Wavefront Control in a Shaped-Pupil Coronagraph:
First Results from the Princeton Testbed

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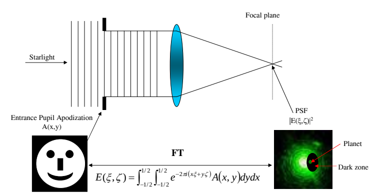
SHAPED PUPIL CONCEPT

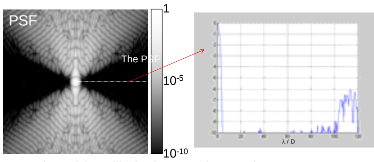
Pupil Apodization Overview



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

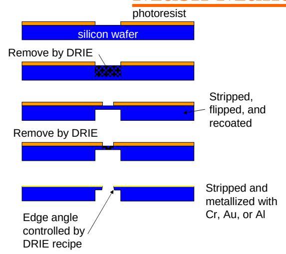
- Can design PSFs by apodizing the pupil
- Use nonlinear optimization to find A(x,y) for desired PSF
- Optimization metrics
  - Inner and outer working angles (IWA and OWA)
  - contrast
  - throughput

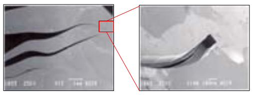
Our Current Mask



- Designed for elliptical TPF primary shape
- IWA = 4 λ/D in 45° arc, throughput (airy) = 30%
- Simpler to manufacture and less polarization sensitivity than e.g. barcode masks
- Central obstruction can be used for secondary

Mask Manufacture

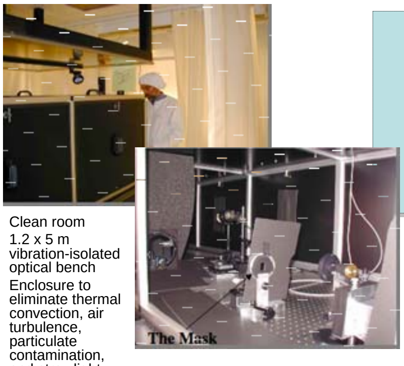




- Manufactured by JPL
- Commercial Si wafer
- Double-sided Deep Reactive Ion Etch (DRIE) to make holes
  - First etch: wafer thinned to 50 micron thickness around openings
  - Second etch: through etch to complete holes
  - Optional thin metal coating
- Mask size 25mm and 10mm
- Efficient, repeatable process

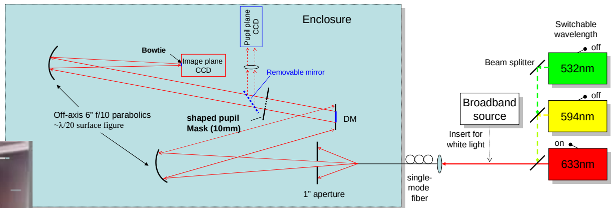
THE TPF@PRINCETON LAB

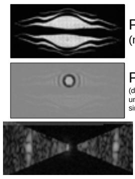
Inside the Lab



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

Optical Layout Schematic





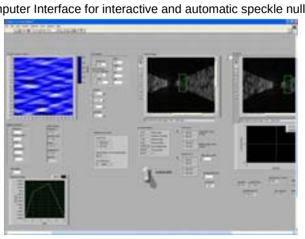
- Can select from any combination of 3 laser wavelengths, or insert a broadband white light source (halogen lamp)
- Single mode fiber creates a simulated star
- First parabolic brings the star out to infinity
- DM has 32x32 actuators, 10mm aperture, made by Boston Micromachines
- Removable mirror can be used to see the pupil plane
- Second parabolic focuses the light onto the CCD
- Image-plane mask (bowtie mask) placed on CCD chip to block bright portions of the PSF

Algorithm: Speckle Nulling

Algorithm:

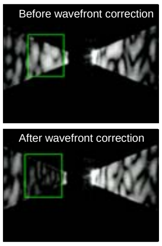
- Look for the brightest pixel in the dark zone
- Compute a DM ripple that would place a speckle centered on that pixel
- Find phase which minimizes that pixel
- Update DM
- Repeat

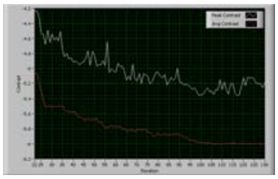
Computer Interface for interactive and automatic speckle nulling



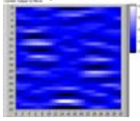
RESULTS

Typical Experimental SN Run





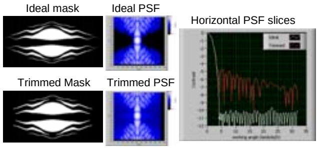
DM Setting after correction



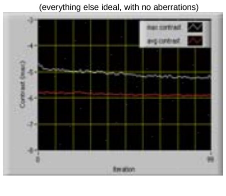
- Speckle pattern depends on position of the shaped pupil. Hence, the speckle pattern is dominated by wavefront aberrations and not the shaped pupil.
- Control region was taken to be 5 to 12 λ/D
- Tweaking the algorithm does not seem to improve the asymptotic contrast, only rate of convergence
- Setup is very stable: can set the DM pattern the next day, and the dark hole reappears
- The required range of the DM is only a small fraction of its total range

Simulations

Effects of Trimming

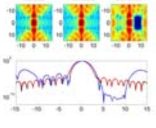


Simulation of SN with trimmed mask and a 32x32 DM (everything else ideal, with no aberrations)



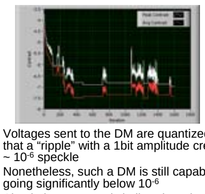
- Trimming occurs because of manufacturing limitations. (workarounds exist but not yet implemented)
- Trimming produces long thin speckles, similar to the ones that remain after speckle nulling in the lab
- Speckle nulling works well on large speckles but fails on thin speckles
- Trimming is probably the main limiting factor in the lab right now
- Can be beat by appropriate mask design or another correction algorithm

Peak-a-boo with trimming



- Peak-a-boo is an estimation algorithm that can eliminate speckles due to trimming
- Much faster than speckle nulling, but harder to implement.

Effects of DM voltage quantization



- Voltages sent to the DM are quantized such that a "ripple" with a 1bit amplitude creates a ~ 10^{-6} speckle
- Nonetheless, such a DM is still capable of going significantly below 10^{-6}
- Simulation assumed similar aberation levels as in the lab, and 32x32 quantized DM. Everything else is ideal.
- Tends to get stuck, needs perturbations.

Contrast Roadmap

Contrast @ 4λ/D	Effects and Milestones
$>10^{-3}$	• Airy pattern
$>10^{-4}$	• Core of PSF saturates, camera blooms
$>10^{-5}$	• 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 • CCD/occulter reflections if they are in the same plane and occulter isn't perfect (?) • Air (?) • Trimming of 1" ripple3 • Speckle nulling with 25mm ripple3 (Princeton experiment at HCIT) in monochromatic and broadband light (Feb 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}**
- **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 peak-a-boo).**

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