Title of Investigation:

Sub-nanometer Precision Metrology for Static Wavefront Correction

Principal Investigator:

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Initiation Year:

FY 2004

Funding in FY 2004:

$60,000

Funding for FY 2005:

No funds received, 0.3 FTE

Actual/Expected Expenditure of FY 05 Funding:

No funds received; FTEs to assemble/align the optics.

Status of Investigation at End of FY 2005:

Continue in FY 2006 with the proposed Discovery mission—Extra-Solar Planetary Imaging Coronagraph (EPIC)

Expected Completion:

September 2006

Purpose of Investigation:

The goal of this investigation is to demonstrate accurate static optical wavefront correction (~1 nm rms wavefront error (WFE)) with applications for using a coronagraph for detection and characterization of planets outside the solar system. An off-axis, parabolic, coated mirror of 120 mm clear aperture was fabricated and tested by ASML at ~6 nm rms surface error in the spatial frequency band of 0 to 50 cycles/aperture. A flat uncoated reflective optic (120 mm clear

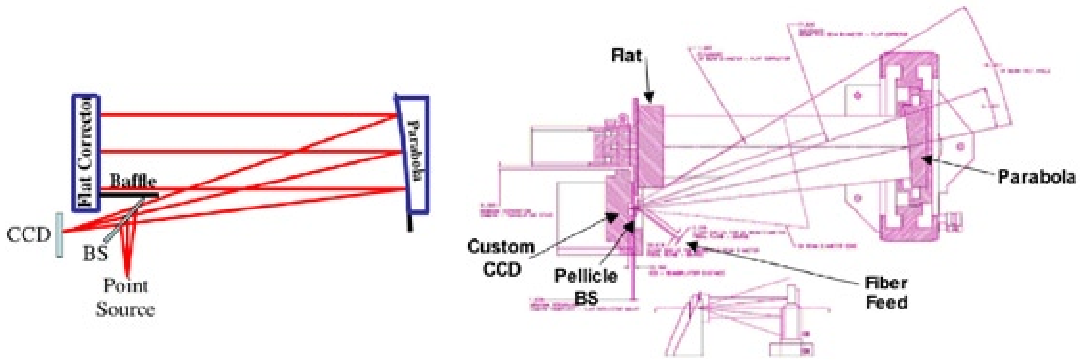

Figure 1. Coronagraphic TestbedLeft: Simplified schematic for clarity
Right: Detailed drawing of testbed

aperture) was manufactured and tested to ~12 nm rms surface error, as a corrector mirror for the parabola. At each location of a bump (or pit) on the parabola, a pit (or bump) was polished into the flat, such that when the optics are used in the configuration shown in Figure 1, they effectively null each others wavefront to 1 nm rms WFE or 1/500 the wavelength of light. Wavefronts of this quality, or better, are required for coronagraphic detection of exo-solar planets such as in the Terrestrial Planet Finder Mission (TPF) [1,2] and/or the Extrasolar Planetary Imaging Coronagraph (EPIC) [3].

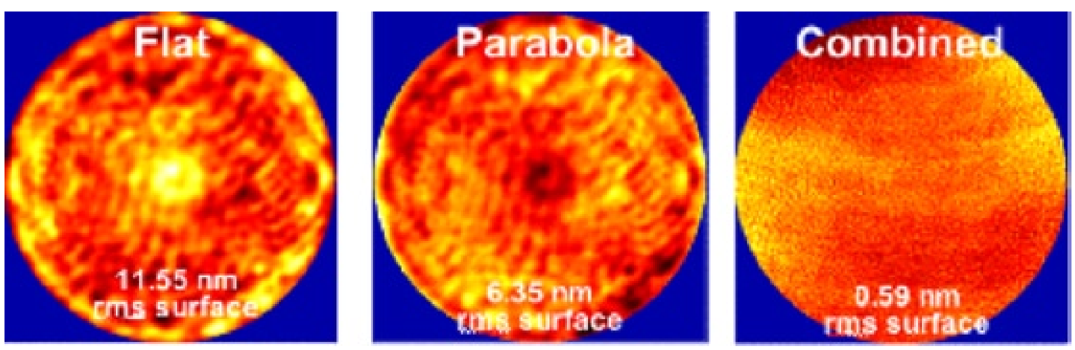

Figure 2. Surface of as-delivered optics
Left: Corrector flat with 11.55 nm rms surface error
Center: Off-axis parabola with 6.35 nm rms surface error
Right: Combined nulled surface with 0.59 nm rms surface error

Accomplishments to Date:

The specifications for our very high-quality optics were set in terms of rms wavefront error per spatial frequency band, i.e., power spectral density, and ASML elected to fabricate, test, and deliver the optics. The optical surfaces are shown in Figure 2; the middle graphic shows the parabola's surface and the graphic on the left shows the flat 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). The fact that wavefront correction can be performed in this manner without active optical wavefront sensing and control is quite an extraordinary result. ASML discussed these results in a published article [4].

In a flight system, ground metrology 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.

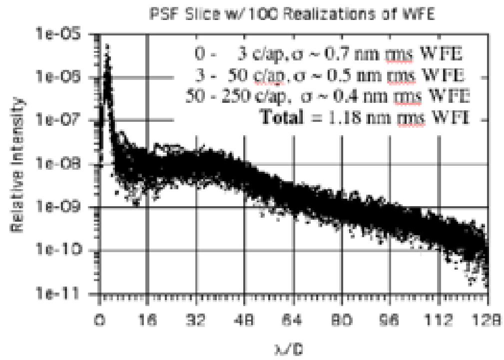

Figure 3. Expected Point Spread Function thru Lab testbed

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 stably held to better than 10^{-8} (success criteria).

The "as fabricated" and tested optics were folded into our system-level sensitivity and error budget analysis, and then flowed down to component-level specifications. Optical and mechanical designs and drawings were completed (Figure 1). The laser and fiber source, custom CCD camera, custom pellicle, optical mounts, and breadboard were procured. Clean Room space was secured in Building 5 (class 10,000) for optical assembly, alignment, and testing. The optics were mounted and the fiber source was assembled along with the pellicle beam splitter.

Planned Future Work:

All of the procured components have arrived and have been assembled in the clean room. They have been initially aligned. The next step is to fine-tune the alignment using phase retrieval. Focal plane images will be collected and processed through the phase-retrieval algorithm to recover the wavefront and the optics will be dithered to minimize the rms wavefront error. Once the alignment is completed, the observed wavefront error will be validated against the vendor's measurement of the wavefront error. The results will be documented and published.

Key Points Summary:

The project's innovative features: We achieved static wavefront correction by measuring and polishing an inverse shape into optic. We did this to an angstrom-level precision that has never before been achieved. Validation of this via phase retrieval and direct contrast measurement is a new and innovative technology.

Potential payoff to Goddard/NASA: This procedure provides NASA projects with an alternative new technology that allows correction of mid-spatial frequency wavefront error to an unprecedented level. This positions NASA/GSFC to demonstrate much-needed technology for coronagraphic direct detection of exo-planets. It also allows us to identify and assess risks and determine the likelihood of this technology as a potential flight technology. It also allows GSFC to develop industry partners for high-precision optics and optical testing, accelerating the insertion into space applications.

The criteria for success: For this project, success meant the manufacture and testing of the inverse nulling optics. This criterion has been met by delivery of the ASML optics. The tests showed stable measurement of the point spread function contrast to $<10^{-8}$ at greater than five Airy rings; high-contrast phase retrieval to measure wavefront and cross-validate the recovered wavefront against ASML measured wavefronts; and separation of the wavefront (via shearing) into wavefront components for the parabola and the corrector flat.

Technical risk factors: The non-contact optical polishing process would not yield sub nanometer wavefront results. This is no longer a risk factor in that it has been successfully demonstrated. Laboratory environmental stability and stray light is still a risk. The funding of this DDF did not allow us to rigorously assess some of the required environmental conditions that include vibration isolation versus temporal frequency, air path turbulence, air path scatter, temperature drift and straylight. If one or more of these contributors becomes a problem, we may have to reassess or develop workarounds. This may add time and expense to the experiment plan.

References:

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[2] R. G. Lyon, J. M. Hollis, and J. E. Dorband, Comparative Optical Analysis of Extra-Solar Planetary Imaging Techniques, *SPIE Astronomical Telescopes and Instrumentation,* 22–28 August 2002, Waikoloa, Hawaii, USA

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

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