

# PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](http://SPIDigitalLibrary.org/conference-proceedings-of-spie)

## Terrestrial planet finder interferometer: 2006-2007 progress and plans

P. R. Lawson, O. P. Lay, S. R. Martin, C. A. Beichman, K. J. Johnston, et al.

P. R. Lawson, O. P. Lay, S. R. Martin, C. A. Beichman, K. J. Johnston, W. C. Danchi, R. O. Gappinger, S. L. Hunyadi, A. Ksendzov, B. Mennesson, R. D. Peters, D. P. Scharf, E. Serabyn, S. C. Unwin, "Terrestrial planet finder interferometer: 2006-2007 progress and plans," Proc. SPIE 6693, Techniques and Instrumentation for Detection of Exoplanets III, 669308 (19 September 2007); doi: 10.1117/12.734914

**SPIE.**

Event: Optical Engineering + Applications, 2007, San Diego, California, United States

# Terrestrial Planet Finder Interferometer 2006–2007 Progress and Plans

P.R. Lawson<sup>1</sup>, O.P. Lay<sup>1</sup>, S.R. Martin<sup>1</sup>, C.A. Beichman<sup>2</sup>, K.J. Johnston<sup>3</sup>, W.C. Danchi<sup>4</sup>,  
R.O. Gappinger<sup>1</sup>, S.L. Hunyadi<sup>1</sup>, A. Ksendzov<sup>1</sup>, B. Mennesson<sup>1</sup>, R.D. Peters<sup>1</sup>, D.P. Scharf<sup>1</sup>,  
E. Serabyn<sup>1</sup>, and S.C. Unwin<sup>1</sup>

<sup>1</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

<sup>2</sup>Michelson Science Center, California Institute of Technology, Pasadena, CA, USA

<sup>3</sup>US Naval Observatory, Washington, DC, USA

<sup>4</sup>NASA Goddard Space Flight Center, Greenbelt, MD, USA

## 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. The overall technology roadmap is presented and progress with each of the testbeds is summarized. The current interferometer architecture, design trades, and the viability of possible reduced-scope mission concepts are also presented.

**Keywords:** Interferometry, astronomy, extrasolar planets, nulling, formation flying

## 1. INTRODUCTION AND OVERVIEW

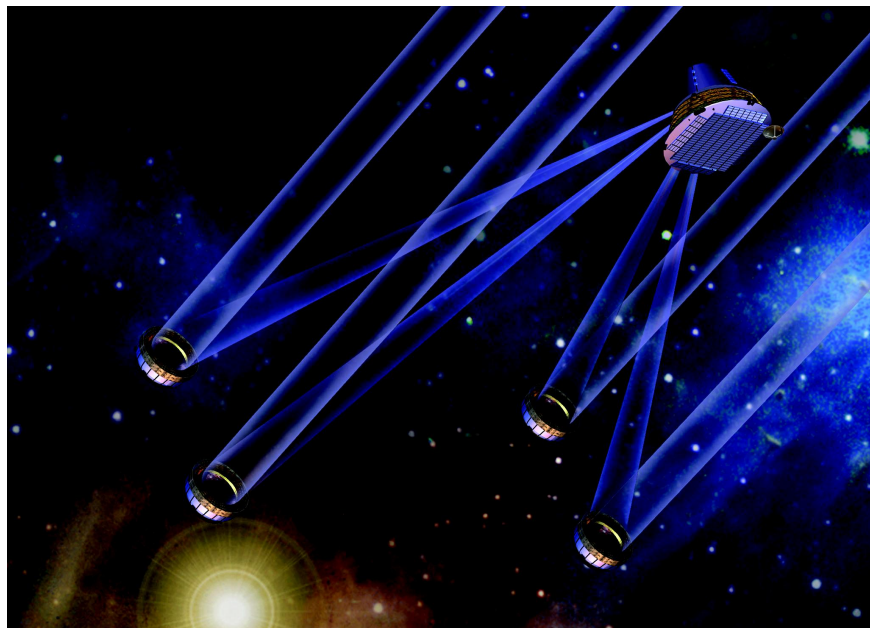
The Terrestrial Planet Finder Interferometer (TPF-I) is a formation-flying interferometer designed to measure mid-infrared spectra of the atmospheres of Earth-like exoplanets. The primary goal of the mission is to find evidence of biological activity on planets around nearby stars. The mid-infrared provides several key biomarkers and a favorable planet-star contrast ratio. An interferometer is a compelling choice for the design of a such a mid-infrared observatory because the interferometric baselines provide unrivaled angular resolution. This is vital for unambiguous orbit determination, robust separation of multiple planets, and discrimination against structure in the exozodiacal disk. This angular resolution also provides a compact inner working angle, giving access to a very broad range of target stars. In this regard, TPF-I far exceeds the predicted capability of other planet-finding missions. TPF-I is being developed as a future collaboration between NASA and the European Space Agency (ESA). ESA's Darwin mission closely parallels TPF-I, and the cost of the joint mission would be shared between the two agencies. The general astrophysics applications of TPF-I would also be revolutionary — the 2000 Decadal Survey noted “there will be few areas of astrophysics untouched by the power of an infrared interferometer with the resolution and sensitivity of TPF.”

This paper provides an update to the review presented at the SPIE conference on *Advances in Stellar Interferometry* in Orlando, Florida, in 2006.<sup>1</sup> The major achievements and/or changes during this period have included the following:

- The 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 across a 3 micron band centered at 10-microns.
- The demonstration of nulling over a 32% bandwidth centered at a wavelength of 10 microns at a level of  $1.2 \times 10^{-5}$  using the Adaptive Nuller.
- An increased emphasis on the design of a reduced-scope mission.

---

Further author information: Send correspondence to Peter Lawson, Jet Propulsion Laboratory, MS 301-451, 4800 Oak Grove Drive, Pasadena CA 91109-8099, USA. E-mail: Peter.R.Lawson@jpl.nasa.gov, Telephone: +1 (818) 354-0747.



**Figure 1.** The Emma X-Array Design for TPF-I (spacecraft image by T. Herbst, MPIA).

- 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.
- An understanding and resolution of the differences between performance estimates for Darwin and TPF-I.
- The start of experiments at the International Space Station using three SPHERES (MIT).

During this period, and in the early stages of preparation for the 2010 Decadal Survey in Astronomy, NASA's advisory groups have stressed the need for a better understanding of the lifecycle costs of missions. Also, the Space Interferometry Mission was halted by NASA prior to its entry to Phase C/D, reduced to a technology program, and deferred indefinitely. The notional cost of a planet finding mission for 2010–2020 was strongly suggested by NASA Headquarters could be no more than \$600M. The National Science Foundation and NASA also organized the Exoplanet Task Force (ExoPTF) to advise them on future priorities and to report in October 2007. The European Space Agency requested and received proposals for the *Cosmic Vision 2015–2025*, including the Darwin proposal, to be evaluated by late 2007. In brief, the period of 2006–2007 has seen a marked re-evaluation of existing mission concepts with the aim of better managing future costs. The response of the TPF-I Project has been to study the design and performance of the Emma architecture, depicted in Fig. 1, and to adopt it as its baseline design. Compared to previous designs this architecture significantly reduces the cost and complexity of the collector spacecrafts, without sacrificing the science capability, and offers almost full sky coverage over a year of observation. Table 1 illustrates the properties of this point design, described later in the text.

Despite the programmatic upheaval, TPF-I continues to make excellent technical progress. The most remarkable new development has been the demonstration of the Adaptive Nuller, described later in this paper. This approach to the design of an achromatic phase shifter promises to completely change the way nulling interferometers are designed.

## 2. SCIENCE GOALS AND OBJECTIVES

The major scientific objectives of TPF-I are: (1) search for and detect any Earth-like planets in the habitable zone around nearby stars; (2) characterize Earth-like planets and their atmospheres, assess habitability, and

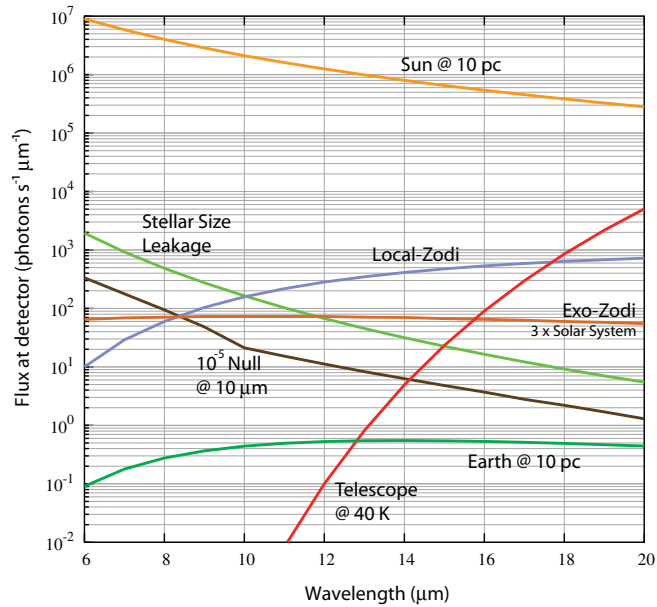
**Table 1.** Illustrative Properties of a TPF-I Observatory Concept

Parameter	4-Telescope Chopped X-Array Design
Collectors	Four 2-m diameter spherical mirrors, diffraction limited at 2 $\mu\text{m}$ operating at 50 K
Array shape	6:1 Rectangular Array
Array size	400 $\times$ 67 m to 120 $\times$ 20 m
Wavelength range	6–20 $\mu\text{m}$
Inner working angle	13–43 mas (at 10 $\mu\text{m}$ , scaling with array size)
Angular resolution	2.4 mas to 8.2 mas (at 10 $\mu\text{m}$ , scaling with array size)
Field of view	1 arcsec at 10 $\mu\text{m}$
Null depth	10 <sup>-5</sup> at 10 $\mu\text{m}$ (not including stellar size leakage)
Spectral resolution $\Delta\lambda/\lambda$	25 for planets; 100 for general astrophysics
Sensitivity	0.3 $\mu\text{Jy}$ at 12 $\mu\text{m}$ in 14 hours ( $5\sigma$ )
Target stars	153 (F, G, K, and M main-sequence stars)
Detectable Earths	72 (2 year mission time, 1 Earth per star)
Exozodiacal emission	Less than 10 times our solar system
Biomarkers	CO <sub>2</sub> , O <sub>3</sub> , H <sub>2</sub> O, CH <sub>4</sub>
Field of regard	Instantaneous 45° to 85° from anti-Sun direction, 99.6% of full sky over 1 year
Orbit	L2 Halo orbit
Mission duration	5 year baseline with a goal of 10 years
Launch vehicle	Ariane 5 ECA or equivalent

search for signatures of life; (3) carry out a study of gas giants and icy planets, as well as terrestrial planets within the 5 AU of nearby stars (at a nominal distance of 10 parsecs from the Sun) within the field-of-view of a 10- $\mu\text{m}$  interferometer; (4) carry out a program of comparative planetology; and (5) enable a program of revolutionary general astrophysics. A mission lifetime of 5 years, possibly extended to 10 years, is foreseen.

The motivation to observe at mid-infrared wavelengths is threefold: the star-planet contrast is more favorable than at shorter wavelengths; there are clear biomarkers; and the optical tolerances of the observatory are relaxed. The science requirements define the characteristics of the observatory design and the mission. The facility must provide a sensitivity that will enable spectroscopic measurements of the light from the planet to determine the type of planet, its gross physical properties, and its main atmospheric constituents.

With a low-resolution spectrum covering the 6–20  $\mu\text{m}$  region, TPF-I would be able to determine directly the effective temperature of the planet. Coupled with the total flux density and orbital location, TPF-I measurements also determine a planet's radius and albedo. Beyond simple physical characterization, TPF-I would be able to search for potential signs of a habitable planet and signs of life itself. In the mid-IR, the most studied and robust signature of biological activity is the combined detection of the 9.6- $\mu\text{m}$  O<sub>3</sub> band, the 15- $\mu\text{m}$  CO<sub>2</sub> band, and the 6.3- $\mu\text{m}$  H<sub>2</sub>O band or its rotational band that extends longward from 12  $\mu\text{m}$ .<sup>2,3</sup> The ozone absorption feature in the planetary thermal emission becomes detectable for O<sub>2</sub> levels higher than 0.1% of the present terrestrial atmospheric level,<sup>4</sup> and can thus trace a photosynthetic biological source of oxygen. The Earth's spectrum has displayed this feature during the past 50% of the age of the Solar System. Other spectral features of potential biological interest include methane, ammonia, and nitrous oxide, which would not be detectable by TPF-I in an exact Earth analog, but might be present in measurable quantities in a potentially habitable (or inhabited) planet at earlier evolutionary phase. Methane, for instance, was biologically sustained at a level producing a deep detectable feature at 7.4  $\mu\text{m}$  during most of the period that predated the rise of oxygen on Earth,<sup>5</sup> and Earth's spectrum also exhibited a deep methane feature, simultaneously with ozone during a 1.5 billion year period after the rise of oxygen.<sup>6</sup> This situation where a reduced species like methane is detected along with O<sub>3</sub> is a very strong indication of a biological release.<sup>7,8</sup> The three strongest bands in the Earth-analog spectrum, O<sub>3</sub> band, CO<sub>2</sub> band, and H<sub>2</sub>O, could all be detected with a spectral resolution of 10–25. Models show that these features are present and vary in important ways in planets covering a broad range of ages and hosted by stars of different spectral types.<sup>4,6</sup>



**Figure 2.** Sources of Photon Noise: The task of nulling interferometry is to reduce the stellar photon noise to a level below other noise sources, while not obscuring the signal from the planet. The noise sources and their relative contributions are shown here.

In addition to its program of planet detection and characterization, the TPF-I mission would have at least 25% of mission time available for a revolutionary program of general astrophysics, providing a sensitivity to rival JWST but with angular resolution of 1–10 mas, depending on wavelength and array configuration. As described in the recent report of the TPF-I Science Working group,<sup>9</sup> such a facility would make dramatic new observations in areas of: 1) Star and planet formation and early evolution; 2) Stellar and planetary death and cosmic recycling; 3) The formation, evolution, and growth of black holes; and 4) Galaxy formation and evolution over cosmic time.

### 3. ARCHITECTURE STUDIES

In the mid-infrared the required angular resolution of  $< 50$  mas would necessitate a single telescope with a primary mirror larger than 40 m across, making an interferometer an obvious choice for the overall design. Nulling interferometry is used to suppress the on-axis light from the parent star, whose photon noise would otherwise overwhelm the light from the planet. Off-axis light is modulated by the spatial response of the interferometer: as the array is rotated, a planet produces a characteristic signal which can be deconvolved from the resultant time series.<sup>10, 11</sup> Images of the planetary system are then formed using an extension of techniques developed for radio interferometry.

Several interferometer implementations have been studied. A structurally-connected version with a deployable 36-m boom was studied (the maximum size that can be accommodated in the shroud of a Delta IV Heavy launch vehicle), but the 90 mas inner working angle and poor angular resolution greatly restricted its capability for finding Earth-like planets. Tethered spacecraft were also considered and rejected. Formation-flying has become the platform of choice for both NASA and ESA, and after many years of study, the architecture for TPF-I that seems the most promising is the X-Array, configured in an out-of-plane geometry known as the Emma design.

#### 3.1. X-Array

An architecture trade study in 2004 favored the X-Array over other architectures.<sup>12</sup> The X-Array is configured as two pairs of telescopes, where each pair acts as a separate nulling interferometer. The distance between

telescopes in each pair therefore can be tuned to best suppress background stellar leakage around the null. Then the distance between one pair and the other can be adjusted to provide the angular resolution necessary to unambiguously isolate the light from a planet. In most other designs, the baselines for nulling are coupled with those that provide the angular resolution — and in those designs it is difficult to simultaneously suppress stellar leakage and have high angular resolution. The X-Array has other advantages: it uses only two types of spacecraft designs, has a simple beam-relay geometry, and its performance degrades gracefully. The X-Array also provides a means of eliminating noise due to “instabilities” in the servo systems that maintain the null. Instability in the null — the analog of speckle noise in a coronagraph — can otherwise mimic the fringe modulation due to the presence of a planet. With the X-Array design, a null depth to  $10^{-5}$  would satisfy the flight requirements.<sup>13</sup>

### 3.2. Emma Design

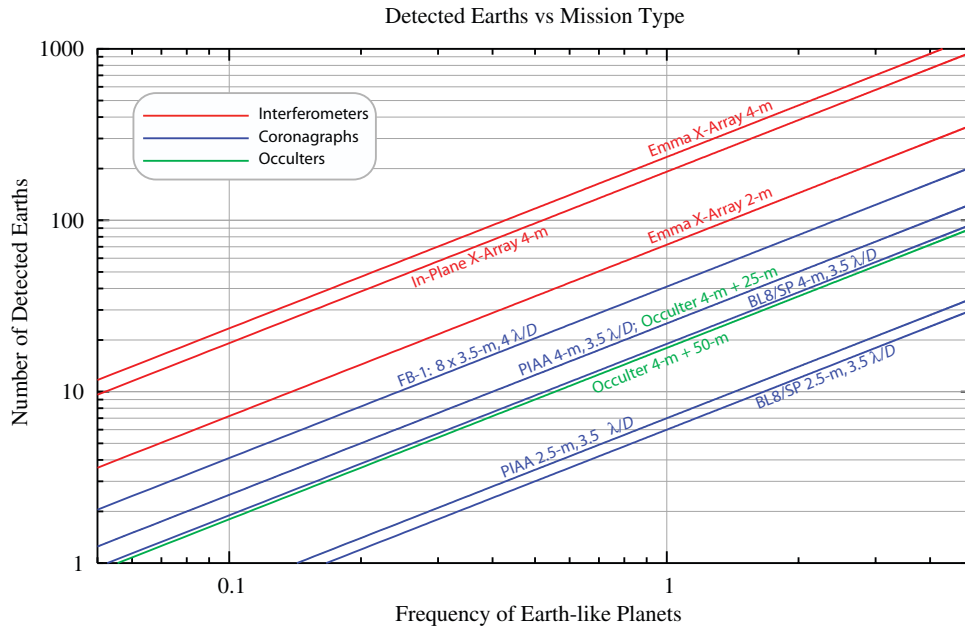
ESA, as part of its design studies, considered the “Emma” architecture, shown in Fig. 1. In this design the combiner is moved out towards the star by about 1 km, and the collectors are reduced to simple spherical mirrors. The Emma design offers significant advantages. Its appeal lies primarily in its simplification of the collector optics: all deployable structures are eliminated and the layered sunshields are protected by a hard shell. The collector diameter can be scaled up or down to suit the mission performance requirements, with minimal impact on the combiner design. The designs of TPF-I and Darwin have now converged on this architecture. The description of Darwin contained in the Darwin *Cosmic Vision* proposal is essentially indistinguishable from the current baseline design<sup>14</sup> for TPF-I. Moreover, the differences that have existed in the performance models for Darwin and TPF-I are now well understood.

## 4. PERFORMANCE MODELING

The integration times required to achieve an SNR of 5 for an Earth-sized planet at the center of the habitable zone, have been calculated for each of 1014 candidate target stars using the TPF-I Interferometer Performance Model.<sup>15</sup> In contrast to a fixed structure or primary mirror, formation-flying interferometry allows a flexible array size that can be tailored to maximize the SNR for each star. The long baselines are sufficient to resolve the habitable zone around all nearby stars. Planets are easiest to detect around nearby K stars. Integration times increase through the A and F stars as a result of the higher stellar leakage. For the Earth-Sun system at 10 pc, 14 hours of integration time is required for detection. The Interferometer Performance Model is the source of requirements on both the flight system and the technology testbeds, and provides inputs to the mission-level model.

The mission-level model estimates the number of target stars observable in a given mission duration.<sup>15</sup> The algorithm optimizes the observing schedule to maximize the number of planets found in the habitable zone. Based on the same completeness analysis developed for TPF-C, the model uses a Monte Carlo distribution of planetary orbits, includes a high-fidelity representation of the instrument, and accounts for which targets are available during each week of the mission. We assume that 2 years of the nominal 5 year mission are set aside for the initial survey, including overheads for re-targeting, calibration, etc. Each target requires only a single visit in the optimized scenario, resulting from the combination of the very small inner working angle and, in the mid-infrared, a constant planet-brightness throughout each orbit. If every star has one Earth-sized planet, randomly distributed over the range of possible habitable orbits, then an Emma X-Array with 2-m collectors can detect an average of 72 Earths by observing 153 target stars. Observations of nearby stars have a completeness close to one, i.e. almost all potentially habitable planets are detected, but as the distance increases it proves to be most productive to observe a larger number of stars at lower completeness than fewer stars at high completeness. In this case the net completeness for the survey is  $\sim 47\%$ . For 4-m collectors the average planet yield increases to 230 with 450 targets. Figure 3 shows how these values compare with various coronagraph and occulter designs, that use the very same optimization. The lines represent the points for one Earth per star, scaled linearly to other values. Candidate detections require 2–3 follow-up observations to establish the orbit and discriminate against background sources. TPF-I’s superior angular resolution and compact inner working angle are ideally suited to the task.

Simultaneous full resolution ( $R\sim 100$ ) spectroscopy for all objects within the field of view is a natural by-product of interferometric observing. While data from the detection and orbit determination phases should be



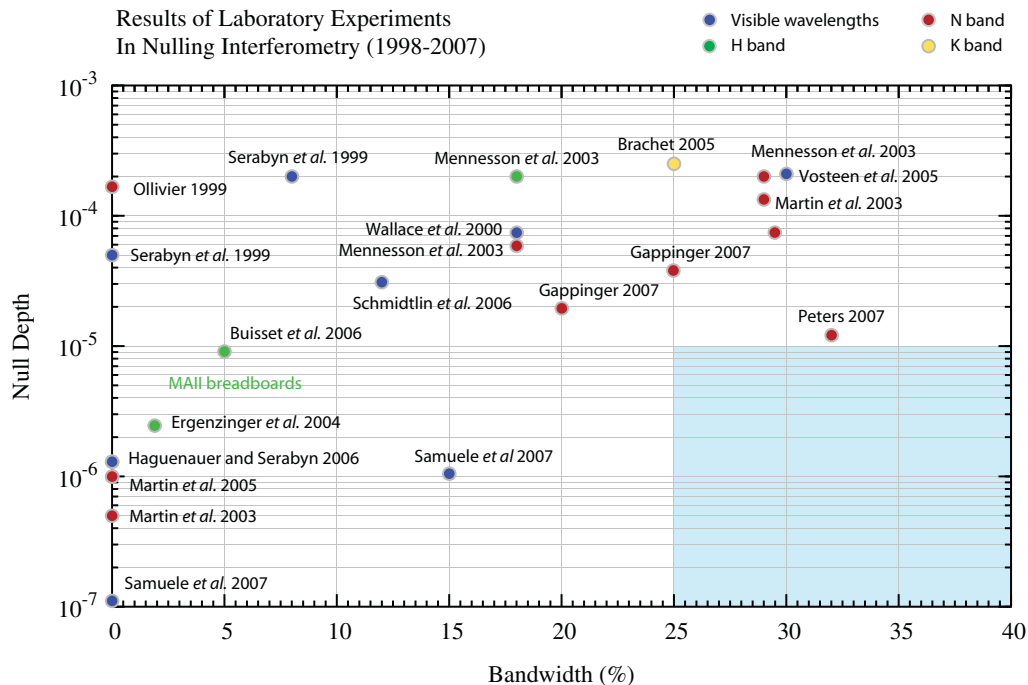
**Figure 3.** Performance of various planet-detection missions. The performance of each mission concept is represented by one data point, calculated with the assumption of there being 1 Earth around very star, and the performance is then scaled linearly to predict the performance for greater or fewer Earth-like planets. A timeline of mission performance for TPF-I is presented elsewhere in these proceedings.<sup>15</sup> “FB-1” is the TPF-C flight baseline design with a  $3.5 \times 8$ -m primary and inner working angle of  $4 \lambda/D$ ; “BL-8” is a band-limited 8th order mask coronagraph; “SP” is a shaped pupil mask coronagraph; “PIAA” is a Phase-Induced Amplitude Apodization coronagraph; the occulters shown here have a 50-m shade at 72,000 km and a 25-m shade at 30,000 km and a 6-day slew (in each case a telescope with a 4-m primary is assumed). The inner working angle in all cases is  $3.5 \lambda/D$ , except for FB-1, which uses  $4\lambda/D$ . In all the examples, the yield scales linearly with the prevalence of Earth-like planets.

sufficient for a coarse spectrum, a deep characterization will require significant integration time. Detection of  $\text{CO}_2$  for an Earth at 5 pc with 2-m collectors will require  $\sim 24$  hours of integration (SNR of 10 relative to the continuum). The narrower ozone absorption line requires 16 days at 5 pc. For ozone at 10 pc, integration times as long as 40 days could be needed, falling to  $\sim 6$  days with 4-m diameter collectors. Integrating deep into the noise for these observations is made possible by the very specific combination of modulations imprinted on the planet signal that distinguish it from the noise: a characteristic low frequency variation from array rotation, the fast switching of phase chopping, and the oscillating wavelength dependence of the interferometric response in the spectral domain.

## 5. TECHNOLOGY FOR STARLIGHT SUPPRESSION

The suite of technology testbeds being undertaken for TPF-I are all being done during Pre-Phase A of the project. For other missions this is equivalent to the *proposal* phase. The work is therefore directed at demonstrating the feasibility of the techniques that will be used. The requirements for the nulling testbeds, described in the following sections, are summarized in Table 2.

The technology of mid-infrared nulling is nearing maturity. This is illustrated by the plot shown in Fig. 4. With TPF-I’s current requirement of nulling at a level of  $1 \times 10^{-5}$ , it is clear that experiments in laser nulling<sup>16</sup> produce results that routinely surpass flight requirements, and that broadband nulling experiments (with the Adaptive Nuller, noted as “Peters 2007”) have produced nulls that only fall short of flight requirements by a factor of 1.2. In May 2007, broadband nulling was demonstrated at a level of  $1.2 \times 10^{-5}$  by the Adaptive Nuller testbed using a 32% bandwidth centered on  $\lambda = 10 \mu\text{m}$ . Interferometric planet detection has also been



**Figure 4.** State of the Art in Nulling Interferometry: Laser experiments have shown that achromatic effects (predominantly pathlength variations) can be controlled in the lab at a level that allows nulls better than  $1 \times 10^{-6}$  to be achieved repeatedly. The best broadband nulls achieved to date have been  $1.2 \times 10^{-5}$ , with the Adaptive Nuller. The laser results therefore exceed the TPF-I requirements, and the broadband results are just shy of the TPF-I goal.

**Table 2.** Comparison of 2007 flight requirements with Pre-Phase A nulling testbed requirements

Parameter	Flight Performance	Achromatic Nuller	PDT	Adaptive Nuller
Null depth	$1 \times 10^{-5}$	$1 \times 10^{-5}$	$1 \times 10^{-5}$	$1 \times 10^{-5}$
Intensity Control	0.13%	Derived	0.12%	0.2% (static)
Phase Control	1.5 nm	Derived	2 nm	5 nm (static)
Stability timescale	50,000 s +	100 s	5,000 s	100 s
Bandwidth	7–17 $\mu\text{m}$	8.3–10.7 $\mu\text{m}$ (25%)	$\lambda = 10.6 \mu\text{m}$	8.4–11.6 $\mu\text{m}$ (32%)

demonstrated in the lab with a four-beam nulling interferometer (the Planet Detection Testbed) using a source for a planet 2 million times fainter than the source representing its star. Mid-infrared single-mode fibers have also been produced in chalcogenide glass, 20-cm long, showing 40% throughput and 30 dB suppression of higher order modes.

### 5.1. Adaptive Nuller Testbed (AdN)

The Adaptive Nuller<sup>17</sup> was conceived as a device that would demonstrate the compensation of wavelength-dependent intensity and phase errors. The concept is to disperse the light in each arm of the interferometer and image each spectrum onto a deformable mirror (DM), using the pixels of the DM to adjust intensity and phase at individual wavelengths. The Adaptive Nuller is shown in Fig. 5(a). In March/April 2007, the AdN reached its goal of demonstrating an intensity compensation to 0.2% and phase compensation to better than 5 nm across a bandwidth of 3 microns in the 8–12  $\mu\text{m}$  band. This was demonstrated in three 6-hour experiments, each spaced a





**Figure 5.** TPF-I Mid-Infrared Broadband Nulling Testbeds. Shown here are the Adaptive Nuller (left) and the Achromatic Nulling Testbed (right).

week apart. The Adaptive Nuller is being modified to improve its performance and attain an average null better than  $1 \times 10^{-5}$ . The Principal Investigator of the Adaptive Nuller is Robert Peters.

### 5.2. Achromatic Nulling Testbed (ANT)

The Achromatic Nulling Testbed<sup>18</sup> is a two-beam nulling interferometer which is currently configured as a Mach-Zehnder interferometer, with a series of rooftop prisms after the first beamsplitter to provide an achromatic  $\pi$  phase shift prior to the recombination of beams. This testbed has been the focus of discussion within the TPF-I group during the past year. Its goal is to reach a null depth of  $1 \times 10^{-5}$ , consistent with the current flight requirements, using a bandwidth of 25% at a central wavelength of  $10 \mu\text{m}$ . The interferometer is pictured in Fig. 5(b). TPF-I Milestone #3 will be the broadband nulling milestone for which the ANT was originally built. However, because of the success of the Adaptive Nuller, the Adaptive Nuller is being adapted to compete for this milestone as well. The ANT has achieved rejection ratios (inverse of the null depth) of 51,000:1 with a 20% bandwidth, and 26,000:1 with a 25% bandwidth. However, its limiting noise source has so far not been identified, and work is ongoing. The Principal Investigator of the Achromatic Nulling testbed is Robert Gappinger.

### 5.3. Planet Detection Testbed (PDT)

The leading candidate architectures for the TPF Interferometer are four-beam nullers that use interferometric chopping to detect planets in the presence of a strong mid-infrared background. The Planet Detection Testbed<sup>19</sup> (PDT) was developed to demonstrate the feasibility of four-beam nulling, the required null stability, and the detection of faint planets using an approach similar to the ones contemplated for a flight-mission. In 2006 the Planet Detection Testbed was in the process of being rebuilt to include new servo loops to stabilize tilt and shear, thus replacing the dither algorithms used previously. Testing of the PDT should be complete by the end of 2007, in preparation for its milestone in early 2008. The Principal Investigator of the Planet Detection Testbed is Stefan Martin.

### 5.4. Mid-Infrared Single-Mode Spatial Filters

The TPF-I project has had several contracts for the development and production of single-mode mid-infrared fibers.<sup>20</sup> As a result of this work the project has approximately 16 high-quality single-mode fibers that include Chalcogenide fibers from the Naval Research Laboratory, and Silver Halide fibers from the University of Tel Aviv. Our Chalcogenide fibers have a 30 dB rejection of higher order modes and a transmission loss of about 8 dB/m. Our Silver Halide fibers have a 25 dB rejection of higher-order modes with transmission losses of about 14 dB/m. All our testing has been at a wavelength of 10 microns. Both the ANT and the Adaptive Nuller use Chalcogenide fibers. The Principal Investigator of TPF-I spatial filter technology is Alexander Ksendzov.

## 6. TECHNOLOGY FOR FORMATION FLYING

### 6.1. Formation Control Testbed (FCT)

The Formation Control Testbed<sup>21</sup> (FCT) is the testing-ground for flight software developed for formation flying for TPF-I. The testbed includes two robots that carry cylinders of compressed air and have linear air bearings to float freely above a polished metal floor. A spherical air bearing supports a stage upon which are housed the avionics and processors of each robot. The robots have a master-slave relationship and algorithms for autonomous guidance. Work in 2006–2007 has included hardware upgrades to the robots to improve the performance of their thrusters, as well as preparations for installation of a new vertical stage for one of the robots, due in August 2007. TPF-I Milestone #2 is the precision performance milestone for the FCT, which is scheduled for late September 2007. The formation flying requirements are largely independent of the requirements for nulling interferometry. Each telescope in the formation will have its own delay line, and a delay of several tens of centimeters, and perhaps as large as a meter, will be available to co-phase the array. The objective for the FCT is to (1) establish relative range control between robots to within 5 cm,  $1\sigma$ ; (2) demonstrate fault-tolerant algorithms; and (3) demonstrate collision-avoidance maneuvers. The robots are now working well in cooperative testing, and should reach these milestones in 2007–2008. The Principal Investigator of the Formation Control Testbed is Daniel Scharf.

### 6.2. SPHERES Guest Scientist Program

SPHERES is a satellite formation flight laboratory developed by the Massachusetts Institute of Technology (MIT) Space Systems Laboratory and currently operating at the International Space Station (ISS). Each twenty-centimeter diameter unit has the full functionality of a nano-satellite with twelve cold-gas thrusters for propulsion, ultrasonic and infrared transmitters and receivers for position sensing, on-board processing, wireless communications, and power storage. Six SPHERES have been built. Three remain on the ground for use at a terrestrial testbed. As of December 2006, three were on the International Space Station. At the ISS, MIT has tested its own algorithms for slew, docking, and station-keeping as well as two-SPHERES formation control, attitude tracking and position following. In April 2007 MIT performed the three-SPHERES formation rotation test.

In 2007, JPL is adapting TPF-I formation algorithms to run on-board the nano-satellites to test aspects of formation guidance and collision avoidance. Prior to testing on the ISS, the TPF-I formation algorithms will be tested in the ground-based laboratory at MIT. Test sessions on the ISS will occur approximately every three months. Therefore, researchers from the TPF-I Project will nominally have four test sessions on the ISS per year, resulting in eight test sessions over two years. Within each test session, 20 minutes of testing time is available. This estimate is conservative based upon past operational experience on the ISS. If more test sessions become available, more test time can be provided to TPF-I. The Principal Investigator for SPHERES is Prof. David W. Miller, the Director of the MIT Space Systems Laboratory, and the Principal Investigator for Formation Flying Algorithms is Dr. Fred Hadaegh of the Jet Propulsion Laboratory.

## 7. COLLABORATION WITH THE EUROPEAN SPACE AGENCY

The Darwin mission has been studied in Europe with support of the European Space Agency since the mid-1990s. Its technology development, design studies, and architecture trades, have been paralleled in the United States by closely similar work for TPF-I. Although the two missions have been distinct, the ties between the two projects have been so strong, that it has been long envisaged that the two missions would be combined through formal agreements between the two agencies. The desire for the two missions to be joined as a single mission is even stated in NASA's strategic plans. In Table 7.2 of the *Science Plan for NASA's Science Mission Directorate 2007–2016*<sup>22</sup> (page 145) TPF-I is described as a “proposed joint project with ESA's Darwin mission.”

A Letter of Agreement between NASA and ESA concerning collaboration between Darwin and TPF-I was in place from March 2002 until December 2006. The intent of the Letter was to facilitate a collaborative selection of the baseline mission architecture, planning of future technology development efforts, and the definition of respective roles and responsibilities for a single mission. Although considerable technological progress was made during this period, many of the programmatic goals were not achieved, due principally to programmatic uncertainties.

## 7.1. The Darwin Cosmic Vision Assessment Phase Study

In 2007 if ESA and NASA support an assessment phase study of Darwin within the Cosmic Vision, the collaboration would continue and lead to the development of a well-defined joint mission concept. The Darwin proposal includes a common baseline design, but does not formally state the role and responsibilities of partners. This division of roles would be established as part of the Assessment Phase, which would conclude in June 2009. During the ESA Assessment Phase, it would be reasonable to assume that a joint ESA/NASA Science Working Group would be established to continue the collaboration and refine the mission concept, further develop key technologies, and refine the science case. During this period the eventual division of responsibilities between ESA and NASA would be defined. The work in this phase probably includes aspects of each of the following:

1. *Architecture and Science Mission Plan:* Through the establishment of a common ESA/NASA Science and Technology Definition Team (STDT), unify the currently separate projects under a single name and resolve the remaining differences between TPF-I and Darwin. This will include:
  - (a) Develop a single unified set of science requirements. There are very few differences between Darwin and TPF-I science requirements, but the remaining differences will need to be resolved.
  - (b) Formally agree upon details of the common baseline architecture design, including the array geometry, beam combination concept, an improved mass model, and an agreed upon launch vehicle.
  - (c) Develop a unified performance estimator for the mission.
  - (d) Develop a unified science mission plan. This will include science planning tools, data reduction tools, as well as a proposed mission time-line for observations.
2. *Technology Demonstration:* Develop component technology and demonstrate at a system level the performance required of 1) mid-infrared nulling interferometry and 2) formation flying, to a Technology Readiness Level of 5–6.
3. *Implementation Strategy:* Develop a common flight design and implementation strategy. This will include
  - (a) Launch accommodation and deployment
  - (b) Integration and test concepts
  - (c) Accommodate programmatic partitioning of the elements of the project
4. *Costing:* Develop a more detailed costing for the mission based on the best current parametric and other costing methods.
5. *Division of Responsibilities:* Propose to NASA and ESA the division of responsibilities that will contribute to the mission. Subjects that are assignable to one agency or the other may include:
  - (a) Lead science center
  - (b) System engineering
    - i. Formation flying systems
    - ii. Optical system engineering
  - (c) Beam combiner spacecraft, including optics
    - i. Nulling planet detection instrument
    - ii. Fringe detection system
    - iii. Fine pointing system
    - iv. General astrophysics science instrument
  - (d) Collector spacecraft
    - i. Service module
    - ii. Optics
  - (e) Integration and test facilities
  - (f) Flight Operations center
  - (g) Launch vehicle

## 8. SUMMARY

Technology development for the Terrestrial Planet Finder Interferometer is proceeding well, and the technology for nulling interferometry is reaching maturity. The performance of the Adaptive Nuller has yielded null depths just shy of the flight requirements and promises to dramatically change the course of our present technology development. Both TPF-I and Darwin now have a common interferometer architecture that reduces the cost and complexity of a mid-infrared formation flying mission. However, all planet-finding missions within the Navigator Program are being reassessed prior to the 2010 Decadal Survey, because of concerns for mission lifecycle costs. Darwin/TPF-I will certainly be a very ambitious mission, and this collaboration is now under review both within NASA and at ESA as part of the *Cosmic Vision* planning.

## ACKNOWLEDGMENTS

The authors would like to thank the TPF-I Science Working Group for their efforts on behalf of the project in 2006–2007. These individuals include R.L. Akeson (Caltech), J. Bally (Univ. Colorado), D. Crisp (JPL), C. Eiroa (Univ. Autónoma de Madrid), P. Falkowski (Rutgers), P.M. Hinz (Univ. Arizona), J.M. Hollis (NASA/GSFC), D.C. Hyland (Texas A&M), B.F. Lane (MIT), G. Laughlin (UCSC), R. Liseau (Univ. Stockholm), J.D. Monnier (Univ. Michigan), A.C. Quillen (Univ. Rochester), H.J.A. Röttgering (Univ. Leiden), D.J. Wilner (Harvard CfA), and N.J. Woolf (Univ. Arizona). This paper is partly based on a whitepaper presented to the ExoPlanet Task Force, which included contributions from A. Léger (IAS), O. Absil (LAOG), D. Defrère (Univ. de Liège), L. Kaltenegger (CfA), and F. Selsis (ENS Lyon).

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Reference in this paper to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

## REFERENCES

1. P. R. Lawson, A. Ahmed, R. O. Gappinger, A. Ksendzov, O. P. Lay, S. R. Martin, R. D. Peters, D. P. Scharf, J. K. Wallace, and B. Ware, “Terrestrial Planet Finder Interferometer: Technology status and plans,” in *Advances in Stellar Interferometry*, J. Monnier, M. Schöller, and W. Danchi, eds., *Proc. SPIE* **6268**, p. 626828, 2006.
2. F. Selsis, D. Despois, and J.-P. Parisot, “Signature of life on exoplanets: Can Darwin produce false positive detections?,” *Astron. Astrophys.* **388**, p. 985, 2002.
3. D. J. Des Marais, M. O. Harwit, K. W. Jucks, J. F. Kasting, D. N. C. Lin, J. I. Lunine, J. Schneider, S. Seager, W. A. Traub, and N. J. Woolf, “Remote sensing of planetary properties and biosignatures of extrasolar terrestrial planets,” *Astrobiology* **2**, pp. 153–181, 2002.
4. A. Segura, K. Krelove, J. F. Kasting, and et al., “Ozone concentrations and ultraviolet fluxes on Earth-like planets around other stars,” *Astrobiology* **3**, p. 689, 2003.
5. A. A. Pavlov, J. F. Kasting, L. L. Brown, K. A. Rages, and R. Freedman, “Greenhouse warming by CH<sub>4</sub> in the atmosphere of early Earth,” *J. Geophys. Res.* **105**, pp. 11981–11990, 2000.
6. L. Kaltenegger, W. A. Traub, and K. W. Jucks, “Spectral evolution of an Earth-like planet,” *ApJ* **658**, p. 598, 2007.
7. J. E. Lovelock, “The recognition of alien biospheres,” *Cosmic Search* **2**(4), p. 2, 1980.
8. C. Sagan, W. R. Thompson, R. Carlson, D. Gurnett, and C. Hord, “A search for life on Earth from the galileo spacecraft,” *Nature* **365**, pp. 715–721, 1993.
9. P. R. Lawson, O. P. Lay, K. J. Johnston, and C. A. Beichman, *The Terrestrial Planet Finder Science Working Group Report*, Jet Propulsion Laboratory, Pasadena, California, 2007. JPL Pub 07-1.
10. R. N. Bracewell, “Detecting nonsolar planets by spinning infrared interferometer,” *Nature* **274**, p. 780, 1978.
11. N. Woolf and J. R. Angel, “Astronomical searches for Earth-like planets and signs of life,” *Ann. Rev. Astron. Astrop.* **36**, p. 507, 1998.

12. O. P. Lay, S. M. Gunter, L. A. Hamlin, C. A. Henry, Y. Li, S. R. Martin, G. H. Purcell, B. Ware, J. A. Wertz, and M. C. Noecker, "Architecture trade study for the Terrestrial Planet Finder Interferometer," in *Techniques and Instrumentation for Detection of Exoplanets II*, D. R. Coulter, ed., *Proc. SPIE* **5905**, pp. 8–20, 2005.
13. O. P. Lay, "Removing instability noise in nulling interferometers," in *Advances in Stellar Interferometry*, J. D. Monnier, M. Schöller, and W. C. Danchi, eds., *Proc. SPIE* **6268**, p. 62681A, 2006.
14. S. R. Martin, "TPF-Emma: concept study of a planet finding space interferometer," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. these proceedings, 2007.
15. O. P. Lay, S. R. Martin, and S. L. Hunyadi, "Planet-finding performance of the TPF-I Emma architecture," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. these proceedings, 2007.
16. S. R. Martin, R. O. Gappinger, F. M. Loya, B. P. Mennesson, S. L. Crawford, and E. Serabyn, "A mid-infrared nuller for the Terrestrial Planet Finder: Design, progress, and results," in *Techniques and Instrumentation for Detection of Exoplanets*, D. R. Coulter, ed., *Proc. SPIE* **5170**, pp. 144–154, 2003.
17. R. D. Peters, O. P. Lay, and M. Jeganathan, "Adaptive nulling in the mid-ir for the Terrestrial Planet Finder Interferometer," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. these proceedings, 2007.
18. R. O. Gappinger, R. T. Diaz, S. R. Martin, F. M. Lloya, and P. R. Lawson, "Current progress on TPF-I achromatic nulling at the Jet Propulsion Laboratory," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. these proceedings, 2007.
19. S. R. Martin, P. Szwajkowski, F. M. Loya, and K. Liewer, "Progress in testing exo-planet signal extraction on the TPF-I Planet Detection Testbed," in *Advances in Stellar Interferometry*, J. Monnier, M. Schöller, and W. Danchi, eds., *Proc. SPIE* **6268**, p. 626818, 2006.
20. A. Ksendzov, E. Bloemhof, V. White, J. K. Wallace, R. O. Gappinger, J. S. Sanghera, L. E. Busse, W. J. Kim, P. C. Pureza, V. Q. Nguyen, I. D. Aggarwal, S. Shalem, and A. Katzir, "Measurement of spatial filtering capabilities of single mode infrared fibers," in *Advances in Stellar Interferometry*, J. Monnier, M. Schöller, and W. Danchi, eds., *Proc. SPIE* **6268**, p. 626838, 2006.
21. D. P. Scharf, J. A. Keim, F. Y. Hadaegh, E. G. Benowitz, and P. R. Lawson, "Flight-like ground demonstration of precision formation flying spacecraft," in *Techniques and Instrumentation for Detection of Exoplanets III*, D. R. Coulter, ed., *Proc. SPIE* **6693**, p. these proceedings, 2007.
22. *Science Plan for NASA's Science Mission Directorate 2007–2016*, National Aeronautics and Space Administration, Washington, DC, 2007. [http://science.hq.nasa.gov/strategy/Science\\_Plan\\_07.pdf](http://science.hq.nasa.gov/strategy/Science_Plan_07.pdf).