A Review of Coronagraph Laboratory Results

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ABSTRACT

This brief paper, and the attached figures, is a summary of a talk given at the 4th International TPF/Darwin Workshop, held on November 8–10, 2006 in Pasadena, CA. The workshop brought together researchers from around the world to discuss progress in developing a joint program for searching for and characterizing exosolar earthlike planets from space. The talk upon which this paper is based summarized the current status of experimental work to develop and test various coronagraph concepts for achieving high contrast in a filled aperture telescope. It is based on work at a myriad of laboratories and the author is indebted to the researchers who generously cooperated and provided the information and images for the paper.

1. Introduction

There are two approaches for creating high contrast in order to image extrasolar planets: coronagraphy, where a single aperture telescope is combined with some method for blocking the starlight, either internally or externally, and interferometry, where the light from multiple satellites is combined to null the starlight. Both are being pursued, though current expectations are that the first mission to fly will involve some type of coronagraph. There is much still to do, and much to learn about the way to design and implement coronagraphs and how to combine with a wavefront control system. Nevertheless, progress has been tremendous in the past few years. In this brief paper I will summarize progress and results in roughly a dozen laboratories around the world, each studying and experimenting with a different type of coronagraph and/or method of correcting the wavefront. It is thus by necessity a broad overview with only minimal explanation and detail; I also make no claims to be exhaustive. I will not try and present the theoretical basis or a performance analysis of each method; for that there are many useful papers. I will also not try and compare different coronagraphs. Instead, I focus only on the laboratory results to give a snapshot in time of our successes and failures, of actual measured results, at achieving high contrast.

I have many objectives. Of course, first is simply to give a summary and overview of laboratory activities in coronagraphs for both ground and space; this should provide the reader with both a sense of the broad base of research and the great strides being made toward TPF level performance. I will also try, however, to place these various laboratory results into the larger context and give a sense of how they support a pathway to a space telescope for finding planets. I will highlight the various limitations of ground experiments to show the difficult problems being tackled and the steps that still need to be taken. I also hope to provide a flavor of the diversity of coronagraph approaches being proposed and worked on and the various implementation issues for each. And, finally, I hope to get the reader thinking about the difficult questions that need to be asked and answered and how close (or far) we are to a space ready system.

2. Why Experimental Work?

While this may seem like an obvious question, it is useful to reflect briefly on the importance of performing laboratory research and experimental verification of the various concepts. At its most basic, successfully achieving high contrast in the laboratory provides of proof of principle that we are pursuing an achievable goal. Any TPF design, or progress of the TPF program, must be preceded by a clear an unambiguous demonstration in the laboratory that high contrast in a coronagraph is possible. As we'll see, the most recent results at JPL are remarkably close.

Experimental work is more than that, however. By moving from the notebook to the laboratory we discover what the most difficult problems actually are and uncover a myriad of surprises. No matter how careful we are in our analyses, nothing replaces laboratory work and there is always something new to learn. Additionally, the experience we gain in manufacturing and in testing will prove indispensable when we begin an actual program.

The act of performing experimental tests in an of itself is also a source of frequent inspiriation for new ideas and approaches. Finally, the facilities we are developing today will become the test labs for tomorrow for demonstrating the feasibility of a flight ready system.

What is our overall goal? Simply stated, it is to demonstrate a contrast of at least 10^{-10} in a realistic lab environment with a full, integrated, flight like system. This is an ambitious goal and not one that will be achieved quickly or precipitously. The distributed effort I will describe across multiple institutions reflects a measured and incremental approach, slowly reaching for deeper contrast and attempting to understand the limitations and roadblocks at each step. These limitations fall into five broad categories, and articulating them here will help us understand the status of many of the experimental results to come:

1. Design Limitations
2. Practical Limitations
3. Manufacturing Limitations
4. Algorithmic Limitations
5. Experimental Limitations

Design limitations refer to inherent characteristic of a given coronagraph that might prevent it from achieving the broadband contrast we seek (a good example are chromatic limitations of certain designs). Practical limitations refer to the realities of implementing a coronagraph that aren't captured by the idealized model (a good example are polarization and edge effects). Manufacturing limitations refer to the difficulty of making masks, stops, and the like (examples include chromatic image plane masks, fine structures in shaped pupils, surface grinding of pupil mapping mirrors, and others). Algorithmic limitations refer to the performance of various wavefront sensing and control algorithms when integrated with various coronagraphs (an example here is the interaction of classical speckle nulling with errors induced by shaped pupil truncation). Finally, experimental limitations refer to the fidelity of the test environment (detector performance, thermal variations, vibrations, etc.).

Interestingly, the first four of these issues apply both to the ground testing as well as to a final space mission, so understanding and overcoming them is fundamental to the eventual design of a TPF coronagraph. The fifth, on the other hand, is unique to the laboratory environment and simply limits our ability to measure and assess coronagraph performance. These either need to be well understand, and corrected for, or reduced to below the level where they influence performance. One of the distinctions among the various laboratories is the degree to which they have reduced these interfering affects (the High Contrast Imagine Testbed (HCIT) at JPL is by far the highest fidelity test environment available).

3. Uncorrected Performance

This section and the next encompass the heart of the presentation. In these two sections I make a distinction between the achieved performance in what I call the "raw" coronagraph, that is, the coronagraph alone without a wavefront sensing and control system, and corrected performance where the coronagraph is integrated with one or more deformable mirrors (or other wavefront correction device). This separation of the coronagraph from the correction scheme is typical of all the design teams and sensible for this stage of research. In other words, we want to understand the coronagraph as well as we can and find its limits of performance and then augment it by a WFSC system to determine what level of correction is possible. However, in my final remarks, I'll discuss briefly the need to start viewing these as an integrated high contrast system and understanding how to optimize design and performance of both together.

Figure 1 is a graphical depiction of what has been accomplished by coronagraphs alone. The first two arrows give a sense of what needs to be achieve at the smallest inner working angles (here I assuming an inner working angle of roughly 4 λ/D). At that angle, the Airy function has a contrast of roughly 10^{-3} compared to the needed contrast of 10^{-10}. Note that all coronagraphs, by design, theoretically achieve this contrast in monochromatic light (for some, the optical vortex in particular, there is no accepted design approach yet that maintains contrast in broadband light).

The inability to reach the high contrast results from a variety of sources. As shown by the right arrow, the newest coronagraph, the optical vortex, has the worst uncorrected performance, not much better than the Airy function. This comes mostly for the difficulty manufacturing the vortex mask. The PIAA tests at Subaru have achieved roughly a factor of 10 improvement over the Airy function without correction. The error here arises from the difficulty manufacturing the two mirrors, M1 and M2, performing the mapping. The poor optical quality of those mirrors, and the use of only a single post-apodizer, results in a severe degradation in contrast. The remaining coronagraphs all cluster around roughly 10^{-5}. This seems to be a canonical uncorrected contrast level for most facilities. There is general agreement that this residual contrast is due to phase errors on the optical components. In fact, the goal of every laboratory is to reach the point where performance is limited by the optical quality. Then, wavefront control is necessary.

Two facilities have achieved contrast quite a bit better, reaching down to as low as 10^{-7} without correction, the ExAO testbed at Santa Cruz and the experiments for SPICA at ISAS in Japan. This improved performance is due entirely to the much smaller size of the optics (and masks); SPICA, for instance, is using 1 mm masks in their shaped pupil tests. These smaller masks are much easier to super polish and have dramatically reduced phase errors. The third high contrast results occurred at the University of Colorado at Boulder in tests of the Occulter. The only laboratory experiments to date for the occulter have also achieved a contrast level of 10^{-7}. This improvement is due to the insenstivity of the occulter to wavefront error. The primary limitations in the occulter experiment were due to light scattering of the tips and edges of the mask.

Figures 2 to 19 show the various laboratory facilities and summarize the uncorrected performance at each.

4. Corrected Performance

Figure 20 is a reprise of Figure 1 but now with the addition of corrected results. These should be used with care, however, as different approaches and algorithms have been used for correction with the various coronagraphs and many are transportable to other concepts. However, it does provide a useful snapshot of the progress being made in wavefront control. There are also few systems displayed since only a small subset of the facilities have deformable mirrors and the capability of performing high fidelity wavefront control. Details of the wavefront control implementation and the various results are shown in Figures 21 to 33.

At the high end are the shaped pupil experiments at Princeton, pupil mapping at Subaru, and the visible nuller operating in a 15% band at JPL, all of which are operating at roughly 10^{-6} contrast. Here, there are a variety of limitations and no consistent reason for this level of contrast; it is mostly coincidental. This following figures go into more detail.

The ExAO testbed at Santa Cruz and the Visible Nuller group at JPL have both achieved a contrast of 10^{-7} in monochromatic light. The primary limitation in the ExAO results arises from amplitude errors on the optics, which were not being corrected, as well as scattered light (this is consistent with results at Princeton and JPL, where amplitude errors seem to kick in at roughly a contrast level of 10^{-7}). The primary limitation in the Visible Nuller was from errors in the optical lengths. It should also be noted that stability limitations limit to contrast to short time windows of a few seconds. It should also be noted that these results are for only a single subaperture using a translation stage rather than a DM; no results have been reported on a full pupil experiment.

The only facility to achieve higher contrast has been the HCIT. There, contrasts of 10^{-8} were achieved with shaped pupils using classical speckle nulling last winter. More recently, a contrast of 10^{-9} was reached in monochromatic light with a bandimited Lyot coronagraph and classical speckle nulling. Unfortunately, contrast degraded by roughly a factor of 10 when a 10% bandwidth was tried. It is believed that the main polychromatic distortion was caused by chromatic phase shifts in the image plane masks. Current work is directed at new materials and manufacturing approaches to improve the wideband performance. Development of a larger format DM is also proceeding to increase the size of the dark field. Finally, a number of groups, including Princeton, Subaru, and JPL have begun experiments with optimal dark field algorithms to improve convergence speed.

5. Acknowledgements

This presentation would not have been possible without the generous help and cooperation from many researchers around the world. They provided me with numerous images and patiently responded to all of my questions, no matter how trivial. By name they are O. Guyon of the Subaru Telescope, NAOJ, J. Evans and B. Macintosh of the Lawrence Livermore National Laboratory and the Laboratory for Adaptive Optics, S. Shaklan, J. Trauger, and M. Levine of the Jet Propulsion Laboratory (JPL), W. Cash of the University of Colorado, J. Schneider, A. Boccaletti, and P. Baudoz of the Paris Observatory, A. Labeyrie of the Collège de France, J. Codona of the Steward Observatory at the University of Arizona, G. Swartzlander, also of the University of Arizona, K. Enya of the Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency (ISAS/JAXA), and R. Belikov of Princeton University. While I extend my thanks for their contributions, all errors, omissions, misrepresentations, or blunders are solely my own.

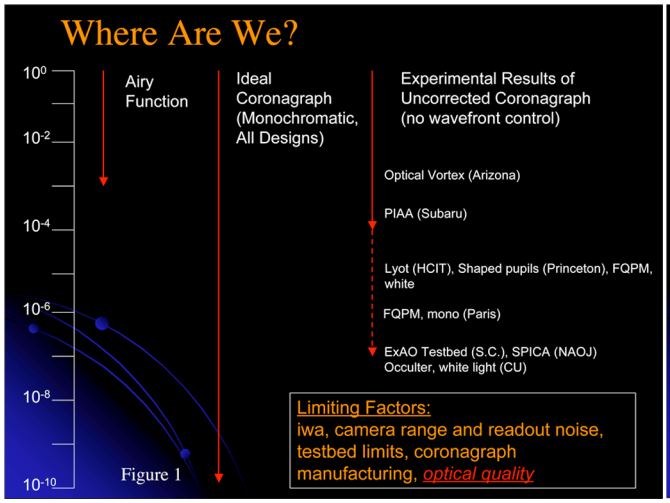


Figure 1

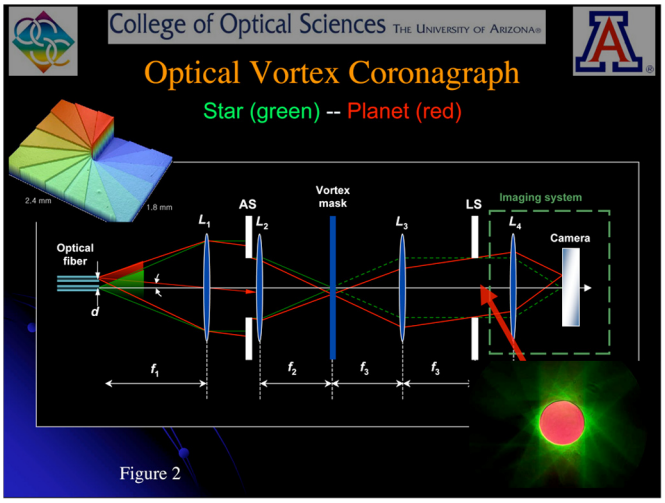


Figure 2

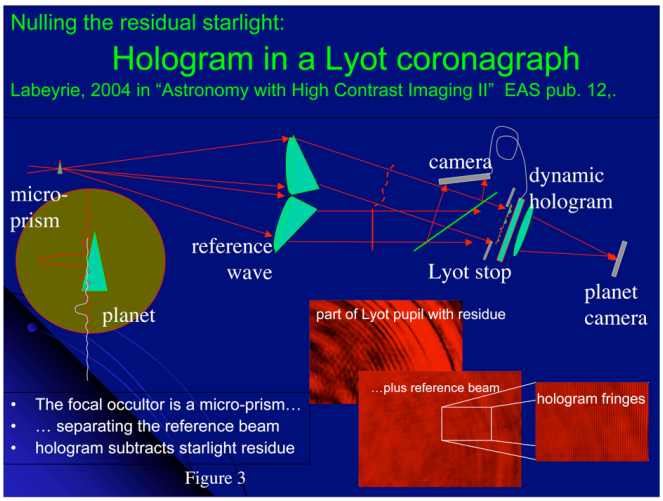


Figure 3

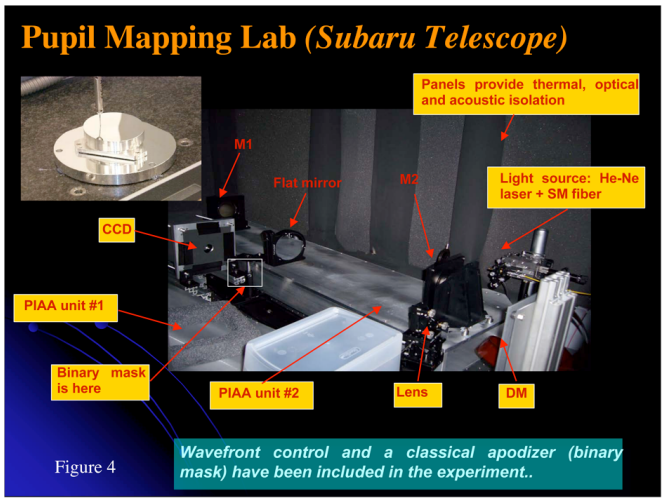
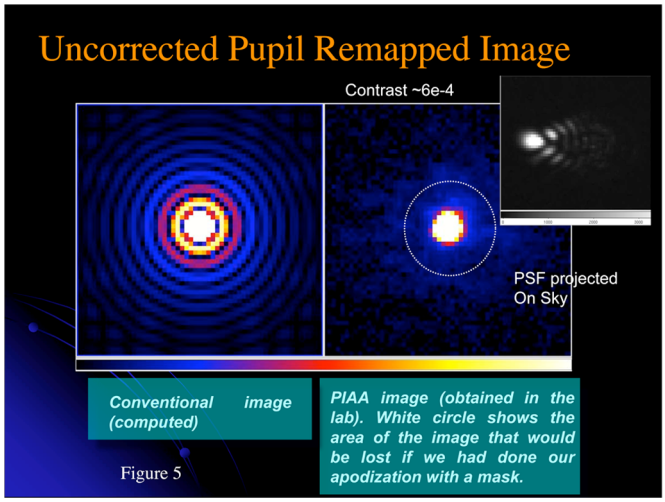
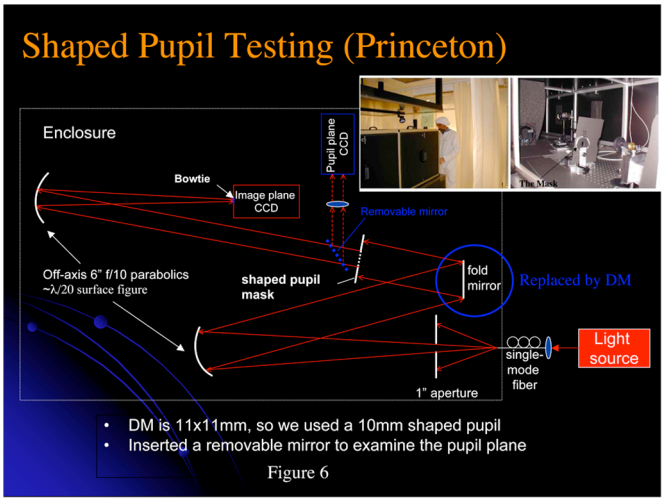
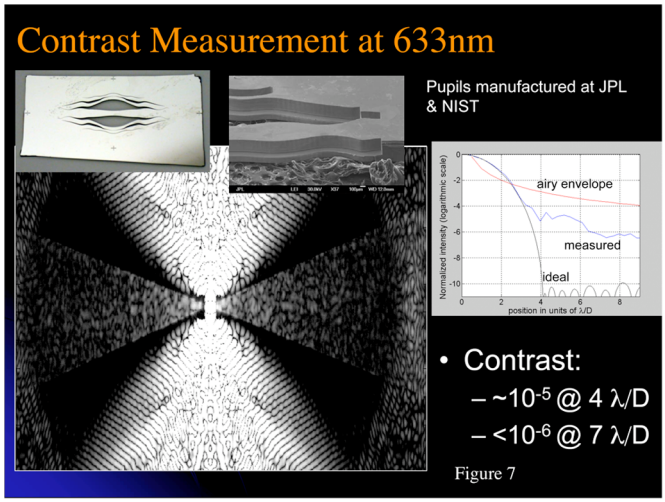
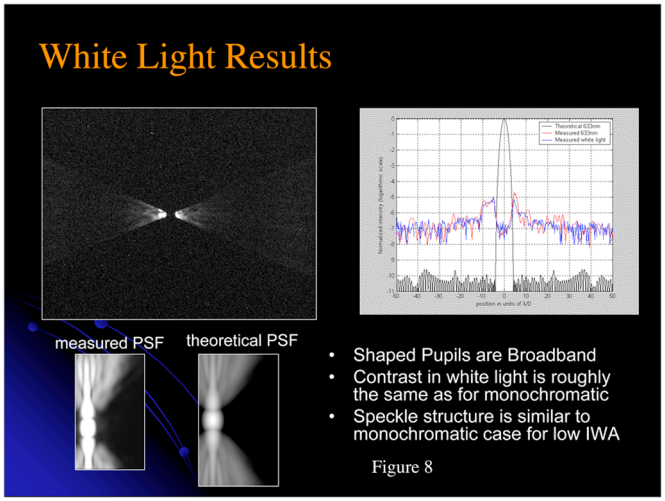


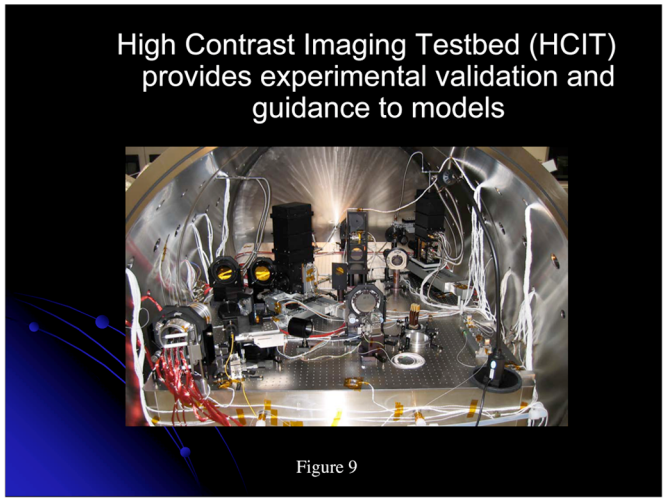
Figure 4

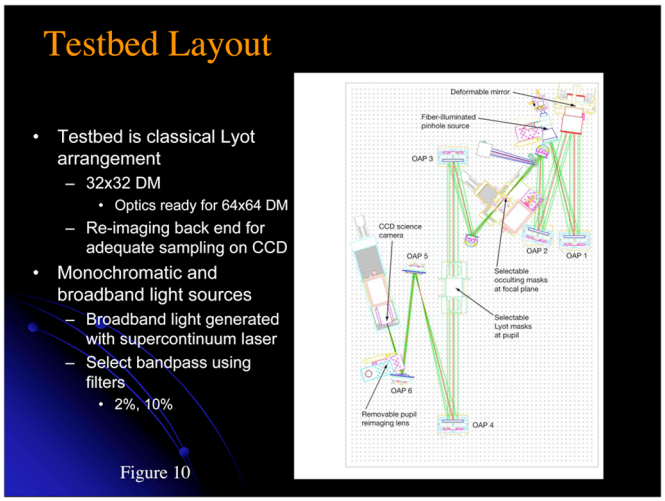

Uncorrected Pupil Remapped Image
Contrast ~6e-4
PSF projected On Sky
Conventional image (computed)
PIAA image (obtained in the lab). White circle shows the area of the image that would be lost if we had done our apodization with a mask.
Figure 5


Shaped Pupil Testing (Princeton)
Enclosure
Bowtie
Image plane CCD
Pupil plane CCD
Removable mirror
Off-axis 6" f/10 parabolics ~λ/20 surface figure
shaped pupil mask
fold mirror
Replaced by DM
Light source
single-mode fiber
1" aperture
• DM is 11x11mm, so we used a 10mm shaped pupil
• Inserted a removable mirror to examine the pupil plane
Figure 6


Contrast Measurement at 633nm
Pupils manufactured at JPL & NIST
airy envelope
measured
ideal
• Contrast:
– ~10-5 @ 4 λ/D
– <10-6 @ 7 λ/D
Figure 7


White Light Results
measured PSF
theoretical PSF
• Shaped Pupils are Broadband
• Contrast in white light is roughly the same as for monochromatic
• Speckle structure is similar to monochromatic case for low IWA
Figure 8


High Contrast Imaging Testbed (HCIT) provides experimental validation and guidance to models
Figure 9


Testbed Layout
• Testbed is classical Lyot arrangement
– 32x32 DM
• Optics ready for 64x64 DM
– Re-imaging back end for adequate sampling on CCD
• Monochromatic and broadband light sources
– Broadband light generated with supercontinuum laser
– Select bandpass using filters
• 2%, 10%
Deformable mirror
Fiber-illuminated pinhole source
OAP 3
CCD science camera
OAP 5
OAP 2
OAP 1
Selectable occulting masks at focal plane
Selectable Lyot masks at pupil
OAP 6
Removable pupil reimaging lens
OAP 4
Figure 10

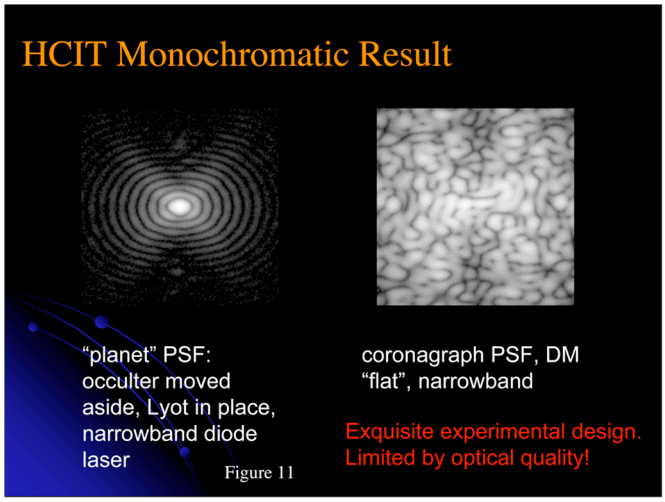


Figure 11

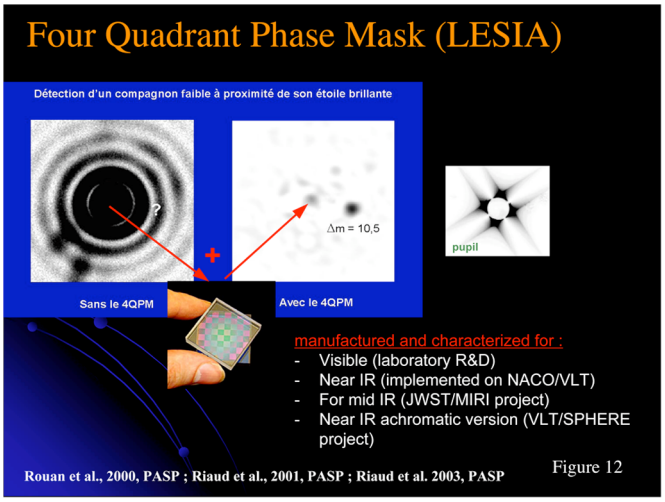


Figure 12

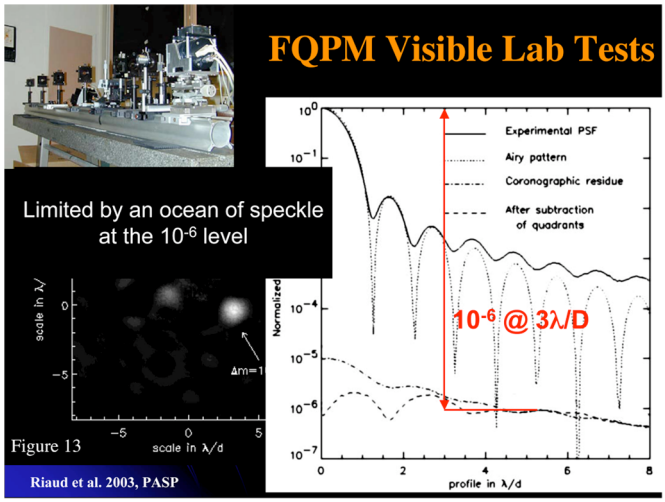


Figure 13

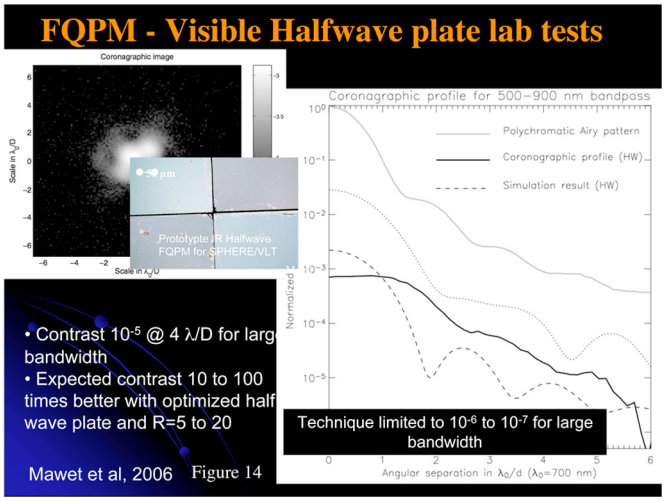


Figure 14

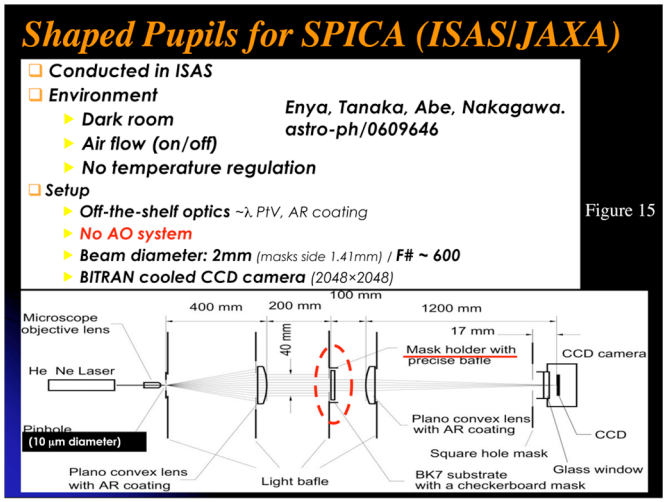


Figure 15

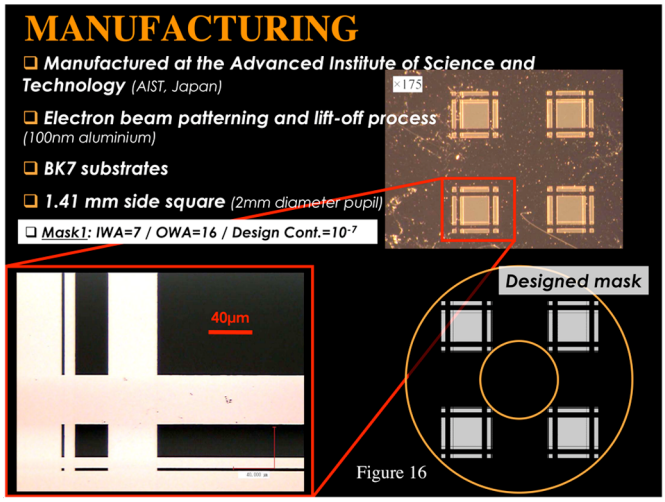
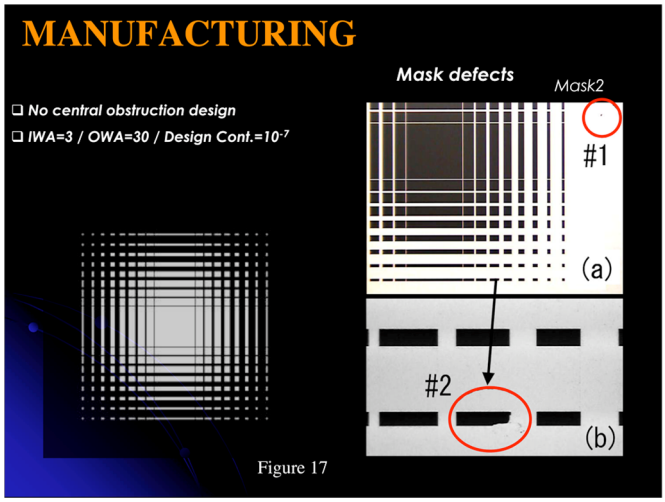
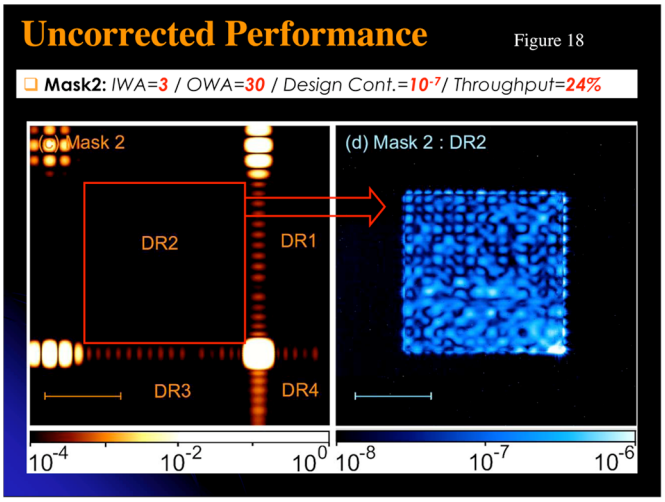
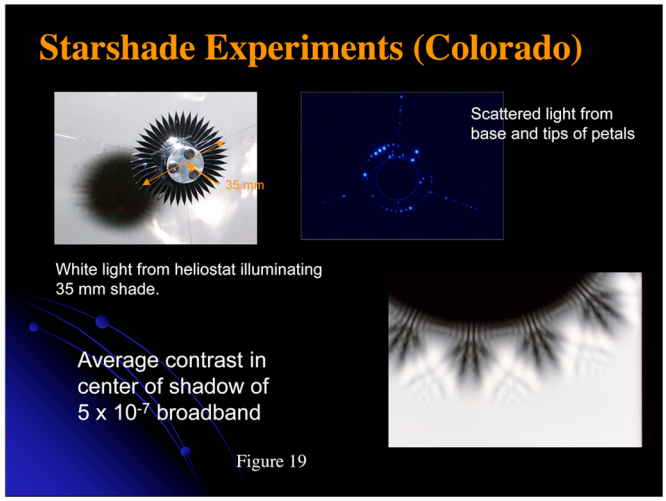
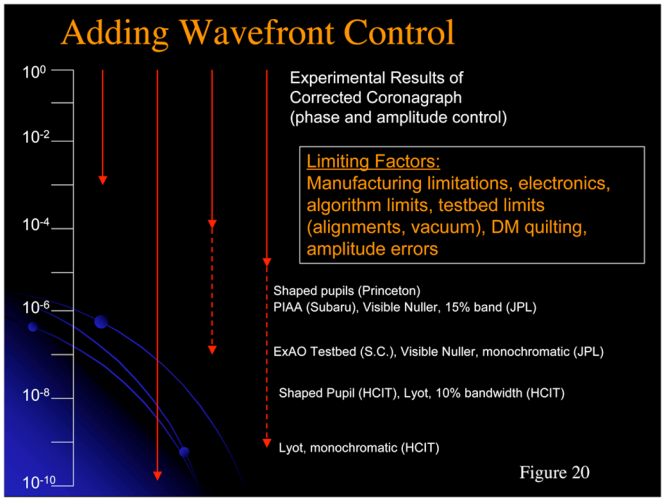


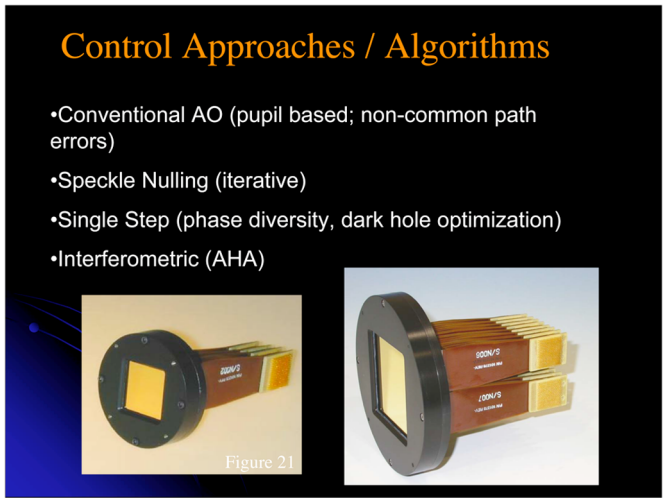
Figure 16

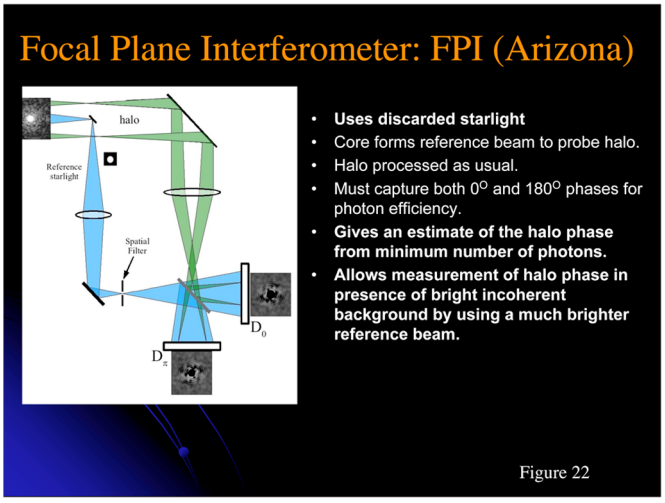

MANUFACTURING
Mask defects
Mask2
No central obstruction design
IWA=3 / OWA=30 / Design Cont.=10-7
#1
(a)
#2
(b)
Figure 17


Uncorrected Performance
Figure 18
Mask2: IWA=3 / OWA=30 / Design Cont.=10-7 / Throughput=24%
(c) Mask 2
(d) Mask 2 : DR2
DR1
DR2
DR3
DR4
10-4
10-2
100
10-8
10-7
10-6


Starshade Experiments (Colorado)
35 mm
Scattered light from base and tips of petals
White light from heliostat illuminating 35 mm shade.
Average contrast in center of shadow of 5 x 10-7 broadband
Figure 19

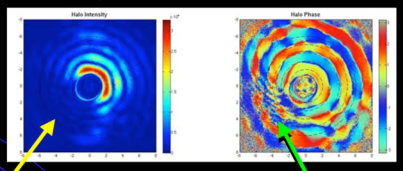

Adding Wavefront Control
100
10-2
10-4
10-6
10-8
10-10
Experimental Results of Corrected Coronagraph (phase and amplitude control)
Limiting Factors:
Manufacturing limitations, electronics, algorithm limits, testbed limits (alignments, vacuum), DM quilting, amplitude errors
Shaped pupils (Princeton)
PIAA (Subaru), Visible Nuller, 15% band (JPL)
ExAO Testbed (S.C.), Visible Nuller, monochromatic (JPL)
Shaped Pupil (HCIT), Lyot, 10% bandwidth (HCIT)
Lyot, monochromatic (HCIT)
Figure 20


Control Approaches / Algorithms
•Conventional AO (pupil based; non-common path errors)
•Speckle Nulling (iterative)
•Single Step (phase diversity, dark hole optimization)
•Interferometric (AHA)
Figure 21


Focal Plane Interferometer: FPI (Arizona)
halo
Reference starlight
Spatial Filter
D0
Dπ
Uses discarded starlight
Core forms reference beam to probe halo.
Halo processed as usual.
Must capture both 0° and 180° phases for photon efficiency.
Gives an estimate of the halo phase from minimum number of photons.
Allows measurement of halo phase in presence of bright incoherent background by using a much brighter reference beam.
Figure 22

Using the FPI to drive a Pupil DM (PDM)

Using a simple speckle-steering algorithm, we used the FPI complex amplitude measurements to suppress the halo in closed loop.



Suppressed 90° sector

When fully suppressed, phase will become completely random. This simple system could have gone another 1-1.5 decades fainter.

Figure 23

Anti-Halo Apodization for 360 degree Suppression - AHA

Use AHA complex spatial light modulator to directly imprint a detailed "anti-halo" which interferes destructively with the star's halo

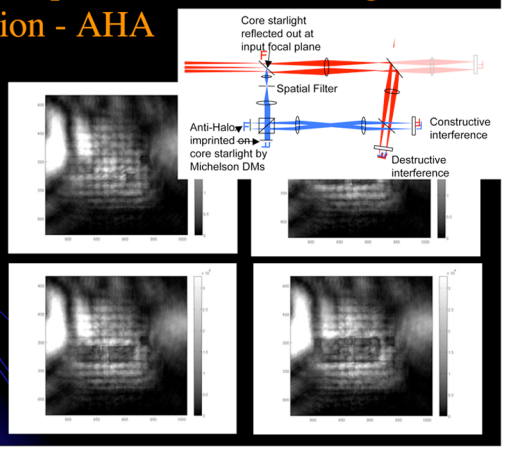
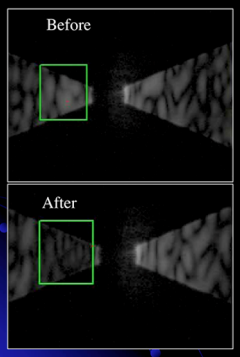
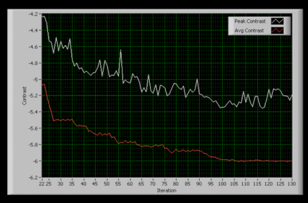


Figure 24

Speckle Nulling Results (Princeton)

Using single 32 x 32 MEMS DM from Boston Micromachines





- Dark hole: 4.5 to 12 l/D
- Peak contrast of 1e-5.2
- Average contrast of 1e-6
- Repeatable and stable
- Limited by mask accuracy and speckle nulling algorithm

Figure 25

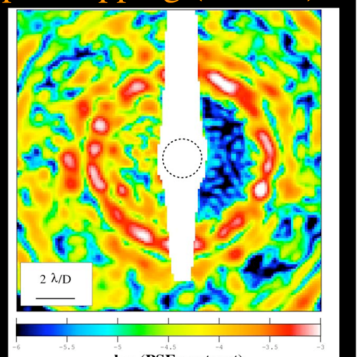
Dark Hole with Pupil Mapping (Subaru)

32x32 DM

Direct algorithm using DM induced diversity

Currently limited by variable alignment between beam and binary mask (binary mask closer to focus than pupil)

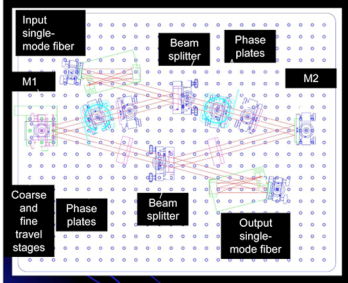
No mask block starlight currently subject to camera dynamical range



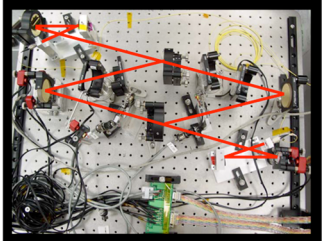
Average contrast in dark region = 2.5e−6
Vertical white feature is due to CCD saturation
Central circle is 1 lambda/D radius
Note: all distances are measured using the system chief ray

Figure 26

Visible Light Shearing Nuller



(Symmetric) Nuller Layout

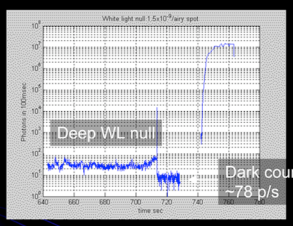


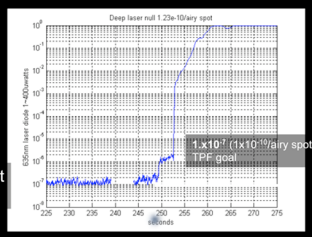
Experimental set up

- **All experiments have been run in vacuum chamber at 1 atm, with the door shut**

Figure 27

Monochromatic and White Light Contrast





- White light data
  - null over 60 sec ~1.06x10^{-6}
  - ~15% bandwidth around 650nm.
- Better control of dispersion correction will deepen null to same limit as the laser null
- Laser data:
  - Optical path error of 90 picometer will cause 2x10^{-7}
  - rms vibration and drift over ~15 sec is ~60pm

Figure 28

ExAO Testbed (Santa Cruz)

"Conventional" AO approach

- Phase Shifting Diffraction Interferometer (PSDI) for metrology
- Low wavefront-error optical design
- MEMS DM controlled in closed loop via:
  - PSDI or
  - SF Shack-Hartmann WFS
- Shaped pupils to suppress diffraction
- Science Camera in far-field for contrast measurements

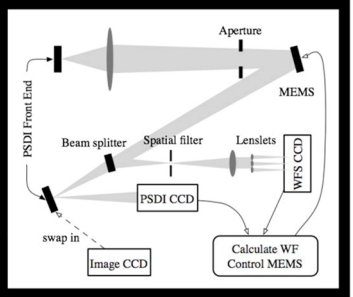
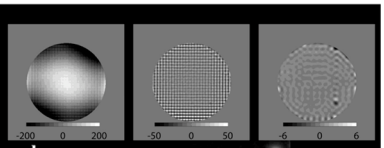
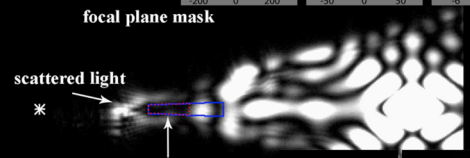


Figure 29

Contrast with MEMS

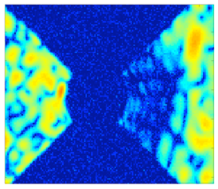


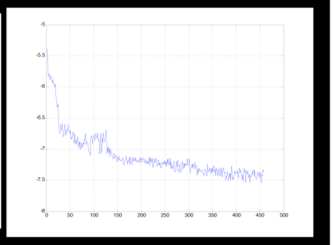


- Contrast from 8-11 λ/D: 2 x 10^{-7}
- Contrast from 8-13 λ/D: 6 x 10^{-7}
- Region of interest is limited by scattered light from the focal plane mask and controllable spatial frequencies
- Contrast is limited by phase and amplitude errors

Figure 30

Shaped Pupil Speckle Nulling at HCIT 785nm with Ripple 3



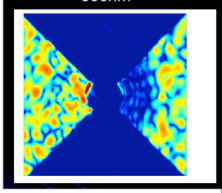


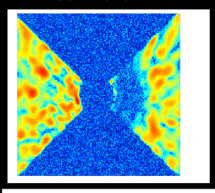
- 457 iterations over a course of 3 days
- Went down from 10^{-5} contrast to 4×10^{-8} between 4 and 9 λ/D
- Some wavefront correction on the opposite side, until we hit amplitude errors

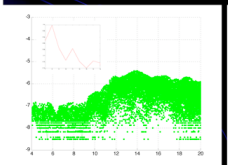
Figure 31

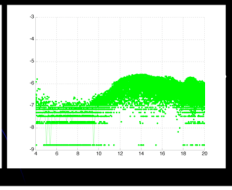
Shaped Pupils at the HCIT Monochromatic and Broadband Performance

836nm 760nm-840nm





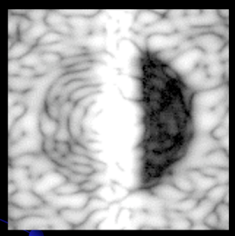


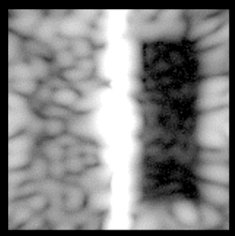


- After switching from 785 to 836nm
  - Contrast degrades very slightly
  - After a few speckle nulling iterations, contrast dips below 4×10^{-8}
  - longer wavelengths see lower aberrations
- After switching to broadband light (760-840nm), contrast remained about the same

Figure 32

HCIT Monochromatic Result





Better than 1e-9 Contrast
4-5 Airy rings.
5e-10, 4-10 Airy rings.

10% bandwidth, Xenon lamp,
4-10 λ/D contrast = 6e-9,
Same spatial scale as
narrowband images

Figure 33