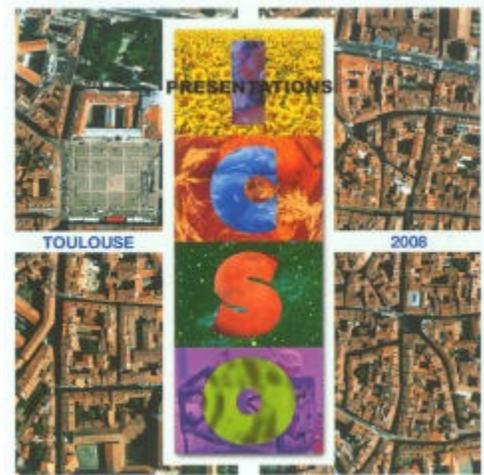# International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas

Technology challenges for exoplanet detection with mid-IR interferometry

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TECHNOLOGY CHALLENGES FOR EXOPLANET DETECTION WITH MID-IR INTERFEROMETRY

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ABSTRACT

This paper provides an overview of technology development for the Terrestrial Planet Finder Interferometer (TPF-I). TPF-I is a mid-infrared space interferometer being designed with the capability of detecting Earth-like planets in the habitable zones around nearby stars.

1. INTRODUCTION AND OVERVIEW

The Terrestrial Planet Finder Interferometer (TPF-I) is a concept for a NASA mission to detect and characterize the mid-infrared spectra of Earth-like exoplanets [1, 2]. The mission has been developed in close collaboration with the European Space Agency over the past decade as well as with members of the Darwin proposal team [3]. The primary objective is to find evidence of biological activity on planets around nearby stars.

The mid-infrared waveband of 6–20 μm provides a favorable planet/star contrast and key biosignatures, including those of water vapor, methane, oxygen, and carbon dioxide.

The designs for TPF-I and Darwin have been based on the use of formation-flying arrays of telescopes, with interferometer baselines of 40 m or more providing the angular resolution necessary to detect Earth-like planets around 200–300 stars.

The relative positions of the telescopes need only be controlled to tens of centimeters, because delay lines are used within the beam combiner to provide nanometer-level relative phasing of the incoming starlight.

This design is a compelling choice for a mid-infrared observatory; the formation flying baselines provide unrivaled angular resolution. This is vital for unambiguous orbit determination, the ability to distinguish multiple planets, and provides discrimination against structure in the exozodiacal disk. The angular resolution also provides a small inner working angle, giving access to a very broad range of target stars. In this regard, TPF-I and Darwin far exceed the predicted capability of other proposed planet-finding missions [4].

Fig. 1. Artist's concept of the TPF/Darwin mid-infrared formation flying array. (Spacecraft image courtesy of T. Herbst, MPIA)

The major technology challenges for the mission include (1) the design of guidance, navigation and control for a formation flying array; (2) cryogenic designs for passive cooling of the optics and active cooling of detectors, and (3) the implementation of interferometer systems for starlight suppression and planet detection. The overall mission risk is dominated by the reliance on a coordinated use of multiple spacecraft. Aspects of cryogenic design and cooling are being addressed by missions such as Herschel and the James Webb Space Telescope, and these topics are not discussed here. This paper is primarily devoted to a discussion of technology progress in the areas of starlight suppression and formation flying. Recent technology highlights include the following:

(i) Completion of TPF-I Milestone #1: the compensation of intensity and phase demonstrated by the Adaptive Nuller testbed. Intensity was compensated to within 0.2% and phase to within 5 nm rms across a 3-μm band centered at 10-μm [5]. This is consistent with the flight requirement of the mission.

(ii) The demonstration of nulling over a 32% bandwidth centered at a wavelength of 10 μm at a level of 1.1×10^{-5} which is close to flight requirements.

(iii) Completion of TPF-I Milestone #2: a demonstration of precision formation maneuvers in a ground-based robotic testbed, with performance traceability to flight [6].

(iv) Demonstrations of rendezvous and docking maneuvers in space by DARPA's Orbital Express and ESA's Autonomous Transfer Vehicle, Jules Verne.

(v) The adoption of the Emma X-Array by both the TPF-I Project and the Darwin proposal team as the baseline mission design for TPF-I and Darwin [3].

The results of most testbed work for TPF-I accomplished to date have now been submitted for publication in refereed journals. In 2008-2009 the focus of continuing work will be on broadband adaptive nulling (Milestone #3) and a system-level demonstration of planet detection by four-beam array rotation with chopping and averaging (Milestone #4 and Milestone #5). Continued progress in formation flying is anticipated through in-space testing over the next five years with missions sponsored by ESA and its European partners.

2. TECHNOLOGY FOR STARLIGHT SUPPRESSION

A mid-infrared interferometer must suppress starlight by a factor of approximately 1 part in 100,000 and integrate to extract planet spectra despite a background (due to local and exozodiacal dust) that is still 100 times brighter than the planet light.

2.1. Mid-IR spatial filter development

Spatial filters are an essential technology for nulling interferometry. They significantly reduce the optical aberrations in wavefronts, making extremely deep nulls possible. The most basic form of a spatial filter is a simple pinhole, and pinholes have indeed been used to achieve the deepest laser nulls so far at mid-infrared wavelengths. However, pinholes only operate well over a narrow bandwidth and so are ill-suited for broadband spatial filtering for science instruments. In addition, they do not reject very low spatial-frequency wavefront aberrations. The development of improved broadband techniques for spatial filtering at mid-infrared wavelengths may be crucial to the success of TPF-I, and has been a focus of research at JPL. Although fiber optics at near-infrared wavelengths are extensively used by the telecommunications industry, low-loss, mid-IR, single-mode spatial filters are not yet commercially available. The goal of this work has been to develop single-mode spatial filters with a throughput of 50% or better with a modal suppression of 25 dB for non-fundamental modes.

Description of research

Spatial filters may be implemented in a variety of ways, including single-mode fiber-optics made from chalcogenide or silver halide glasses, metalized waveguide structures micro-machined in silicon, or through the use of photonic crystal fibers. By promoting the parallel development of various spatial filter technologies, it was hoped that we would demonstrate the necessary spatial filter performance in the 6–20 μm spectrum using no more than two technology types. The development of mid-infrared spatial filters was funded by TPF-I from 2003 through 2008. The performance of the single-mode filters that were developed under contract with TPF-I were tested and characterized in-house at JPL. The scope of the work included prototypes of hollow waveguide filters designed by Christopher Walker at the University of Arizona; completed chalcogenide fibers designed by Dr. Jas Sanghera at the Naval Research Laboratory (NRL); and completed silver halide fibers designed by Prof. Abraham Katzir at Tel Aviv University (TAU) in Israel.

Results

The results of this research have been published by Ksendzov *et al.* [7, 8]. The fibers that have been developed for TPF-I represent the state of the art. About 16 mid-infrared single-mode fibers were delivered and tested at JPL, showing excellent single-mode behavior at 10 μm.

The 20-cm-long chalcogenide fibers developed by the Naval Research Laboratory were shown to demonstrate 30 dB rejection (a factor of 1000) of higher order modes and have an efficiency of 40%, accounting for both throughput and Fresnel losses. The transmission losses were measured at 8 dB/m, and the fibers are usable up to a wavelength of about 11 μm. The chalcogenide fibers developed at the Naval Research Laboratory were used in the Achromatic Nulling Testbed and continue to be used in the Adaptive Nuller testbed.

The 10–20 cm long silver halide fibers that were developed by Tel Aviv University were shown to demonstrate 42 dB rejection (a factor of 16,000) of higher order modes with transmission losses of 12 dB/m. This high rejection of higher-order modes was accomplished with the addition of aperturing of the output of the fibers, made possible by the physically large diameter of the fiber cladding. Silver halide fibers should in principle be usable up to a wavelength of about 18 μm, although the laboratory tests at JPL were conducted only at 10 μm. This is the first time silver halide fibers were shown to have single-mode behavior.

Future technology development

An important step in future work will be to demonstrate single-mode performance over the entire wavelength band that TPF-I will use (6–20 μm). To date, experiments that test single-mode behavior have been limited to a narrow wavelength range near 10 μm. The spatial filtering capabilities of photonic crystal fibers should be investigated for use at mid-infrared wavelengths, because

of the improved throughput that they may provide. Moreover, the suitability of these fibers for use in a cryogenic environment should be tested.

2.2. Achromatic phase shifter studies

The Achromatic Nulling Testbed (ANT) was developed to study achromatic phase shifting techniques to achieve, broadband, dual-polarization, two-beam mid-infrared nulls. The two-beam nuller is the basic building block of all flight architectures that have been considered. Three approaches to achromatic phase shifting were investigated, with the aim of demonstrating, through one of the approaches, two-beam nulling to a level of 1 part in 100,000 with a 25% bandwidth in the 6–20 μm range. A longer-term objective was the development of a cryogenic nulling interferometer that would meet the above requirements while operating at a temperature of 40 K.
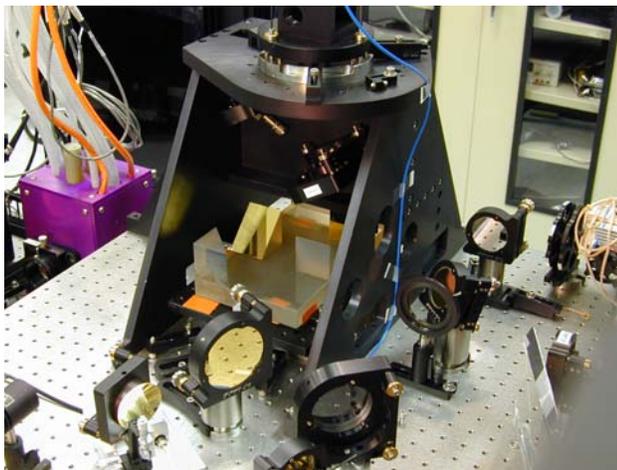
Fig. 2. View of the periscope assembly of the Achromatic Nulling Testbed.

Testbed description

Three different methods of implementing achromatic phase shifts were investigated: (1) pairs of dispersive glass plates to introduce a wavelength-dependent phase delay; (2) A through-focus field-flip of the light in one arm of the interferometer; and (3) successive and opposing field-reversals on reflection off flat mirrors in a periscope arrangement. A close-up view of the periscope mirror is shown in Fig 2. These methods were tested in the same lab, on adjacent optical benches, using a common mid-infrared laser and white-light source.

Results

The results of this work have been summarized by Gappinger *et al.* [9]. The most successful approach was the use of periscope mirrors, yielding an average rejection ratio of 51,000:1 at 20% bandwidth and 27,000:1 using a

25% bandwidth. The through-focus approach yielded a rejection ratio of 2000:1 with a 17% bandwidth. Pairs of glass plates provided a rejection ratio of 10,000:1 with a 25% bandwidth.

Future technology development

Of the methods of achromatic phase shifting that were tested by the ANT, the approach using the periscope mirrors produced the best results. Although these results fell short of the goal of 100,000:1 at 25% bandwidth, this goal appears to be well within reach of the Adaptive Nuller. An adaptive nuller used in conjunction with a periscope phase shifter would appear to be a viable approach. Future developments in broadband mid-infrared nulling are now being devoted to improving the performance of adaptive nulling. The Achromatic Nulling Testbed was dismantled in January 2008.

2.3. Adaptive nulling

The Adaptive Nuller was designed to correct phase and intensity variations as a function of wavelength, in each of two linear polarizations. This should allow high performance nulling interferometry, while at the same time substantially relaxing the requirements on the interferometer's optical components.

The goal of the testbed was to demonstrate, in a 3 μm band centered at a wavelength of 10 μm, the correction of the intensity difference to less than 0.2% rms (1 σ) between the interferometer's arms, and at the same time correct the phase difference across the band to < 5 nm rms (1 σ). This overall correction is consistent with a null depth of 10^{-5} (1 part in 100,000) if all other sources of null degradation can be neglected.

Testbed description

The Adaptive Nuller uses a deformable mirror to adjust amplitude and phase independently in each of about 12 spectral channels. The incident beam is first split into its two linear polarization components, and is dispersed. The dispersed spectra are then imaged onto a line of pixels on a deformable mirror, so that the piston of each pixel independently adjusts the phase of each channel. Tilt in the orthogonal direction is independently adjusted, which shears the output pupil at that wavelength; this shear, in combination with an output stop, selectively reduces the intensity in that channel. The various component beams are recombined to yield an output beam that has been carefully tuned for intensity and phase in each polarization as a function of wavelength. A photograph of the testbed is shown in Fig. 3.

Progress to date

The results of this research up until 2007 have been published by Peters *et al.* [5]. In March/April 2007, the

testbed achieved its primary goal of demonstrating phase compensation to better than 5 nm rms across the 8–12 μm band and intensity compensation to better than 0.2%. In June 2008 the mid-infrared Adaptive Nuller demonstrated a null depth of 1.1×10^{-5} (93,000:1 rejection ratio), over a bandwidth of 32%, as shown in Fig. 4. This is the deepest broadband null ever achieved by a mid-infrared nulling interferometer, and almost attains the TPF-I flight requirement. Long term plans now include improving the attainable null depth to better than 1.0×10^{-5}, and the possible design of a cryogenic version of this testbed.
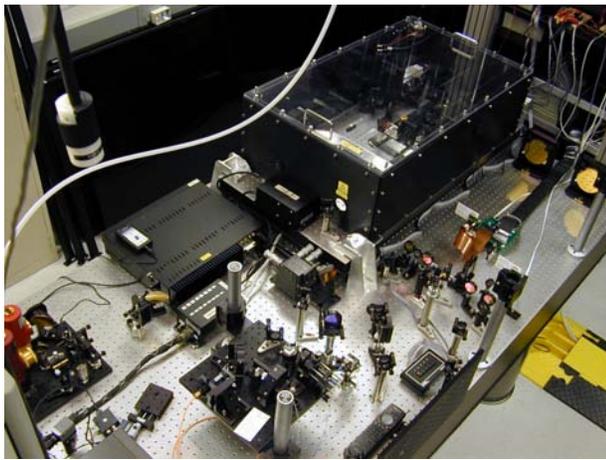
Fig. 3. The Adaptive Nuller Testbed (AdN). The Adaptive Nuller demonstrated phase and intensity compensation of beams within a nulling interferometer to a level of 0.12% rms in intensity and less than 5 nm rms in phase. This version of the AdN operates over a wavelength range of 8–12 μm. The long-focus parabolas, used in AdN are seen on the upper right.
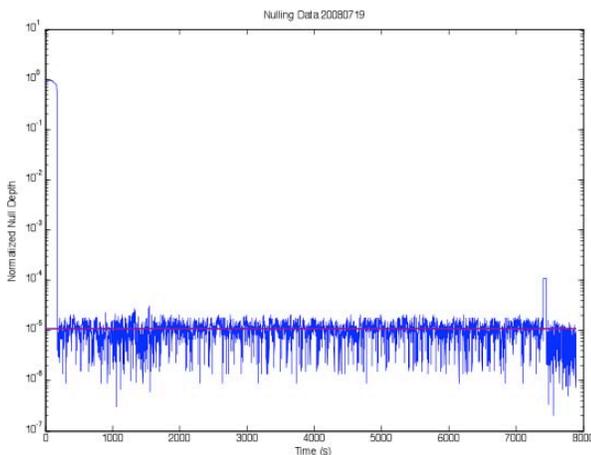
Fig. 4. Results from the Adaptive Nuller testbed show stable nulls at a level of 93,000:1 over a period of two hours. A bandwidth of 32% was used centered on 10 μm.

The milestone documents for these tests are as follows:

TPF-I Milestone #1 Whitepaper: Amplitude and Phase Control Demonstration, Edited by R.D. Peters, P.R. Lawson, and O.P. Lay (Jet Propulsion Laboratory, December 2006).

TPF-I Milestone #1 Report: Amplitude and Phase Control Demonstration, Edited by R.D. Peters, P.R. Lawson, and O.P. Lay, JPL Document 38839 (Jet Propulsion Laboratory, July 2007).

TPF-I Milestone #3 Whitepaper: Broadband Startlight Suppression Demonstration, Edited by P.R. Lawson, R.O. Gappinger, R.D. Peters, and O.P. Lay (Jet Propulsion Laboratory, October 2007).

2.4. Planet Detection Testbed

The Planet Detection Testbed, pictured in Fig. 5, was developed to demonstrate the feasibility of four-beam nulling, the achievement of the required null stability, and the detection of faint planets using approaches similar to the ones contemplated for a flight-mission. The most promising architectures for a flight mission use synthesis imaging techniques with four-beam nulling interferometers and interferometric chopping to detect planets in the presence of a strong mid-infrared background. The flight mission would use a phase chopping technique to modulate a sensitivity/fringe pattern around the star. This modulation technique is in many ways similar to the use of a chopper wheel that allows the detection of infrared sources against a thermal background and/or drifting detector offsets. In this case the thermal background on the sky includes the local and exozodiacal light.

The primary objective of the Planet Detection Testbed is to simulate this observing scenario and demonstrate the instrument stability needed to make this process work. The detected signal is the difference in the measured photon flux between the two chop states and this signal has both stochastic and systematic noise components. Integration over time reduces the stochastic components and good instrument stability is needed to minimize systematic components which may appear as low frequency fluctuations with timescales similar to a planet signal. Some of these systematic components can be removed by signal processing using expected correlations across the broadband light spectrum.

Testbed description

The PDT has the following main components: a star and planet source to generate a planet to be observed, a pair of nullers to null out the starlight, and a cross-combiner to allow modulation of the detected planet signal. To provide the necessary stability, the testbed has pointing and shear control systems, laser metrology systems and fringe trackers to maintain the phase on the star.

The PDT combines simulated star and planet beams in pairs to produce four star/planet beams that enter the testbed as if detected through four separate telescopes. Delay lines are used for the planet light relative to the star-light to simulate the path delays that would be observed as the array rotates with respect to the star/planet system. Two beam pairs are nulled and then cross-combined. A π phase shift is introduced into one of each beam pair by a combination of optical path differences in glass and air. The beam-pairs are chopped using a standard infrared approach and the difference in chop-states is recorded.

The testbed is described in greater detail in the milestone whitepaper by Martin *et al.* (below), and in a companion paper [10].

Fig. 5. The Planet Detection Testbed (PDT). The PDT is a four-input nulling interferometer that uses 10 μm laser light and servo loops to perform experiments related to instability noise, interferometric chopping, and planet detection. The testbed configuration shown here has obtained laser nulls between 500,000:1 and 800,000:1 and detected a simulated planet with a contrast ratio of 2,000,000:1.

Progress to date

The PDT is now fully operational. Experiments in 2008 have yielded null pairs with null depths between 500,000:1 and 800,000:1. In April 2008 the milestone criteria for the initial planet detection demonstrations were established:

Exoplanet Interferometry Milestone #4 Whitepaper: Planet Detection Demonstration, Edited by S. R. Martin, A. J. Booth, O. P. Lay, and P. R. Lawson (Jet Propulsion Laboratory, May 2008).

(i) Detect a planet at a contrast of $\leq 10^{-6}$ relative to the star at a signal to noise ratio of ≥ 10.

(ii) Show residual starlight suppression from phase chopping, averaging and rotation ≥ 100.

(iii) The tests in (i) and (ii) must each run for a total duration of 10,000 s and may include one or more planet rotations at timescales $\geq 2,000$ s.

(iv) The tests in (i) and (ii) must be satisfied simultaneously on three separate occasions with at least 48 hours between each demonstration.

This constitutes a demonstration of three of the four main parts of the starlight suppression technique: deep interferometric nulling, phase chopping and formation rotation to modulate the planet. The fourth part is the extraction of a planet signal using a broadband spectral filtering technique [11]. The current plan is to attempt this additional milestone with the PDT in 2009.

3. TECHNOLOGY FOR FORMATION FLYING

Technology for rendezvous and docking has been successfully tested in space by DARPA's Orbital Express mission in 2007, as well as ESA's Autonomous Transfer Vehicle, Jules Verne in 2008. Remarkable advances in technology have been demonstrated in recent years.

Efforts in support of TPF-I have been undertaken to demonstrate the guidance, navigation, and control necessary for precision formation maneuvers.

3.1. Formation Control Testbed
The Formation Control Testbed (FCT) was built to provide an end-to-end autonomous formation flying system in a ground-based laboratory. The FCT provides an environment for system-level demonstration and validation of formation control algorithms. The algorithms are validated using multiple floating test robots that emulate real spacecraft dynamics. The goal is to demonstrate algorithms for formation acquisition, formation maneuvering, fault-tolerant operations, as well as collision-avoidance maneuvering.

Testbed description

The FCT is comprised of two robots with flight-like hardware and dynamics, a precision flat floor for the robots to operate on, ceiling-mounted artificial stars for robot attitude sensing and navigation, and a "ground control" room for commanding the robots and receiving telemetry. The layout of the FCT emulates the environment of a formation of telescopes that is restricted to maneuvering in the same plane in space, normal to the direction of the target star. To be as flight-like as possible, each robot is equipped with a typical single-spacecraft attitude control suite of reaction wheels, gyros, and a star tracker. Thrusters are also available for attitude control.

Each robot has a lower translational platform and an upper attitude platform. The attitude platform/spacecraft houses the avionics, actuators, sensors, inter-robot and "ground"-to-robot wireless communication antennae, and the spacecraft processors. The translational platform provides both translational and rotational degrees of freedom to the attitude platform via (i) linear air bearings (the black, circular pads at the base of each robot) that allow the entire robot to float freely on the flat floor, (ii) a vertical stage, and (iii) a spherical air bearing at the top of the vertical stage.

Each robot has six degrees-of-freedom: three in translation and three in rotation. The robots can translate wherever necessary on the flat floor; however, the pitch and roll axes of each robot's motion are limited to ±30 degrees (a physical limitation of the spherical air bearings). The vertical air bearings have a range of ±25 cm. The formation algorithms are designed for all six degrees-of-freedom.

Results

In 2007 the Formation Control Testbed demonstrated its milestone for precision maneuvers using two robots, showing autonomous initialization, maneuvering, and operation in a collision free manner. The key maneuver that was demonstrated was representative of TPF-I science observations. Repeated experiments with the robots demonstrated formation rotations through greater than 90 degrees at ten times the flight rotation rate while maintaining a relative position control to 5 cm rms. Although the achievable resolution in these experiments was limited by the noise environment of the laboratory, it was nonetheless demonstrated (through modeling) that in the relatively noise-free environment of space, the performance of these algorithms would exceed TPF-I flight requirements.

Details of the performance milestone for TPF-I are contained in the following documents:

TPF-I Milestone #2 Whitepaper: Formation Control Performance Demonstration, Edited by D.P. Scharf (Jet Propulsion Laboratory, May 2007).

TPF-I Technology Milestone #2 Report: Formation Control Performance Demonstration, Edited by D.P. Scharf and P. R. Lawson, JPL Pub. 08-11 (Jet Propulsion Laboratory, January 2008).

Future technology development

The next steps for technology maturation that could be done using the robots within the FCT include demonstrating new capabilities such as (1) reactive collision avoidance, (2) formation fault detection, and (3) autonomous reconfiguration and retargeting maneuvers. Using the real-time simulation environment of FAST we could also need to demonstrate the performance with full formation-flight complexity, that is with five interacting spacecraft showing synchronized rotations, autonomous reconfigurations, fault detection, and collision avoidance.

Although NASA has no immediate plans to continue supporting formation flying research, national agencies in Europe are actively advancing the technology, with flight missions starting in 2009–2014. The European Space Agency and national space agencies in Europe have a program of precursor missions to gain experience in formation flying to support XEUS and Darwin.

In 2009 the Swedish Space Agency will launch the Prisma mission. This is primarily a rendezvous and docking mission, but will also test RF metrology designed for Darwin. In 2012 ESA plans to launch Proba-3, which is specifically a technology precursor to XEUS, and will include optical metrology loops for sub-millimeter range control over a 30-m spacecraft separation. The French and Italian space agencies are planning to launch Simbol-X in 2014. Simbol-X is an X-ray science mission with an architecture very similar to XEUS, but with a 20-m spacecraft separation. Simbol-X should enter Phase B of development in the summer of 2008.

The greatest advance in maturing technology for formation flying would certainly be to have a modest-scale technology mission devoted to verifying and validating guidance and control algorithms, and to further include the interferometric combination of starlight from separated platforms. A ground-based facility such as the FCT will continue to provide the means to test and improve real-time formation-flying algorithms as the technology matures, even while the technology is being proven in space.

4. SUMMARY

The technology program for the Terrestrial Planet Finder Interferometer is now close to achieving all of its milestones in starlight suppression. The basic component technology for starlight suppression at mid-infrared wavelengths is now at Technology Readiness Level (TRL) 4. TRL 5 requires testing in a relevant environment, which for TPF/Darwin would be in vacuum at cryogenic temperatures near 40 K. Most research so far has been undertaken in air at room temperature. However, sufficient progress has now been made that the greatest advance in this area would be to proceed to brass-board designs of already successful components and sub-systems.

The flight requirement for TPF/Darwin is to achieve a mean rejection ratio of 100,000:1 across the full science band of 6–20 μm. Laboratory work with the Adaptive Nuller has yielded mid-infrared rejection ratios of

93,000:1 nulls with bandwidths of 32% at a mean wavelength of 10 microns. These results show that the Adaptive Nuller is a viable solution to the design of achromatic phase shifters, and moreover that the chalcogenide single-mode fibers it uses are viable in the lower wavelength range of the science band (6–12 μm). Adaptive nulling is straightforward to generalize over the full science band, and with continued support could be demonstrated within a cryogenic vacuum, bringing the technology to TRL 5.

The single-mode fibers used in the Adaptive Nuller are made of chalcogenide material and have been demonstrated to yield 25 dB or more rejection of higher-order spatial modes, thus meeting the flight requirements. Because this material becomes opaque at wavelengths above 12 μm, other materials must be used in the 12–20 μm wavelength band. Silver halide single-mode fibers have been demonstrated to meet flight requirements at 10 μm, and should also work well at longer wavelengths. Although this performance is sufficient for flight, it would be greatly advantageous to improve the throughput of these devices, to test them throughout the full wavelength range they are intended for, and to test them cryogenically. Spatial filter technology would then be at TRL 5. It would furthermore be advantageous to implement mid-infrared spatial filters and beam combiners using integrated optics, so as to reduce the risk associated with the complexity of the science instruments.

In summary, excellent progress has been made, and the technology for broadband starlight suppression is now at a level mature enough to proceed with component brassboard designs, more ambitious system-level demonstrations, and extensive cryogenic testing.

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