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TECHNOLOGY FOR FUTURE EXOPLANET MISSIONS

Peter Lawson, Michael Devirian, and Jakob van Zyl
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
Peter.R.Lawson@jpl.nasa.gov, Michael.Devirian@jpl.nasa.gov, Jakob.J.vanZyl@jpl.nasa.gov

A central theme in NASA’s and ESA’s vision for future missions is the search for habitable worlds and life beyond our Solar System. This presentation will review the current state of the art in planet-finding technology, with an emphasis on methods of starlight suppression. At optical wavelengths, Earth-like planets are about 10 billion times fainter than their host stars. Starlight suppression is therefore necessary to enable measurements of biosignatures in the atmospheres of faint Earth-like planets. Mission concepts based on coronagraph, starshade, and interferometers will be described along with their science objectives and technology requirements.

I. INTRODUCTION

This paper describes NASA’s technology development effort for future missions within NASA’s Exoplanet Exploration Program (ExEP). The long-term goal of this technology development is to enable a mission capable of detecting and characterizing the spectra of Earth-like exoplanets and measuring the atmospheric signatures of life. Through this work it should also be possible in the near term to enable other missions whose science is compelling and essential to understanding the birth and evolution of planetary systems and the conditions that lead to life in the Universe.

The subjects covered here are only those most directly relevant to recommendations in the 2010 US Astrophysics Decadal Survey [1], with regard to a New Worlds Technology Development Program and a future New Worlds Mission. We therefore place the greatest emphasis on the detection of Earth-like planets around Sun-like stars and the development of starlight-suppression technology.

The greatest advances in exoplanet science have been through what could be called “combined-light” techniques, where no attempt is made to suppress starlight. The foremost of these is the radial velocity technique, which has detected more than 90% of the almost 600 planets detected to date. Ground-based transit observations have been made of about 25% of all confirmed planets, and NASA’s Kepler mission, has detected an additional 1235 planet candidates, several of which are Earth-sized in the habitable zone of their host stars. Ground-based microlensing measurements have furthermore detected about a dozen Super-Earth planets in Earth- and Mars-like orbits. Astrometric measurements, although attempted from the ground, have not yet been shown to detect exoplanets. These approaches infer the presence of planets by measuring small changes in the intensity, spectrum, or relative angular position of stars, and are limited in sensitivity either by aperture size, especially in the case of radial-velocity measurements, or by atmospheric scintillation and phase noise in the case of transit, microlensing, and astrometry measurements. For all but the radial velocity approach, there are great advantages of going to space, and few if any technical challenges. The limitations are primarily those of cost.

For this reason, transit and microlensing missions are currently being studied as part of NASA’s and ESA’s mission portfolio in the coming decade. However, the spectra of Earth-like exoplanets are too faint to be measured without some form of starlight suppression. The central goal of NASA’s Exoplanet Exploration Program is to find evidence of life elsewhere in the Universe, and for this objective new technology developments are needed. These efforts are described in this paper.

The goals of the Exoplanet Exploration Program for technology development are described in Section II. The driving science requirements and the technology priorities are described in Section III. Details of future technology milestones for coronagraphs, starshades, and interferometers are then given in sections IV, V, and VI respectively.

II. PROGRAM GOALS

The 2010 Decadal Survey in Astronomy and Astrophysics (NRC 2010) recommended the creation of a New Worlds Technology Development Program to advance the technological readiness of the three primary starlight suppression architectures: coronagraphs, starshades, and interferometers. The Survey further recommended that—if the scientific groundwork and design requirements were sufficiently clear—an architecture downselect should be made at the mid-
decade, and a significantly increased technology investment over the latter half of the decade should be focused to prepare a mission concept based on this architecture for consideration by the 2020 Survey. NASA's Exoplanet Exploration Program supports activities that will contribute to the selection and advancement of one or more exoplanet mission concept to a high Technology Readiness Level (TRL). The Program funds and facilitates experiments and analyses selected by NASA HQ through yearly solicitations, and provides support through the infrastructure, expertise, and test facilities that have been developed in prior years.

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### Table 1: Exoplanet Technology Research funded through the Technology Development for Exoplanet Missions component of NASA's solicitation on Strategic Astrophysics Technology. Awards for calls from 2009 and 2010 are listed.

<table>
<thead>
<tr>
<th>Year</th>
<th>PI</th>
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<td><strong>CORONAGRAPH STARLIGHT SUPPRESSION TECHNOLOGY</strong></td>
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<td>2009</td>
<td>Olivier Guyon</td>
<td>Univ. of Arizona</td>
<td>Phase-Induced Amplitude Apodization Coronography Development and Laboratory Validation</td>
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<td>2009</td>
<td>Martin Noecker</td>
<td>Ball Aerospace</td>
<td>Advanced Speckle Sensing for Internal Coronagraphs and Methods of Isolating Exoplanets from Speckles</td>
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<td>2009</td>
<td>John Trauger</td>
<td>JPL/Caltech</td>
<td>Advanced Hybrid Lyot Coronagraph Technology for Exoplanet Missions</td>
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<td>2010</td>
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<td>Advances in Pupil Remapping (PIAA) coronography: improving Bandwidth, Throughput and Inner Working Angle</td>
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<td>2010</td>
<td>Eugene Serabyn</td>
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<td>Demonstrations of Deep Starlight Rejection with a Vortex Coronagraph</td>
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<td><strong>CORONAGRAPH MODELING AND MODEL VALIDATION</strong></td>
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<td>2009</td>
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<td>2010</td>
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<td><strong>STARSHADE TECHNOLOGY</strong></td>
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<td>2009</td>
<td>N. Kasdin</td>
<td>Princeton University</td>
<td>Starshades for Exoplanet Imaging and Characterization: Key Technology Development</td>
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<tr>
<td>2010</td>
<td>N. Kasdin</td>
<td>Princeton University</td>
<td>Verifying Deployment Tolerances of an External Occulter for Starlight Suppression</td>
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<td><strong>DETECTOR TECHNOLOGY</strong></td>
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NASA currently funds technology development through the Astrophysics Research and Enabling Technology (APRET) solicitation and the Technology Development for Exoplanet Missions (TDEM) component of the Strategic Astrophysics Technology (SAT) solicitation. APRET covers low TRL technologies and SAT-TDEM covers mid-range TRL technologies. This two-stage approach supports the advancement of technology envisaged by the Decadal Survey. TDEM tasks funded in 2009 and 2010 are listed in Table 1.

The goal of exoplanet technology development is to enable a future mission by demonstrating selected key technologies. This effort must include the establishment of performance error budgets tied to flight requirements and experimental demonstrations that the error budgets, or key components of the error budgets, can be met. Furthermore, models must be validated that demonstrate that the physics of the limiting error sources in those experiments are understood well enough to reliably predict the performance of the flight mission.

This architecture would ideally have demonstrated several of its key milestones and moreover have developed a credible path forward to complete its remaining milestones by the end of the decade. The architecture selection would probably not be so specific as to select a particular instrument design, but it would limit the continuing effort to maturing the design and technology of the selected architecture.

III. SCIENCE & TECHNOLOGY OBJECTIVES

III.I Science Objectives

The science objectives that motivate technology development within the Exoplanet Exploration Program are focused on the discovery and characterization of Earth-like exoplanets. The principal goals are to detect and characterize Earth-like planets around nearby stars and to search for signs of habitability and life. For observations at optical and near-infrared wavelengths, the science objectives apply as formulated in 2006 by the Terrestrial Planet Finder Coronagraph (TPF-C) Science and Technology Definition Team (STDT) [2]. The first four objectives, describing terrestrial planet science, are as follows:

1. Directly detect terrestrial planets within the habitable zones around nearby stars or, alternatively, show that they are not present.
2. Measure orbital parameters and brightnesses for any terrestrial planets that are discovered.
3. Distinguish among planets, and between planets and other objects, through measurements of planet color.
4. Characterize at least some terrestrial planets spectroscopically, searching for absorption caused by O₃, O₂, H₂O, and possibly CO₂ and CH₄. It is highly desirable to measure Rayleigh scattering and photosynthetic pigments; such information may provide evidence of habitability and even of life itself.

Closely similar science objectives were also established for the Terrestrial Planet Finder Interferometer (TPF-I) for observations at mid-infrared wavelengths [3].

Up until now, the TPF science objectives have not been reformulated for the Program. Until such time, the TPF science objectives [2][3] are being adopted.

These science objectives have been used to derive the required starlight rejection, angular resolution, inner working angle, sensitivity, bandwidth, and corresponding error budgets for the TPF missions. They can be equally applied to deriving performance requirements for a future New Worlds Mission.

III.II Performance Requirements

The key instrument performance requirement is the ability to suppress starlight to a level where the detection of Earth-like planets becomes possible. At visible wavelengths an Earth-like planet would be 25 magnitudes fainter than the star around which it orbits. This implies a performance level enabling contrasts of \(10^{-10}\) at visible wavelengths, or starlight suppression of \(10^{-6}\) to \(10^{-7}\) at mid-infrared wavelengths.

These starlight suppression requirements hold true irrespective of the mission architecture. The technology Milestones described in the TPF technology plans [4][5] remain valid. In those plans, demonstrated laboratory performance within an order of magnitude of the flight requirement—\(10^{-9}\) at visible wavelengths and \(10^{-5}\) to \(10^{-6}\) at mid-infrared wavelengths—was deemed sufficient to proceed to Phase A. These performance requirements have therefore also been adopted.

III.III Technology Priorities

The recommendation by the Decadal Survey was to continue to pursue the development of coronagraph, external occulter, and interferometer technologies to allow an architecture downselect by the mid-Decade. Nevertheless, NASA has endorsed a suggestion from the Exoplanet Exploration Program Analysis Group (ExoPAG) that, for both cost and technical readiness reasons, infrared interferometry should be of lower priority as the basis for a New Worlds Mission than either of the coronagraph or starshade architectures.

The highest priority technology demonstrations for all architectures are the following:

1. Experimental demonstrations that the necessary starlight suppression is achievable; and
2. The validation of models and error budgets that demonstrates the physics of starlight suppression including the dominant sources of instrument noise are understood within the accuracy required for on-orbit performance prediction.
Demonstrations that emphasize approaches that provide high-sensitivity and a small inner working angle are particularly valued as they may greatly increase the science return from a mission.

The above demonstrations by themselves take precedence over any other related technologies, including detector technology, mirror technology (with the exception of adaptive systems), telescope assembly technology, sunshields and isothermal control, propulsion systems, vibration isolation systems, spacecraft pointing control, or formation flying technology.

The following sections outline the technology milestones for coronagraphs, starshades, and interferometers.

IV. CORONAGRAPH MILESTONES

There are several approaches to the design of coronagraph instruments. Such instruments may include implementations of intensity masks [6], phase masks [7], phase-induced amplitude apodization [8], visible nulling coronagraphs [9], or hybrid designs [10].

The state of the art demonstrated in the lab is summarized in Fig. 1. Most notable amongst these results is a contrast of $5 \times 10^{-10}$ with a 10% bandwidth at $4\lambda D$ achieved through the use of $4^\text{th}$ order intensity masks [12]. Using similar masks, contrasts of $3 \times 10^{-9}$ have been achieved with a 20% bandwidth at $3\lambda D$ [13]. Models exist that match these results, although they have not yet been formally validated. The other results plotted in Fig. 1 are described later in the text.

Four high-level technology milestones were developed for TPF-C. The milestones below are paraphrased from the TPF-C Technology Plan [6] and Milestone documents [12][13][14]. The first milestone demonstrates the feasibility of the technique. The second demonstrates that it is applicable over a representative science band. The third demonstrates that the physics models are well understood and the known sources of noise are controlled, thus validating the error budget for the most problematic sources of system degradation. The fourth demonstrates through observatory simulation, combined with experimental results, that the mission could achieve its stated science goals. These milestones are progressive and sufficiently generalized to be applicable to any optical coronagraph mission concept. These are the most significant high-level milestones to be accomplished in pre-Phase A.

**Milestone 1.** Narrow-band Starlight Suppression. Demonstrate monochromatically the technology for Earth-like planet detection by optical starlight suppression to a level within an order of magnitude of the required flight performance. Using monochromatic light at an optical wavelength in the intended science band, a contrast of less than $1 \times 10^{-9}$ must be achieved in a target dark hole whose inner working angle is representative of the flight mission. The demonstration must be repeated on three separate occasions.

**Milestone 2.** Broad-band Starlight Suppression. Demonstrate with broadband light the technology for Earth-like planet detection by optical starlight suppression to a level within an order of magnitude of the required flight performance. Using broadband light with a fractional bandwidth $\Delta \lambda / \lambda \geq 10\%$ centered at an optical wavelength in the intended science band, a contrast of less than $1 \times 10^{-9}$ must be achieved in a target dark hole whose inner working angle is representative of the flight mission. The demonstration must be repeated on three separate occasions.

**Milestone 3A.** Model Validation of Starlight Suppression. Demonstrate that starlight suppression performance predictions from high-fidelity optical models of experiments, using measured data on specific testbed components, are consistent with actual measured results on the testbed. The correlation of model predictions with experimental testbed results thus validates models at a baseline contrast ratio of better than $1 \times 10^{-9}$ (goal $1 \times 10^{-10}$). The measurement to be evaluated is the comparison between the contrast predicted by the model and the contrast achieved in the experiment. In each open loop test, the perturbation to be introduced shall change the model contrast from nominal by at least $s \times 10^{-9}$, where $s$ is the step number (1, 2, 3) and shall be in agreement with the model prediction to $1 \times 10^{-9}$. In closed loop tests, the change in model contrast is evaluated after the wavefront control system (WFCS) has operated. Closed loop perturbations shall change the post-WFCS model contrast by at least $2 \times 10^{-9}$ from nominal. Multiple step closed loop tests do not necessarily involve progressive delta contrast steps. Broadband light must be used with a fractional bandwidth $\Delta \lambda / \lambda \geq 10\%$ centered at an optical wavelength in the intended science band. The contrast metrics must be demonstrated in a target area representative of the flight mission.

**Milestone 3B.** Demonstrate, using the modeling approach validated against experimental results (above) combined with appropriate telescope models and the current mission error budget, that a coronagraph could achieve a baseline contrast of $1 \times 10^{-10}$ over the required optical bandwidth necessary for detecting Earth-like planets, characterizing their properties and assessing habitability.

Progress toward achieving the above high-level milestones could be marked by milestones in other key technologies. Related activities could include (a) demonstrations of wavefront control through the simultaneous use of two deformable mirrors, (b) the development of special-purpose optics such as image-plane masks or apodizing optics, (c) advances in modeling high-contrast imaging optical systems.
Another important area of research would be the implementation of testbed optics that would simulate a telescope front-end. This would test a coronagraph’s ability to suppress starlight in the presence of realistic low-order wavefront errors.

Future milestones in Phase A would include those related to structural, thermal, and spacecraft technology demonstrated at the component, subsystem, and system level. A key milestone in this regard would be a precision structure stability demonstration.

### IV.I Progress and Plans

**Band-limited Lyot Masks**

Milestones 1 and 2 were completed by the TPF-C Pre-Project for an instrument design employing a linear 4th-order band-limited mask [12][14]. This mask used an intensity-only design.

No further development of masks of this exact same design is anticipated because its performance degrades at larger bandwidths and smaller inner working angles. Subsequent work on masks of this type, described below, has focused on an improved hybrid design that includes a dielectric layer to compensate for small phase errors induced by the metallic intensity mask. Nonetheless, band-limited Lyot masks that were developed by the TPF-C Pre-Project are being used in trials for coronagraph model validation.

**Band-limited Hybrid Lyot Masks**

Experiments with hybrid masks in the High Contrast Imaging Testbed (HCIT) at JPL/Caltech in 2011 achieved a contrast of $3.2 \times 10^{-10}$ with a bandwidth of 2%, $6.0 \times 10^{-10}$ with a bandwidth of 10%, and $2.0 \times 10^{-9}$ with a bandwidth of 20% all at an inner working angle of $3-4 \lambda/D$. The primary goal of recent work has been to obtain contrasts better than $1.0 \times 10^{-9}$ with bandwidths of 20%. The limiting factor was identified as an error in the mask and fabrication, and new masks are now being fabricated. Future work may include operation in two shorter wavelength bands and the implementation of circular rather than linear hybrid masks.

**Phase-Induced Amplitude Apodization**

Phase-Induced Amplitude Apodization (PIAA) uses pairs of aspheric mirrors to reshape the intensity distribution passing through an aperture, proving a Gaussian-like distribution and eliminating diffraction sidelobs. Supporting work toward this goal is being
conducted at the NASA Ames Coronagraph Experiment (ACE) and the JPL/Caltech High Contrast Imaging Testbed (HCIT). The research at ACE is conducted using a thermally stabilized enclosure, permitting initial validation (TRL 1–4) of PIAA and related technologies that can then be validated at higher TRL levels (TRL 4+) using the vacuum facility of the HCIT.

Experiments at ACE in 2011 achieved a contrast of $1.9 \times 10^{-8}$ using a paired-mirror system, in monochromatic light at an inner working angle of $2\lambda/D$. Experiments in the JPL Micro-Arcsecond Metrology (MAM) vacuum chamber in 2011 achieved a contrast of $3.5 \times 10^{-8}$ with paired-mirrors in monochromatic light also at $2\lambda/D$. Diagnostic tests will be conducted at each facility to identify the limiting noise sources. A new low-order wavefront sensor is being implemented to improve the pointing required at small inner working angles.

**Vector Vortex Coronagraph**

Experiments with vector vortex masks in the HCIT in 2011 achieved a contrast of $3.4 \times 10^{-9}$ in monochromatic light, $2 \times 10^{-8}$ with a 10% bandwidth, and $4 \times 10^{-8}$ with a 20% bandwidth, all at an inner working angle of $2.5–12\lambda/D$. Identical masks have been used to detect exoplanets with the Palomar 5-m telescope. New masks are being developed for continued testing in 2012.

**Visible Nulling Coronagraph**

A visible nulling coronagraph uses an interferometer back-end to reject starlight via interferometric nulling with a sheared pupil. This approach uses an array of single-mode fibers and is well adapted to the geometry of segmented-pupil telescopes.

Experiments with single-fibers have yielded null depths of $1 \times 10^{-7}$ [15]. In separate experiments at both JPL/Caltech and NASA/GSFC, the necessary wavefront sensing and control has been demonstrated to phase the coronagraph. New coherent fiber bundles have been acquired and successfully tested. Results to date suggest that contrasts of $10^{-8}$ and $10^{-9}$ are achievable [10][17], and experiments are continuing.

**Shaped Pupil Masks**

Vacuum experiments with shaped-pupil masks in the HCIT have yielded contrasts of $1.16 \times 10^{-9}$ with a 2% bandwidth and $2.4 \times 10^{-9}$ with a 10% bandwidth, both at inner working angles of $4\lambda/D$ [18].

Ongoing work being undertaken at Princeton University includes the implementation of a hybrid design that combines shaped pupils with a pair of deformable mirrors with the goal of enabling a higher throughput at a smaller inner working angle [18].

**Model Validation of Band-limited Coronagraphs**

The milestone objective is to validate coronagraph performance models using the HCIT, as described in Coronagraph Milestone 3A.

Initial experiments were undertaken for a period of two weeks in Q2 of FY2011 using a band-limited Lyot mask. Results were encouraging, but the trials did not yet demonstrate model agreement at milestone levels. Future plans would include the completion of Coronagraph Milestone 3A, with work to recommence in FY2012 contingent upon funding and access to the HCIT.

**Efficient Coronagraph Optical Modeling**

The milestone objective is to identify, implement in code, and verify efficient numerical methods for representing wavefront modification by the Hybrid Band-Limited Coronagraph (HBLC), the Vector Vortex Coronagraph (VVC), and the Phase-Induced Amplitude Apodization (PIAA) coronagraph that are accurate to 1% or better relative to the mean field contrast for contrasts down to $10^{-10}$. This represents a related activity because it does not currently include experimental validation of the models, as required in Coronagraph Milestone 3A. This work is being conducted at JPL/Caltech.

The first phase of work, to validate the code against known reference solutions, has been completed for the Vector Vortex and PIAA models, but not yet for band-limited masks. When the first phase is completed, work will then proceed to a second phase to predict coronagraph performance with realistic wavefront errors.

**Rapid Wavefront Sensing & Control**

The milestone objective is to use coherent speckle detection methods, and demonstrate the capability to measure speckles of about $1 \times 10^{-8}$ contrast with uncertainty, stability, and repeatability of 20% in intensity and 1 radian in phase with 90% statistical confidence, in a window at least $2 \times 2 \lambda/D$ wide at $<10\lambda/D$ from the star, in one spectral band of width $>10\%$, with a uniform incoherent background of at least $1 \times 10^{-8}$ in the area covered by the PSF. The goal is to provide a faster servo loop to improve the stability of measurements requiring long integration times. This represents a related activity which may improve the stability of experiments represented by Coronagraph Milestones 1, 2, and 3A.

This work is being led by Ball Aerospace and Technology Corporation. Experimental work has not yet begun, but is anticipated to begin in early FY2012 using the HCIT.
V. STARSHADE MILESTONES

There are two similar approaches to the design of external occulters currently being studied, differing by whether an analytical petal shape is used [20] or whether it derives from a mathematical optimization [21]. Each approach is following a different technology path for the packaging and deployment of a starshade: the first proposes to use deployable booms [23][24], while the second proposes to use an unfurling truss [25].

The technology development for starshades would follow several parallel paths in Pre-Phase A. Unlike the case for the coronagraph, whose laboratory work unites many separate technologies in a progressive series of starlight suppression milestones, there are no comparable unifying milestones for the occulter. A full-scale space-borne starshade would be many tens of meters across and placed at tens of thousands of kilometers from its host telescope. It is therefore impossible run full-scale tests of starlight suppression with such a system on the ground. Laboratory tests with subscale masks have yielded very encouraging results, but they do not demonstrate the key technology, described below, that would be needed for a space mission, nor validate error budgets that would be traceable to flight. The critical component and subsystem technologies can nonetheless be successfully demonstrated in Pre-Phase A, if pursued as separate parallel tasks. Therefore by the end of Pre-Phase A, modeling at the component, and subsystem level should enable the prediction of the future flight performance.

The subject areas for external occulter milestones are listed below. In this list, the first four topics are technology areas that should be demonstrated in Pre-Phase A. These are related to the materials, design, fabrication, and optical performance of components and subsystems. The fourth is analogous to the final pre-Phase A milestone for coronagraphs: a demonstration that the on-orbit performance is achievable based upon a well-grounded understanding of the error budget, backed by the necessary laboratory results. The remaining milestones cover topics that must be demonstrated at the system level and include deployment, dynamic behavior, as well as guidance, navigation, and control.

- Petal manufacturing: Demonstrate that a single petal can be manufactured to the design tolerances. This may include a demonstration of the manufacturing of petal edges, tips, and valleys. A representative set of manufacturing tolerances shall be demonstrated that derive from known error budget allocations.
- Control of scattered light: Demonstrate with a baseline external occulter design that the brightness of light scattered from the occulter would be less than the brightness of exozodiacal light. This may include demonstrations of control of scattered sunlight from petal edges, light transmitted through the occulter fabric, or from other identified sources.
- Sub-component model validation: Demonstrate that the structural behavior of elements of a starshade can be predicted to the accuracy required for a flight mission. This may include predictions of materials and structural properties as a function of temperature, anchored by coupon tests.
- Modeling: Demonstrate, using the modeling approach validated against experimental results combined with appropriate telescope models and the current mission error budget, that a external occulter could achieve a baseline contrast of $1 \times 10^{-10}$ over the required optical bandwidth necessary for detecting Earth-like planets, characterizing their properties and assessing habitability.
- Starshade deployment. 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 previously been demonstrated.
- Dynamic stability: Demonstrate that a deployed shape can be controlled to within the budgeted tolerances for anticipated flight conditions of science operations. This may include demonstrations of thermal and mechanical stability.
- Formation flying: Demonstrate that the guidance, navigation and control algorithms of an external occulter can achieve the budgeted alignment tolerances. This may include hardware and/or software simulations that demonstrate traceability to flight conditions.

Experiments that demonstrate the error budget can be met for a particular starshade design are undertaken in Pre-Phase A, leading up to a final Pre-Phase A modeling milestone that incorporates these experimental results. Milestones related to deployment and formation flying demonstrations would be undertaken in Phase A and B.

Because there are two different technology paths being proposed for starshade packaging and deployment, the starshade structure and subcomponents may be very different in each case. It follows that milestones accomplished for one approach might not be relevant to the technology advancement of the other.

Progress and Plans

Starlight Suppression Experiments

Starlight suppression experiments using scaled starshades have produced contrasts of $2.6 \times 10^{-7}$ at the starshade mask's inner working angle [22] and features as faint as $5 \times 10^{-10}$ have been detected outside the inner working angle.
Laboratory tests using subscale silicon-etched occulter masks have demonstrated contrasts of $2.6 \times 10^{-7}$ at the inner working angle, in radially averaged data, [22]. Ongoing research is investigating various aspects of the manufacturability of petals.

These experiments are designed to measure the starshade’s shadow at the same Fresnel number as would be used in an actual flight-system, but not at the same inner working angle. The masks are centimeters in diameter and placed at tens of meters from the detector. Future efforts would depend on continued funding.

**Precision Petal Manufacturing.**

The milestone objective is stated as follows. On a single full-scale petal made of flight-like materials, measure the edge position relative to a fiducial origin at a sufficient number of locations along the edge. Using optical modeling tools, verify that the predicted mean contrast in the image plane past an occulter with petals of the measured shape in an annulus of width equal to the full-width half-max of the telescope point spread function at the smallest inner working angle is $3 \times 10^{-10}$ or better, the allocated contrast to static errors. Repeat the measurements and analysis a sufficient number of times to give 95% confidence that the predicted contrast is correct.

This work is being led by Princeton University. The experimental and modeling work is anticipated to begin in late FY2011 and continue through FY2012.

**VI. INTERFEROMETRY MILESTONES**

Interferometry technology will ultimately provide higher angular resolution and thus the ability to detect and characterize a larger sample of exoplanets than is possible with either coronagraph or external occulter architectures. A summary of interferometer milestones is given below. Milestone 1 is a demonstration of adaptive correction of wavefront errors necessary for to attain deep null depths. Milestone 3 is a demonstration of starlight suppression over a broad bandwidth using a two-element interferometer. Milestone 4 is a system demonstration using a four-element interferometer. Milestone 5 demonstrates the techniques of spectral fitting, which is the final step in starlight suppression necessary to detect exoplanets at mid-infrared wavelengths. These starlight suppression milestones are equally applicable to connected-structure and formation-flying concepts. Milestone 2 is a laboratory demonstration of formation-flying guidance, navigation & control.

**Milestone 1.** Using the Adaptive Nuller, demonstrate that optical beam amplitude can be controlled with a precision of $\leq 0.2\%$ rms and phase with a precision of $\leq 5$ nm rms over a spectral bandwidth of $> 3$ $\mu$m in the mid IR for two polarizations. This demonstrates the approach for compensating for optical imperfections that create instrument noise that can mask planet signals. This goal is consistent with starlight suppression of $1 \times 10^{-5}$.

**Milestone 2.** Using the Formation Control Testbed (FCT) as an end-to-end system-level hardware testbed, demonstrate that a formation of multiple robots can autonomously initialize, maneuver and operate in a collision free manner. A key maneuver, representative of TPF-I science will be demonstrated by rotating through greater than 90° at ten times the flight rotation rate while maintaining a relative position control to 5 cm 1σ per axis. This is the first step in a full validation of the formation control architecture and algorithms and the testbed models developed by the Formation Algorithms & Simulation Testbed while physically demonstrating a scaled version of the approach to achieving the angular resolution required for the detection of terrestrial planets.

**Milestone 3.** Using either the Adaptive Nuller or the Achromatic Nulling Testbed, demonstrate that mid-infrared light in the 7–12 $\mu$m range can be suppressed by a factor of $\geq 10^5$ over a waveband of $\geq 25\%$. This demonstrates the approach to broadband starlight suppression (dimming of light across a range of wavelengths) needed to characterize terrestrial planets for habitability. Flight-like nulls are to be demonstrated at room (non-flight) temperature.

**Milestone 4.** Using the Planet Detection Testbed, demonstrate detection of a simulated planet signal at a star/planet contrast ratio of $\geq 10^6$. This demonstrates that several opto-mechanical control loops can be integrated and operated in a testbed configuration that includes the principal functional blocks of the flight instrument. These functional blocks include fringe tracking, pathlength metrology, beam shear and pointing control, 4-beam combination and phase chopping. Success shows that an instrument can be operated with a stability representative of flight requirements and within an order of magnitude of the contrast that permits the detection of the signal from an earth-like exoplanet in the habitable zone around a nearby star.

**Milestone 5.** Using the Planet Detection Testbed demonstrate the starlight suppression technique of spectral fitting. The spectral fitting technique uses measurements which can be obtained from a broad band of nulled wavelengths to detect and remove the effect of opto-mechanical disturbances on the null, thereby effectively suppressing the starlight by another factor of ten.

Milestones 1, 2, 3, and 4 were completed by the TPF-I Pre-Project.

Laboratory demonstrations of interferometric nulling at mid-infrared wavelengths have been successful at
reaching the performance needed to support a flight mission. The Milestone 1 demonstration of phase and intensity control of fringes was demonstrated at the required level [26]. The Milestone 3 demonstration of starlight suppression of $1 \times 10^{-7}$, was demonstrated with a 30% bandwidth [27] at such a level that the planet signal would be dominated by exozodiacal light, not starlight. The Milestone 4 system demonstration using two pairs of interferometers achieved contrasts of $1.65 \times 10^{-8}$ in the lab using laser sources, with an experimental subtraction of noise using infrared chopping and averaging [28][29].

Work in progress on Milestone 5 is described below. In addition, further work is needed to demonstrate the same noise subtraction techniques over broader bandwidths and in a cryogenic environment. This would necessitate the testing of cryogenic mid-IR single-mode fibers, deformable mirrors, adaptive nullers, and more comprehensive system testing at liquid nitrogen temperatures.

Whereas a coronagraph architecture would be an extrapolation of existing space telescopes designs, it is very likely that an interferometer would have no precursor in space—whether it be a connected-structure design or a formation-flying mission. The Milestone 2 demonstrations of formation flying were successfully completed in a lab environment with hardware in the loop and 5-degrees of freedom for the two controlled satellites [30][31]. Nonetheless, the technology development for a formation flying interferometer may follow a path that includes one or more technology space missions prior to its full implementation.

The milestone to be demonstrated is Milestone 5, above, using the Planet Detection Testbed.

Work has been underway in FY2011 to modify the Planet Detection Testbed and upgrade a broadband mid-infrared detector for use with this milestone. This milestone would complete the suite of room-temperature starlight suppression experiments that had been planned for mid-infrared interferometry.

VII. OTHER MILESTONES

The Milestone to be demonstrated is a measurement of the performance of a photon-counting $256 \times 256 \times 256$ Geiger-Mode Avalanche Photodiode (GM-APD) focal plane array after radiation exposure. The array is designed to provide zero read-noise, ultra-high dynamic range, and highly linear response. The following characteristics are to be measured: dark current, intrapixel response, total quantum efficiency, afterpulsing, persistent charge, and crosstalk. The measurements will be made before and after 50 krad (Si) ~60 MeV proton irradiation. Important performance parameters include read noise, dark counts, and total quantum efficiency. This work is being conducted through the Rochester Institute of Technology.

This effort is a demonstration of new detector technology that may greatly improve the science throughput of coronagraph and starshade mission concepts. Its development, funded prior to the SAT-TDEM exclusion of detector technology in the 2010 solicitation, is subject to the same milestone process and review as other milestones described in previous sections.

Future work, subject to continued funding, would include the performance validation of focal plane arrays with a larger number of pixels ($1024 \times 1024$ vs $256 \times 256$) and a higher fill-factor, along with additional radiation testing.

VIII. CONCLUSION

The 2010 Astrophysics Decadal Survey recommended the creation of a technology development program for a potential future exoplanet mission to mature starlight-suppression technology for the detection of spectra of Earth-like exoplanets. The Exoplanet Exploration Program is supporting a community-based process to help NASA Headquarters select a single architecture before 2015, and to mature the selected concept for recommendation in the 2020 Decadal Survey. This paper describes technology development that will lead toward that goal by specifying the technology milestones that each architecture must address in Pre-Phase A.

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X. REFERENCES


