

An analysis of technology gaps and priorities in support of probe-scale coronagraph and starshade missions

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ABSTRACT

This paper provides a survey of the state-of-the-art in coronagraph and starshade technologies and highlights areas where advances are needed to enable future NASA exoplanet missions. An analysis is provided of the remaining technology gaps and the relative priorities of technology investments leading to a mission that could follow JWST. This work is being conducted in support of NASA's Astrophysics Division and the NASA Exoplanet Exploration Program (ExEP), who are in the process of assessing options for future missions. ExEP has funded Science and Technology Definition Teams to study coronagraphs and starshade mission concepts having a life-cycle cost cap of less than \$1B. This paper provides a technology gap analysis for these concepts.

Keywords: Technology, exoplanets, coronagraphs, occulters, starshades, starlight suppression

1. INTRODUCTION

The NASA *Astrophysics Implementation Plan*[†] describes the activities currently being undertaken by the Astrophysics Division of NASA's Science Mission Directorate to respond to recommendations by the Decadal Survey within current budgetary constraints. It includes studies for exoplanet probe-scale missions as possible alternatives to the Wide-Field Infrared Survey Telescope (WFIRST). In 2013 separate Science and Technology Definition Teams (STDTs) were formed to study the feasibility of coronagraph and starshade missions having a budget cap of \$1B. The teams involved in these efforts developed detailed observatory and mission designs, as well as an independent list of technology gaps and priorities, publishing their interim reports in April 2014. The interested reader is encouraged to consult the reports directly at <http://exep.jpl.nasa.gov/stdt/>. This paper describes the state-of-the-art in exoplanet technology and the work that remains to prepare these missions for flight. The summary lists of technology gaps for coronagraphs and starshades are given in Tables 1 and 2 respectively.

The technology development for exoplanet coronagraphs and starshades has been funded by NASA's Strategic Astrophysics Technology Program¹ and in particular its element of Technology Development for Exoplanet Missions (TDEM). References to TDEM are found throughout this paper. It is worth noting that many of the goals of Exo-C technology development are identical or closely related to those of the AFTA-WFIRST coronagraph.² Until a strategic decision is made by NASA concerning the continuation and implementation of WFIRST, Exo-C will continue to benefit from AFTA technology development.

2. CORONAGRAPH TECHNOLOGY REQUIREMENTS

The Probe coronagraph, Exo-C,³ would have a primary mirror 1.5 m, observe over a spectral range of 450–1000 nm and provide an inner working angle of 0.22 arcsec at 800 nm. A raw contrast of 10^{-9} would be obtained with a contrast stability of 10^{-10} over 48 hours. The observatory uses a Kepler-like spacecraft bus and would be placed in an Earth-trailing orbit for a three-year mission. The coronagraph is designed to operate with a $2\lambda/D$ inner working angle using an unobscured aperture. A Hybrid Lyot coronagraph⁴ was adopted for the baseline design, while the Vector Vortex⁵ and PIAA-CMC⁶ (Phase Induced Amplitude Apodization Complex Mask Coronagraph) are being retained as possible options for further study.

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[†]<http://science.nasa.gov/astrophysics/documents/>

Table 1: Coronagraph Technology Gaps Listed in Priority Order.

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide improved planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks with a larger discovery space and IWA $\leq 3\lambda/D$ with contrasts 1×10^{-9} .
C-2	Low-order Wavefront Sensing & Control	Slowly varying large-scale optical aberrations may mimic the signature of an exoplanet.	Tip/tilt errors have been sensed and corrected in vacuum with a stability of 0.001 λ/D at sub-Hertz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to maintain raw contrasts of $\leq 1 \times 10^{-9}$.
C-3	Coronagraph System-level Performance Demonstration	High-fidelity laboratory contrast demonstrations that include simulated science targets and flight-like perturbations.	Star-only (no planet) contrast demonstrations in vacuum with an unobscured pupil and semi-static wavefront errors.	Testing in a flight-like dynamic environment with star, planet, and optical telescope assembly simulator with the telescope-specific pupil obscuration.
C-4	Ultra-low Noise Detector	Low-noise detectors for exoplanet characterization with an Integral Field Spectrograph.	Read noise of $< 1e/\text{pixel}$ has been demonstrated with EMCCDs in a $1k \times 1k$ format.	Read noise $< 0.1e/\text{pixel}$ in a $\geq 2k \times 2k$ format in a flight-like radiation environment.
C-5	Deformable mirrors	Maturation of deformable mirror technology toward flight readiness.	Xinetics DMs and MEMS DMs have undergone partial environmental testing.	Development of flight-like electronics. Full environmental system testing with post-test performance validation.

2.1 Specialized Coronagraph Optics (C-1)

For Exo-C a continuing program to advance the performance of coronagraph optics is needed. Experiments that have been conducted to date with the baseline coronagraph and the two backup designs are described here. Demonstrated results in this area are summarized in previous SPIE Proceedings.⁷

2.1.1 Hybrid Lyot Masks

The state of the art demonstrated in the lab is a contrast of 2×10^{-10} with a 2% bandwidth and 2×10^{-9} with a 20% bandwidth at 3–15 λ/D achieved through the use of linear 4th order band-limited Lyot hybrid masks. Models exist that match these results, although they have not been formally validated.

The Hybrid Lyot masks that have been developed to date are image-plane masks that appear as a linear fringe pattern of metal deposited on glass, with an additional (thus hybrid) layer of dielectric to compensate for residual phase errors.

One deformable mirror (DM) has been used in the experiments, whereas two would be used in flight. The masks that have been used have all been linear masks, because the manufacturing process is simpler. Circularly symmetric masks would no doubt be manufactured for a flight mission. Although the designs of circular masks exist, none have been fabricated. The current limitation in performance is understood to be the ability to accurately deposit the required thickness of dielectric.

The laboratory demonstrations used an effective pupil shear of 36% thus yielding a throughput of 56% past the Lyot stop. Polarizers are not used.

John Trauger (JPL/Caltech) with a 2009 TDEM award demonstrated mean raw contrasts of 3.2×10^{-10} with a 10% bandwidth in a $284 (\lambda/D)^2$ field extending from 3–16 λ/D . Raw contrasts of 1.3×10^{-10} were demonstrated with a 20% bandwidth.

2.1.2 Phase-Induced Amplitude Apodization

One of the alternate coronagraphs is the PIAA-CMC. A PIAA design uses pairs of aspheric mirrors to reshape the pupil-plane intensity distribution, providing a Gaussian-like (prolate spheroidal) distribution and eliminating diffraction sidelobes. The PIAA-CMC design also includes a focal plane mask that off-loads the work of the PIAA mirrors, effectively reducing the curvature of the mirrors required for the same amount of apodization—thus making the mirrors themselves easier to manufacture. PIAA results using bandwidths of up to 10% have been reported, and are described below. No PIAA-CMC results have yet been published.

For the flight configuration, there would be two DMs located before the input PIAA optics and there would be a second (inverse) set of PIAA optics after the focal-plane mask and prior to the science camera. With this arrangement the outer working angle is limited by the number of actuators on the DM, as is the case with other coronagraphs. However, for the laboratory demonstrations there has been only one DM located between the input PIAA optics and focal-plane mask and no inverse PIAA optics. Having the DM located after the PIAA optics is a convenience that simplifies the wavefront control, because the mapping of the DM elements is not altered by the PIAA optics. The angular extent of the dark holes that are demonstrated in the lab are limited by the number of actuators on the DM and the mapping of the PIAA. The mirror pairs used in the HCIT were not optimized for operations at broad-bandwidths, and new mirrors would be manufactured for flight. Polarizers were used in these experiments to improve the measured contrast. The challenge of implementing PIAA optics lies in the design and manufacturing of these aspheres. The PIAA optics would ideally have a throughput of 100%, however pupil and image-plane stops reduce the effective throughput to 92%. Because polarizers were used in these experiments, the actual throughput was approximately 46%.

Olivier Guyon (Univ. Arizona) with 2009 & 2010 TDEM awards demonstrated mean raw contrasts of 1.0×10^{-8} with a 10% bandwidth in a field of $10 (\lambda/D)^2$ extending from 2.2–4.6 λ/D . Raw contrasts of 1.3×10^{-10} were demonstrated with in monochromatic light.

2.1.3 Vector Vortex Masks

Another option being retained is the Vector Vortex. A Vector Vortex is an image-plane mask that adjusts the phase of the incoming field, producing a rotational phase ramp of two or more even number of cycles to cancel the on-axis starlight. For the results shown here, a liquid-crystal polymer vector vortex was used.

The optical configuration is essentially identical to that of the Hybrid Lyot architecture, having only one DM for current testing, but no doubt using two for flight. No fundamental change to the mask design would be needed for flight. The current limitation in performance is related to the ability to manufacture masks with a vortex pattern that is maintained to very small offsets from the center of rotation, and to extend the designs to broadband multi-layer masks. For the current experiments, a polarizer is required prior to the pinhole of the source.

The throughput would ideally be 100%, but the Lyot stop was undersized to 85% for the monochromatic demonstrations and to 92% for the broadband demonstrations, yielding a 72% and 85% transmission respectively. Additionally a polarizer is used at the source (as mentioned above), and so the effective throughput is approximately 36% monochromatic and 43% broadband.

Eugene Serabyn (JPL/Caltech) with a 2010 TDEM award demonstrated mean raw contrasts of 3.2×10^{-8} with a 10% bandwidth in a $60 (\lambda/D)^2$ field extending from 2.4–9.4 λ/D . Raw contrasts of 4.4×10^{-10} were demonstrated in monochromatic light.

2.2 Low-order Wavefront Sensing & Control (C-2)

A slight misalignment of the coronagraph would cause starlight to appear at the edge of the dark hole of the coronagraph and could mimic the presence of a planet. It is therefore important to validate the design of a suitable pointing control system for a coronagraph. This would integrate the control of the coronagraph's fine-steering mirror with the control of the body pointing of the spacecraft.

A first step in this direction was accomplished with the development of the Phase-Induced Amplitude Apodization coronagraph system in the HCIT-2 testbed. Sub-milliarcsecond pointing stability was demonstrated in vacuum with a servo system, with the intent of eventually expanding it to demonstrate low-order wavefront sensing and control. A low-order wavefront sensor uses the bright starlight that is rejected by the coronagraph and measures not only pointing changes but low-order aberrations such as defocus, coma, and spherical aberration. Static and dynamic low-order wavefront errors are anticipated due to slight imperfections in the optical design and thermally induced mechanical distortions of the optics that might be experienced in flight. The corrections of low-order wavefront errors—other than pointing—has not yet been demonstrated.

High-order wavefront sensing, on the other hand, is accomplished by modulating the input wavefronts with reflection off one or more deformable mirrors and measuring phase changes in speckles at the science camera. However the sensing is accomplished in the dark hole, using the relatively few photons collected there by the coronagraph, and operates over much longer timescales. High-order wavefront sensing and control is routinely accomplished in the lab and is not currently an area of concern.

2.3 Coronagraph System-level Performance Demonstration (C-3)

To date all of the highest-contrast coronagraph demonstrations have been undertaken in the lab in a static vacuum environment, subject only to slow ambient changes in the temperature of the lab. These demonstrations have been limited to contrast measurements only, without the presence of a simulated planet source.

In order to demonstrate coronagraph performance in a flight-like environment, the expected on-orbit disturbances to pointing and low-order wavefront errors must be simulated and compensated for using the necessary servo systems, as described above. Moreover, the planet detection demonstrations should be tailored to the inner working angle, spectral bandwidth, and raw contrast floor that are required in flight.

2.4 Ultra-low Noise Visible Detectors (C-4)

Exo-C will need high-performance low-light level detectors for use in its science camera and its integral field spectrograph. Advances are needed in the achievable noise performance and in particular the quantum efficiency achievable in the wavelength range of 0.9–1.0 μm . There are several options, notably as the Electron-Multiplying CCDs manufactured by e2v.

2.5 Deformable Mirror Technology (C-5)

Wavefront aberrations less than 1/10,000th of a wave must be maintained in a coronagraph if contrasts of 1×10^{-10} are to be achieved. At visible wavelengths, this implies wavefront control at the level of 0.5 \AA , and deformable mirror (DM) technology is therefore required to compensate for residual optical aberrations.

Two DMs are required to create a symmetric dark hole around the image of a star, correcting both amplitude and phase errors across the full available field of view. The standard practice in lab experiments up until 2013 has been to use only a single DM and create a half dark-hole, offset to one side of the star.

Jeremy Kasdin (Princeton University) and collaborators were funded through a 2010 TDEM award to demonstrate 2-DM wavefront control using a Shaped Pupil Coronagraph. Their goal was to achieve better than 1×10^{-9} raw contrast at 10% bandwidth. Raw contrasts of 3.6×10^{-9} were achieved using an optical configuration that was not optimized for the demonstrations. A final report on these tests is pending.

Deformable mirror development is needed in two specific areas: 1) Miniaturization of drive electronics using low-power Application-Specific Integrate Circuits (ASICs) suitable for flight. 2) A continuing program of work with DMs in 64x64 format, including operational testing of existing devices and investigation of development paths for smaller pitch and improved surface quality.

Table 2: Starshade Technology Gaps Listed in Priority Order.

ID	Title	Description	Current	Required
S-1	Control of Scattered Sunlight	Sunlight scattered from starshade edges and surfaces risk being the dominant source of measurement noise.	Several preliminary designs of edge shapes have been studied through laboratory tests having edge radius $\geq 10 \mu\text{m}$.	Edges manufactured of high flexural strength material with edge radius $\leq 1 \mu\text{m}$.
S-2	Validation of starshade optical models	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~ 100 to contrasts of 4×10^{-10} , but with poor agreement near petal valleys and tips.	Experimentally validate models of starlight suppression to $\leq 1 \times 10^{-11}$, and perturbation intensities to 20% at Fresnel number of 10–20.
S-3	Starshade Deployment	Demonstrate that a starshade can be deployed to within the budgeted tolerances.	Millimeter-wave mesh antennas have been deployed in space with diameters up to $17\text{m} \times 19\text{m}$ and a out-of-plane accuracy of 2.4-mm.	Demonstrate using a half-scale or larger prototype the budgeted in-plane deployment tolerances, which are millimeter to sub-millimeter depending on the specific error terms.
S-4	Petal Prototype Demonstration	Demonstrate a high-fidelity prototype starshade petal.	Low-fidelity petals have been assembled and precision petal manufacturing has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces.
S-5	Formation Flying GN&C	Demonstrate that the GN&C system for an occulter will enable the required slew from star to star and positional stability for science observations.	Simulations have shown that sensing and GN&C is tractable, though sensing demonstrations of lateral control has not yet been performed.	Sensors demonstrated with errors $\leq 0.25 \text{ m}$. Control algorithms demonstrated with lateral control errors $\leq 1\text{m}$.

3. STARSHADE TECHNOLOGY REQUIREMENTS

The Probe starshade, Exo-S, would use a commercial off-the-shelf Exelis telescope⁸ with a 1.1-m primary mirror diameter, observe over three spectral bands of 450–630 nm, 510–825 nm, and 600–1000 nm, and provide an inner working angle of 75 mas, 95 mas, and 115 mas in the respective bands. A raw contrast of 10^{-9} would be obtained with a contrast stability of 10^{-10} over 48 hours. The observatory would be placed in a Heliocentric Earth-drift away orbit. The starshade diameter would be 34 m and the starshade would be positioned 37,000 km from the telescope. The telescope, rather than the starshade, would be maneuvered for each observation. The observatory would be equipped with an imager and low-resolution spectrograph.

External occulters, or starshades, block starlight by shadowing the entrance pupil of a telescope, using a physical separation between starshade and telescope sufficient to provide the necessary inner working angle. This typically requires the starshade to be tens of meters in diameter and located tens of thousands of kilometers from the telescope.

A starshade may have numerous petals that are each tapered to produce a desired apodization function, as seen from the telescope. The petal shapes also eliminate most edges that would otherwise diffract starlight toward the center of the image—thus suppressing the Poisson spot that would be present if a circular occulter were used. Independent optical modeling predictions have shown excellent agreement concerning the contrast sensitivity to petal shape errors, and detailed preliminary error budgets have been proposed.

An initial challenge of constructing a starshade is to demonstrate that the mechanical tolerances for a petal can be met, as derived from a complete starshade error budget. Prior work at NGAS demonstrated that precision petal tips and valleys are manufacturable to the required tolerances. Work led by N. J. Kasdin (Princeton University) and collaborators also successfully demonstrated in 2012 that the edge of a petal could be manufactured to the required tolerances.⁹

3.1 Control of Scattered Sunlight (S-1)

Sunlight scattered from an occulter may potentially overwhelm light from astrophysical sources in the field of view and risks being the dominant source of measurement noise. Of particular concern is wide-angle scattering of sunlight from the edges of starshade petals. Initial progress in this area has been reported by Martin (JPL/Caltech) and collaborators.¹⁰

A milestone in the control of scattered light would be to demonstrate with a baseline external occulter design that the brightness of sunlight scattered from the occulter would be less than the brightness of exozodiacal light. This may include demonstrations of the control of light scattered from petal edges, transmitted through the occulter fabric, or reflected from other identified sources such as the Earth or Moon.

Research in this area will be conducted by S. Casement (Northrop Grumman) through a 2012 SAT-TDEM award with work to begin in early 2014.

3.2 Validation of Starshade Optical Models (S-2)

Laboratory and field experiments have substantially validated the theoretical models of starshade performance. These demonstrations have included the following: (1) Monochromatic tests done at Princeton University;¹¹ (2) 50% bandwidth tests done through a 42.8-m vacuum chamber at Northrop Grumman Aerospace Technologies (NGAS); and (3) 50% bandwidth tests conducted by NGAS on the desert floor in Death Valley National Park.¹²

At Princeton University, the theoretical diffraction integral commonly used for occulter design has been optically validated for contrasts to 4.5×10^{-10} . At Northrop Grumman Aerospace Systems (NGAS) starlight suppression experiments using scaled starshades have produced rotationally-averaged contrasts of 2.6×10^{-7} at the starshade mask's inner working angle where the optical throughput drops to 50%. Beyond the inner working angle yet within the apodized field-of-view, features as faint as 5×10^{-10} have also been detected through experiments both at Princeton University and at the University of Colorado. These experiments are designed to measure the starshade's shadow at the same Fresnel number as would be used in an actual flight-system, although not with the same inner working angle. The masks are centimeters in diameter and placed at about ten or tens of meters from the detector.

The throughput of the occulter is 100% for objects lying at angular positions beyond the tips of the starshade.

Although the predicted starlight suppression has been demonstrated, forward scattering from the petal tips and valleys produces bright features that are not well modeled and are likely the result of extremely small edge errors in those regions. It is anticipated that those bright features will be largely suppressed through the use of physically larger test articles, because the manufacturing tolerances of the valley and tips will be reduced.

Tiffany Glassman (NGAS) has been funded through a 2012 TDEM to further pursue starshade optical testing using a multi-kilometer test range. Preliminary results using a 60-cm starshade have been reported in the literature.¹²

3.3 Starshade Petal Deployment (S-3)

After the static mechanical tolerances are demonstrated, a subsequent challenge is to demonstrate that the deployment tolerances for a petal can be met, as derived from a complete starshade error budget. The state-of-the-art in large space apertures, a closely related topic, is summarized in the Keck Institute for Space Studies workshop on this topic.[‡]

A Milestone for starshade deployment is to demonstrate that an external occulter can be deployed repeatedly to within the budgeted tolerances. This may be accomplished using single or multiple petals whose manufacturing tolerances have been demonstrated previously.

N. J. Kasdin (Princeton University) and collaborators were funded through a 2010 SAT-TDEM award to demonstrate starshade deployment.¹³ The goal was to demonstrate that fiducials at the base of starshade petals could be deployed with radial and lateral position errors less than 1 mm ($3\text{-}\sigma$) with 90% confidence. Preliminary results have shown deployments with position repeatability better than 125 μm ($3\text{-}\sigma$).

3.4 Petal Prototype Demonstration (S-4)

An additional step in the technology maturation of a starshade petal is to integrate in a single demonstration 1) the manufacturing of the required profile, technologies for the control of scattered sunlight (sunlight baffles, sub-micron edges); 2) the multi-layer blankets that cover the opaque regions of the starshade; 3) packaging restraints, and 4) deployment mechanisms.

A Milestone for a petal prototype demonstration would be to demonstrate through hardware and modeling that all the static and dynamic error budget allocations will be met with a design-specific high-fidelity petal.

3.5 Formation Flying Sensors (S-5)

The starshade and telescope must move one with respect to the other between targets and maintain alignment during science observations. The required technology may include beacons and sensors to detect relative position, and algorithms for high-precision alignment.

A Milestone in formation flying guidance, navigation and control would be to demonstrate that the GN&C algorithms and sensors of an external occulter can achieve the budgeted alignment tolerances. This may include hardware and/or software simulations that demonstrate traceability to flight conditions.

4. CONCLUSION

The Exoplanet Exploration Program is currently supporting studies of probe-scale missions to help NASA select the next astrophysics mission after JWST. The selection is anticipated by about 2015, with formulation to begin in 2017. This paper has described the state-of-the-art in exoplanet technology and the future development required to enable those missions.

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[‡]<http://www.kiss.caltech.edu/workshops/apertures2008/>

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