High Contrast Imaging Testbed for the Terrestrial Planet Finder Coronagraph[1,2]

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Abstract—One of the architectures under consideration for Terrestrial Planet Finder (TPF) is a visible coronagraph. To achieve TPF science goals, the coronagraph must have extreme levels of wavefront correction (~1 Å rms over controllable spatial frequencies) and stability to get the necessary suppression of diffracted starlight (10^{-10} contrast). The High Contrast Imaging Testbed is the TPF platform for laboratory validation of key coronagraph technologies, as well as demonstration of a flight-traceable approach to coronagraph implementation. Various wavefront sensing approaches are under investigation on the testbed, with wavefront control provided by a precision high actuator density deformable mirror. Diffracted light control is achieved through a combination of an occulting or apodizing mask and stop; many concepts exist for these components and will be explored. Contrast measurements on the testbed will establish the technical feasibility of TPF requirements, while model and error budget validation will demonstrate implementation viability. This paper describes the current testbed design and preliminary experimental results.

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1. INTRODUCTION

Terrestrial Planet Finder (TPF), scheduled for launch in 2015, will detect and characterize earth-like planets around nearby stars [1]. TPF is currently in a formulation phase, exploring design trades and developing the technology needed to support a mission. Two candidate architectures are under study: an infrared interferometer that will detect light radiated from an extra-solar planet and a visible coronagraph that will detect light from the parent star that is reflected or scattered by the planet. The requirements are challenging for either approach.

The driving requirement for a coronagraph is 10^{-10} contrast at an angular resolution of $4\lambda/D$, where λ is the wavelength and D is the telescope diameter (or largest dimension in the case of a non-circular aperture). The contrast value is the intensity difference between a typical star and a terrestrial-sized planet located within the habitable zone around that star. The angular separation requirement is a function of the telescope diameter and the integration time needed to identify and study planets. For a telescope primary mirror sized to fit into an existing launch vehicle and an integration time derived from the science goals for the number of stars to be fully characterized over the expected mission lifetime, that separation is $\sim 4\lambda/D$. To achieve these requirements, a coronagraph needs extreme levels of wavefront sensing and control; a highly stable optical system; occulting or apodizing masks and stops; suppression of stray light; uniform coatings with minimal polarization effects; and accurate diffraction models to allow simulation and study of these issues. To validate these critical technologies and to demonstrate readiness for a coronagraph space mission, TPF has built the High Contrast Imaging Testbed (HCIT) [2].

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[2] IEEEAC paper #1383, Version 1, Updated October 6, 2003

2. TESTBED DESCRIPTION

Facility

The HCIT consists of an optical bench inside a vacuum tank, with supporting hardware located outside the chamber. A picture of the testbed is shown in Figure 1. The chamber is pumped to ~10^{-3} Torr, adequate to eliminate atmospheric effects and provide a stable (and dark) environment for experimentation. A thermal control system maintains the chamber temperature to ±0.1K. Several racks outside the tank contain electronics to control the deformable mirror, actuators, and cameras; a source module; and the computers used to control the testbed hardware.

Optical Bench and Layout

The bench consists of a commercial off-the-shelf (COTS) vibration-damped optical table, semi-custom optics, and vacuum-compatible COTS optical mounts and stages supported by custom risers and standoffs. The current layout, a classical Lyot coronagraph, is shown in Figure 1.

off-axis light that might come from an accompanying planet. A third OAP recollimates the beam and provides an accessible pupil plane, conjugate to the DM. The starlight that is not attenuated by the occulter will be concentrated in a ring near the outside of the pupil. An undersized Lyot stop clips this diffracted light while allowing light from the planet to pass through. A fourth OAP sends the light to a second focus, where a field stop may be located. (Alternately, an apodized stop, such as a Spergel mask [3], may be placed at the Lyot stop with a blocking disk placed at this second focus, creating an apodized coronagraph.) A final pair of OAP's change the magnification of the beam to give Nyquist or better sampling of the image at the science camera.

Both the science camera and a second camera (selectable at the first focus) are mounted on translation stages to permit through focus alignment and wavefront sensing techniques. Another alignment feature is a diffuser source that provides a uniform background in lieu of the fiber; this allows easier location and alignment of the occulting disk, not to mention providing a source for flat fielding the cameras.

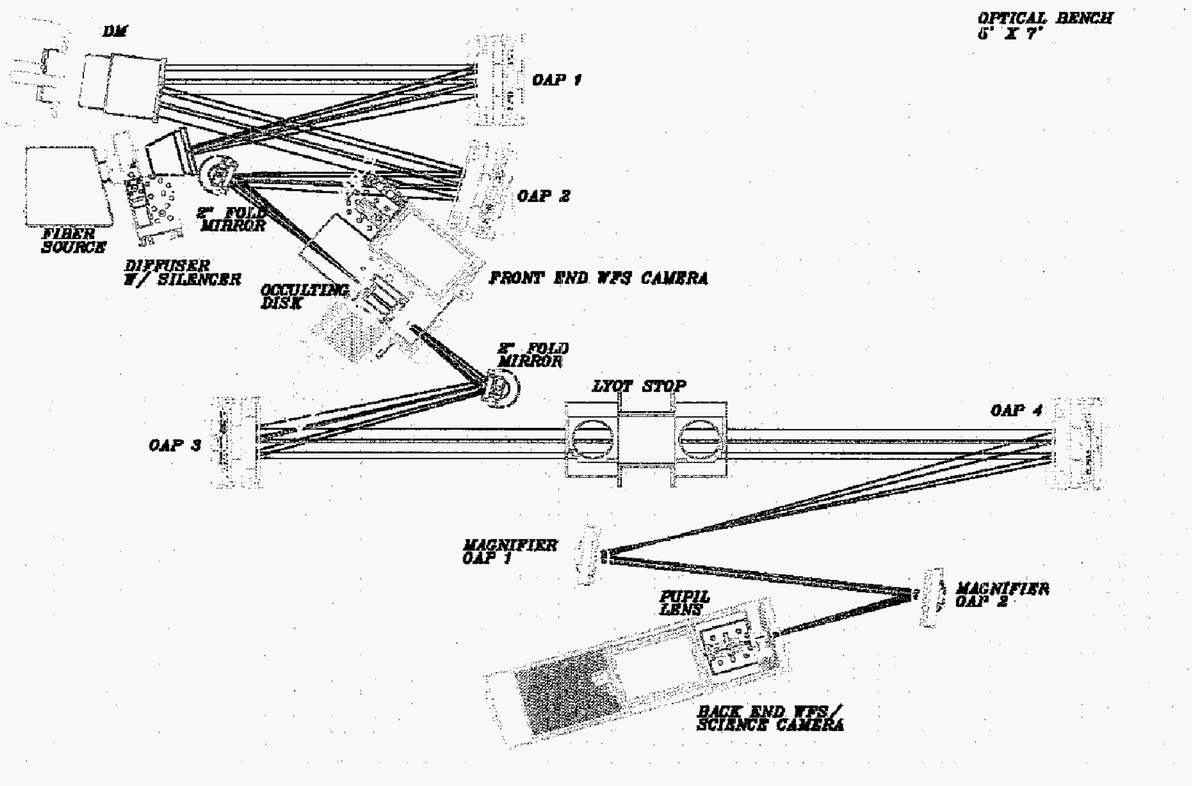


Figure 1 – Testbed Layout

A single-mode fiber, fed from a source outside the chamber, simulates the image of a star. An off-axis parabolic mirror (OAP) collimates the beam and directs it to a high-density deformable mirror (DM). The resulting [corrected] wavefront is refocused by a second OAP. In coronagraph mode, the light passes through an occulting disk that suppresses the on-axis starlight while minimally attenuating

The bench and chamber are instrumented with temperature sensors and accelerometers. Thermal control electronics have been developed for precise (milli-Kelvin) control of the sensitive DM, as well as control of the optical bench and components as needed.

Wavefront Sensing and Control System

The heart of the testbed is a high-density DM. This is the enabling technology for a coronagraph and is the product of several years of development at Xinetics [4]. The testbed currently uses a 1024 actuator (32x32 array) DM, picture in Figure 2. A larger 4096 actuator (64x64 array) DM is under development. The DM enables wavefront correction at the unprecedented level of 1 Å rms. The inter-actuator spacing on these mirrors is 1 mm, with a stroke on the order of 500 nm. The 1024 actuator DM is driven by a Xinetics-built multiplexer (XiMUX). Our XiMUX system does not have a sufficient number of channels to drive a 4096 actuator mirror. Rather than purchase additional electronics that are not flight traceable, we have developed a high voltage low power ASIC for use in a new multiplexer to drive the larger mirror.

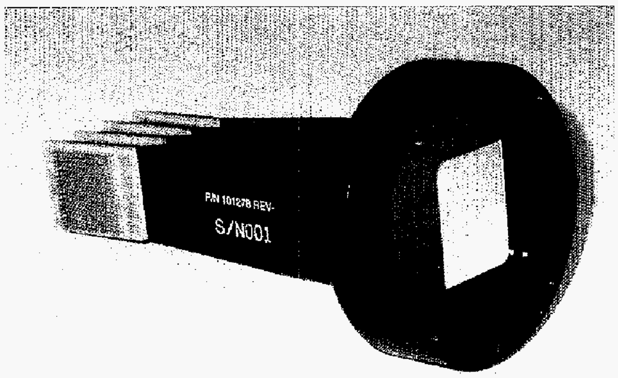


Figure 2 – 32x32 DM

Two wavefront sensing approaches are under investigation. Our primary method to date, termed "front-end sensing," uses the front camera and translation stage for focus diverse phase retrieval. We use a modified Gerchberg-Saxton (MGS) algorithm, an iterative Fourier transform approach that uses images taken at different defocus positions and a pupil image to extract the wavefront [5, 6]. This wavefront is used to calculate a control for the DM; the goal is to present a near-perfect image to the occulter. The small (7.5μm) pixels on the front camera have a noticeable amount of blurring due to inter-pixel crosstalk, which will ultimately limit the accuracy of this wavefront sensing approach. There will also be errors introduced by sampling. The image is Nyquist sampled with a 32x32 DM, but will be undersampled with the 64x64 DM.

The second wavefront sensing approach, termed "back-end" sensing, will be used to achieve ultimate performance. The back-end approach attempts to quash individual speckles in the occulted image. The algorithm dithers the DM, observes the change in the speckles, and calculates a control. One variant of this approach, the so-called "half-hole" algorithm, improves performance in one half of the image plane at the expense of the other half. The back end approach has the ability to compensate for amplitude nonuniformity in the system, which may be the limiting error source if the phase is perfectly corrected as attempted by the front-end approach. The front-end MGS approach will be used to get good performance before using back-end sensing as the final tweak to get maximum contrast.

Diffracted Light Suppression

Our current baseline occulting mask is written on high energy electron beam sensitive glass [7]. TPF is exploring other approaches to masks and stops, both at JPL and through industrial and university partners. The design of these components will be modeled using rigorous electromagnetic theory. Metrology instrumentation is under development to characterize both the amplitude and phase properties of these devices.

Diffracted light suppression will not yield the desired contrast if the background light level is too high. The science camera has a very low noise level, and the vacuum chamber prevents external sources from affecting our measurements. The fiber may introduce light outside the core (e.g., from cladding modes); this must be characterized and eliminated. The remaining background source, potentially a limiting factor, is stray light in the testbed. A specialist will analyze the system and design appropriate baffle and apertures to suppress stray light from ghost reflections, scattering, and diffraction from optical and mechanical components. Contamination on optical surfaces may at some point limit the achievable stray light level.

Modeling

Full diffraction models of the testbed have been developed. TPF has a separate modeling effort that will improve the tools used for these calculations. An important function of the testbed is to validate these models, to increase confidence in predictions of system behavior that cannot be easily investigated in the laboratory. Another use for these models is in generation of an error budget for the testbed. Development and validation of an error budget is a well established approach for building flight hardware; use of such a deterministic approach on the testbed will demonstrate that our contrast achievements can be duplicated in a flight mission.

3. Experimental Results

Preliminary experiments began in October 2002 with the testbed operating in a clean tent under ambient conditions using a less-than-perfect DM. The bench was moved into the vacuum chamber in April 2003, with experiments commencing in June. These initial experiments used a high quality flat mirror in place of the DM to establish baseline performance of the system. A fully functional 1024-actuator DM was integrated in October 2003.

Baseline Performance

With the flat in place of the DM, extensive studies of wavefront sensing repeatability were conducted [8]. The results in Figure 3 show a highly stable measurement. The system measured wavefront error is 10 nm rms. The repeatability on a pixel-by-pixel basis is on the order of $\lambda/1000$ rms, which very little variation over two days. A more relevant measure is the repeatability over those spatial frequencies controllable by the DM, since higher frequencies will mostly fall outside the region of diffracted light suppression; that value is $\sim\lambda/10,000$ rms. A baseline system contrast measurement was also performed (Figure 4). At an angular separation of $4\lambda/D$, contrast is worse than 10^{-5}; at $10\lambda/D$, contrast is 10^{-6}.

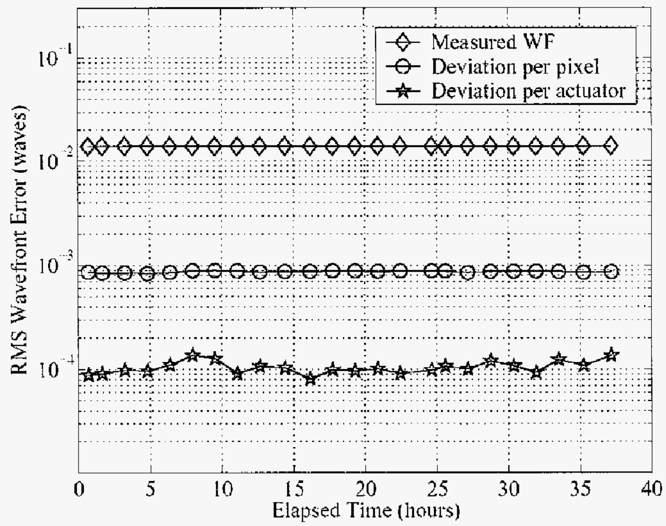
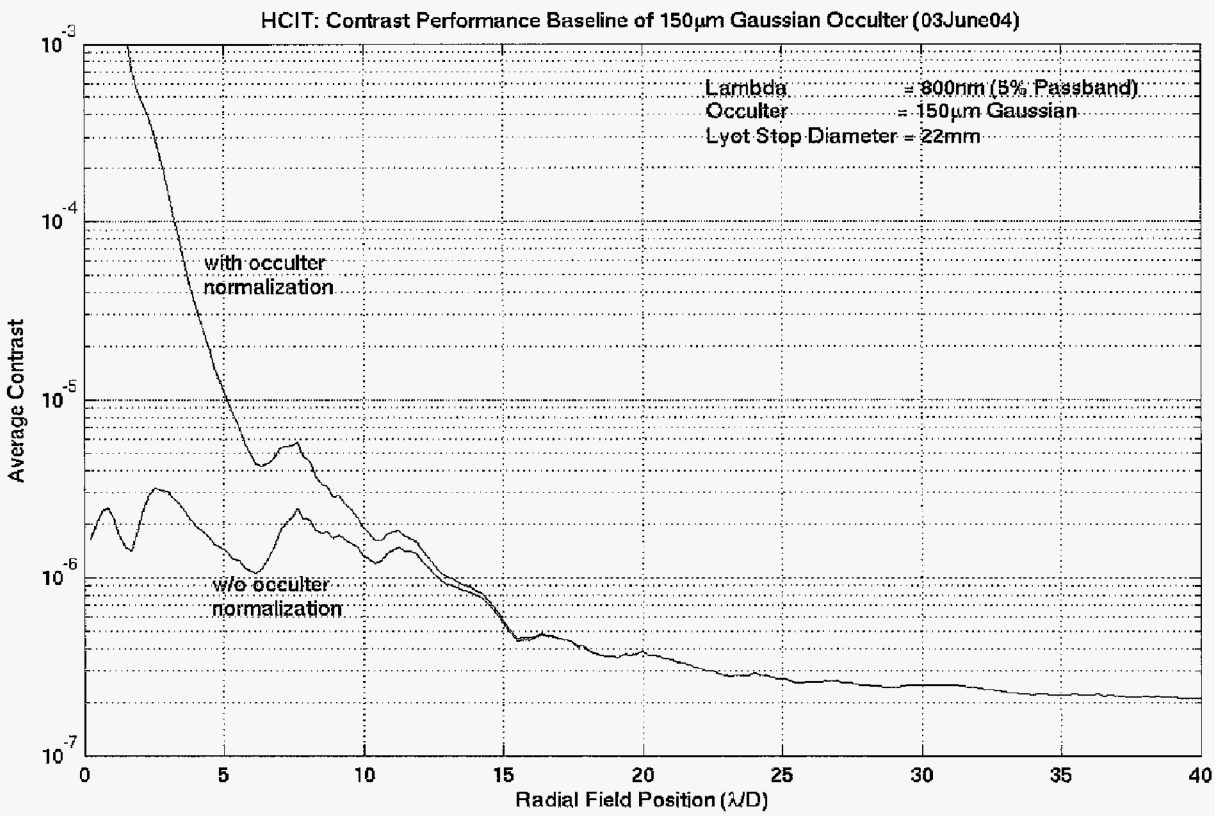


Figure 3 – Wavefront Sensing Repeatability



Deformable Mirror Performance

Prior to testing in vacuum, the surface figure of the DM was 18 nm, giving a wavefront error of 36 nm. However, there is an observed change in figure between ambient conditions and vacuum (due to a humidity effect) and between unpowered and powered conditions (due to nonuniform gains). Most of stroke of the DM is used to correct itself.

Vacuum measurements were made using a custom Twyman-Green interferometer. Sparse patterns of actuators were applied relative to the nominal operating bias and gains were calculated based on the deflections. Successive levels of control were applied to the DM to flatten the wavefront in the interferometer, as shown in Figure 5. In the final measurement, the rms wavefront error over those spatial frequencies controllable by the DM was 1.5 Å in a 25x25 window.

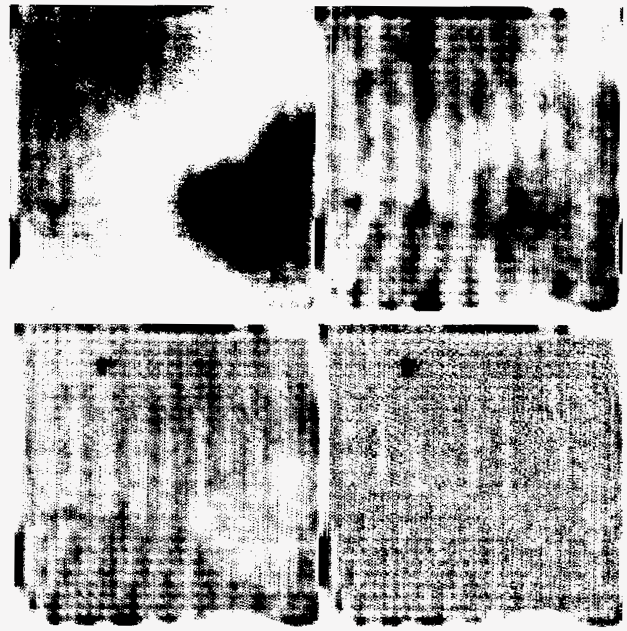


Figure 5 – Successive DM Measurements

Contrast Measurement

After integrating the 32x32 DM into the testbed, contrast measurements were taken. The initial measurement is shown in Figure 6. The contrast is ~10^{-6} at a wavelength of 800 nm for angles greater than 4λ/D. Optimization of the experiment and refinements to the system and components are expected to reduce this to 10^{-7} by mid-2004, with a goal of 10^{-9} by mid-2006.

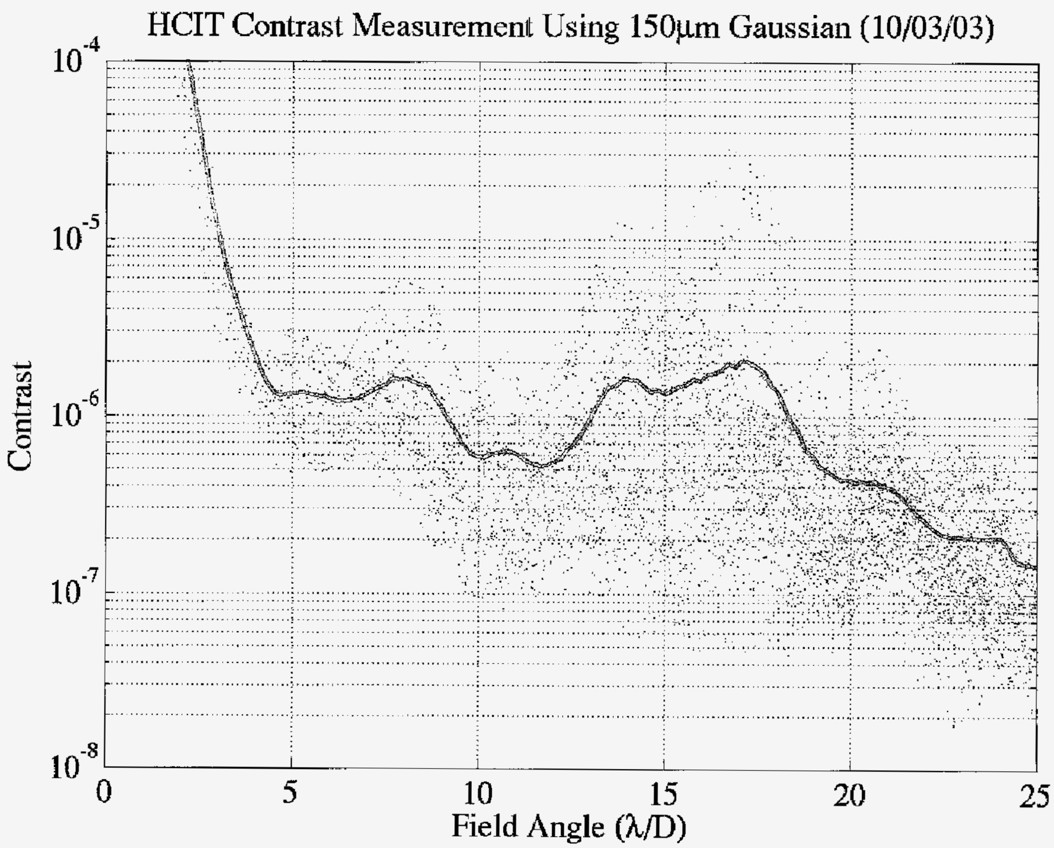


Figure 6 – Initial Contrast Measured using 32x32 DM

4. CONCLUSION

TPF's coronagraph technology development platform is the High Contrast Imaging Testbed. The testbed design provides a stable vacuum environment and all the elements needed for high performance, with the flexibility to test individual components and explore alternate coronagraph configurations. We have demonstrated wavefront correction to 1.5 Å and contrast to 10^{-6} in the visible using a 1024 actuator deformable mirror. Further refinements in the testbed and improved deformable mirrors are expected to push the contrast to 10^{-9}.

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] Terrestrial Planet Finder web site, http://tpf.jpl.nasa.gov

[2] J. T. Trauger, A. Hull, F. Shi, B. Gordon, J. J. Green, A. Lowman, K. Hiroshi, S. Macenka, D. Moody, D. Redding, S. Shaklan, "High-contrast imaging testbed for coronagraphic technologies and analytic models," Proc. Soc. Photo-Opt. Instrum. Eng. **5170** (San Diego, 2003).

[3] N. J. Kasdin, R. J. Vanderbei, D. N. Spergel, M. G. Littman, "Optimal shaped pupil coronagraphs for extrasolar planet finding," Proc. Soc. Photo-Opt. Instrum. Eng. **4860** 240-250 (2003).

[4] J. T. Trauger, D. Moody, B. Gordon, Y. Gürsel, M. A. Ealey, and R. B. Bagwell, "Performance of a high-density deformable mirror for extremely high contrast imaging astronomy from space," Proc. Soc. Photo-Opt. Instrum. Eng. **4854** 1-8 (2003).

[5] D. C. Redding, S. A. Basinger, A. E. Lowman, A. Kissil, P. Y. Bely, R. Burg, R. G. Lyon, G. E. Mosier, M. Femiano, M. E. Wilson, R. G. Schunk, L. Craig, D. N. Jacobson, J. Rakoczy, J. B. Hadaway, "Wavefront sensing and control for a Next Generation Space Telescope" Proc. Soc. Photo-Opt. Instrum. Eng. **3356**, 758-772 (1998).

[6] R. W. Gerchberg and W. O. Saxton, "A practical algorithm for the determination of phase from image and diffraction plane pictures," Optik **35**, 237-246 (1972).

[7] D. W. Wilson, P. D. Maker, J. T. Trauger, A. B. Hull, "Eclipse apodization: realization of occulting spots and Lyot masks," Proc. Soc. Photo-Opt. Instrum. Eng. **4860** 361-370 (2003).

[8] J. J. Green, S. A. Basinger, D. Cohen, A. F. Niessner, D. C. Redding, S. B. Shaklan, J. T. Trauger, "Demonstration of extreme wavefront sensing performance on the TPF high contrast imaging testbed," Proc. Soc. Photo-Opt. Instrum. Eng. **5170** (San Diego, 2003).

BIOGRAPHY

Andrew Lowman is a senior optical engineer and manager of the High Contrast Imaging Testbed at JPL. He has designed and implemented hardware for several active optics testbeds, including the JWST Wavefront Control Testbed and Phase Retrieval Camera. His interests span the design, analysis, and testing of optical systems with an emphasis on space telescope technology. He has a PhD in Optical Sciences from the University of Arizona.