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Coronagraph instrument for WFIRST-AFTA

M. Charley Noecker,[a,*] Feng Zhao,[a] Rick Demers,[a] John Trauger,[a] Olivier Guyon,[b,c] and N. Jeremy Kasdin[d]
[a]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109, United States
[b]Subaru Telescope, National Astronomical Observatory of Japan, 650 N. A'ohoku Plane, Hilo, Hawaii 96720, United States
[c]University of Arizona, UAz Steward Observatory, 933 North Cherry Avenue, Tucson, Arizona 85721, United States
[d]Princeton University, C234 Engineering Quadrangle, Princeton, New Jersey 08544, United States

Abstract. The Wide-Field Infrared Survey Telescope (WFIRST) is a NASA observatory concept, now in phase A study, which is designed to perform wide-field imaging and slitless spectroscopic surveys for dark energy research and other astrophysical studies. It will also perform microlensing surveys to look for distant exoplanets in our galaxy, and direct imaging studies of some of the very nearest exoplanets. The current astrophysics focused telescope assets (AFTA) design of the mission makes use of an existing 2.4-m telescope, which yields enhanced sensitivity and imaging performance in all these science programs. AFTA also enables the addition of a coronagraph instrument (CGI) for direct imaging and spectroscopy of nearby giant exoplanets (including some that were discovered by radial velocity and other methods), and also for observing debris disks around the candidate host stars. This paper outlines the context for the other papers in this special volume on the WFIRST-AFTA CGI, covering the science, design, engineering, and technology development of the observatory and its CGI. [DOI: 10.1117/1.JATIS.2.1.011001]

Keywords: astronomy; space telescope; exoplanet; coronagraph; WFIRST-AFTA.

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1 Introduction

The first discovery of planetary companions to Sun-like stars was, along with the discovery of dark energy, one of the greatest breakthroughs in modern astronomy.[1–3] These discoveries have excited the astronomical community and the broader public as well. Since then, the pace of exoplanet discovery has increased each year. There are now more than 1955 confirmed exoplanets, and Kepler has identified almost 3700 other candidates that await confirmation.[4–6]

Nature has surprised astronomers with the enormous and unexpected diversity of exoplanetary systems, containing planets with physical properties and orbital architectures that are radically different from our own solar system. Since the very first discoveries, we have struggled to understand this diversity of exoplanets and, in particular, how our solar system fits into this menagerie.

Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets (WFIRST-AFTA) (Ref. 7, Fig. 1) will advance our understanding of exoplanets along two complementary fronts: the statistical approach of determining the demographics of exoplanetary systems over broad ranges of properties and the detailed approach of characterizing the properties of a handful of nearby exoplanets. (The latter is the topic of this paper).

First, through its comprehensive statistical census of the outer regions of planetary systems using microlensing, including planets with separations spanning from the outer habitable zone to free floating planets, and analogs of all of the planets in our solar system with the mass of Mars or greater, WFIRST-AFTA will complete the statistical census of planetary systems begun by Kepler.[7,8]

Second, using a coronagraph instrument (CGI), WFIRST-AFTA will be capable, for the first time in human history, of directly imaging planets that closely resemble those in our solar system—such as cool giants in 1- to 10-year orbits. It will make detailed studies of the properties of giant planets around nearby stars and characterize their debris disks at visible wavelengths with unrivaled sensitivity and spatial resolution. It may also measure photometric properties of some mini-Neptune or super-Earth planets—objects that Kepler has shown to be the most common planets in our galaxy, but with no analog in our own solar system. It will also be the testbed for future coronagraphs capable of detecting signs of life in the atmospheres of Earth-like exoplanets.

With these two complementary surveys, WFIRST-AFTA will provide the most comprehensive view yet of the formation, evolution, and physical properties of planetary systems. In addition, information and experience gained from both surveys will lay the foundation for, and take the first steps toward, the discovery and characterization of a pale blue dot—a habitable, Earth-like planet orbiting a nearby star.

1.1 *Birth of Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets*

The report of the National Research Council's (NRC) Decadal Survey of Astronomy and Astrophysics of 2010, titled "New Worlds, New Horizons in Astronomy and Astrophysics" (NWNH), outlined a set of priorities and recommendations for the years 2010 to 2020 in space- and ground-based astronomy. As its highest priority recommendation for large space missions, the committee chose an observatory they called WFIRST, performing a combination of dark energy science and a microlensing search for exoplanets. As its highest recommendation for medium space missions, they chose a New Worlds Technology

*Address all correspondence to: M. Charley Noecker, E-mail: charley.noecker@jpl.nasa.gov

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Development Program, to prepare for a later mission to perform direct imaging of exoplanets.

In 2012, the U.S. National Reconnaissance Office transferred to NASA two space-ready telescopes, which were no longer needed. Although many hardware elements were not included, nevertheless this opportunity provided NASA a very high-quality front-end telescope. In April 2013, WFIRST-AFTA Science Definition Team concluded[8] that WFIRST-AFTA would be significantly more capable than the smaller version described in NWNH, for similar cost, and would also allow the addition of an advanced coronagraph to accelerate the NWNH direct-imaging science and to further develop the technology. In 2014, an NRC review committee[9] endorsed the WFIRST-AFTA concept and a coronagraph, with caveats about project cost growth and cost risk, and overall NASA program balance. (Subsequent technical progress described in this volume has helped address these concerns).

1.2 *Modeling Coronagraph Mission Performance*

For more than 20 years, NASA has been pursuing studies of coronagraph missions that could detect and characterize exoplanets that orbit nearby stars. Through a series of such efforts to design an observatory and a mission observing plan, and the steady progress of coronagraph technology development in the lab, we are close to acquiring the technical means to observe exoplanet systems like our solar system around nearby stars by direct imaging.

The WFIRST-AFTA CGI baseline design contains within it two types of coronagraphs (primary) and one potentially higher-performing backup, to block the glare of nearby stars, revealing the light from planets orbiting those stars. We are proving and improving these designs in the laboratory: learning the subtleties of wavefront control algorithms, correcting drift and other errors in the telescope, and developing low-noise CCD detectors. We have advanced mission models, which perform mock missions with observing schedules, probabilistic detections, rescheduling contingent on those detections, and statistical estimates of science harvest (by several metrics). These analytical tools enable detailed estimates of the science harvest for a mission and instrument with specified capabilities. This in turn provides confidence that the systems we know how to build are capable of the science we want.

With direct imaging of previously known and newly discovered giant exoplanets, we will be able to analyze their spectra to understand their atmospheric chemistry. If we are lucky to see a small, rocky planet in an Earth-like orbit around a very favorable star, we may even be able to confirm an atmosphere and a habitable environment there. These are stepping stones toward finding evidence of life as we know it on other exoplanets.

The WFIRST-AFTA coronagraph will be a major step in the journey toward finding Earth-like planets and evidence of life. Already we can demonstrate these techniques in the laboratory and on ground-based telescopes. We are approaching the required technology readiness to allow direct detection and spectroscopy of giant planets and the dusty debris disks from which they formed and in which they are embedded. The success of this mission will serve as a stepping stone for larger, more capable coronagraphs that can perform deeper and more sensitive surveys for exoplanets.

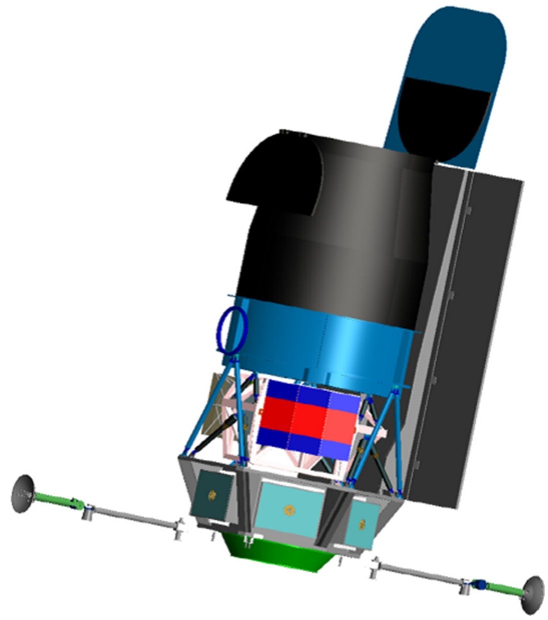

Fig. 1 Artist's drawing of the WFIRST-AFTA observatory.

1.3 *Recent History of Exoplanet Coronagraphs*

Concepts for direct imaging of planets were proposed more than 50 years ago. In 1962, a monumental paper by Spitzer[10]—a visionary "half-century survey" of space astronomy—predicted much of the space astronomy we have seen since then, including large, visible-light space telescopes and direct imaging of exoplanets.

Direct imaging is difficult because exoplanets are much fainter than their host stars (typically 100 million to 10 billion times fainter), while the angular separations are very small (typically <0.2 arcsec $= 1$ μrad). The wavelength and the required angular resolution drive the lateral size of the observatory, but we still face two significant challenges: diffraction from the instrument aperture and scatter arising from wavefront errors in the instrument. Lyot's techniques for solar coronagraphy[11] are the foundation for several methods of suppressing the aperture diffraction in stellar coronagraphs, while deformable mirrors are used to correct the wavefront and clear out scattered starlight to make a very dark region around the star image in the science focal plane.

A design for a stellar coronagraph is shown in Fig. 2. This layout provides the ability to switch between two coronagraph designs, hybrid Lyot coronagraph (HLC) and shaped pupil coronagraph (SPC), simply by selecting different masks in filter wheels. A third design, known as phase induced amplitude apodization–complex mask coronagraph (PIAA-CMC), is compatible with this layout, but is not filter-wheel selectable, and may require a dedicated optical bench. The faintness of planet light and challenges of speckle suppression and calibration drive us to separate the problems of detecting a planet and measuring its characteristics. Of the two primary designs, HLC is better for detection and SPC is better for measuring spectra.

These designs are manifestations of two strategies to make a stellar coronagraph.

- Optimizing a focal plane mask to concentrate diffracted starlight before a subsequent pupil plane mask (HLC, PIAA-CMC).

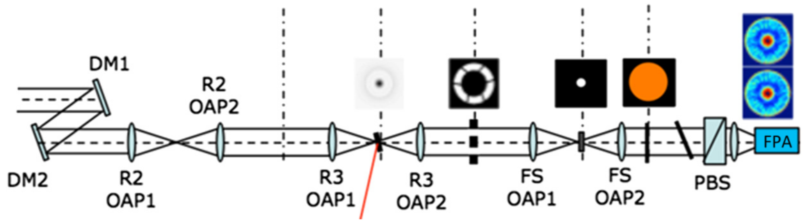

Fig. 2 Coronagraph diagram. Starlight enters at left via a fast steering mirror (not shown). Two deformable mirrors (DM1 and DM2) correct the wavefront phase and amplitude. Masks can be inserted at pupil or field images, indicated with dashed lines, to implement either the HLC or SPC coronagraph design (the masks shown here are examples of an HLC design). After a polarizing beamsplitter (PBS), the image of exoplanets and surrounding dust is formed on a focal plane array (FPA) detector, with the central star suppressed. Relay optics are off-axis parabolas (OAP). An IFS, not shown, can be used instead of the FPA.

- Optimizing the amplitude profile in the pupil plane so as to concentrate diffracted starlight before the focal plane mask (SPC, PIAA-CMC).

Previous coronagraph designs and technology development[12–14] were based on unobscured monolithic telescopes (filled circular aperture); this starting point generally enables better performance in terms of diffraction suppression, inner working angle (IWA) (the smallest practical angle at which planets can be detected in the diffracted starlight background), and planet throughput, and in some designs is required for competitive performance. Researchers had worked hard to reduce IWA below $4\lambda/D$ while maintaining high throughput, to allow low-cost precursor science missions using smaller telescopes.[15,16] The experience gained in those efforts was invaluable in the invention of new designs that are practical and compatible with the AFTA telescope's obscured aperture, at even smaller IWA.

The dual coronagraph architecture for WFIRST-AFTA, known as the occulting mask coronagraph, which was selected in a structured collaborative process to find a low-risk option with compelling scientific performance, was presented to NASA in December 2013. A significant new constraint was AFTA's obscured aperture, and this drove a frenetic pace of invention and performance modeling. In the end, the community and the NRC review team agreed upon a relative ranking that placed SPC and HLC as a joint instrument at top rank, and PIAA-CMC as the second-ranked option. NASA accepted the recommendation in mid-2014. The papers in this volume discuss recent progress on all three designs.

2 Wide-Field Infrared Survey Telescope-Astrophysics Focused Telescope Assets Observatory

The WFIRST-AFTA telescope is existing hardware donated to NASA with a 2.4-m primary mirror, a secondary mirror, stable structures, actuators, some mounting hardware, and an outer barrel assembly for thermal and stray light control. It was built by Exelis (now Harris) and has been structurally qualified and partially assembled. Its mirrors will be lightly refigured to enable the wide field of view of the Wide-Field Imager (WFI), the cornerstone dark energy instrument for WFIRST.

The key components of the AFTA hardware are illustrated in Fig. 3. The existing hardware is shown in magenta and includes the substantive elements of the assembly. The elements shown in green represent new designs and include ancillary hardware such as baffles and struts. The elements shown in blue will be remade from existing designs (e.g., only four of the required six alignment drive actuators are available, and two must be rebuilt). The elements in red represent existing hardware requiring slight modifications. This includes the primary and secondary mirrors, which will be slightly refigured. The elements in yellow represent existing flight-qualified designs requiring slight modifications, such as electronics boards.

To maintain the heritage of prior qualification testing, the telescope and instruments are mounted to a common instrument carrier, rather than mounting the instruments directly to the telescope interface; this actually reduces the load supported by the telescope structure, mitigates the risk of instrument mass growth, and supports robotic servicing in space.

Furthermore, the telescope and outer barrel are nominally kept at their original temperatures (282 and 232 K, respectively). However, the geosynchronous orbit chosen for WFIRST-AFTA provides a thermal environment different from that for which the telescope was designed. This will require a modified thermal design, probably with substantial heater power added.

WFI is the flagship instrument of the WFIRST-AFTA mission. It provides $0.28\ \mathrm{deg}^2$ field of view using eighteen $4\ \mathrm{k} \times 4\ \mathrm{k}$ HgCdTe detectors operating in the near-infrared (0.76 to 2.0 μm). It also provides a $3.0\ \times 3.15$ arcsec integral field unit spectrometer (0.6 to 2.0 μm band) and readouts for fine pointing control using reference stars in the WFI.

CGI is fed from a separate portion of the telescope field of view, with pickoff mirrors across the telescope from WFI. A tertiary and collimator follow, which convert the aberrated intermediate Cassegrain focus to a collimated beam with a very flat wavefront and very low field-dependent aberrations. In a recent design trade, this assembly was relocated on the stable optical structures of the OTA, to move the toughest optical perturbation sensitivities onto the most stable structures. An image of the pupil falls near the CGI's fast steering mirror, which compensates tiny errors in the telescope body pointing, leaving 0.4 to 1.6 milli-arcsec pointing stability at the first coronagraph field occulter—where most of the starlight is blocked. This pointing residual error is a key driver of coronagraph performance.

Coronagraph accommodation is limited to low-cost modifications. The observatory design is driven by the needs of WFI, and CGI requirements generally must adhere to the thermal, structural, and pointing performance provided by that design. But there is also considerable interest in conducting serendipitous parallel observations with the WFI instrument while the CGI has the lead. To enable that, during integration and test, we will adjust the fixed alignments of the WFI and CGI instruments so that they are optimized at the same telescope alignment.

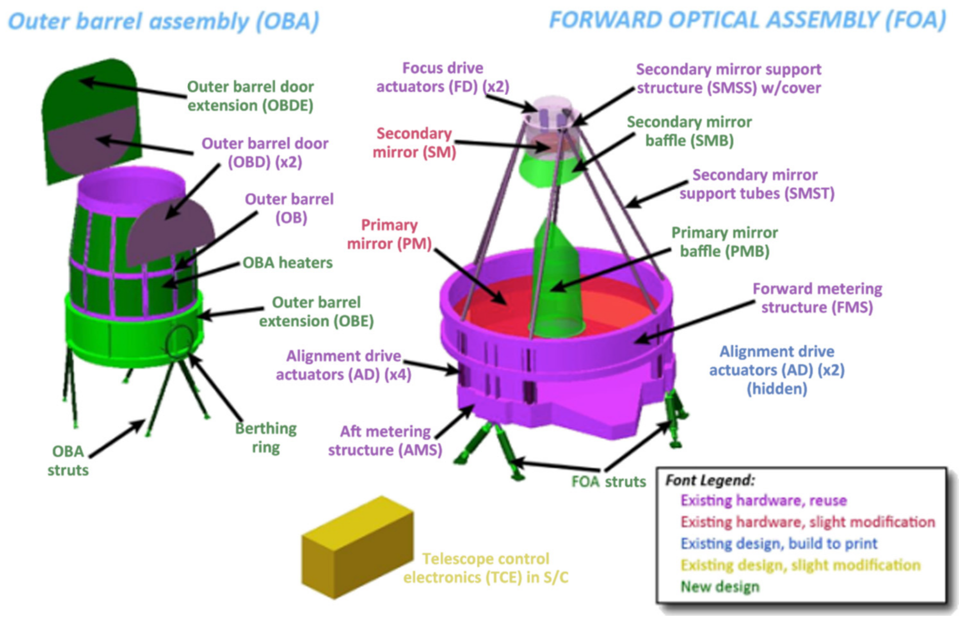

Fig. 3 AFTA telescope heritage; colors identify components that are reused without change, modified, or built anew.

3 Coronagraph Instrument

The current bench design, illustrated in Fig. 4, incorporates a set of masks and filters, which can be selected to create either an HLC or SPC, optimized for imaging in any of several passbands, or for detection in an integral field spectrometer (IFS). The only elements specific to either HLC or SPC are these masks, while everything else is shared: the deformable mirrors (DMs), fast steering mirror, focus adjustment mirror, the low-order wavefront sensor (LOWFS) and control, the imaging camera and filters, and IFS. The PIAA-CMC design requires all these subsystems as well, but the currently favored implementation is difficult to integrate side-by-side with the HLC and SPC.

3.1 *Hybrid Lyot Coronagraph*

The classic Lyot coronagraph begins with a tiny occulting spot at the image of the star, blocking most of the starlight. It is apodized (tapered attenuation profile) to limit the spread of diffracted starlight arriving at the next pupil image. Then a matching Lyot mask in that pupil plane essentially blocks all of that diffracted starlight. HLC is an adaptation of this to accommodate the WFIRST-AFTA obscured aperture. First, the occulting spot has not only an attenuation profile, but also a modified phase profile; the Lyot mask is modified accordingly, and then the two DMs are optimized to suppress the remaining diffracted starlight in the science focal plane array. The resulting DM profiles are nearly equal and opposite, of order 0.5 μm peak-to-valley. This resembles the outcome of an algorithm known as active compensation of aperture discontinuities,[17] which was developed for the same purpose. Apparently, the effect is to redirect starlight into the shadows of the secondary mirror and struts.

3.2 *Shaped Pupil Coronagraph*

SPC uses a binary mask to apodize the entrance pupil of the coronagraph. This produces a concentrated image of the star, with diffraction strongly suppressed in some regions of the focal plane at the expense of much stronger diffraction in other (sacrificial) regions. A matching occulting mask blocks the diffracted light falling in the sacrificial regions, revealing the darker portions of the image that can be cleared of scattered starlight. A disadvantage is that this usually sacrifices large areas in the image, which diminishes its rate for discovering planets; but two advantages are its relative insensitivity to low-order wavefront and pointing errors, and to chromatic effects that limit the wavelength range of an observation.

3.3 *Phase-Induced Amplitude Apodization–Complex Mask Coronagraph*

PIAA uses a pair of highly aspheric mirrors to redistribute light in the entrance pupil, a lossless method of apodizing the pupil. The first mirror produces a beam that is converging in its central region and diverging in its outer region; this produces a desired intensity profile at the second mirror, which flattens the wavefront again. Thus, without any attenuation, the starlight is repacked into an apodized beam, which produces a very compact image of the star with reduced diffraction. In a PIAA-CMC, a complex focal plane mask diffracts starlight out of the pupil to further improve coronagraphic performance. Through adjustment of these mirror shapes, the focal plane mask, and a Lyot mask after that, the PIAA-CMC designs achieve sufficient suppression of starlight diffraction at much smaller IWAs ($1.3\lambda/D$ for the WFIRST-AFTA PIAA-CMC design), while maintaining high planet throughput. This sharp improvement in IWA potentially offers a dramatic improvement in the expected planet harvest of the mission. Although much remains to be understood in the design, and demonstrated in the lab, the PIAA-CMC coronagraph might bring a high payoff in the end. Because the optical design of PIAA-CMC is not easily compatible with existing layout for SPC and HLC, if it proves to be superior to HLC and/or SPC, it probably would replace the current CGI bench rather than be assimilated into it.

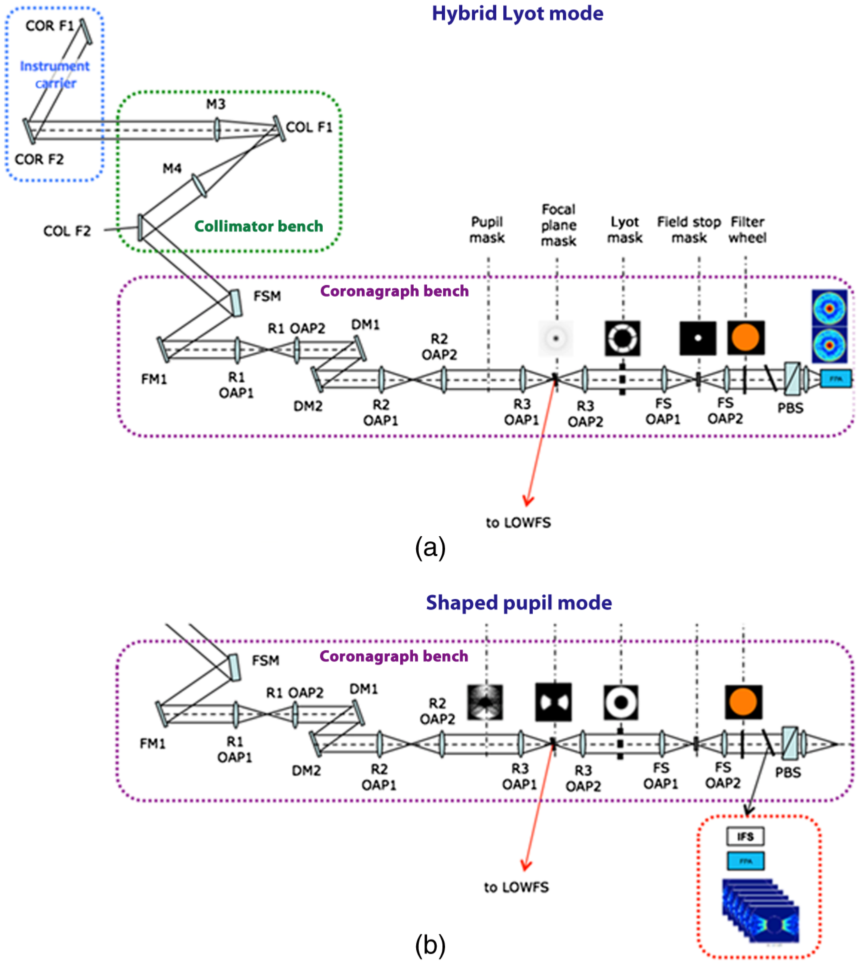

Fig. 4 (a) Coronagraph collimator and bench, shown with typical HLC masks, and with the imaging camera (FPA) selected. A beam to the LOWFS is shown, captured in reflection from the focal plane mask. (b) The same coronagraph bench shown with SPC masks, and with the IFS selected.

3.4 *Core Elements*

Some core elements are shared or similar among the coronagraph instruments, including wavefront estimation and DM control algorithms, LOWFS, IFS with a low-read-noise detector, and end-to-end integrated modeling of the observatory.

The SPC and HLC contain two DMs, which together control the amplitude and phase of the starlight electric fields. One DM, located at an image of the pupil, is used to compensate for wavefront phase errors due to optic surface errors; the other DM enables correction of some amplitude errors as well.[18] Using two DMs together enables control of scattered starlight (speckles) on both sides of the stellar image in the focal plane, which permits faster planet searches around the star. Several teams have developed algorithms for governing two DMs to control speckles,[19–22] and have even incorporated the DMs as an integral element in the design of masks for control of aperture diffraction.[17] The PIAA-CMC design uses a single DM for simplicity, but it would enjoy the same benefits of a second DM.

As the DM-corrected wavefront encounters the focal plane mask, any residual wavefront errors may still pass by the mask. The mid-spatial frequencies fall outside the mask, and are nearly unaffected. Low spatial frequencies, such as from focus and astigmatism errors, are strongly, but not completely, attenuated. These low-order wavefront errors, driven mostly by thermal drift of alignments and mirror shapes, can become large at the entrance to the CGI and cause significant drift in the pattern of starlight reaching the detector. New designs for an LOWFS have been developed to sense and often to control these variations. This improves our detection sensitivity for faint planets without driving the requirements for telescope stability.

In addition, we rely on integrated modeling of structures, optics, and control systems in response to thermal and dynamic disturbances to make sure the requirements for WFIRST-AFTA are feasible and sufficient for the planet observations we hope to see. This is a key link between observed performance in the laboratory and the expected performance on orbit, and it relies on the behavior of several complex control systems.

From that we can develop simplified models of sensitivity, IWA, and integration times for each science observation. Then we can run Monte Carlo studies to estimate the total mission science harvest we can expect in the time allocated to exoplanet observations. This is the final essential link from designs and technical performance to top-level mission requirements.

4 Conclusion

WFIRST-AFTA is an exciting formulation phase project with ambitious science goals derived from two of the highest-priority recommendations from the latest Decadal Survey:

- characterization of dark energy, the most abundant and most mysterious constituent of the universe;
- detection and characterization of known and yet-undiscovered exoplanets.

Both are central elements of the search for our origins and our place in the universe.

The CGI is designed to be the most capable exoplanet coronagraph that has ever been built, and a scientific and technology precursor of future missions to find and characterize Earth-like planets around nearby stars. It capitalizes on the most stable telescope we could have hoped for in our first exoplanet direct imaging mission. And yet, every design feature, hardware element, algorithm, and process we develop here will be needed to reach for those exoplanets, which are even more challenging than those we will see with WFIRST-AFTA.

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References

1. D. W. Latham et al., "The unseen companion of HD114762—a probable brown dwarf," *Nature* **339**, 38 (1989).
2. M. Mayor and D. Queloz, "A Jupiter-mass companion to a solar-type star," *Nature* **378**, 355 (1995).
3. G. W. Marcy and R. P. Butler, "A planetary companion to 70 virginis," *Astrophys. J.* **464**, L147 (1996).
4. C. J. Burke et al., "Planetary candidates observed by Kepler, IV: planet sample from Q1–Q8 (22 months)," *Astrophys. J. Supp.* **210**, 19 (2014).
5. "New Worlds Atlas," http://planetquest.jpl.nasa.gov/newworldsatlas (29 February 2016).
6. "Kepler Planet Candidates," http://kepler.nasa.gov/Mission/discoveries/candidates/ (29 February 2016).
7. D. N. Spergel et.al., "WFIRST-AFTA science definition team final report," 2015, http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Report_150310_Final.pdf (29 February 2016).
8. D. N. Spergel et.al., "WFIRST-AFTA science definition team report," May 2013, http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Final_Report_Rev2_130524.pdf (29 February 2016).
9. F. A. Harrison et.al., "Evaluation of the implementation of WFIRST in the context of new worlds, new horizons in astronomy and astrophysics," http://www.nap.edu/catalog/18712/evaluation-of-the-implementation-of-wfirstafta-in-the-context-of-new-worlds-new-horizons-in-astronomy-and-astrophysics (29 February 2016).
10. L. Spitzer, "The beginnings and future of space astronomy," *Am. Sci.* **50**(3), 473–484 (1962).
11. B. Lyot, "A study of the solar corona and prominences without eclipses," *Mon. Not. R. Astron. Soc.* **99**(8), 580–594 (1939).
12. V. Ford et al., "Terrestrial planet finder coronagraph, flight baseline 1 design interim status report," August 2005, http://exep.jpl.nasa.gov/files/exep/TPFC-FB1_Report.pdf (29 February 2016).
13. J. Trauger, "ACCESS—a science and engineering assessment of space coronagraph concepts for the direct imaging and spectroscopy of exoplanetary systems," presented at *American Astronomical Society Winter Meeting*, Long Beach, CA, NASA Jet Propulsion Laboratory, Pasadena, California (2008).
14. O. Guyon et al., "The exoplanetary circumstellar environments and disk explorer (EXCEDE)," *Proc. SPIE* **8442**, 84421S (2012).
15. R. Belikov et al., "Demonstration of high contrast in 10% broadband light with the shaped pupil coronagraph," *Proc. SPIE* **6693**, 66930Y (2007).
16. O. Guyon et al., "High-contrast imaging and wavefront control with a PIAA coronagraph: laboratory system validation," *Publ. Astron. Soc. Pac.* **122**(887), 71–84 (2010).
17. L. Pueyo and C. Norman, "High contrast imaging with arbitrary apertures: active compensation of aperture discontinuities," *Astrophys. J.* **769**, 102 (2013).
18. S. Shaklan and J. J. Green, "Reflectivity and optical surface height requirements in a broadband coronagraph. 1. Contrast floor due to controllable spatial frequencies," *Appl. Opt.* **45**(21), 5143–5153 (2006).
19. A. Give'on et al., "Broadband wavefront correction algorithm for high-contrast imaging systems," *Proc. SPIE* **6691**, 66910A (2007).
20. A. J. E. Riggs et al., "Demonstration of symmetric dark holes using two deformable mirrors at the high-contrast imaging testbed," *Proc. SPIE* **8864**, 88640T (2013).
21. T. D. Groff et al., "Methods and limitations of focal plane sensing, estimation, and control in high-contrast imaging," *J. Astron. Telesc. Instrum. Syst.* **2**(1), 011009 (2015).
22. A. J. E. Riggs, N. J. Kasdin, and T. D. Groff, "Recursive starlight and bias estimation for high-contrast imaging with an extended Kalman filter," *J. Astron. Telesc. Instrum. Syst.* **2**(1), 011017 (2016).

M. Charley Noecker is an optical engineer at NASA Jet Propulsion Laboratory/Caltech. He received his BA degree in physics from Swarthmore College, Pennsylvania, in 1981 and his PhD in physics from the University of Michigan in 1988. He has been involved in exoplanet studies and space optics since early 1990 at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, and then at Ball Aerospace in Boulder, Colorado. He has authored or coauthored more than 50 journal papers and a U.S. patent. His interests continue to be in advanced optical systems and exoplanet research. He is a member of SPIE.

Feng Zhao is an optical system engineer and manager at NASA's Jet Propulsion Laboratory, with extensive experience in precision optical instruments and missions. He received his PhD in electrical and electronic engineering at Pennsylvania State University.

Rick Demers is an optical engineer at the NASA Jet Propulsion Laboratory/Caltech. He received his BS degree in physics at Rensselaer Polytechnic Institute and his PhD in physics at the University of Illinois at Urbana-Champaign. While at the Astrophysical Observatory of Arcetri (INAF-Florence), he worked on the integration and test of the adaptive optic system for the Large Binocular Telescope. He currently works on the WFIRST coronagraph design as well as the detector and deformable mirror.

John Trauger is a senior research scientist at the Jet Propulsion Laboratory. He has developed science mission concepts and enabling optical technologies for precision optical wavefront control and high-contrast imaging of exoplanetary systems from space. He served as the principal investigator for the Wide Field and Planetary Camera 2 on the Hubble Space Telescope.

Olivier Guyon develops and validates innovative techniques for detecting and characterizing extrasolar planets. His research includes coronagraphy, wavefront sensing techniques for adaptive optics, and astrometry. He developed the phase-induced amplitude apodization (PIAA) coronagraph, a highly efficient optical device to mask light from a star while preserving light from planets around it.

N. Jeremy Kasdin is a professor of mechanical and aerospace engineering and a vice dean of the School of Engineering and Applied Science at Princeton University. He is the principal investigator of Princeton's High Contrast Imaging Laboratory. He received his PhD from Stanford University in 1991. His research interests include space systems design, space optics and exoplanet imaging, orbital mechanics, guidance and control of space vehicles, optimal estimation, and stochastic process modeling. He is an associate fellow of the American Institute of Aeronautics and Astronautics and a member of the American Astronomical Society and SPIE.