Wavefront Control in a Shaped-Pupil Coronagraph:

First Results from the Princeton Testbed

Ruslan Belikov, Amir Give'on, Laurent Pueyo, Eric Cady, Jason Kay, Michael Carr, Robert J. Vanderbei, N. Jeremy Kasdin

TPF@Princeton Lab, Department of Mechanical and Aerospace Engineering, Princeton University, USA

Supported by NASA JPL Contract #1254357 and Michelson Science Center

International TPF/Darwin Workshop, Pasadena, CA, November 2006

Poster converted to slides

Outline

- Shaped Pupil Concept
- The TPF@Princeton Lab
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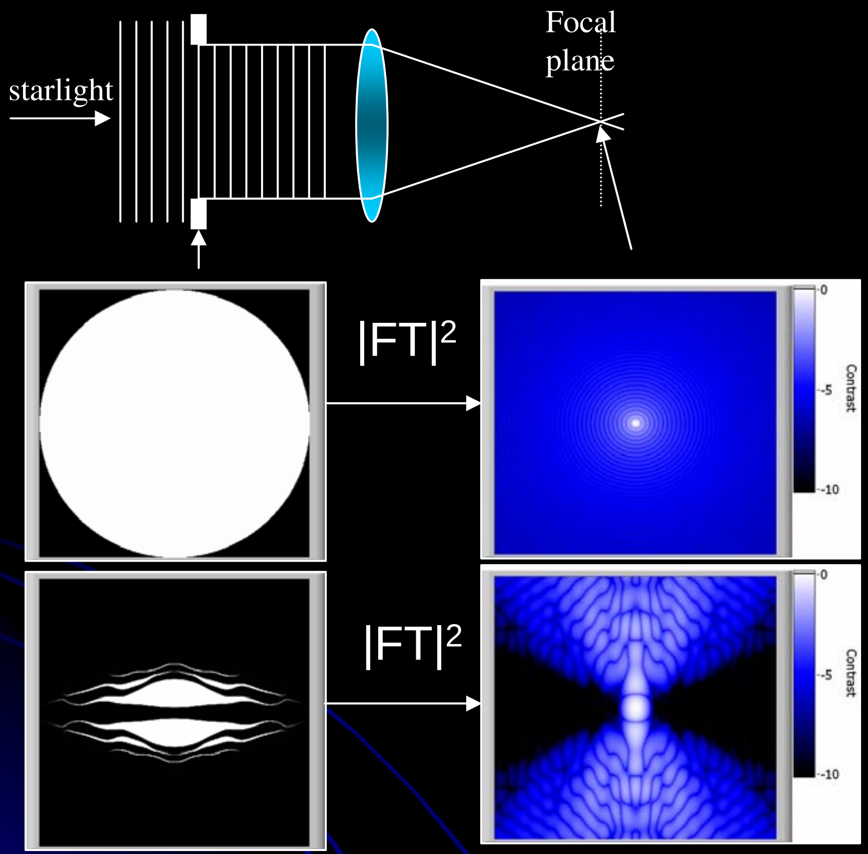
Pupil Apodization Overview



Airy Pattern.
No high contrast terrestrial planet detection zones

Ripple1 PSF

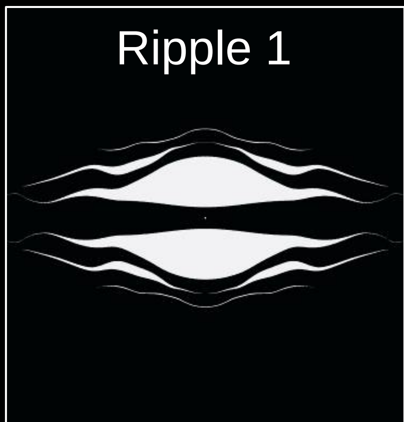
Shaped pupil PSF with High contrast zones

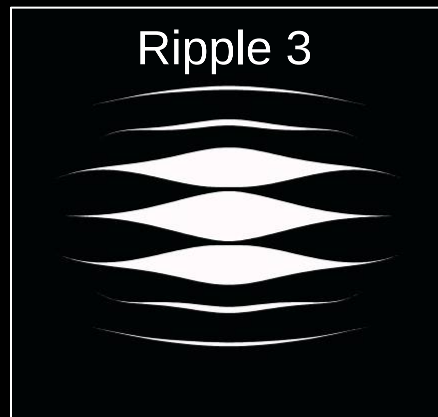
–Advantages:
- •Simplicity of manufacture and integration
- •Inherently broadband
- •Low sensitivity to aberrations
- •Lab validation close to requirements

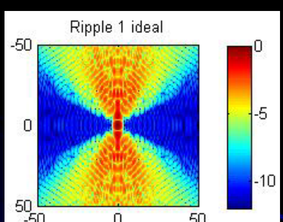
–Disadvantages:
- •throughput (airy) = 12%
- •Inner working angle difficult to make smaller than 4 λ/D

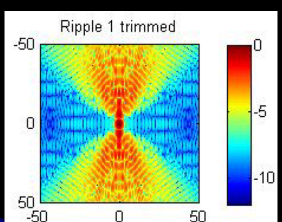
- How do we design shaped pupils?
  - Short answer: nonlinear optimization to find a desired pupil shape for desired PSF. (Developed by Bob Vanderbei)

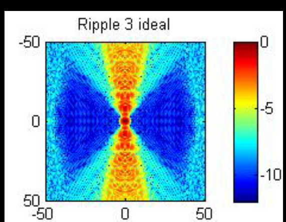
Some manufactured designs

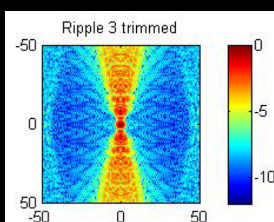


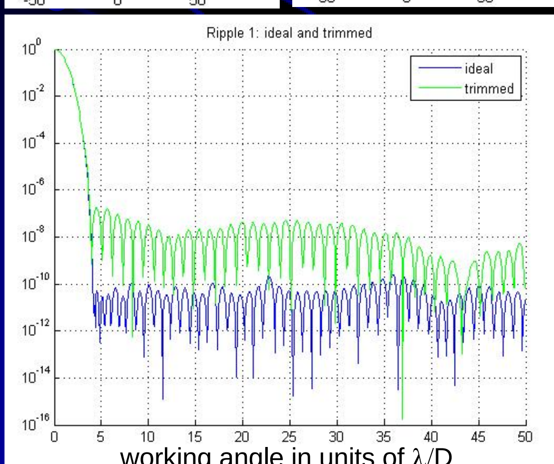


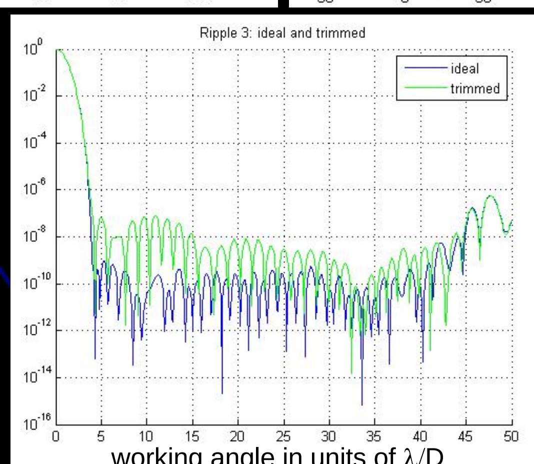








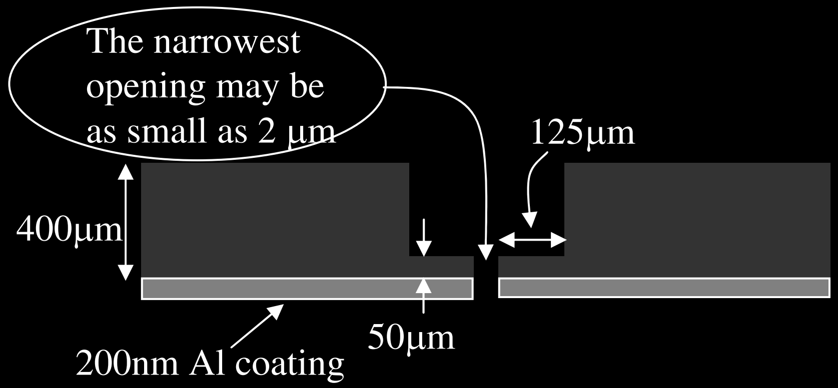




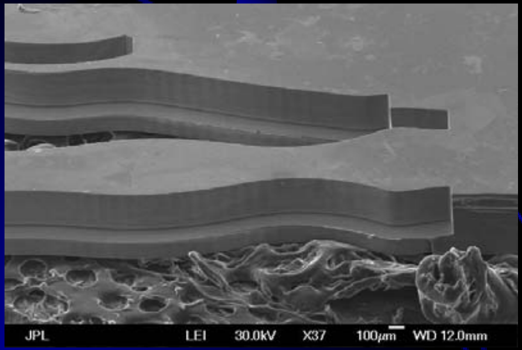
- Free-standing silicon mask
- Ripple designs easiest to manufacture
- Ripple1
  - TPF aspect ratio
  - 45 degree openings
  - ~12% Airy throughput
  - 10^{10} contrast
  - IWA = 4 λ/D
  - OWA~100 λ/D
- Ripple3
  - Circular
  - 90 degree openings,
  - ~10% Airy throughput,
  - <10^{-9} contrast
  - IWA=4, OWA~40.
- Both are 25mm in diameter
- Trimming the edges degrades contrast to ~10^{-8} – 10^{-7}

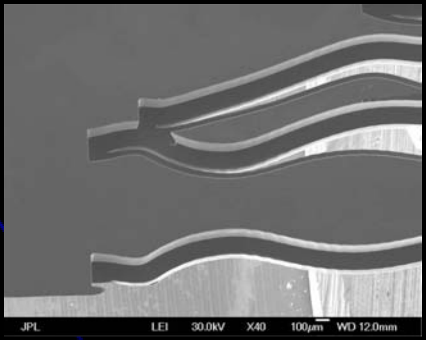
Manufacturing

Design

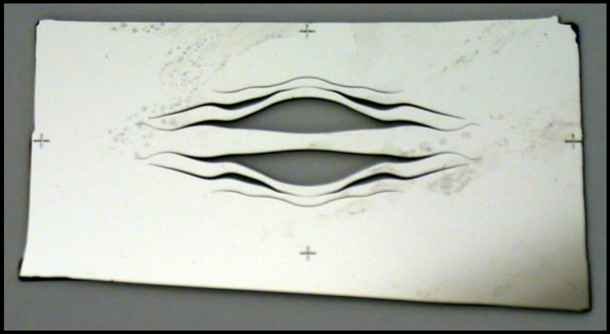


SEM images

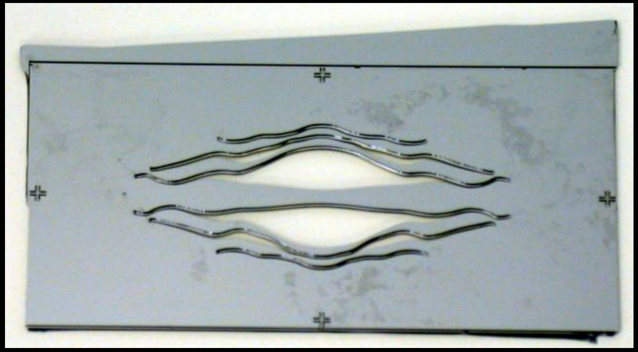




Optical images



Aluminum coated side



uncoated side

Courtesy of K. Balasubramanian (6265-130)

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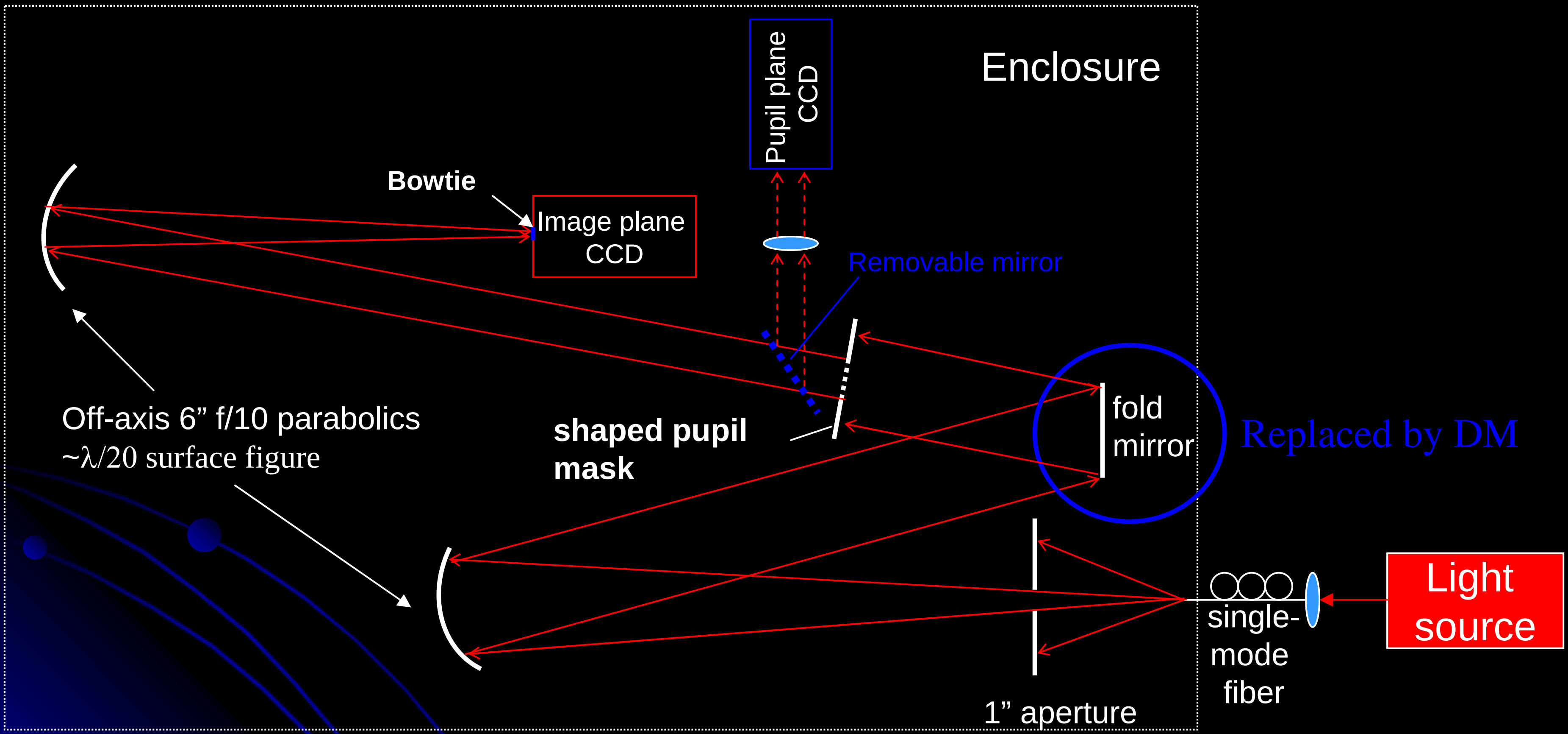
The Princeton Laboratory

- Clean room
- 1.2 x 5 m vibration-isolated optical bench
- Enclosure to eliminate thermal convection, air turbulence, particulate contamination, and stray light

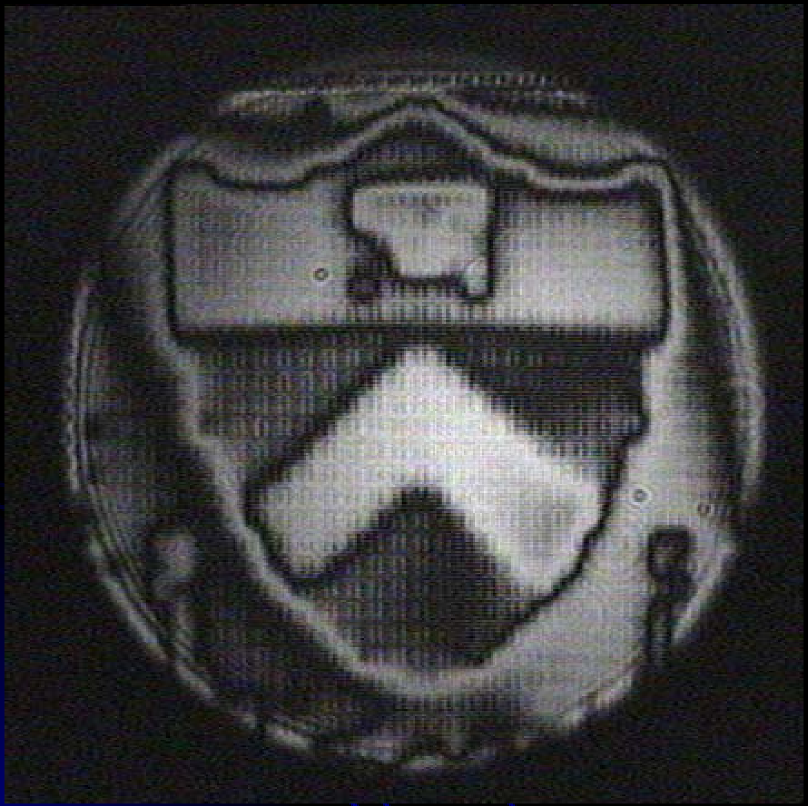
Lab experiments: Princeton testbed



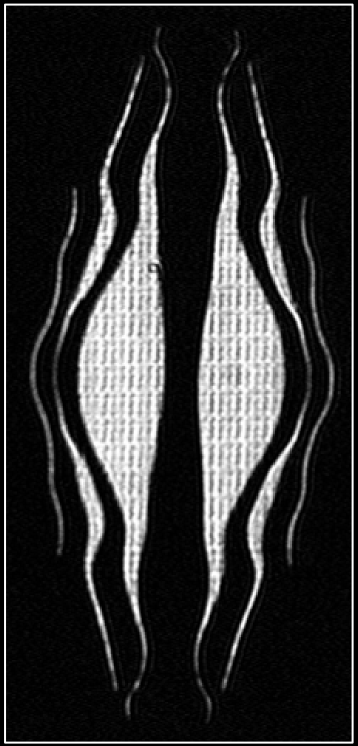
- DM is 11x11mm, so we used a 10mm shaped pupil
- Inserted a removable mirror to examine the pupil plane

DM installed

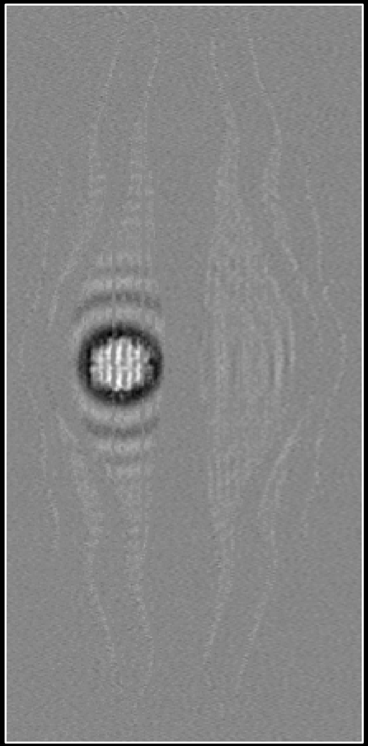
DM Interferogram



Pupil Plane images



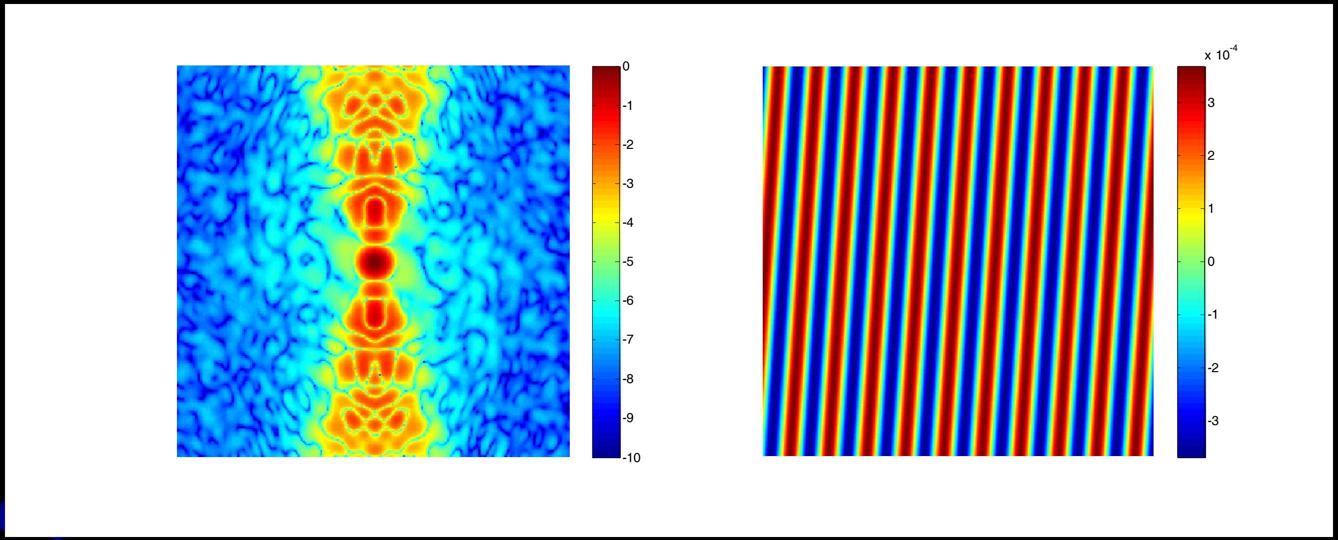
“flat” frame



Difference image
(14,19) @ 100V
minus flat

Speckle Nulling for Wavefront Control

CCD Image (simulation) DM (simulation)



- 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.
- Algorithm:
  - Look for the brightest pixel in the dark zone
  - Compute a DM ripple that would place a speckle centered on that pixel
  - Find phase which minimizes that pixel
  - Update DM
  - Repeat

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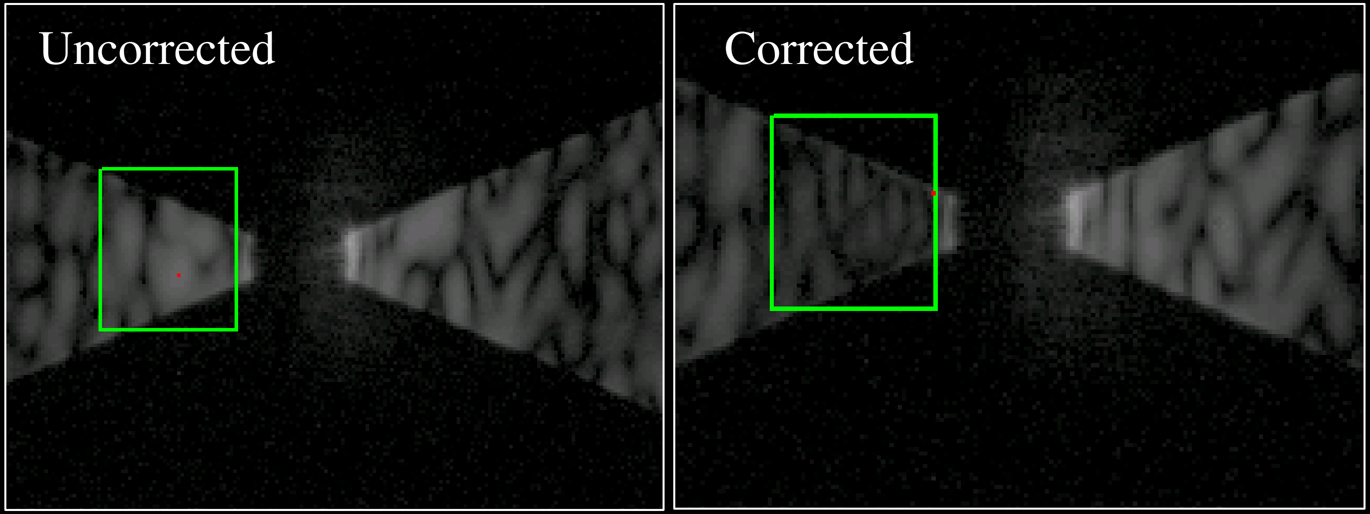
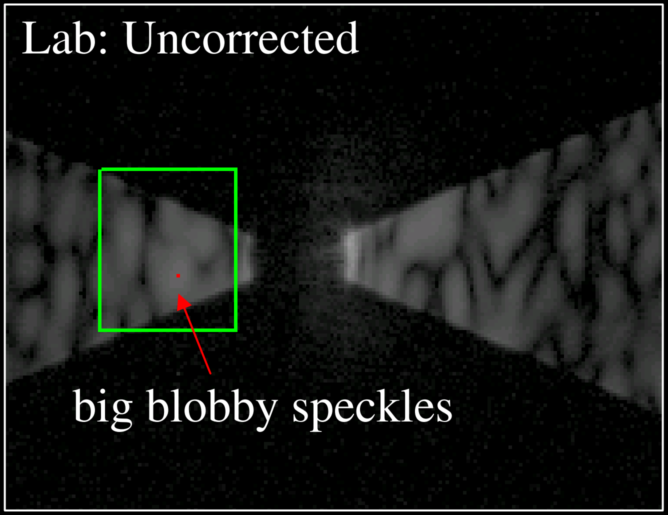
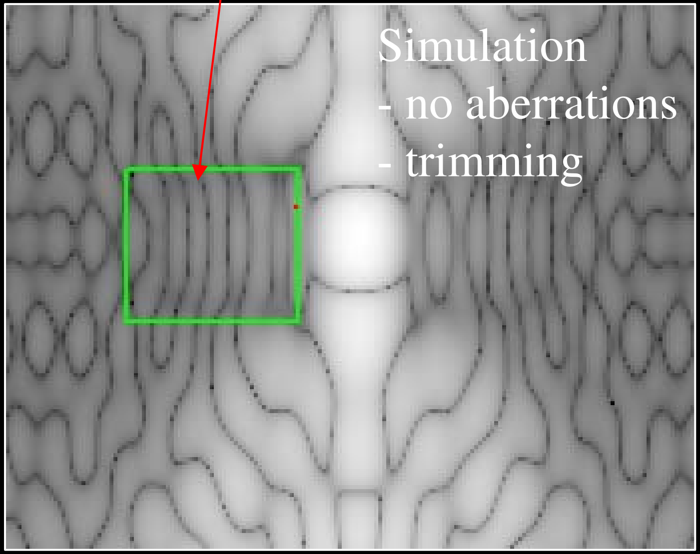
Princeton Testbed, Classical Speckle Nulling (632nm)



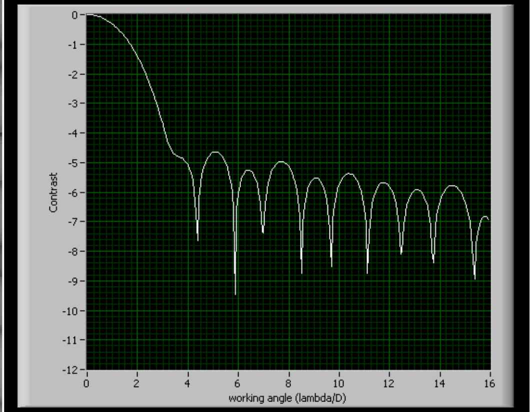
- Average contrast: 10^{-6}
- However, when we performed this experiment at JPL's HCIT, the contrast was 4×10^{-8}, due to their better equipment

Limiting factor



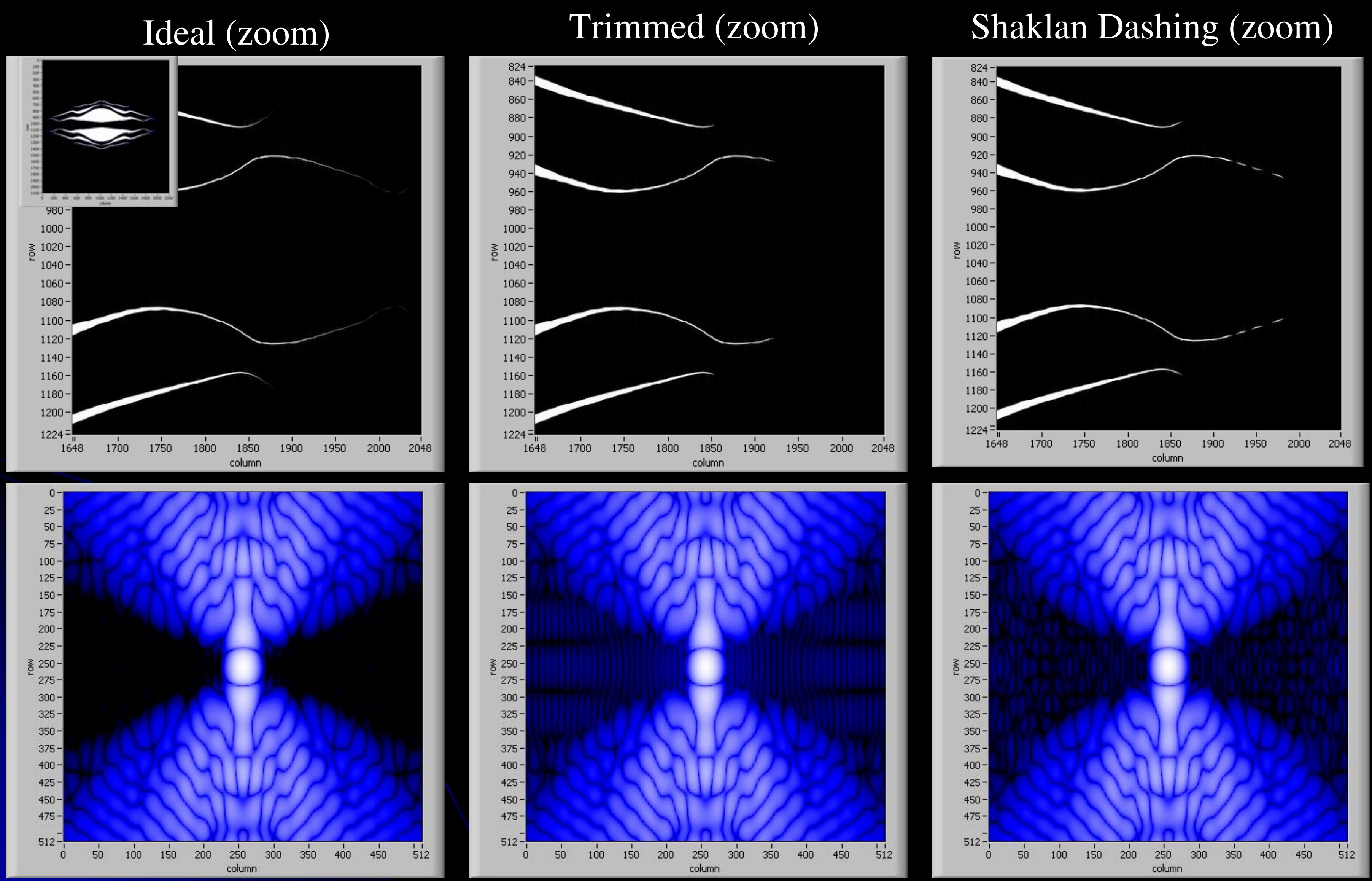


Simulation slice



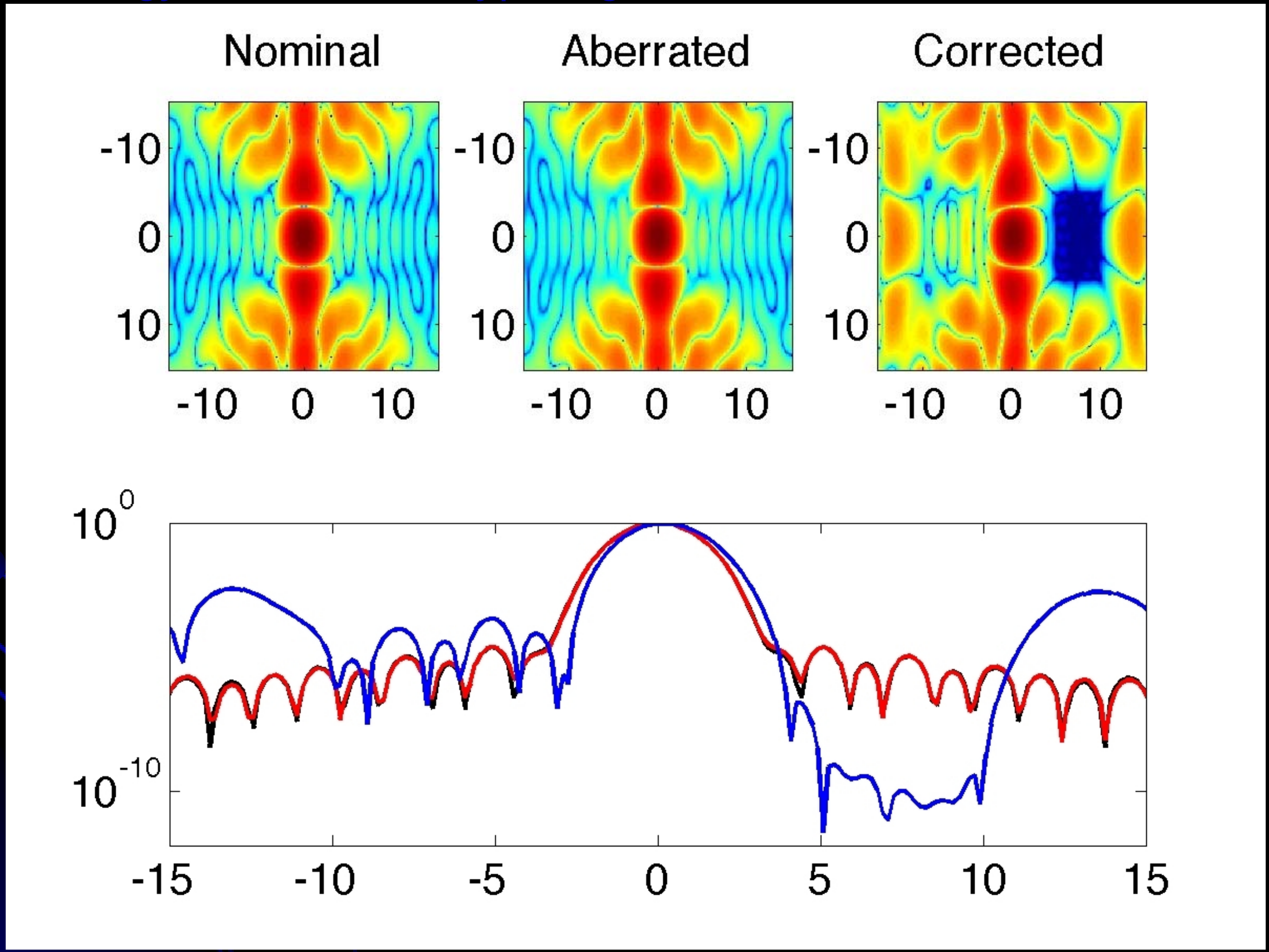
- Mask trimming introduces long thin speckles that cannot be corrected by classical speckle nulling

Solution to trimming



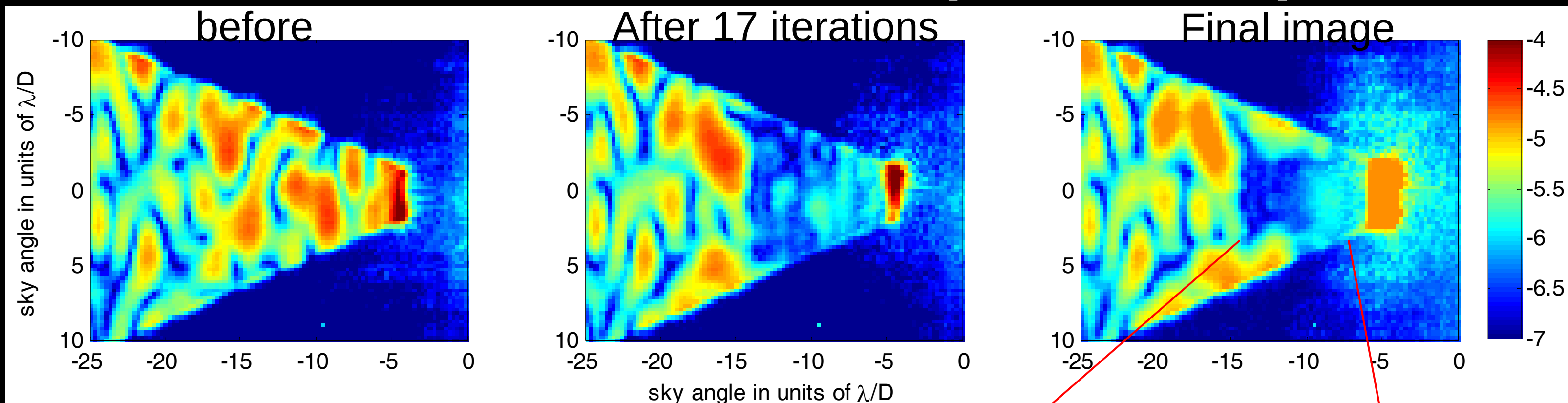
Solution to Speckle Nulling Limitations

Energy Minimization-type algorithm with a trimmed mask



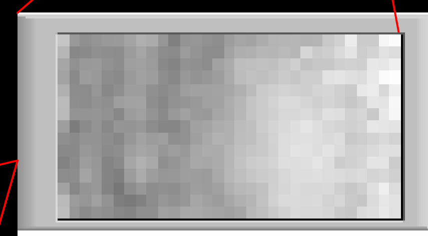
Courtesy of Amir Give'on

Princeton Testbed, Energy minimization (632nm)

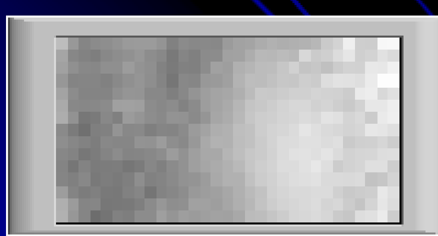


~ 10^{-5} (avg) contrast
5 – 14 λ/D control region

~2 x 10^{-6} (peak) contrast
~6 x 10^{-7} (avg) contrast
6 – 14 λ/D control region



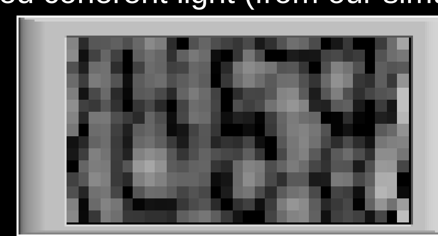
Estimated "incoherent" light
(this effectively simulates zodi and planet)



Contrast:
2 x 10^{-6} peak
6 x 10^{-7} avg

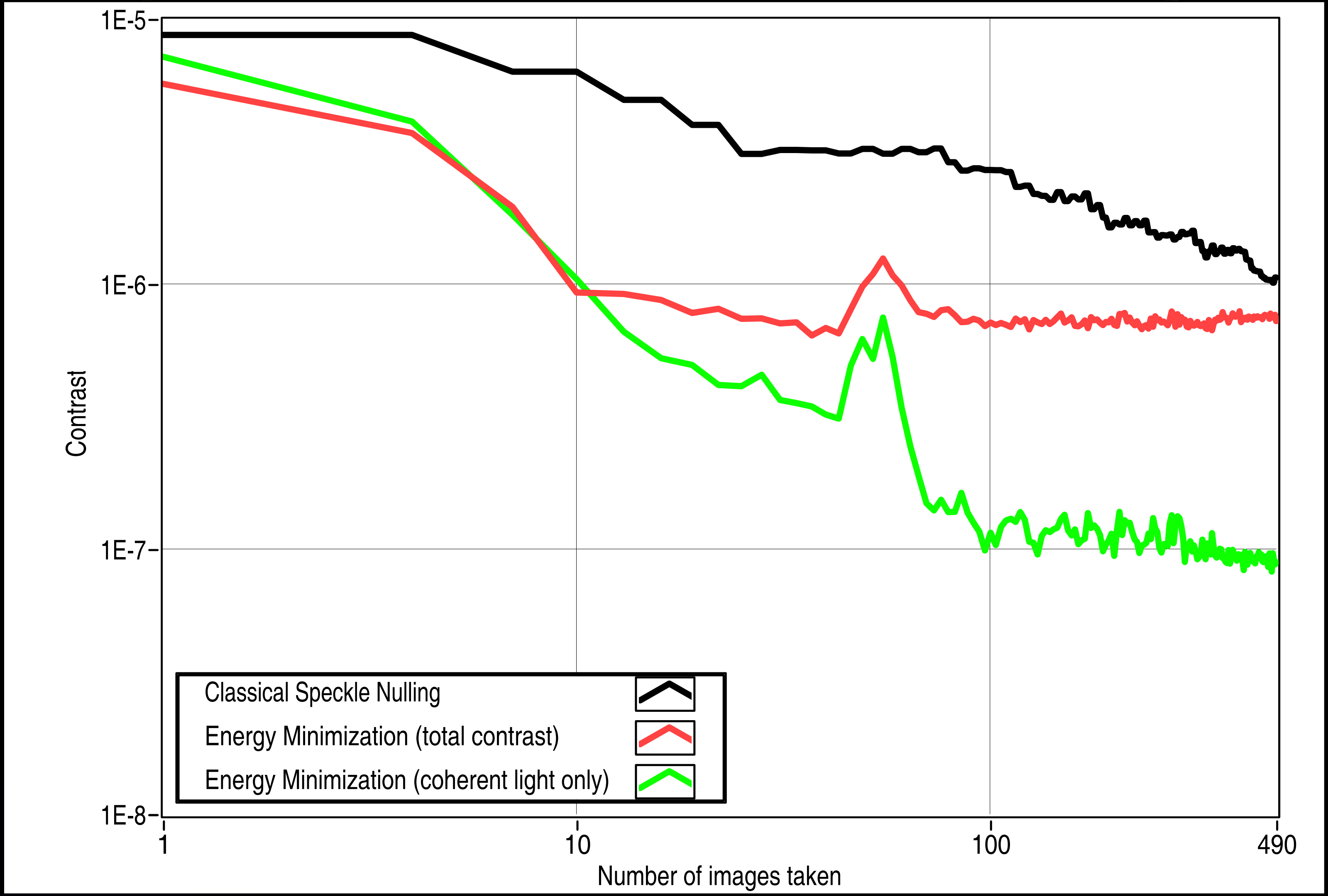
+

Estimated coherent light (from our simulated star)



Contrast:
6 x 10^{-7} peak
9 x 10^{-8} avg

Contrast vs. # of images taken (Princeton testbed, 632nm)



Summary of Lab Results

Contrast @ 4λ/D	Limiting factors, Milestones, and other effects
$>10^{-3}$	● Airy pattern
$>10^{-4}$	● Core of PSF saturates, camera blooms and other undesired artifacts
$>10^{-5}$	● Contrast with unactuated DM (1" SP) and λ/20 optics ● Measured on princeton testbed, w/o WF corrections (Jan 2005)
$>10^{-6}$	● 15 micron trimming for 10mm ripple1 ● Speckle nulling with 10mm ripple1 on princeton testbed (Sep 2006) ● Light thrown into dark zone by BMC DM quilting orders
$>10^{-7}$	● Contrast with commercial optics for 2mm SPs ● Amplitude errors start appearing for 1" SPs at HCIT
$>10^{-8}$	● DM quilting saturates, need to block with star occulter ● Occulter scatter on the CCD if they are in the same plane and occulter has rough edges ● Air (?) ●Speckle nulling with 25mm ripple3 (Princeton experiment at HCIT) in monochromatic and broadband light (Feb 2006) ● Energy minimization with 10mm ripple1 in monochromatic light (Dec 2006)
$>10^{-9}$	● Dust in Princeton testbed (?) ● Thermal stability of DM w/o thermal control (?)
$>10^{-10}$	● Mechanical stability of testbed (?) ● Electronic noise (?) ● DM precision (?)

Conclusions

- Shaped pupils are a promising technology for high-contrast imaging
- Initial runs of speckle-nulling-based wavefront correction achieved contrast of 10^{-6} for IWA of 5 λ/D
- Simulations show that the limiting factor is the inability of speckle nulling to correct for mask trimming
- Two ways of overcoming this limit: better mask (less affected by trimming), or better estimation algorithm (such as energy minimization). Initial runs of the energy minimization algorithm achieved contrast of 10^{-7} for IWA of 5 λ/D