Toward 10^{10} Contrast for Terrestrial Exoplanet Detection:

Demonstration of Wavefront Correction in a Shaped Pupil Coronagraph

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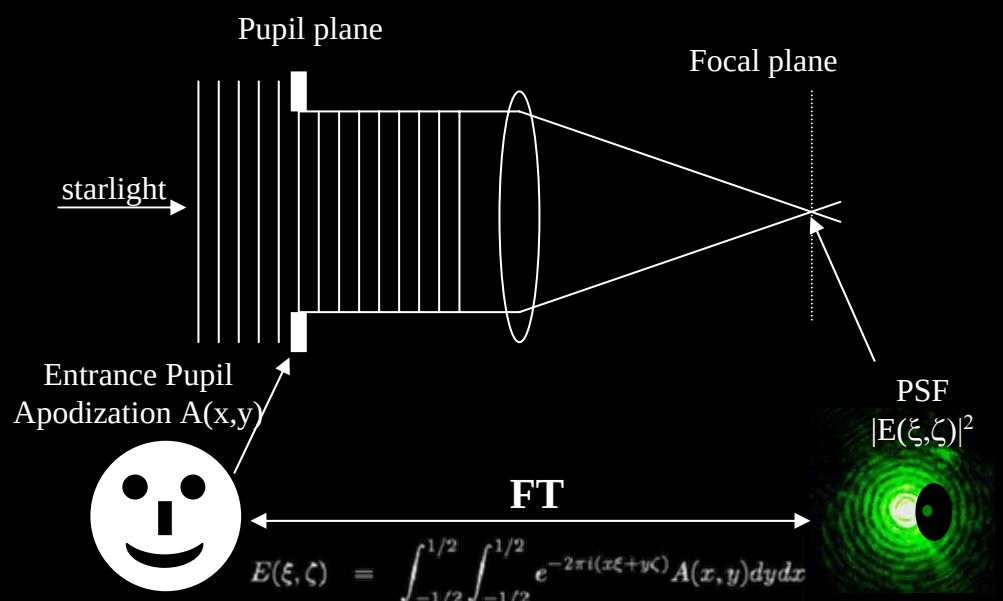
Overview

- Last year (SPIE vol 5905)
  - Manufacture of Shaped Pupil (NIST)
  - Tests on the Princeton Testbed with no wavefront control
    - 10^{-5} contrast at 4 λ/D
    - Contrast maintained across 532, 594, 632nm and broadband
  - Preliminary studies of speckle nulling algorithms
- This year
  - Briefly review the shaped pupil concept
  - Manufacture of Shaped Pupils by JPL (K. Balasubramanian)
  - Tests on JPL's HCIT
    - Wavefront control via speckle nulling
    - ~5×10^{-8} average contrast between 4 and 9 λ/D
    - Contrast maintained across 785, 836nm, and 760-840nm broadband light
    - Preliminary results of estimation techniques (Belikov, SPIE : 6272-191)
  - Analysis of performance limitations

Pupil Apodization Overview



$$E(\xi,\zeta) = \int_{-1/2}^{1/2}\int_{-1/2}^{1/2} e^{-2\pi i(x\xi+y\zeta)} A(x,y)\,dy\,dx$$

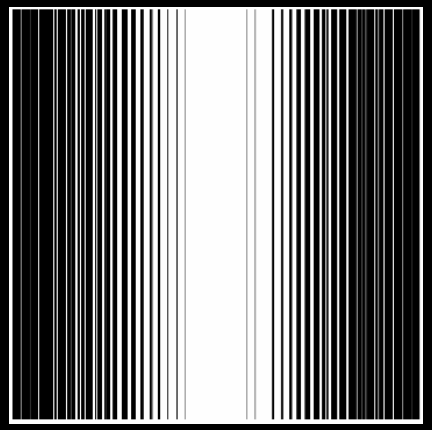
$$\vdots$$

$$E(\rho) = 2\pi \int_0^{1/2} J_0(2\pi r\rho) A(r) r\,dr,$$

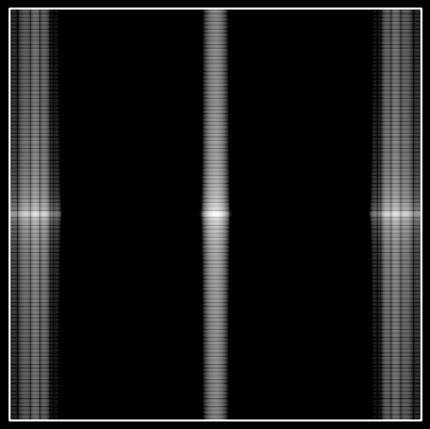
- Use nonlinear optimization to find A(x,y) for desired PSF
- Optimization metrics
  - IWA and OWA
  - contrast
  - throughput

Shaped Pupils

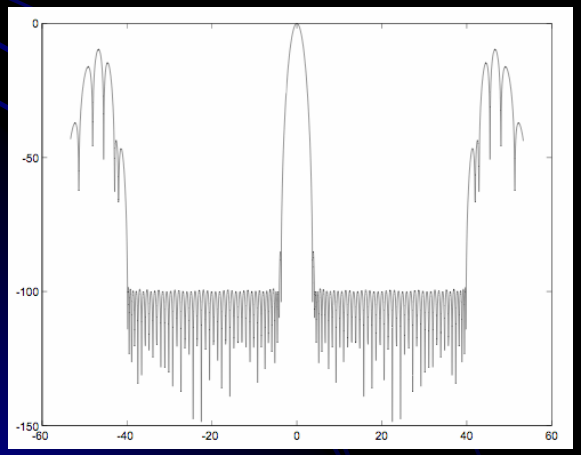
Example: "Barcode" Mask



The Mask



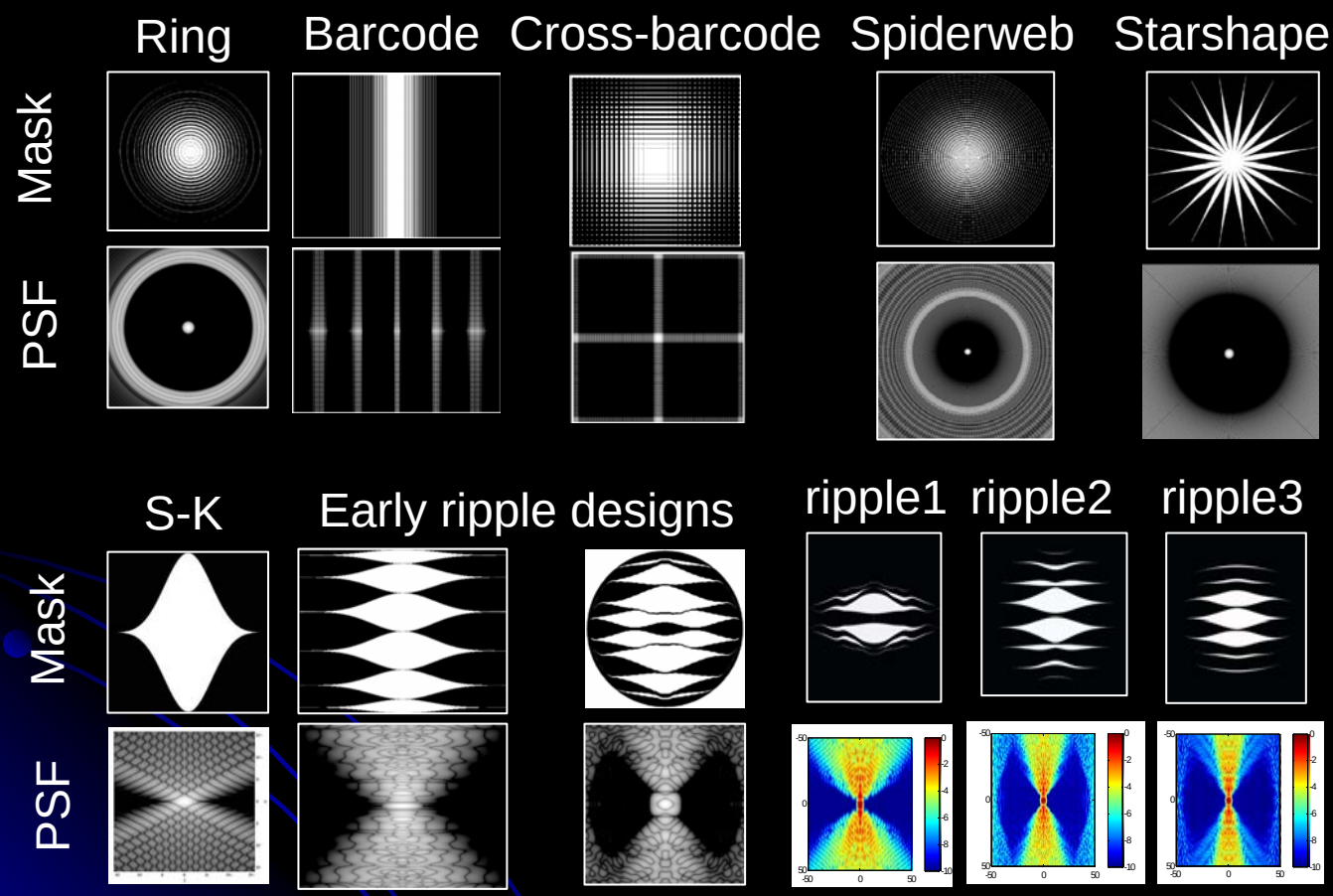
The PSF



PSF Cross Section

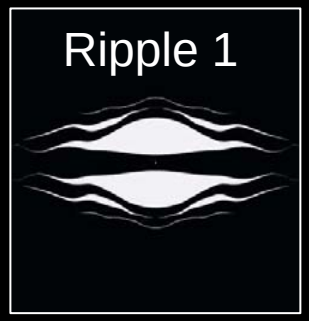
- Shaped pupils: A(x,y) is zero-one valued (holes in masks)
- Advantages:
  - simple to manufacture
  - inherently broadband
  - minimally sensitive to aberrations
  - no off-axis degradation of PSF
- Disadvantages:
  - throughput (comparable to 8th order image masks)
  - IWA (better IWA can be achieved through less discovery space or greater simplicity)

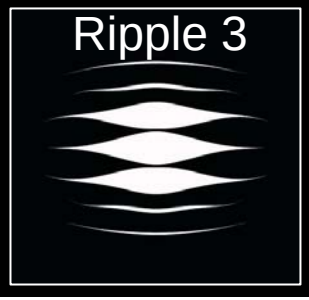
Shaped Pupil Zoo

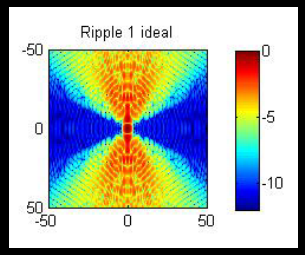


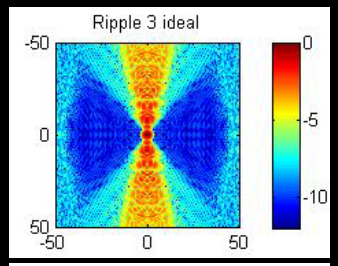
- Choice was made to manufacture a free standing mask instead of a mask on glass substrate
- Ripple designs lend themselves the best for manufacture as free-standing masks

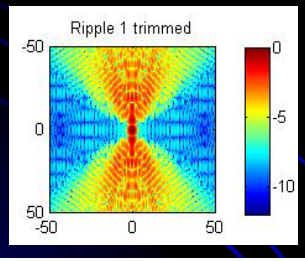
Manufactured designs

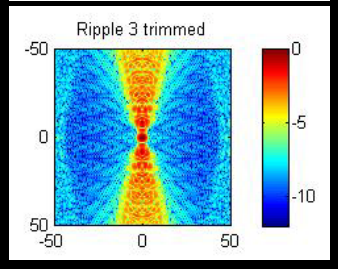


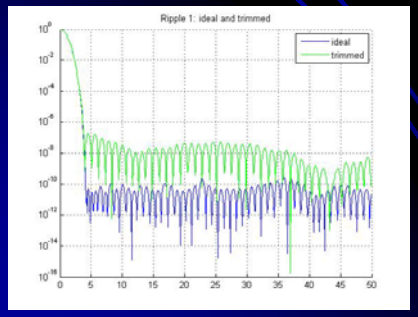


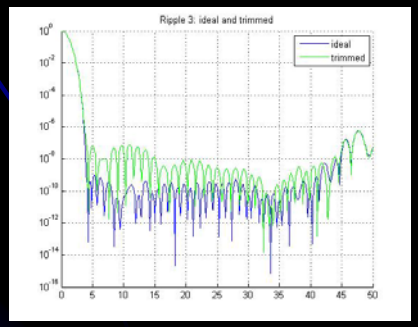












- Ripple1
  - 45 degree openings
- ~12% Airy throughput
  - 10^{10} contrast
  - IWA = 4 λ/D
  - OWA~100 λ/D
- Ripple2 and 3 are circular designs with
  - 90 degree openings,
  - ~10% Airy throughput,
  - <10-9 contrast
  - IWA=4, OWA~40.
  - Ripple 2 has a central obstruction and 3 does not
- Both are 25mm in diameter

Bowtie

For ripple 3
IWA = 4 λ/D @ 532nm

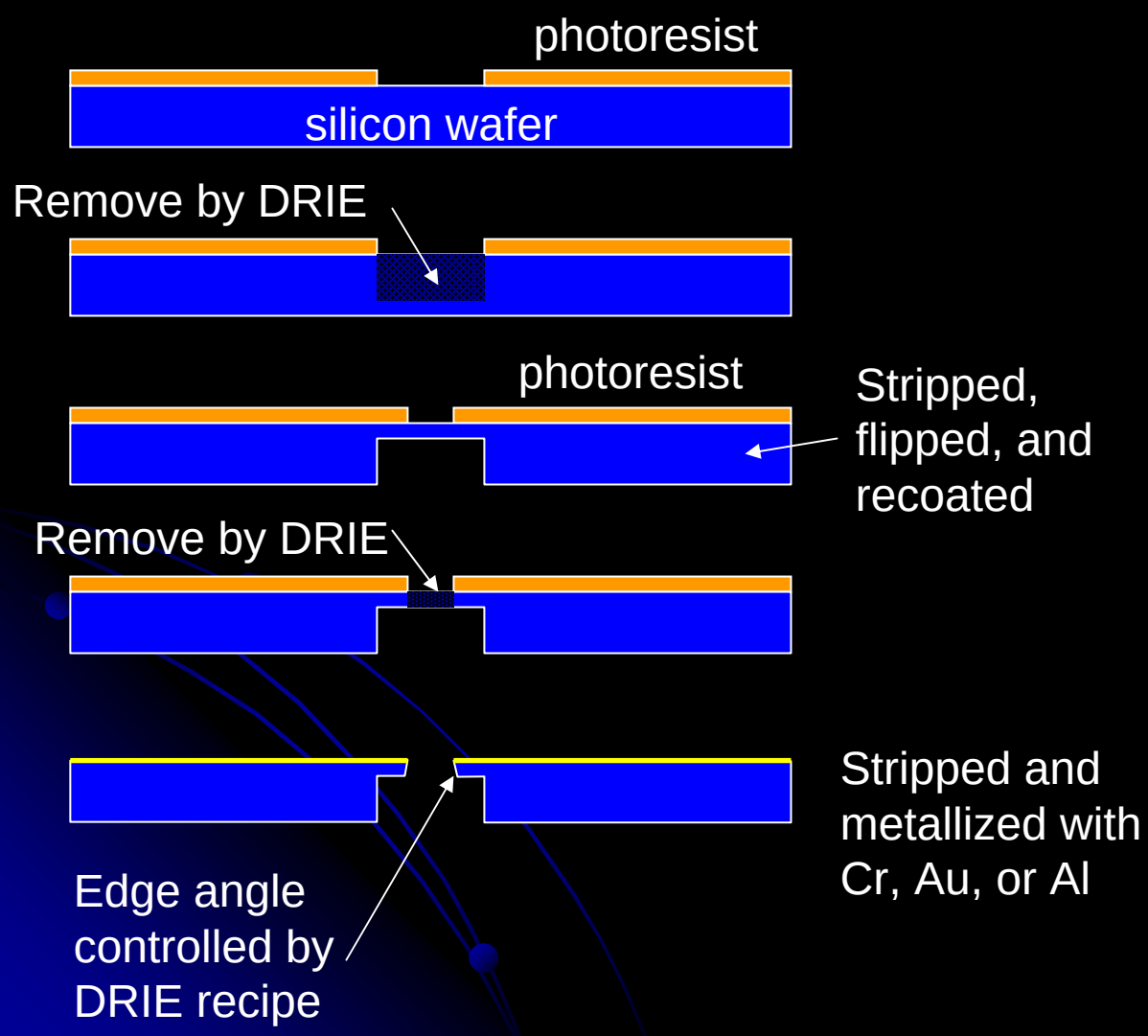
For ripple 1
IWA = 4 λ/D @ 632nm

For Lyot

For ripple 3
IWA = 4 λ/D @ 785nm

For ripple 1
IWA = 4 λ/D @ 836nm

NIST Mask Manufacturing

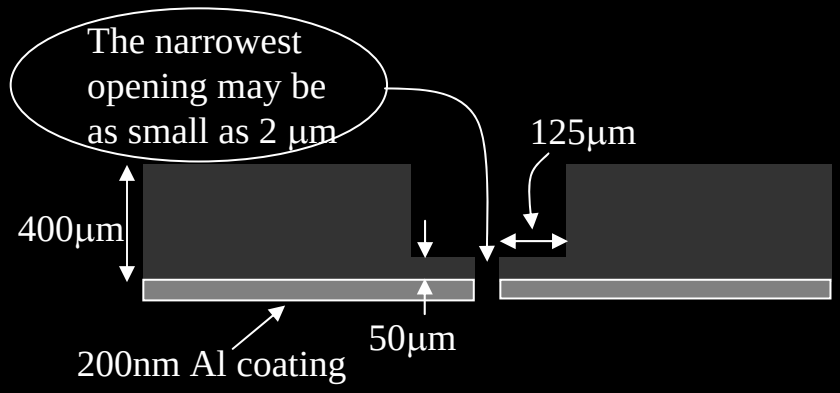


- Manufactured by NIST (for JPL masks, see talk by Balasubramanian et al SPIE 6265-130)
- Commercial Si wafer
  - 76 mm diamter
  - 320 micron thick
  - 1-10 ohm cm, p-type, B doped
  - <1-0-0> oriented
- Double-sided Deep Reactive Ion Etch (DRIE) to make holes
  - First etch: wafer thinned to 50 micron thickness around openings
  - Second etch: through etch to complete holes

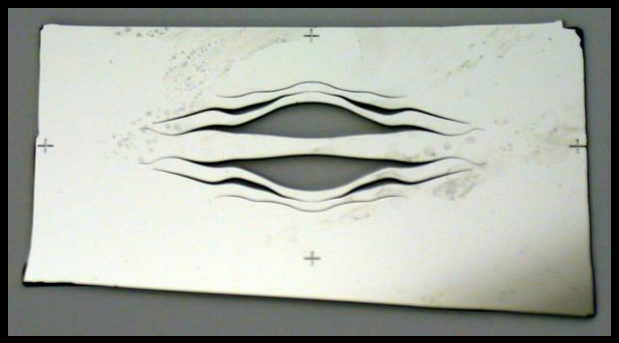
Courtesy of James Beall, NIST

One of Ripple1s

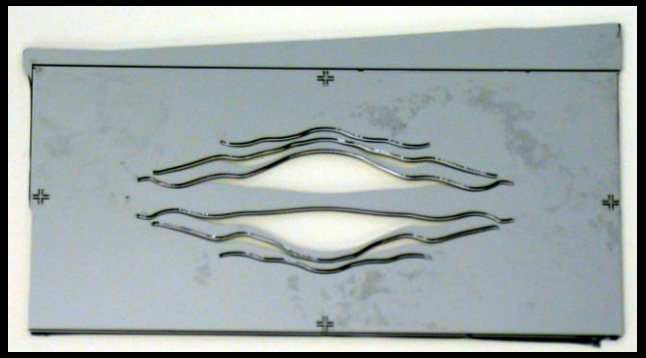
Design



Optical images

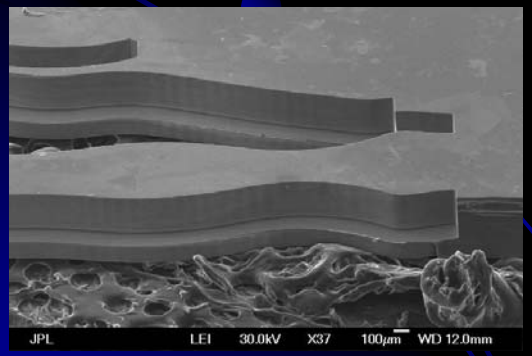


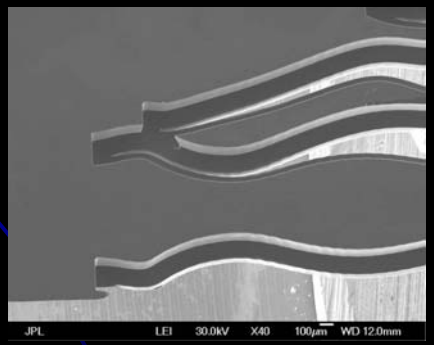
Aluminum coated side



uncoated side

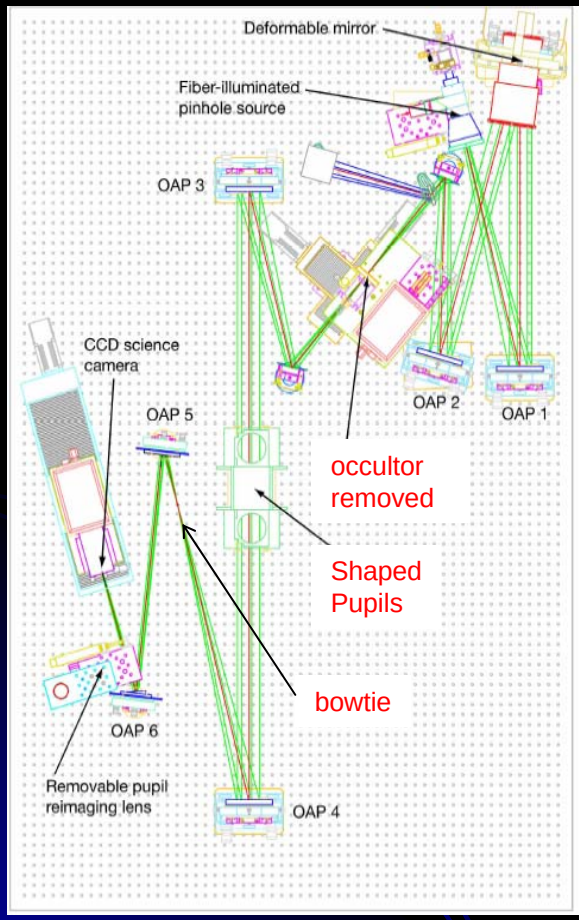
SEM images





Courtesy of K. Balasubramanian

JPL's High Contrast Imaging Testbed

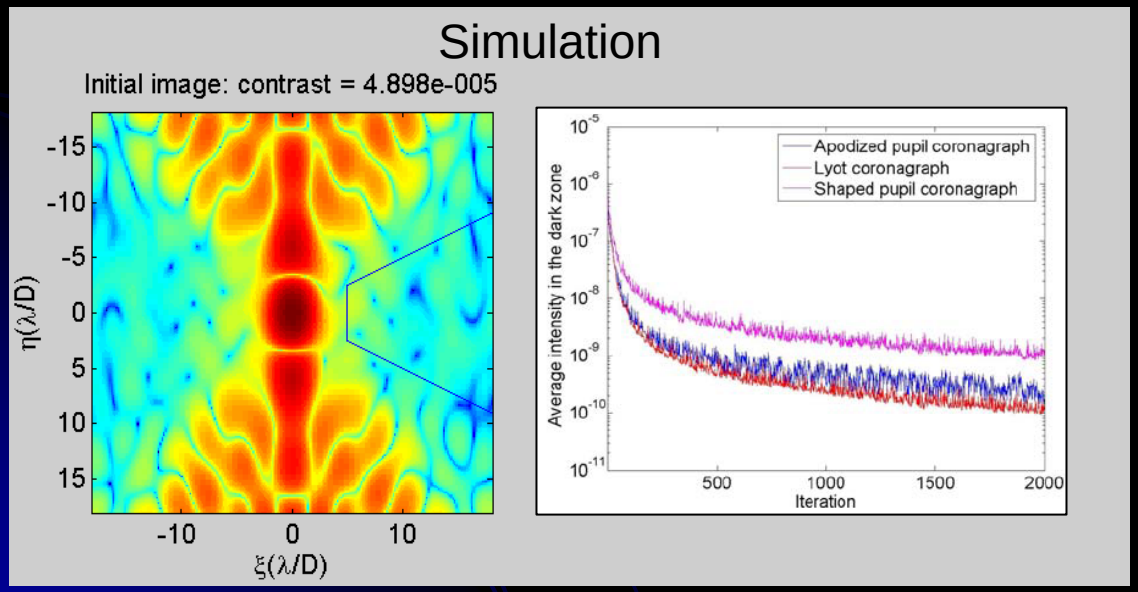


- State-of-the-art facility for testing high-contrast imaging concepts and wavefront correction schemes
- Vacuum chamber
  - 6' diameter
  - 10 mTorr or better
  - 5'x7' vibration isolated optical table
- Xinetics DM
  - 32x32 actuators, 1mm pitch
- 30mm beam
  - 785nm, 836nm, or 760-840 broadband
- Fully automated and remote-controlled

Courtesy of J. T. Trauger

Speckle Nulling for Wavefront Control

- Introduced by Trauger and Burrows (SPIE, 2004)
- Based on iteratively removing brightest speckles
- Phase and amplitude aberrations removed simultaneously on a half-plane, allowing the use of only one DM
- Used primarily to demonstrate high contrast, not a viable method of wavefront correction for planet detection, because it is very slow.

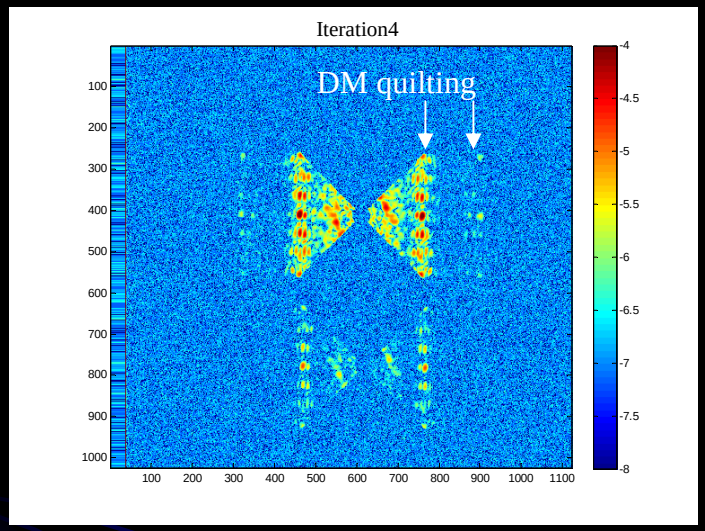


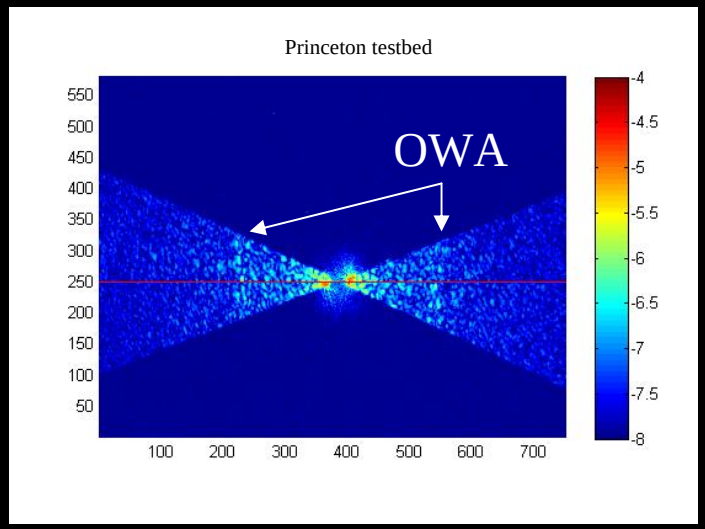
- Example
  - Start with random sinusoidal aberrations corresponding to ~ 5×10^{-5} contrast:
    - Phase: $\lambda/80$ RMS, $f^{-3/2}$
    - Amplitude: 0.005 RMS, f^{-2} PSD
  - After 500 iterations, 3×10^{-9} contrast from 4 to 18 λ/D

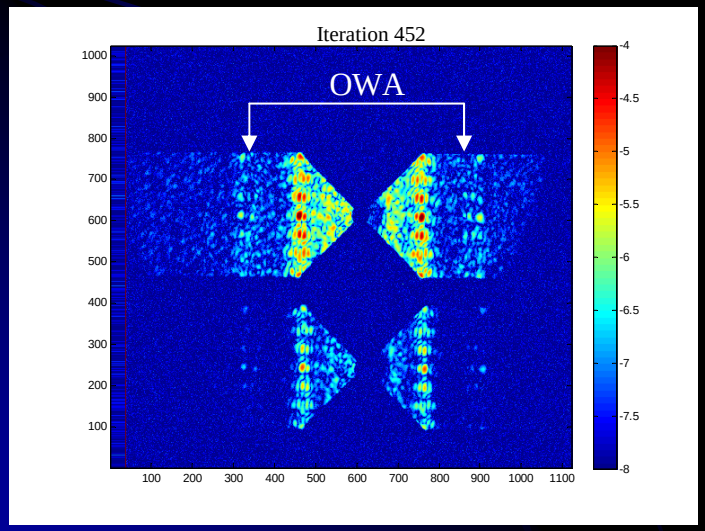
Speckle Nulling Algorithm Description

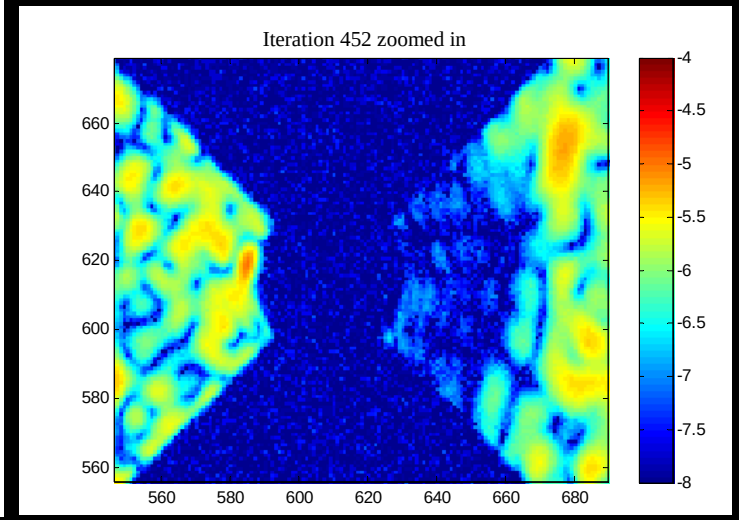
1. Record an image with the current DM configuration
2. Locate the brightest speckle(s) in the discovery region
3. Generate a ripple on the DM corresponding to the location and brightness of the speckle(s), and vary the phase *N* times, taking images for each phase trial.
4. Interpolate the speckle(s) attenuation in 3 to find the phase that gives the best attenuation.
5. Update the DM using the ripple *k*-vector and amplitude from 3 and phase from 4.

JPL speckle nulling @785nm with Ripple 3





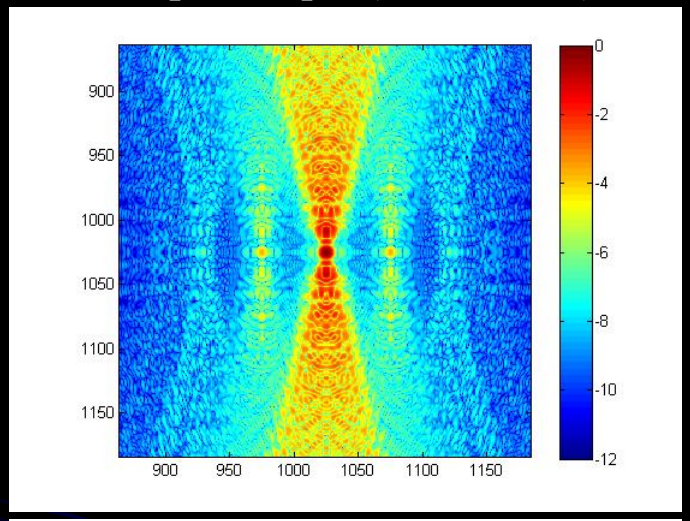


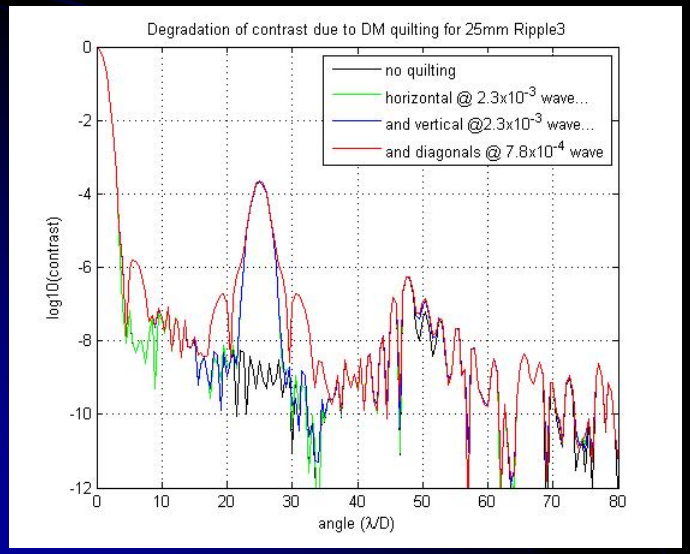


- 457 iterations over a course of 3 days
- Went down from 10^{-5} contrast to 4×10^{-8} between 4 and 9 λ/D
- Features in the images:
  - Two polarizations
  - OWA structure
  - DM quilting
- Wavefront corrected in both polarizations
- Some wavefront correction on the opposite side, until we hit amplitude errors

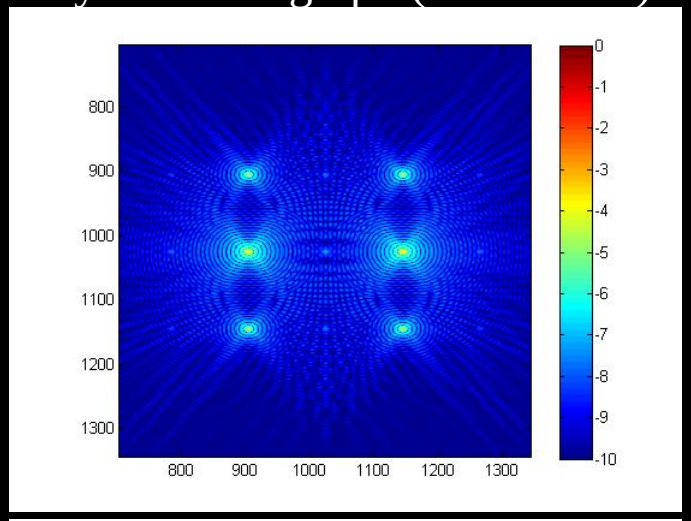
Quilting

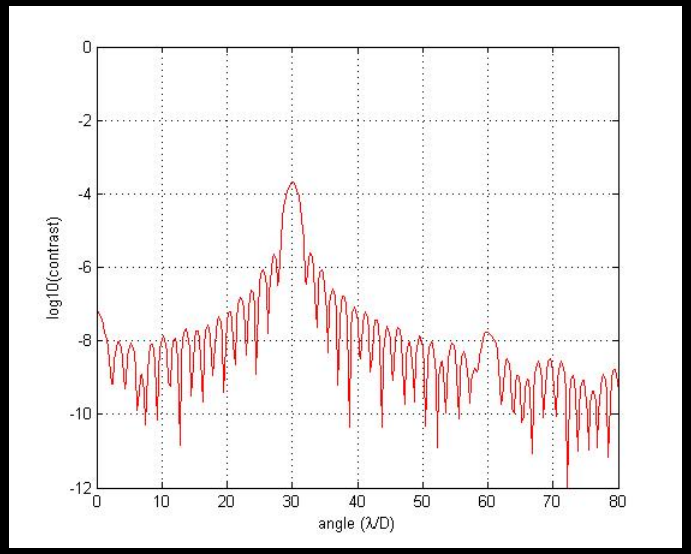
Shaped Pupil (simulation)





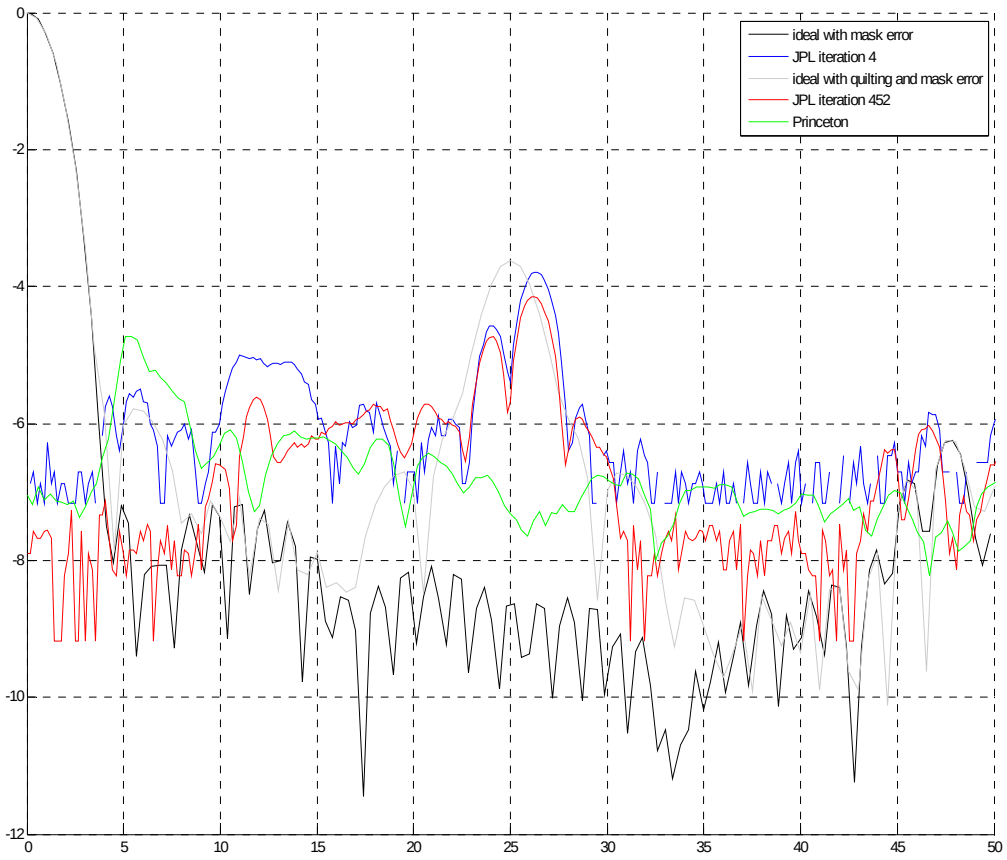
Lyot Coronagraph (Simulation)





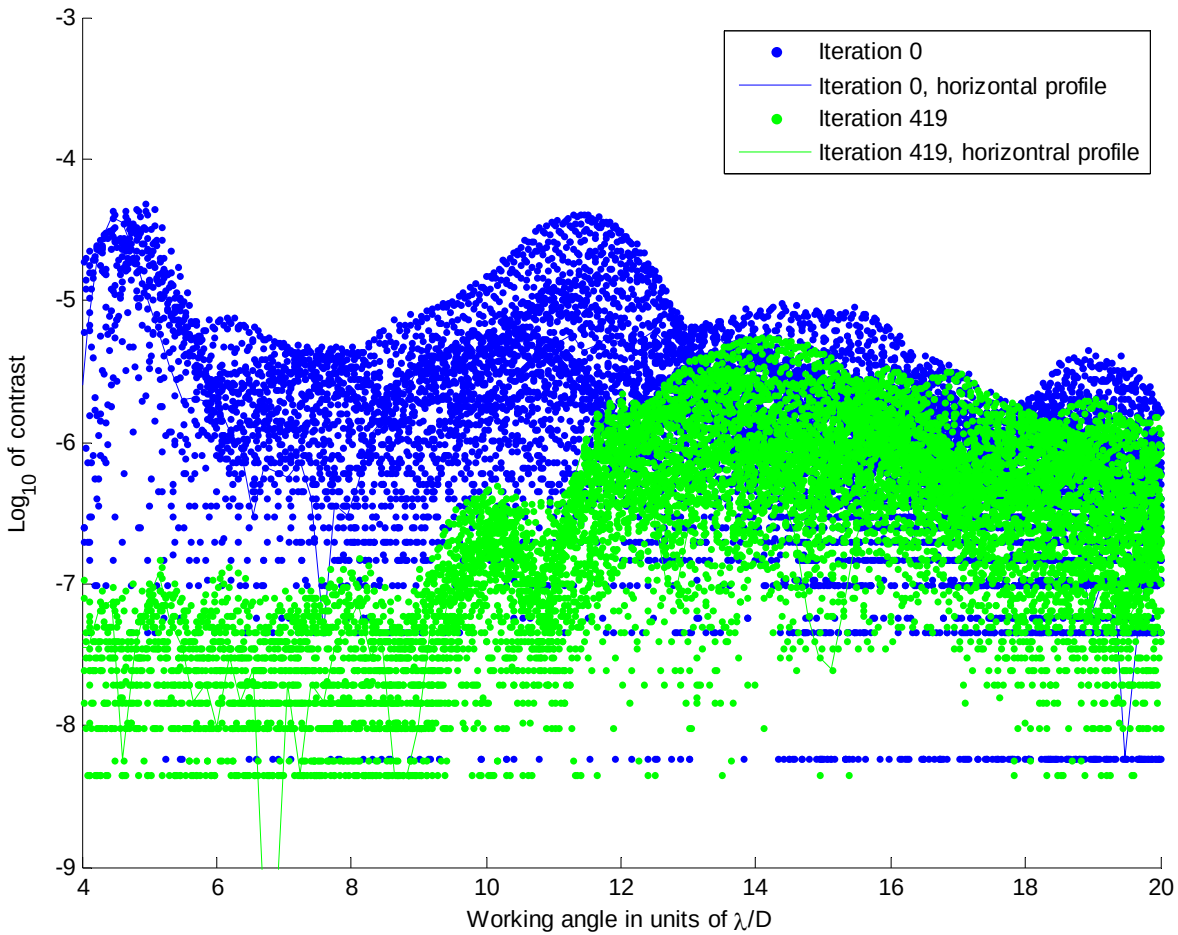
- DM sheet is not completely flat, with the dominant feature being a quilting pattern with same pitch as the actuators (1 cycle/mm)
- This leads to strong (10^{-4}) speckles at 25 λ/D
- Wings of this speckle degrades contrast at inner working angle to 10^{-6}
- This can, and has been, corrected by speckle nulling
- The requirement that the quilting order not saturate limits the exposure time and achievable contrast to at best 3×10^{-9}

Horizontal slice

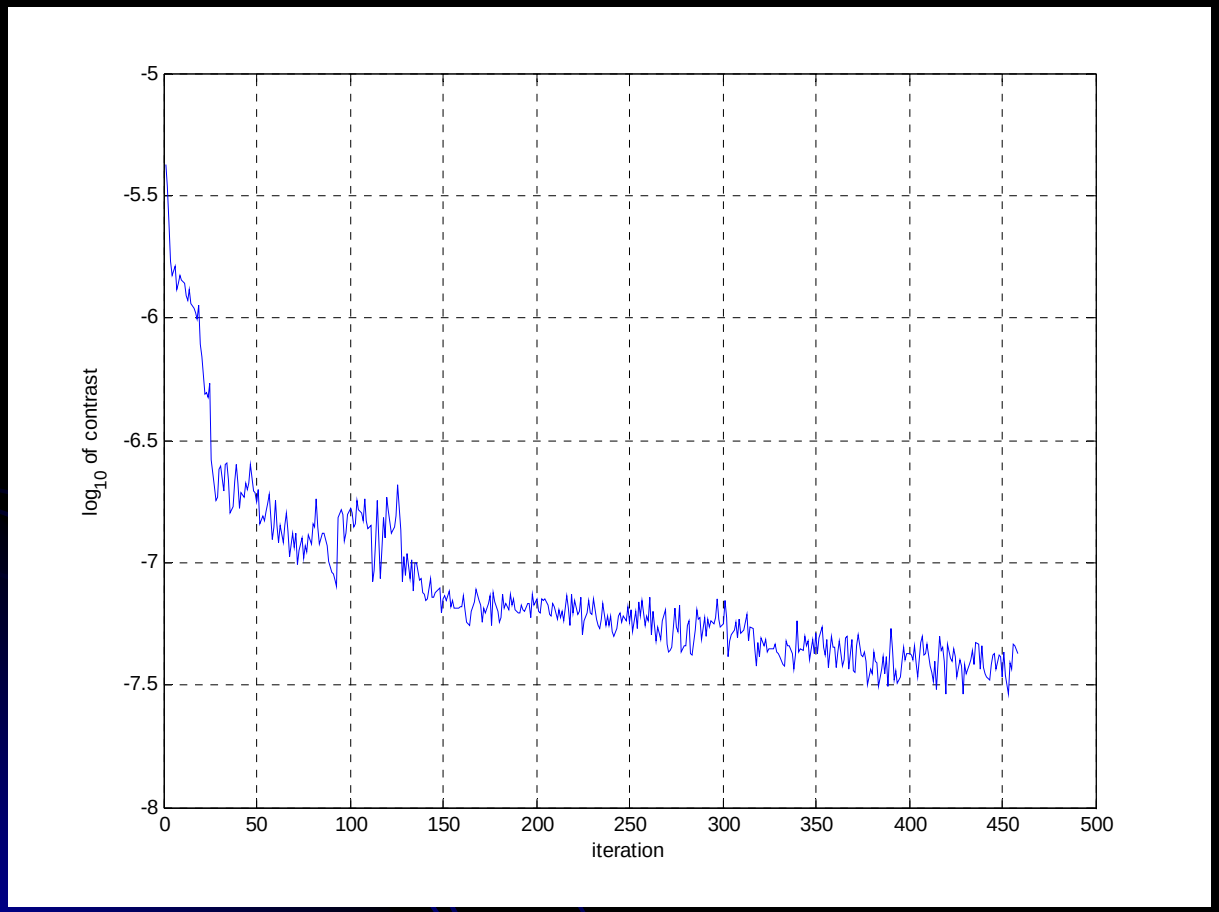


- Note that starting point is very close to the predicted level due to quilting
- Ending point is very close to the ideal (aberration-free) performance
- Speckle nulling may or may not be able to push the contrast lower than the masks were designed for

Horizontal slice

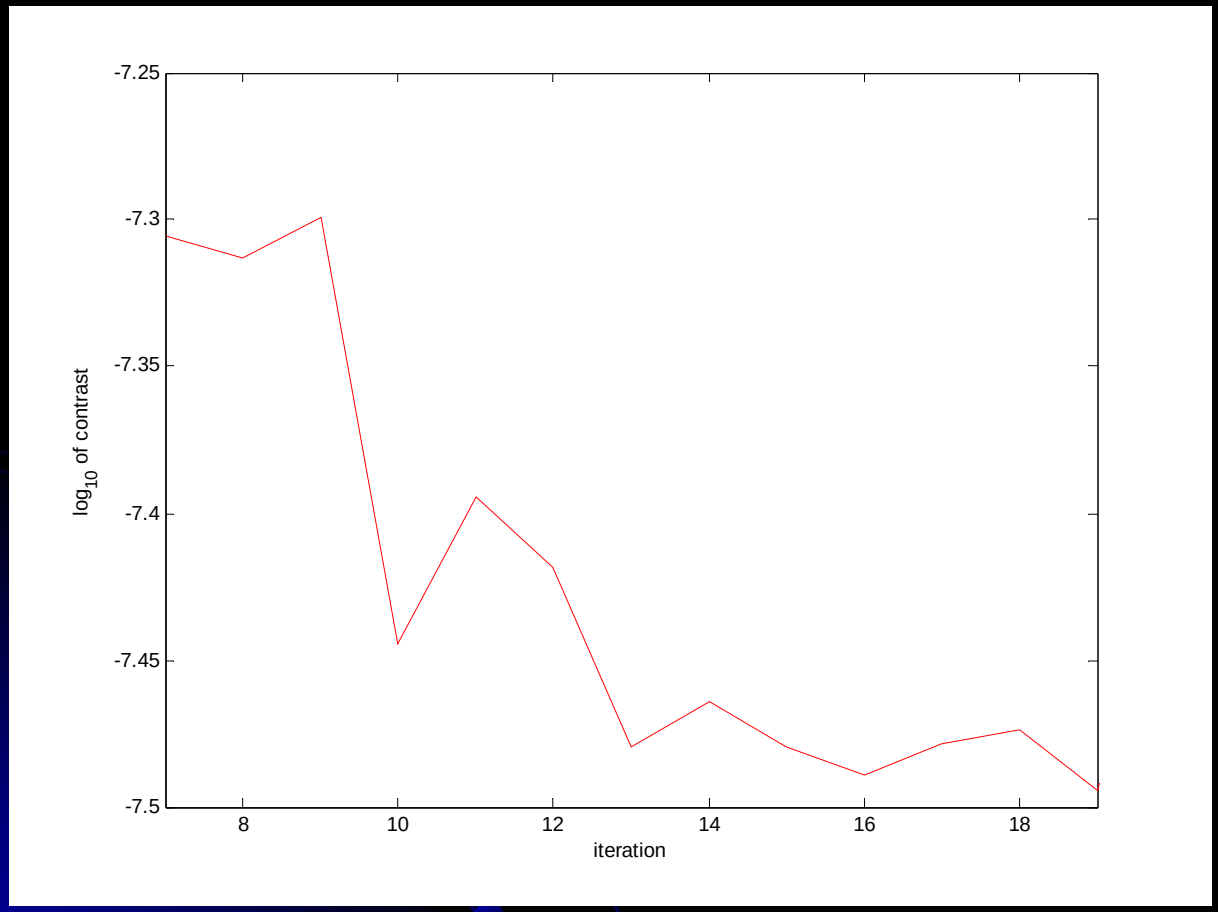


Contrast improvement rate



- Contrast seems to continue to improve. We may not have hit a limit
- Main technical issues
  - Limitation on exposure time due to quilting order
  - Drift due to table flexing requires periodic recalibrations

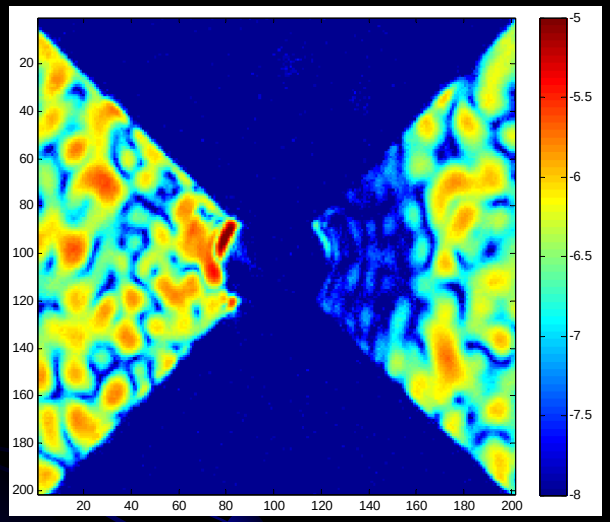
Princeton Speckle Nulling Algorithm



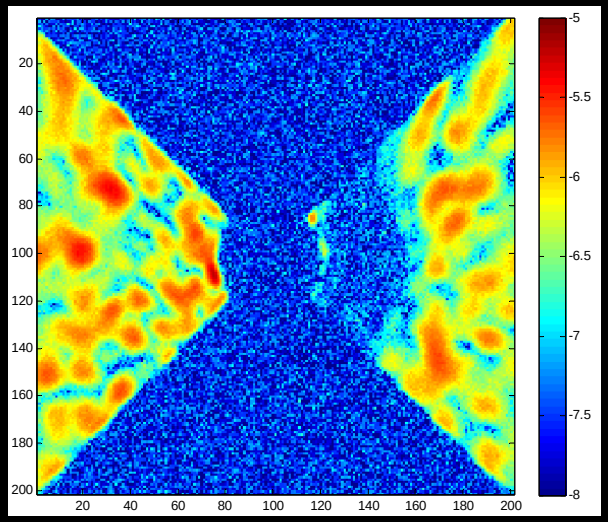
- Main differences from HCIT algorithm
  - Does not resample
  - Looks for a fixed smaller number of speckles (5-10)
  - Larger distances between speckles in any given iteration
  - Looks at a fixed number of speckles at a time
  - Spline interpolation instead of sine fitting
  - Optional mode: vary one speckle per iteration and look at average contrast across the entire dark region
- Not enough iterations for a direct comparison
- The algorithm clearly works

Multi-wavelength and Broadband Performance

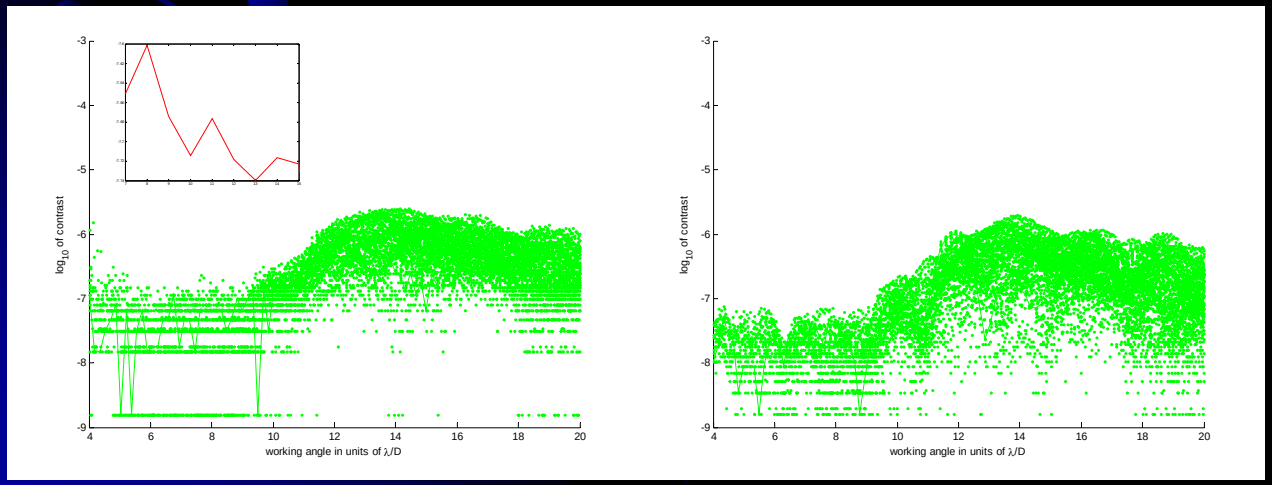
836nm



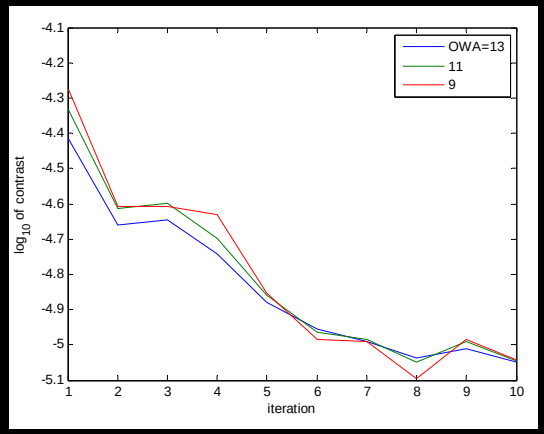
760nm-840nm

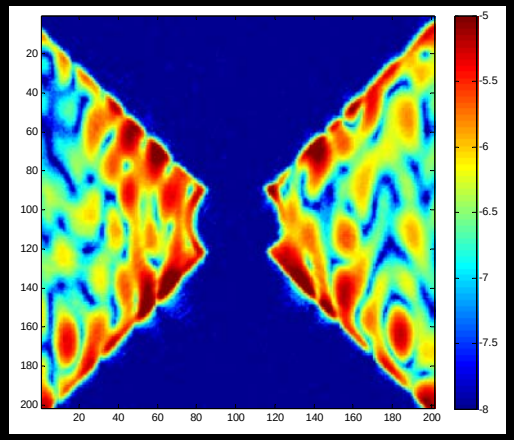


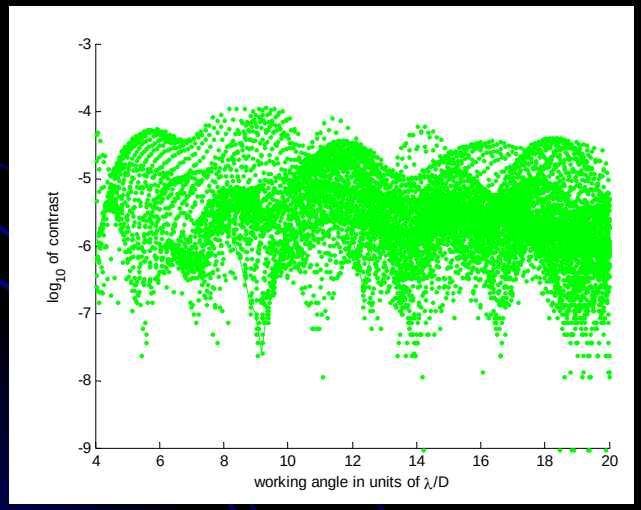
- Switching from 785 to 836nm initially degraded contrast very slightly, but after a few speckle nulling iterations, contrast was below the minimal levels achieved with 785. Presumably this is because longer wavelengths see lower aberrations
- After switching to broadband light, contrast remained about the same



Tests with Ripple1







- Contrast degraded significantly after switching to ripple1, as expected
- Demonstration that speckle nulling works for ripple1, even though numbers of actuarors are effectively reduced
- 90° opening was used instead of the 45 because the edges of the wings are not very bright
- Ripple1 had a pinhole in the middle, but its effect is drowned in the speckle

Conclusions

- Experimental demonstration of wavefront control with shaped pupils
- Contrast level is maintained across different wavelengths and 10% broadband light.
- Further improvements in contrast believed to have been possible with more time and parameter optimizations

Related Talks

- Bala
- Amir
- Laurent
- Jason
- Belikov (phase estimation)
- Etc.