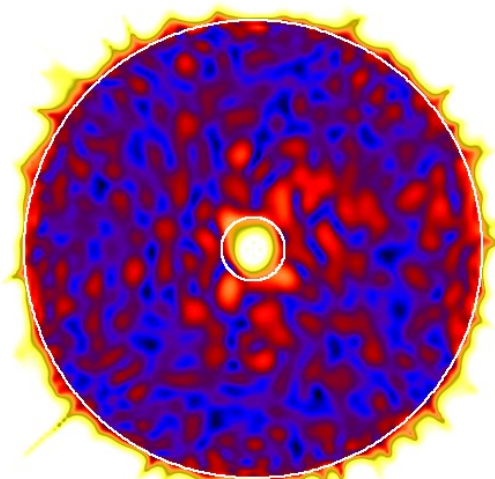


Contrast = 7.6×10^{-7}

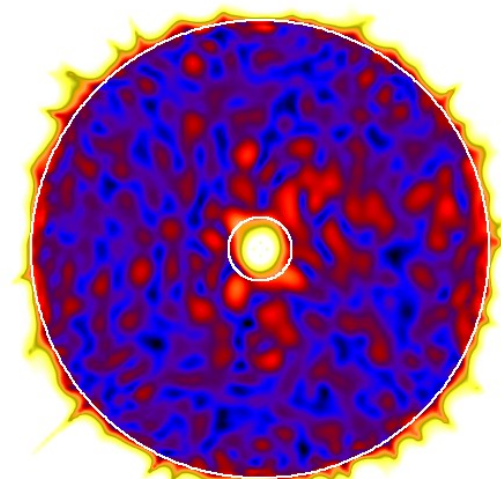
2.0×10^{-9}

2.7×10^{-10}

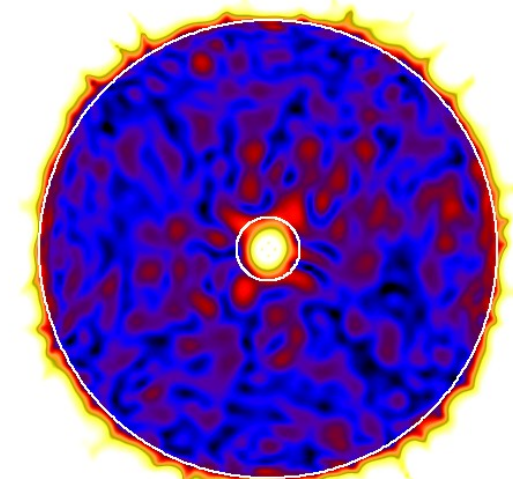
3



4



14



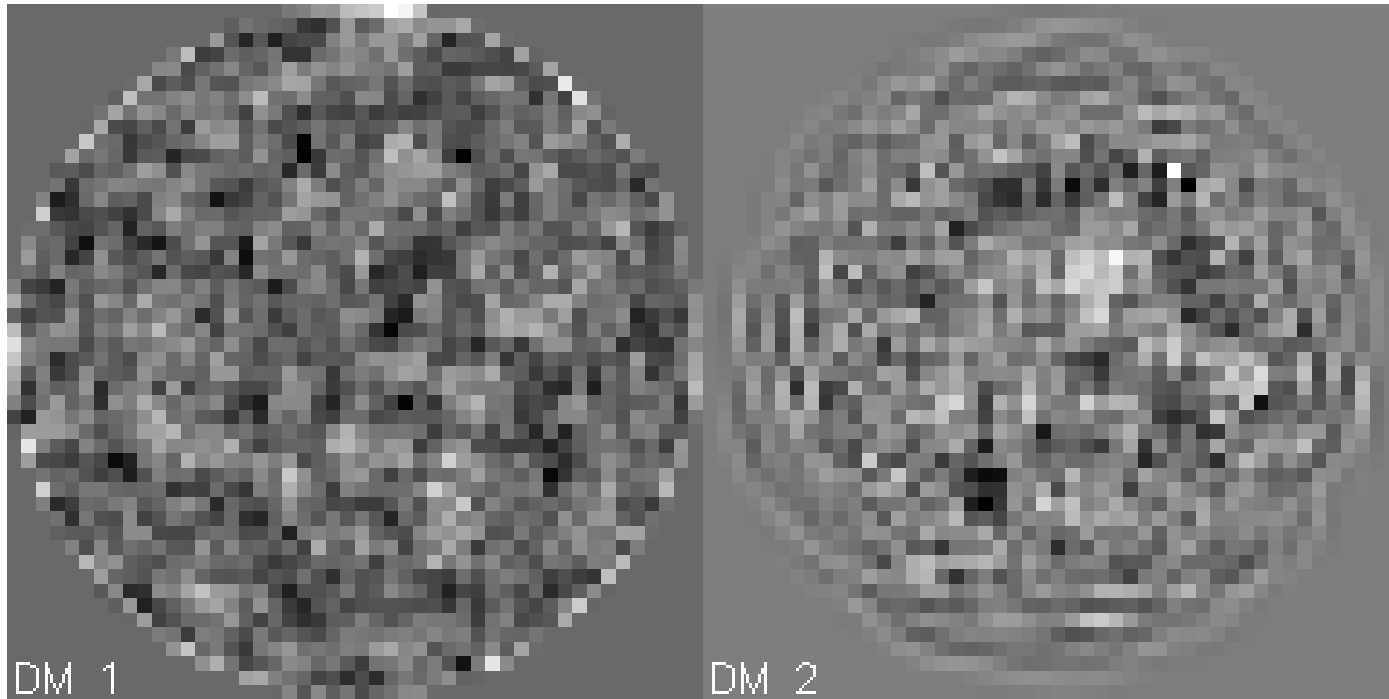
1.9×10^{-10}

1.6×10^{-10}

1.0×10^{-10}

Optimized DM patterns

48 x 48 DMs



-23 to +33 nm

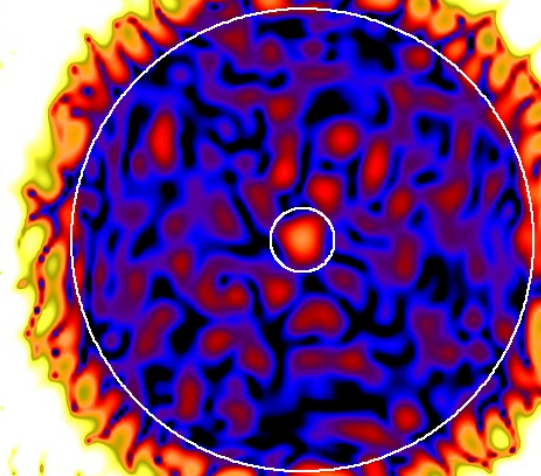
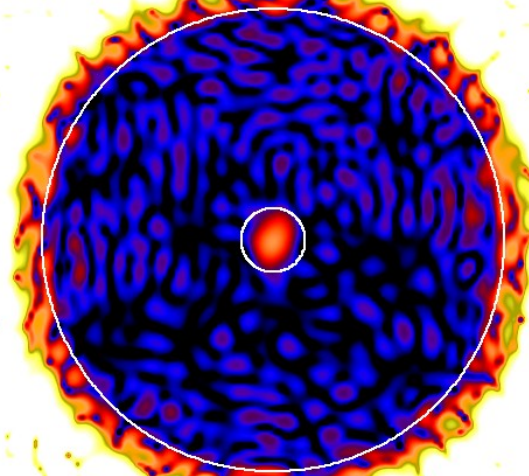
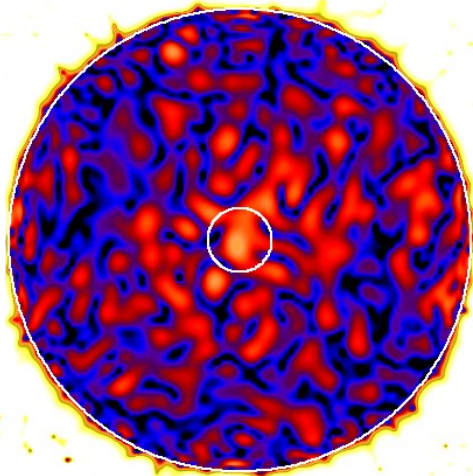
-5 to +5 nm

Dark hole contrast vs. wavelength

500 nm

550 nm

600 nm

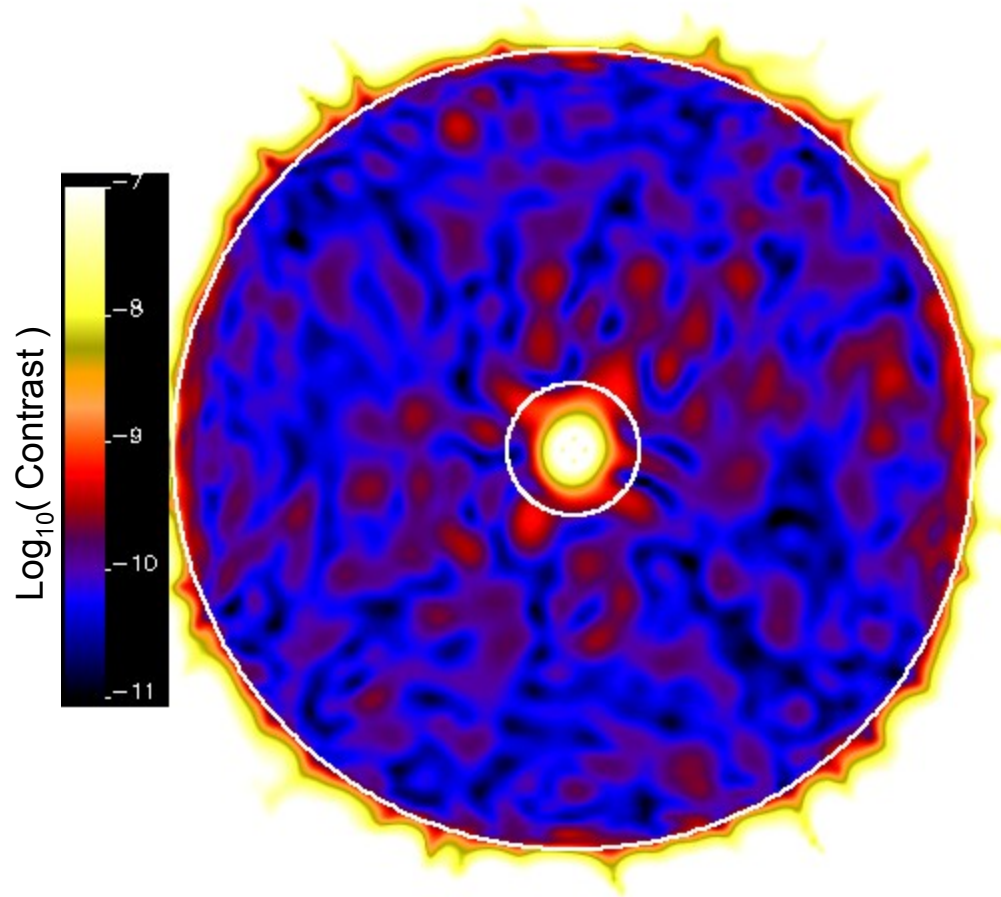


$\text{Log}_{10}(\text{ Contrast })$

Inscribed circles are $r = 2.5, 18 \lambda/D$ @ $l = 550 \text{ nm}$

Broadband dark hole contrast

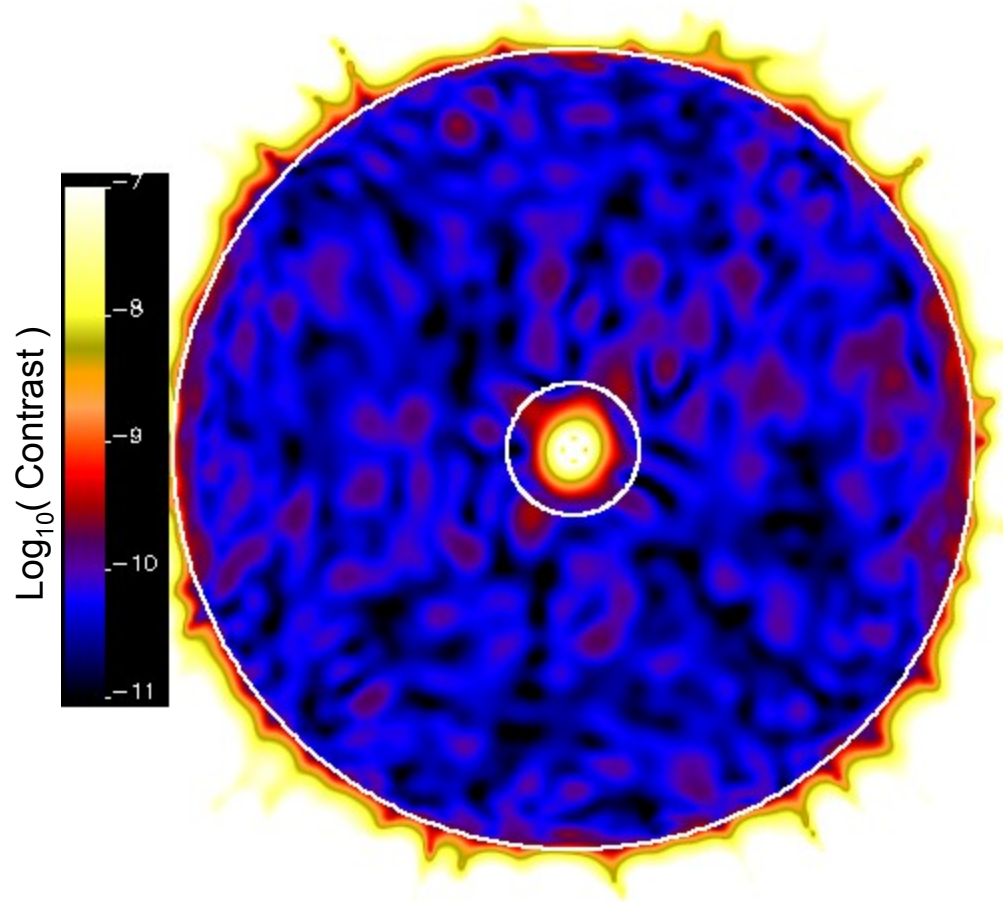
$\lambda = 500 - 600 \text{ nm}$



Mean dark hole contrast = 1.0×10^{-10}

Broadband dark hole contrast

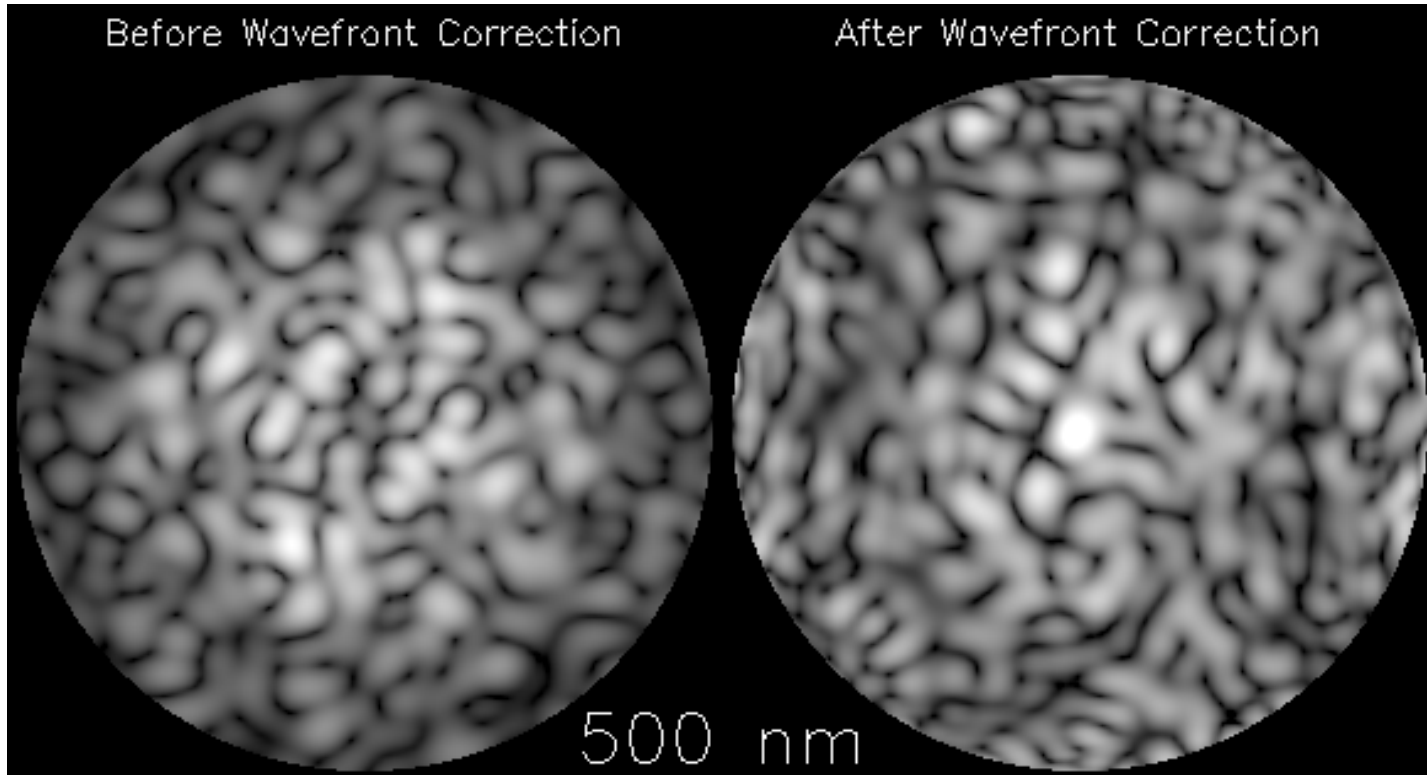
$\lambda = 630 - 770 \text{ nm}$
(separate wavefront solution)



Mean dark hole contrast = 5×10^{-11}

Speckle changes with wavelength

See the separate animated GIF version of this figure,
viewable with a web browser



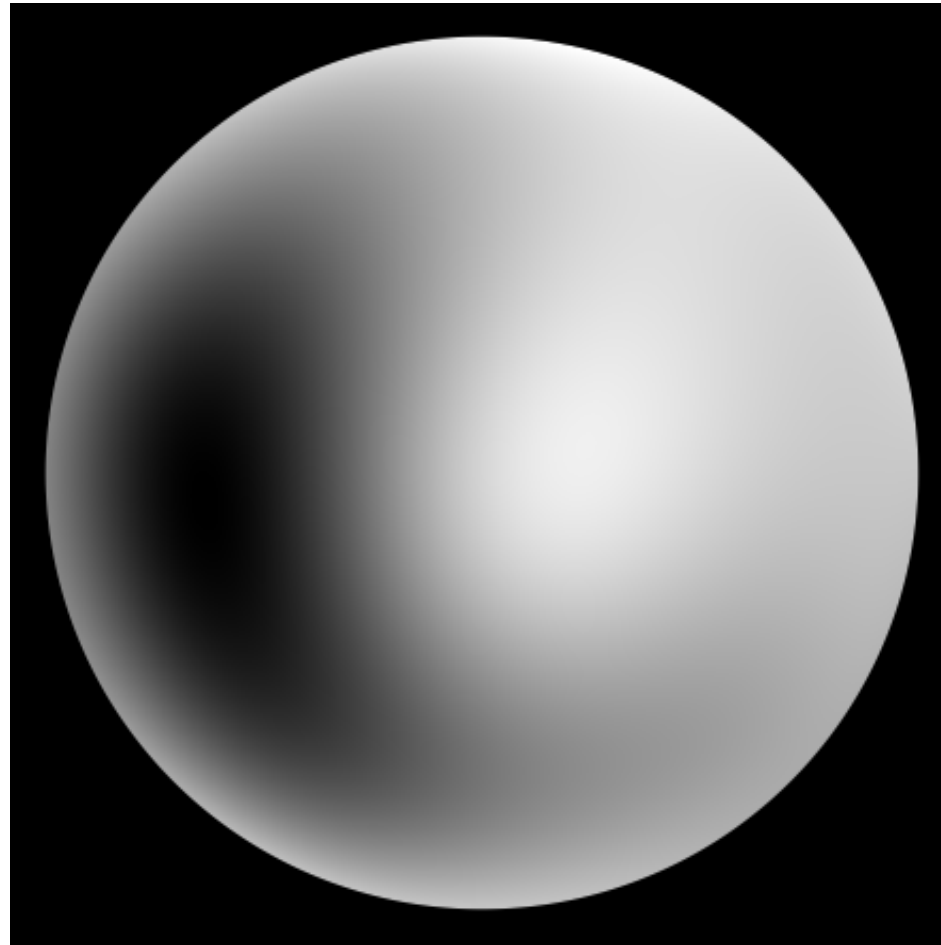
Mean contrast =
 $1 \times 10^{-5} - 4 \times 10^{-4}$

Mean contrast =
 $3 \times 10^{-11} - 4 \times 10^{-10}$

Note: 6 orders of magnitude difference in display intensity scaling

Wavefront after 30° roll

Steady state

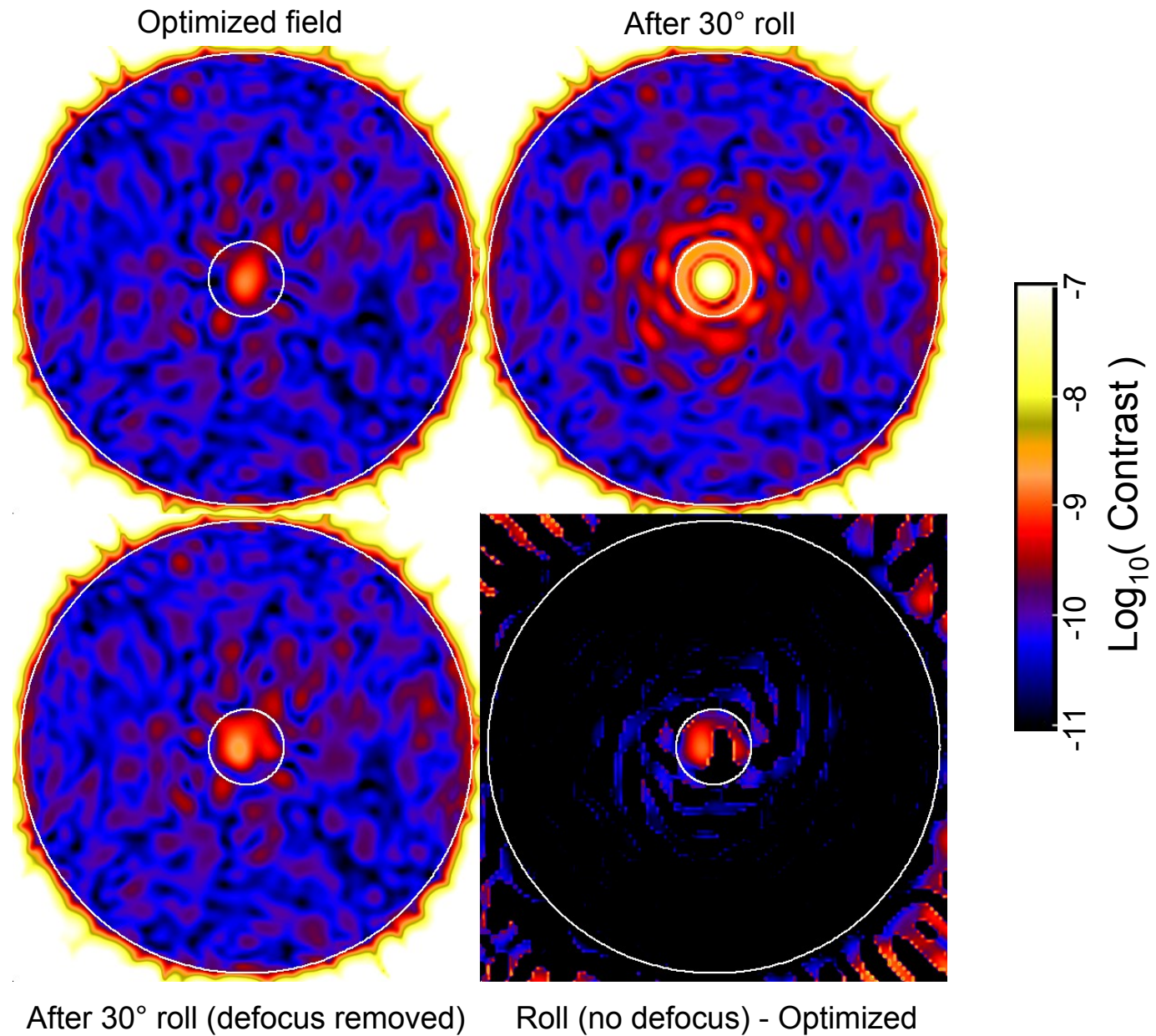


Shown with defocus removed

Defocus = 1.5 Å RMS, other = 0.19 Å RMS

From ACCESS study (Trauger et al.)

Dark hole contrast after telescope roll ($\lambda=500\text{-}600\text{ nm}$)



Some important effects

- Results shown so far are *instantaneous*
- Wavelength dispersion & induced phase changes
- Manufacturing defects
 - Coating irregularities, dielectric pattern misalignment
- Polarization
 - For 10^{-10} contrast, separate polarization channels required for VVC, perhaps HBLC & PIAA
- Off-axis effects
- Time-dependent variations
 - thermal, pointing, structural stresses
- Wavefront sensing
 - Noise
 - Sensing interval
 - Separate low-order wavefront sensing?
- Imperfect DM actuator behavior

My NASA/TDEM Study

(Technology Development for Exoplanet Missions)

- Milestone 1: Develop efficient and accurate propagators for hybrid bandlimited, vector vortex, and PIAA coronagraphs; code to be publicly available
- Milestone 2: End-to-end modeling of each coronagraph in a realistically-aberrated system (ACCESS) to determine wavefront control behavior and specifications for obtaining 10^{-10} contrast over $\lambda = 500\text{-}600$ nm