DDE Annual Report

Title of Investigation:

Sub-nanometer Precision Metrology for Static Wavefront Correction

Principal Investigator:

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In-house Team Members:

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External Collaborators:

Julia Duval (NASA Academy), Peter Petrone (Sigma Space), and Paul Cottle (Sigma Space)

Initiation Year:

FY 2004

FY 2004 Authorized Funding:

$60,000

Actual/Expected Expenditure of FY04 Funding:

In-house: $12,000 for machine shop work; Contracts: $28,000 for vendors and $20,000 to Sigma Space for optomechanical design

Status of Investigation at End of FY 2004:

Continued in FY 2005 with $45,000 expected

Expected Completion:

July 2005

Purpose of Investigation:

The Extrasolar Planetary Imaging Coronagraph (EPIC) is a proposed NASA mission to directly detect and characterize giant gas planets in orbits around other star systems. Typical extrasolar planets are about 1 billion times dimmer than their parent stars and occur at small angular separations on the order of 0.1–0.7 arcseconds from their parent stars (this is about the diameter of a dime as seen from 20 kilometers). Such resolution is not feasible with any conventional telescope system. The planet is lost in the glare of the parent star.

A coronagraphic telescope is an approach which suppresses the stellar light and its glare, while keeping the light from the planet intact. In other words, it increases the contrast of the planet with respect to its parent star. Suppression of the stellar light more than 9 orders of magnitude is a technically demanding task, requiring precise control of light and hence the optics of the coronagraphic telescope. This places very demanding tolerances on the optics. Light propagating through the coronagraph undergoes modifications of its wavefront, amplitude and polarization, that is, of the properties of the beam. Manufacturing limitations, misalignment errors and instabilities cause these modifications. Two primary approaches are possible to correct these errors. The first uses active wavefront control to first sense the errors and to deform optical surfaces to compensate and the second uses static wavefront control. It is this second approach, which we are demonstrating as part of this investigation.

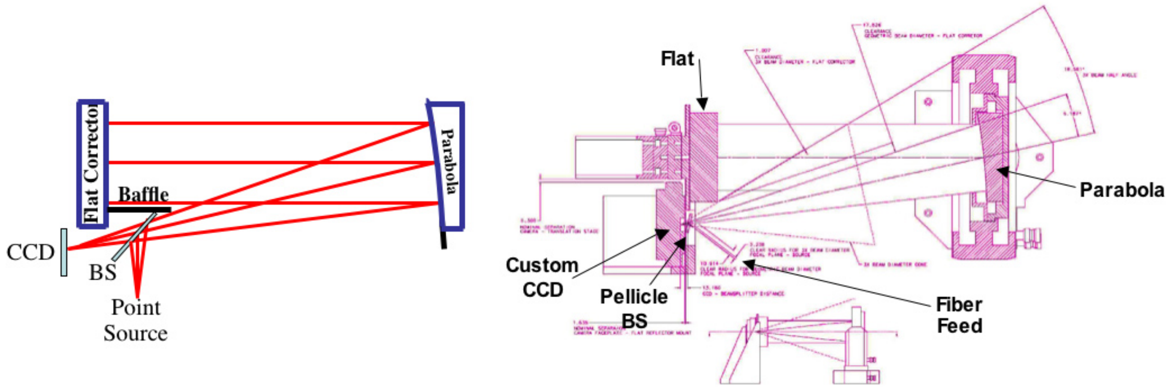


Figure 1. Coronagraphic Testbed; Left: Simplified schematic for clarity; Right: Detailed drawing of testbed

In static wavefront control, optics with very demanding tolerances are used to cancel the fixed-error sources. To demonstrate this in a laboratory environment, an off-axis parabolic reflective optic and a flat optic were both fabricated and tested by ASML, a high-quality optical vendor, and delivered to the Goddard Space Flight Center. The 120-mm diameter parabola has a root-mean-square (rms) surface deviation of 6-nm rms from its ideal mathematical shape. The flat optic was manufactured to 12-nm rms, but in such a manner that each bump (or pit) on the parabola is matched to a pit (or bump) on the flat. In this manner, light first reflecting off the parabola to the flat and then back to the parabola will be corrected to 1-nm rms deviation from perfect beam quality. In other words, its wavefront error will be corrected to 1/500th the wavelength of the light. Wavefronts of this quality, or better, are required for coronagraphic detection of extrasolar planets and would be useful for such missions as the Terrestrial Planet Finder (TPF) Mission and/or the Extrasolar Planetary Imaging Coronagraph (EPIC). See Figure 1.

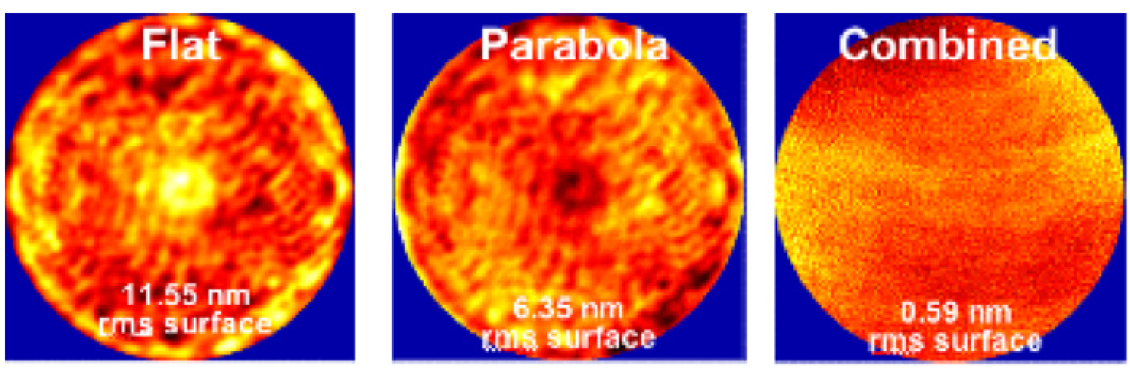
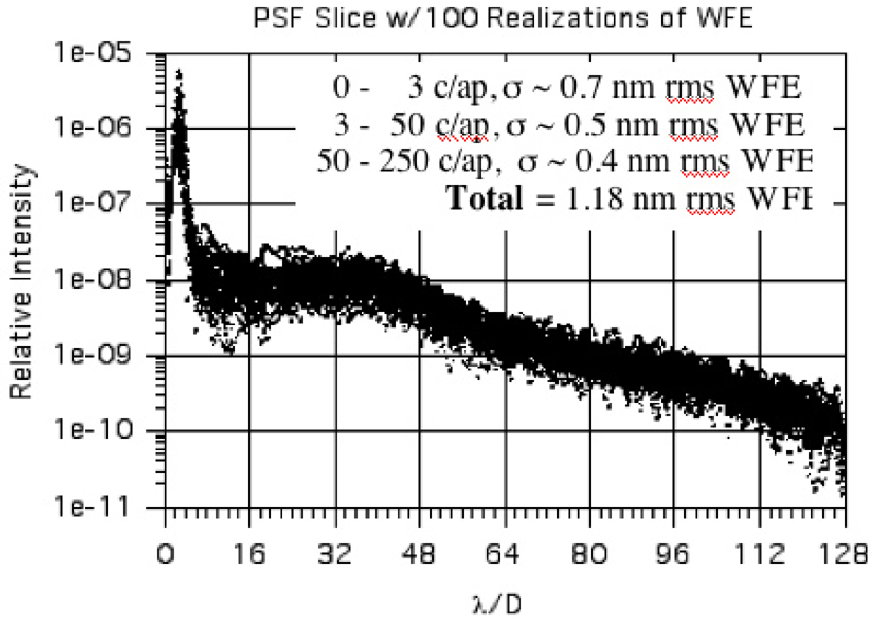


Figure 2. Surface of as delivered optics; Left: Corrector flat with 11.55-nm rms surface error; Center: Off-axis parabola with 6.35-nm rms surface error; Right: Combined nulled surface with 0.59-nm rms surface error

FY 2004 Accomplishments:

The specifications for our very high-quality optics were set in terms of rms wavefront error (WFE) per spatial frequency band. The manufacture, test, and use of the optics were discussed in two published articles. The optical surfaces are shown in Figure 2; the middle graphic shows the parabola's surface and the left graphic shows the flat's surface. Notice that everywhere a bump (bright point) occurs on the parabola, a corresponding pit (dark point) occurs on the flat and vice-versa. The combined wavefront is shown in the graphic on the right and is 0.59-nm rms surface error (1.18-nm rms WFE). This is quite an extraordinary result in that wavefront correction can be performed in this manner without active optical wavefront sensing and control.

Figure 3 shows a plot through the expected point spread function (PSF) of our laboratory testbed. Plotted is the detected intensity versus focal plane position in units of Airy rings. We expect that beyond 5 Airy rings (5 λ/D), the contrast ratio should be stable held to better than 10-8 — our success criteria for the experiment.



Expected point spread function thru lab testbed

In a flight system, ground measurements of the flight primary mirror would be performed and a mid-spatial frequency corrective optic would be manufactured and mounted at an image of the primary (pupil) on a 6-degree of freedom mount. The rigid body rotations of the primary would be sensed and fed back to the static corrector for accurate wavefront control. We have designed a Goddard testbed to demonstrate this technique in the laboratory.

The "as fabricated" and tested optics were folded into our system level sensitivity and error budget analysis and flowed down to component level specifications. Optical and mechanical designs and drawings were completed (Figure 1, on the right). The laser and fiber source, custom CCD camera, custom pellicle, optical mounts, and breadboard were procured. Clean room (class 100) space was secured for optical assembly, alignment, and testing to perform the experiment.

Planned Future Work:

All of the procured components have arrived and are being assembled in the clean room facility. One of the precision optical mounts still needs to be fabricated using the FY 2005 funding. Once all the components are available (February 2005), the entire system will be aligned and the experiment plan will begin and continue through June of 2005.

Published Papers:

[1] M. Clampin, G. Melnick, R. Lyon et.al, Extrasolar Planetary Imaging Coronagraph (EPIC), Proceedings of SPIE Vol. 5487, June 21-25, 2004, Glasgow Scotland.

[2] M. Bigelow and N. Harned, Taking Optical Precision to the Extreme, OE Magazine, November/December 2004.

[3] R. Kestner, C. Witebsky, M. Clampin, R. Lyon, R. Woodruff, Irregularly Figured Plates Correct Wavefront Errors, Laser Focus World, December 2005.

Summary:

Static wavefront correction by measuring and polishing an inverse shape into optics to angstrom-level precision has never before been achieved. Validation of this via phase retrieval — that is, nonlinear algorithmic methods that extract the shape of the errors from observed images — is a new and innovative technology. This technology offers NASA projects the ability to correct mid-spatial frequency wavefront error to an unprecedented level. This positions the Goddard Space Flight Center to demonstrate much-needed technology for coronagraphic direct detection of extrasolar planets. It also allows us to identify and assess risks and to determine the requirements associated with this technology as a potential flight technology. Moreover, it allows Goddard to develop industry partners for high-precision optics and optical testing, accelerating the insertion into space applications.

Success criteria include: (1) manufacture and test of the inverse nulling optics, which we achieved through specification and delivery from the vendor of the custom optics to Goddard, (2) stable measurement of the high-contrast images as seen through these optics, (3) development of high contrast algorithmic techniques (phase retrieval) to measure the errors and cross-validate the errors against the manufacturers measured errors.

Risk factors included the possibility that the vendor's non-contact optical polishing process would not yield the required results. This is no longer a risk since we have successfully demonstrated the requirements through the manufacture and test of the vendor-supplied optics. Laboratory environmental stability and stray light is still a risk. The low funding required us to not rigorously assess some of the required environmental conditions, which include vibration isolation versus temporal frequency, air path turbulence, air path scatter, temperature drift and stray light. If one or more of these contributors becomes a problem, we may have to reassess, or develop alternative solutions. This may add time and expense to the experiment plan.