Extreme Adaptive Optics Testbed: Results and Future work

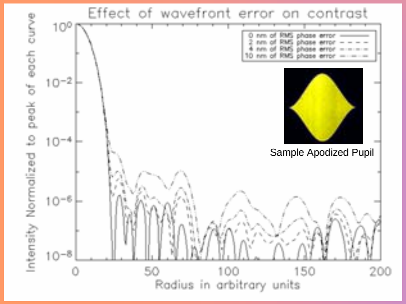
Julia Wilhelmsen Evans[1,2], Gary Sommargren[1], Lisa Poyneer[1], Bruce Macintosh[1,3], Scott Severson[3], Daren Dillon[3], Andrew Sheinis[3], David Palmer[1,3], Jeremy Kasdin[4], Scot Olivier[1]

[1]Lawrence Livermore National Laboratory, [2]University of California/Davis, [3]University of California/Santa Cruz, [4]Princeton University

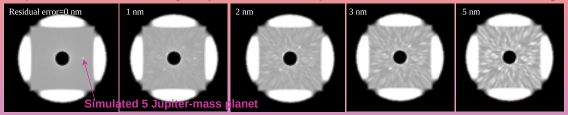
Abstract:

"Extreme" adaptive optics systems are optimized for ultra-high contrast applications, such as ground-based extrasolar planet detection. The Extreme Adaptive Optics Testbed is used to investigate and develop technologies for high-contrast imaging, especially wavefront control. A simple optical design allows us to minimize wavefront error and maximize the experimentally achievable contrast before progressing to a more complex set-up. A Phase Shifting Diffraction Interferometer is used to measure wavefront errors with sub-nm precision and accuracy. We have demonstrated RMS wavefront errors of <1..3 nm and a contrast of $>10^{-7}$ over a substantial region using a shaped pupil. Current work includes the installation and characterization of a 1024-actuator Micro-Electro-Mechanical-Systems (MEMS) deformable mirror, manufactured by Boston Micro-Machines, which will be used for wavefront control. In our initial experiments we can flatten the dm to 1.8 nm RMS wavefront error within a control radius of 5-13 cycles per aperture. Further work with the MEMS will seek to improve the control system to include low frequency errors. Ultimately this testbed will be used to test all aspects of the system architecture for an extrasolar planet-finding AO system.

Motivation:

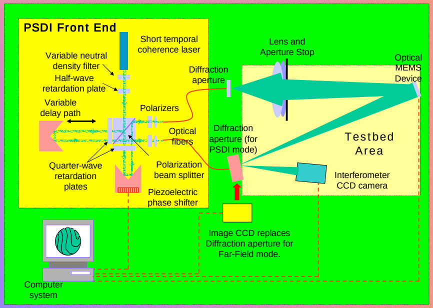


Sample Apodized Pupil



An extreme adaptive optics planet imager will require very low static wavefront error within the correctable frequency range of the deformable mirror. (*See simulations above*.) At just one nm of residual error scattered light is visible and at 3 nm the planet is very difficult to detect. The error budget calls for residual error at the 2 nm level. There is a direct relationship between achievable contrast and wavefront error. The *figure at left* shows calculations of far field images based on a measured wavefront that has been scaled to simulate larger wavefront errors. As wavefront errors increase from 0 to 10 nm the achievable contrast changes from 10^7 to 10^5. The difference in contrast between 0 and 2 nm of rms error is very small indicating that the current set up is not limited by wavefront error.

Experimental set-up:



The ExAO testbed uses a simple optical design to demonstrate experimentally achievable contrast with low wavefront error, while the Phase Shifting Diffraction Interferometer (PSDI) is used for precision wavefront measurements of the system.

Results:

Contrast measurements:

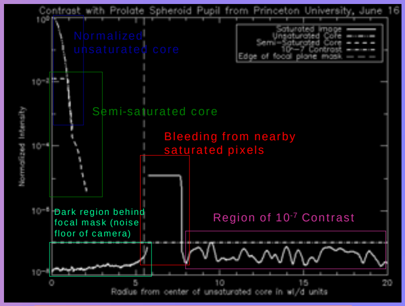
❖The *contrast measurement at right* is a composite of three images taken with varying ND filters and integration time to increase dynamic range.

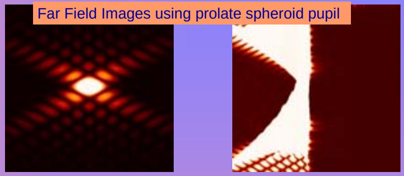
❖In this image the null is at a level of 10^{-7} when compared with the scaled peak of the unsaturated image.

❖A prolate spheroid designed and manufactured by Princeton University was used as the aperture of the system. This shape produces the large dark region seen in the *sample images at right*.

❖Contrast in this system is limited by the edge roughness of the pupil due to manufacturing (laser cutting in this case).

❖The flat mirror used to produce this data has been replaced with a MEMS deformable mirror. After our initial MEMS experiments are complete we will attempt to replicate this contrast data with the MEMS deformable mirror in place.

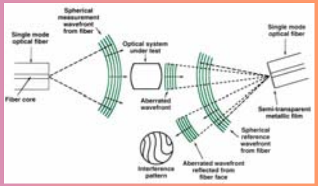


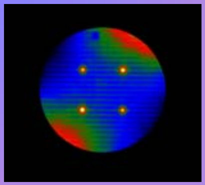


Far Field Images using prolate spheroid pupil

Phase shifting diffraction interferometer:

The phase shifting diffraction Interferometer (PSDI) uses diffraction to generate near perfect spherical wavefronts. Both reference and measurement beams are produced by single mode fibers (*see figure at right*). The resulting interference pattern is measured and numerical propagation calculates the wavefront of the system under test.





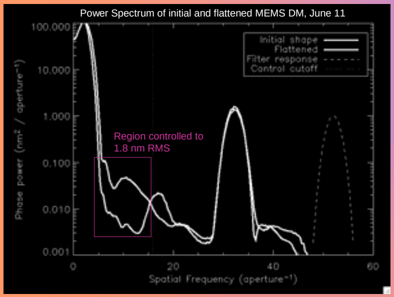
Diffractive configuration removes the limitations of conventional interferometry ...

- ❖ reference surface is eliminated
- ❖ auxiliary optics are kept to a minimum

...while retaining all positive features including

- ❖ phase shifting
- ❖ standard algorithms for data analysis

We are using the PSDI as our wavefront sensor for testing the MEMS deformable mirror. The *image above* shows a phase measurement of the MEMS while four actuators are depressed.

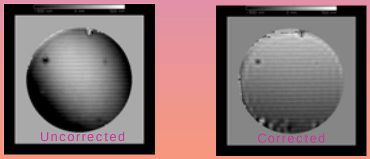


Initial MEMS results:

❖In the initial experiments with the MEMS deformable mirror the PSDI is used as a wavefront sensor in the system operates in closed loop.

❖After flattening, the DM has a wavefront error of 1.8 nm RMS in a control radius of 5 to 13 cycles per aperture (from about 5 nm RMS initially). *See figure at left*

❖Better correction of low frequency errors can be achieved with better calibration of individual actuator gain in the device and the resulting improved control system.

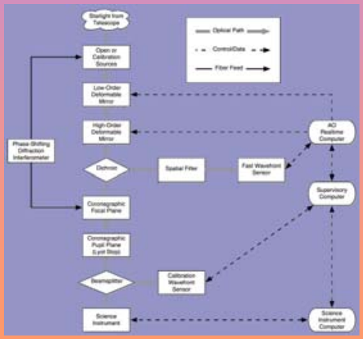


Wavefront of the uncorrected and corrected deformable mirror as measured by the PSDI.

❖The primary aberration remaining in the corrected wavefront is tilt.

❖The striping in both images is due to the physical structure of the MEMS devices.

Conclusions and future work:



Extrasolar planet imager system architecture

❖The Extreme Adaptive Optics testbed has demonstrated that 10^{-7} contrast is achievable in a laboratory setting.

❖We are using this high-contrast environment to test subsystems for an extrasolar planet imager.

❖ MEMS deformable mirror technology is the first subsystem under test. We have demonstrated the necessary flattening over a specific control radius.

❖ Future work will include further MEMS testing and specification and testing other ExAO subsystems such as a spatially filtered wavefront sensor.

References:

Sommargren, G.E., et. al., "100-picometer interferometry for EUVL," Proc. SPIE Vol. 4688, p. 316-328 (2002), Emerging Lithographic Technologies VI, Roxann L. Engelstad; Ed.

Sommargren, G.E., "Phase shifting diffraction interferometry for measuring extreme ultraviolet optics," *OSA Trends in Optics and Photonics Vol. 4, Extreme Ultraviolet Lithography*, G.D. Kubiak and D.R. Kania, Editors (Optical Society of America, Washington, DC 1996), pp. 108-112.

Macintosh, B., et. al., “Extreme Adaptive Optics Planet Imager: XAOPI,” Proc. SPIE Vol. 5170 (2003).

Kasdin, et. al., “Extrasolar Planet Finding via Optimal Apodized Pupil and Shaped-Pupil Coronagraphs,” *Astr.Phys.Journal, Vol 582 p. 1147-1161* (2003).

This work was performed under the auspices of the U.S. Department of Energy, National Nuclear Security Administration by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.