# Status of the Terrestrial Planet Finder Interferometer (TPF-I)

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## ABSTRACT

The interferometric version of the Terrestrial Planet Finder (TPF-I) has the potential to find and characterize earth-sized planets in the habitable zones of over 250 nearby stars and to search for life using biomarkers in the atmospheres of any planets found. The scientific case for such a mission continues to be strengthened by on-going progress in the detection of planets via indirect means. This paper summarizes the status of TPF-I, illustrative scientific requirements for the mission, and its enabling technologies.

**Keywords:** Terrestrial Planet Finder (TPF), planets, infrared, interferometry, formation flying, nulling

## 1. INTRODUCTION

The intellectual promise of the interferometric version of the Terrestrial Planet Finder (TPF-I) is no less than a revolution in our conception of humanity's place in the Universe. Simply by detecting the mid-infrared (6-18 μm) radiation from Earth-like planets orbiting in the habitable zones of nearby solar type stars in a few broad spectral bands, we will be able to determine directly their size and temperature. With low resolution spectroscopy (R~25) we will be

**Table 1.** Planetary Characteristics Measured By Various Planet-Finding Missions[1]

| | SIM | TPF-C | TPF-I |
|---|---|---|---|
| *Orbital Parameters* | | | |
| Stable orbit in Hab. Zone | **Measurement**[2] | **Measurement** | **Measurement** |
| *Characteristics for Habitability* | | | |
| Planet temperature | Estimate[3] | Estimate | **Measurement** |
| Temperature variability due to eccentricity | **Measurement** | **Measurement** | **Measurement** |
| Planet radius | *Cooperative*[4] | *Cooperative* | **Measurement** |
| Planet albedo | *Cooperative* | *Cooperative* | *Cooperative* |
| Planet mass | **Measurement** | Estimate | Estimate |
| Surface gravity | *Cooperative* | *Cooperative* | *Cooperative* |
| Atmospheric and surface composition | *Cooperative* | **Measurement** | **Measurement** |
| Time-variability of composition | | **Measurement** | **Measurement** |
| Presence of water | | **Measurement** | **Measurement** |
| *Solar System Characteristics* | | | |
| Influence of other planets, orbit coplanarity | **Measurement** | Estimate | Estimate |
| Comets, asteroids, and zodiacal dust | | **Measurement** | **Measurement** |
| Indicators of Life | | | |
| Atmospheric biomarkers | | **Measurement** | **Measurement** |
| Surface biosignatures (red edge of vegetation) | | **Measurement** | |

**1**Reproduced from Traub et al. 2006; **2"Measurement"** indicates a directly measured quantity from a mission; 3"*Estimate*" indicates that a quantity that can be estimated from a single mission; and 4"*Cooperative*" indicates a quantity that is best determined *Cooperative*ly using data from several

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able to look for prominent spectral features of carbon dioxide, ozone, and water in quantities equal to or significantly less than are present in the atmosphere of our Earth, and possibly find methane in the large amounts thought to have been present on the primitive Earth. In conjunction with the Space Interferometer Mission (SIM PlanetQuest) and the Terrestrial Planet Finder-Coronagraph (TPF-C), TPF-I would complete the initial characterization of nearby terrestrial and gas-giant planets and the first look for signposts of life (Table 1; Traub et al. 2006, Beichman et al. 2006a).

TPF-I, which is presently conceived as an international collaboration with ESA's Darwin project, achieves its sensitivity by using 3 or 4 cold telescopes of ~3-4 m aperture operating as a nulling interferometer to reject starlight to a level of $10^{-5}$ - $10^{-6}$ (Beichman, Woolf and Lindensmith 1999). A constellation of three to four telescopes located on their own spacecraft together with a beam combiner spacecraft flying in closely controlled formation with baselines between 20 and 500 m is envisioned. With such a system it would be possible to survey as many as 250 stars with 3 visits per star to ensure high completeness in a 5 year mission, to carry out follow-up spectroscopy on at least a two dozen detected planets, and make imaging observations of many targets for general astrophysics. TPF-I complements its coronagraphic sibling, TPF-C, in wavelength coverage but also in the stars it can observe. With its flexible and long baselines, TPF-I can achieve angular resolution 3-5 times smaller than TPF-C bringing the habitable zones of more distant stars or later spectral types into view.

In this brief summary of the status of TPF, we describe some of the scientific requirements (Section 2), the various architectural trade-offs presently being considered to maximize sensitivity in the presence of various sources of random and systematic noise (Section 3); the status of the "physics experiment" underlying the entire concept of TPF (Section 4), interferometric nulling; the status of the formation flying that allows the interferometer to be reconfigured between observations on baselines from tens to hundreds of meters (Section 5); and a brief update on the programmatics for TPF (Section 6).

**Table 2.** Illustrative TPF-I Science Requirements

| *Key Parameter* | *TPF-I* |
|---|---|
| Star types | F G K & others |
| Habitable Zone | 0.7--1.5 AU scaled as $L^{1/2}$ |
| # stars to search | 150-250 stars |
| Completeness for each star | 90% |
| Minimum # visits per target | 3-5 |
| Minimum planet size | 0.5-1 Earth Area |
| Geometric albedo | Earth's |
| Color | At least 3 bands |
| Spectral range and resolution | 6.5-18 μm R=25 [50] |
| Characterization completeness | Spectra of 50% of detected planets |
| Giant planets | Jupiter flux, 5 AU, 50% of stars |
| Maximum tolerable exozodi | 10 times solar system zodiacal cloud |

## 2. SCIENCE CONSIDERATIONS

### 2.1. Summary Science Requirements

Table 2 lists illustrative science requirements for TPF-I developed by the TPF-I Science Working Group. These "requirements" define the properties of the mission consistent with the goals of finding and characterizing habitable planets orbiting nearby stars and searching for signs of life in any detected planets.

### 2.2. TPF-I Target Stars

There are numerous lists of plausible stellar targets for the various planet finding efforts: TPF-C, TPF-C/Darwin, Space Interferometer Mission (SIM), or the search for extra-terrestrial intelligence (SETI; Turnbull and Tarter 2003). Each can be optimized for the strengths and weaknesses of the particular facility (Traub et al. 2006) or for different scientific goals, e.g. an unbiased survey for planets or a highly targeted survey for life. Astro-engineering details will also play a role in target selection, e g. the amount of exo-zodiacal emission which could mask a planet's signal or a star's location in the galaxy which might result in confusion by background stars or relative to the ecliptic plane which might demand an unacceptable spacecraft configuration with regard to solar heating. The final target selection will include considerations as listed in Table 3 (Beichman et al. 2006a) which includes tentative ranges for some parameters. When

**Table 3.** Key Target Star Properties for Habitable Planet Search

| | | | |
|---|---|---|---|
| **Stellar Age** | >1 Gyr for reduced zodiacal emission; development of life | **Evolutionary Phase*** | Dwarf or sub-giant |
| **Spectral Type*** | F-K, some M stars | **Metallicity** | Optimize [Fe/H]> for planet fraction |
| **Variability*** | $\Delta$V<0.1 mag | **Giant Planet Companions*** | None close to habitable zone |
| **Distance*** | < 30 pc for planet brightness, angular separation | **Background Confusion** | Avoid confusion from stars (low galactic latitude) or background galaxies |
| **Multiplicity*** | Nothing within 10" for stable planetary orbits and instrumental confusion effects | **Position in Ecliptic*** | <45 deg for telescope cooling |
| **Exo-zodiacal Emission** | <10-20 times solar system level for noise, confusion | | |

**Parameters included in initial culling of Hipparcos catalog*

these parameters marked with an asterisk are imposed on the stars in the Hipparcos catalog, approximately 620 potential TPF targets remain.

The level of exo-zodiacal emission around TPF targets is not yet known since Spitzer Observations are not precise enough to separate photospheric emission from levels of zodiacal emission in the habitable zone less than 1,000 times that of our own solar system (Beichman et al. 2006b). Observations with ground-based nulling interferometers such as the Keck Interferometer and the Large Binocular Interferometer will be able to reach levels around 10 times our solar system's zodiacal cloud at 10 μm to gather important precursor information on this topic.

Operating on separated spacecraft and using a nulling architecture that allows it to operate with a small inner working angle, TPF-I excels in its angular resolution. For example, operating over a 100 m baseline at 10 μm, TPF-I could resolve an inner working angle of λ/Baseline~25 mas, corresponding to the 1 AU center of the habitable zone around a solar twin at 40 pc or to the 0.25 AU habitable zone of an M star at 10 pc. In this case TPF-I's Inner Working Angle is more than 2 times smaller than the 65 mas presently being considered for the TPF-C coronagraph.

Potential target stars for TPF-I, TPF-C, and SIM are shown in Figures 1 and 2. Figure 2 shows that there is a great deal of overlap between the three mission in the stars studied which is critical to achieve the synergies suggested in Table 1. Approximately 250 stars with open circles (Figure 1) could be observed in the first 2 years of TPF-I's mission with the configuration described below**.** Each star would be visited 3 times to cover the orbits of planets in the system adequately to reject

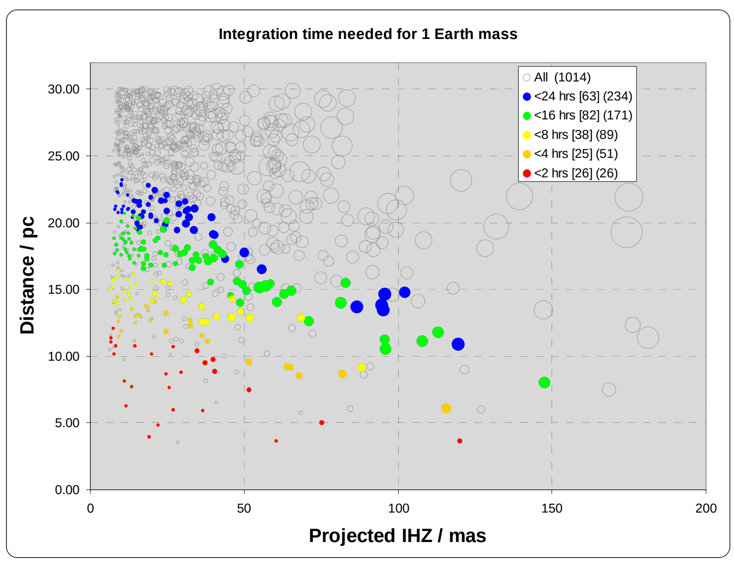


**Figure 1.** The integration times needed to obtain a 5 σ detection of an Earth-size plant at the center of the habitable zone is shown for a sample of nearby stars. Color are used to denote integration times from <2 hours up to 24 hours. Unfilled circles denote stars that cannot be observed due to effects such as ecliptic position, multiplicity, etc. The diameter of the circle is proportional to stellar diameter. In the legend the numbers in brackets correspond to the number of stars in each integration time bin; the numbers in parenthesis give the cumulative number of stars.

background sources, to determine planetary orbits, and to ensure >90% completeness in identifying Earth-sized planets. The remaining time in a nominal 5 year mission would be spent on spectroscopic follow-up observations of up to a few dozen planets detected in the first round of surveying and on general astrophysical investigations. Depending on when TPF-I flies with respect to TPF-C and SIM, TPF-I's target list would be adjusted to characterize already known planets.

## 2.3. Wavelength Coverage

The wavelength coverage of TPF is a challenging tradeoff between astronomical and astrobiological *desiderata* (Figure 3) on the one hand and engineering difficulties on the other. At a minimum, we need adequate wavelength coverage in three broad band colors to define the emission from the planet as that of a blackbody at some temperature, perhaps modified by the presence of atmospheric absorption. From these data alone it would be possible to characterize the gross physical properties of a planet such as its radius and temperature (Table 1), and from multiple observations estimate its orbital parameters.

For the brightest sources, we would like to observe spectral features such as water vapor (7 and 20 μm), carbon dioxide (16 μm), ozone (9.8 μm), methane (7.6 μm), and even nitrous oxide (8 μm). The latter three species are considered important tracers of organic processes (Des Marais et al. 2001; Kasting and Catling 2003). Proper detection of all these species would require wavelength coverage as short as 6 μm which will be difficult due to the rapidly falling planet signal and the steeply increasing stellar signal which together make the nulling extremely challenging. At the long wavelength end, the demands for telescope cooling to below 40 K and for operation at baselines longer than 100 m present their own challenges. On-going engineering studies are exploring the limits of performance at each end of the spectrum. Finally, higher spectral resolution (R>100) than is likely possible will be needed to find methane and particularly nitrous oxide in

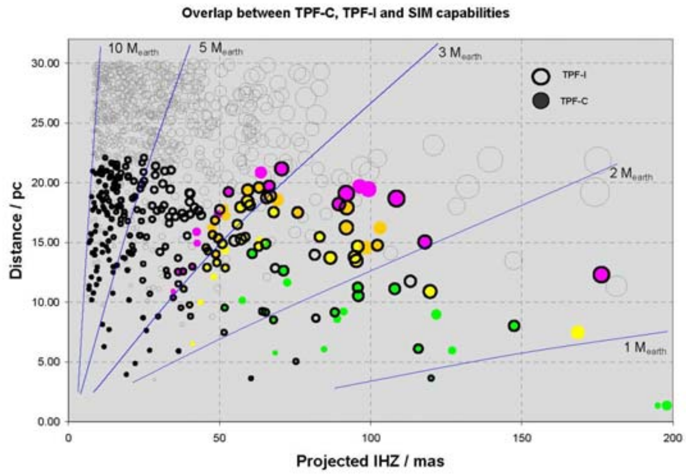


**Figure 2.** Similar to Figure 1 but with the addition of targets suitable for TPF-C (filled circles with colors denoting various degrees of completeness). TPF-I targets are shown as bold, outlined circles. Also indicated are lines of constant astrometric signal for planets of a particular mass in the center of the habitable zone which might be detectable by SIM (Catanzarite et al. 2006). At least 35 stars are observable in common between the three missions ensuring that the synergy goals of Table 1 will be achievable on a good sample of planets.

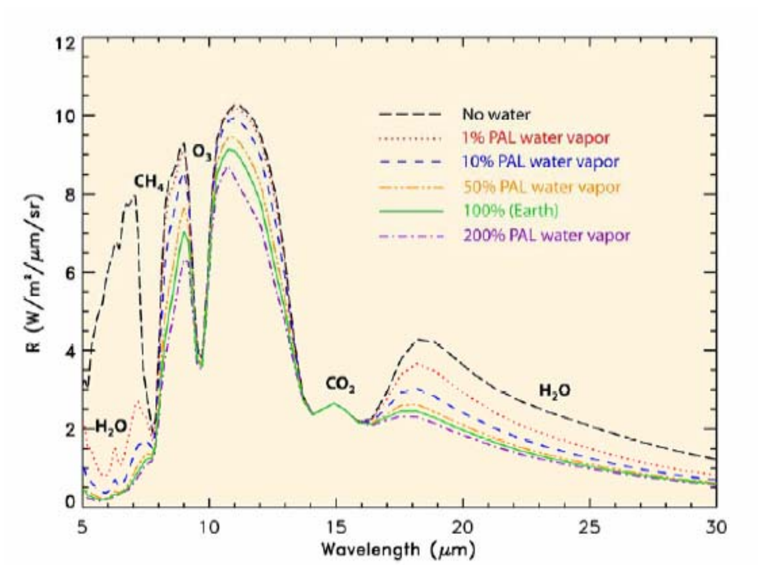


**Figure 3.** A mid-infrared spectrum of an earth-like planet under a variety of assumptions about the amount of water vapor present in the atmosphere. In the complete absence of water vapor, the spectrum shows a pronounced feature due to methane at 7.6 μm (Tinetti et al. 2006 and refs. therein).

the presence of other species such as water. At a minimum, R=25 is required to detect water, carbon dioxide, ozone, and large abundances of methane. Observations at R=50 would be highly desirable and possible from a signal to noise standpoint for the brightest planets.

## 3. ARCHITECTURE TRADE-OFFS

The design team and Science Working Group have examined a number of possible TPF-I designs (Lay et al. 2005) including a Linear Dual Chopped Bracewell (DCB) and the X-Array. Both the DCB and the X-array use four 4-m telescopes cooled to 40 K on separated telescopes operating across distances between 20 and 150 m. Longer baselines up to 200 m are favored for the ability to decrease effects of confusion by multiple planets or exo-zodiacal emission (Lay 2005). The dimension of the longest possible baseline depends on the details of the beam transport and scattered light rejection (Noecker and Leitch, 2005). The currently favored design is the X-array (Lay and Dubovitsky 2004) although this concept has not yet been studied in as much detail as the Linear DCB. The primary advantages of the X-array include the ability to separate the stellar nulling baseline (~35 m along the narrow dimension of the X) from the imaging baseline (100-200 m) thus allowing good angular resolution to reduce confusion effects while not suffering greater stellar leakage (Velsuamy, Beichman, Shao 2000).

Lay (2004) has examined a wide variety of noise sources in the nulling interferometer. Among the most significant are the so-called "instability noise" terms which cannot removed by simple phase chopping schemes. These second-order instrumental effects corrupt the phase and amplitude of the incident wavefronts, resulting in time-variable stellar leakage that can mimic a planet signal. Instability noise currently drives the instrument performance and requires a null depth of $\sim 10^{-6}$. A stretched X-Array with longer imaging baselines, combined with an additional filtering step in the signal processing, can remove almost all the instability noise with minimal impact on the planet signal (Lay 2006), making it possible to relax the nulling requirement from $10^{-6}$ to the $10^{-4}$ and $10^{-5}$ levels already achieved in the laboratory testbeds. This noise filtering is a highly desirable attribute of the X-array.

## 4. STATUS OF IR NULLING

The *Achromatic Nulling Testbed* (ANT) is exploring three separate approaches to broadband mid-infrared nulling with the goal of achieving a $1.0\times10^{-6}$ null across a 25% bandwidth which is close to the $7.5\times10^{-7}$ flight requirement described in the TPF-I Technology Plan (see Lawson et al., this conference). The three approaches include: 1) using a pair of dispersive plates to apply a wavelength-dependent delay; 2) using a through-focus field-flip of the light in one arm of the interferometer; and 3) using successive and opposing field-reversals on reflection off flat optics through a periscope-like set of mirrors.

Since October 2005, efforts with the ANT have been devoted to the third approach, the periscope nuller. The periscope nuller has so far achieved broadband nulls in unpolarized light of about 15,000:1 with a 25% bandwidth. Although this is the best broadband null that any group including ourselves have achieved so far, it also falls well short of our intermediate goal of arriving at 100,000:1 broadband nulls by September 2006. A 10 micron laser was recently used in conjunction with 10-micron polarizers to diagnose the testbed's limitations. These tests revealed that the periscope nuller is very sensitive to misalignment errors. Further, the tests showed that 200,000:1 single-polarization laser nulls are possible through the same

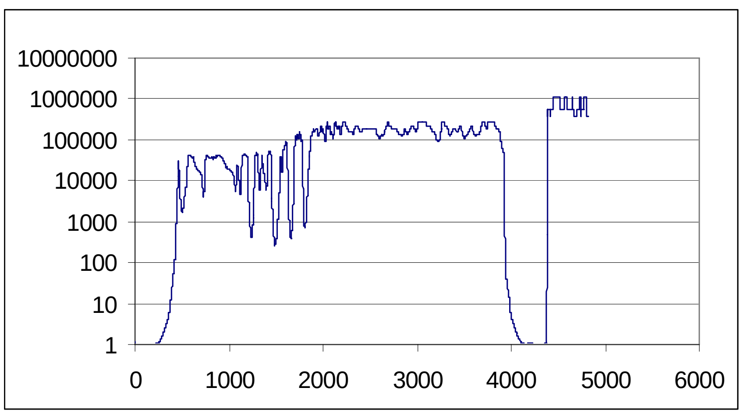


**Figure 4 .** The Achromatic Nuller Testbed (ANT) has produced nulls with a 200,000:1 null achieved in 10 µm laser light and a 15,000:1 null at 25% bandwidth.

optics without any adjustments. The ANT is now undergoing a fine realignment that should be completed in July 2006. The diagnostic tests and error-budget analyses have shown where improvements can be made. Broadband nulls of 100,000:1 are expected later in 2006.

The Planet Detection Testbed (PDT) is being developed as a nulling system-testbed to demonstrate 4-beam nulling, chopping, active control, and the detection of a simulated planet signal (see Martin et al., this conference). Its goals are well aligned with understanding, characterizing, and correcting the effects of instability noise. Since the PDT is not attempting to duplicate the deep broadband nulls of the ANT, laser light can be used. In June-August 2005, null depths greater than 100,000:1 using 4 beams combined simultaneously and a simulated planet was detected that was two million times fainter than the simulated star. The planet detection demonstration in this case did not use interferometric chopping, and so will be repeated in July 2006 with the complete control system of the testbed including tilt and shear compensation.

## 5. ADVENTURES IN FORMATION FLYING

As an enabling technology for separated aperture interferometry for TPF-I, the principal objective of formation flying is to control the relative locations and orientation of multiple collectors and combiner spacecraft so that the beams of starlight that are sampled by each telescope travel the same distance to the beam combiner (Scharf et al. 2004; Aung et al. 2004). At the beam combiner, each optical beam will have its own delay line, with tens of centimeters of adjustable delay so that the separated spacecraft need only be controlled in their relative positions at the level of several centimeters. Fringes can then be found on each baseline using a multi-stage pathlength servo with piezo-electric transducers, or equivalent, to provide nanometer-level control.

Multiple spacecraft in a formation necessitates a distributed architecture for relative sensing, communications, and control. Each spacecraft must sense the relative location of its neighbors and relay this information to each of the other spacecrafts. A hierarchical and distributed precision formation control algorithm is needed to guide the maneuvers. The maneuvers must also be orchestrated to conserve and balance the consumption of propellant amongst the elements of the array. The overall formation system architecture needs to support a high degree of system robustness. Specialized abilities, such as autonomous on-board “lost in space” formation acquisition and collision avoidance, must be designed into the control algorithms to make the system fault-tolerant and to avoid a catastrophic mission.

To develop and validate the distributed formation control architecture with the requisite sensing, communication and control capability, two complementary testbeds have been under development at JPL: the Formation Algorithms and Simulation Testbed (FAST) – a high fidelity distributed real-time simulation testbed,; the Formation Control Testbed (FCT) – a multiple 6-DOF Robots hardware testbed.

The FAST and the FCT develop, demonstrate and validate an end-to-end formation control system with a focus on meeting specific functional and performance requirements for TPF-I. With detailed modeling and development of key formation estimation, guidance and control algorithms, FAST demonstrates the feasibility of five spacecraft TPF-I formation flight performance in simulation. Additionally, FAST models and simulates to predict the performance of FCT multi-robot based hardware-in-the-loop formation flying performance. In turn, FCT test results are used to refine and validate the FAST simulation based predictions. With the FAST implemented formation control architecture and algorithms validated by FCT test results, the FAST simulation can predict a TPF-I five spacecraft flight performance with higher confidence.

### 5.1 Formation Algorithms and Simulation Testbed (FAST)

The Formation Algorithms & Simulation Testbed (FAST) provides a high-fidelity end-to-end software simulation environment to demonstrate realistic mission scenarios of formation flying interferometers including formation acquisition, formation calibration, formation maneuvering, re-configuration, collision avoidance, and nominal observation. FAST uses a common modeling environment and code base to simulate both the TPF flight system and the

Formation Control Testbed robots (Wette et al. 2004). The comparison against FCT experimental data will validate the FAST and bring confidence to performance predictions generated by the TPF-I simulation**.**

### 5.2 Formation Control Testbed (FCT)


**Figure 6.** Two robots are now operating as in tandem in the Formation Control Testbed at JPL.

The Formation Control Testbed is a ground-based laboratory consisting of multiple 6-DOF robots to emulate the TPF-I spacecraft. The FCT Robot hardware is designed to demonstrate TPF-I like formation maneuvering and collision-free operations using the formation algorithms developed in the FAST. A high level of relevance to actual flight hardware was designed into the FCT avionics with on-board flight-like capabilities: a) wireless communication emulating inter-spacecraft and spacecraft-to-ground communication; b) on-board sensing and actuation using star tracker, gyros, thrusters and reactions wheels for attitude; and c) a PowerPC flight control computer on a compact PCI bus under vxWorks Realtime operating system. With multiple FCT robots, FCT will validate the FAST algorithms and the end-to-end formation flying architecture. To emulate the real spacecraft dynamics, the FCT testbed was designed for realistic dynamical behavior, mobility, and agility using linear and spherical air-bearings. With 6 degrees-of-freedom dynamical motion and functional similarity to the TPF spacecraft, the FCT testbed will provide direct emulation of both individual spacecraft and formation behavior under autonomous on-board control. These architectural, functional, and dynamical similarities between the FCT and the TPF will provide a direct migration path of the FCT validated integrated formation control architecture and algorithms to the TPF flight system.

The FCT Robots provide capability for ground validation of end-to-end formation control architecture and algorithms to raise the technology maturity to mid-TRLs – suitable for flight demonstration. Other efforts are planned to perform validation of similar technologies in-orbit. One such example of such a technology validation mission is Prisma mission by the Swedish National Space Board (SNSB) with a planned launch of 2008. Prisma mission consists of a target and a chase spacecraft with on-board optical and RF formation sensors.

### 5.3 Current Status

Two-spacecraft formation control simulation in a flight-like distributed realtime simulation has been completed and demonstrated in FAST. Additionally, a 2-Robot FCT realtime simulation has also been successfully demonstrated as a step toward validating the FAST algorithms against the FCT hardware. Two-Robot based Formation Control has been recently demonstrated at a functional level. Work is underway to perform detailed calibration of the Robots G&C hardware (thrusters, reaction wheels, star tracker, gyros etc.) to achieve the required performance of 5 cm/5arcmin level of control by the end of FY06.

## 6. PROGRAMMATICS

Our European colleagues are well along in developing their version of TPF-I called DARWIN. Scientists in the US and Europe have developed a strong cooperation on TPF-I/Darwin. A Letter of Agreement between NASA and ESA for development of this mission has placed common members both ESA's TE-SAT and NASA's TPFI-SWG. Industrial studies are underway in Europe with the aim of selection of Darwin as a major mission in ESA's Cosmic Vision program.

The TPF-I Science Working Group recognizes that the mission's technical challenges plus the present budgetary environment mean that TPF-I will not be built soon. However, we feel strongly that NASA must maintain a minimum level of support to ensure progress in three key areas: technology development for nulling and formation flying; science studies to ensure TPF-I's observing capabilities (sensitivity, wavelength coverage, angular and spectral resolution) are appropriate to the goals of planetary characterization and the search for signs of life, while also being able to do cutting edge general astrophysics; and mission studies to ensure that TPF-I is capable, affordable, and low risk.

## 7. CONCLUSIONS

The scientific goals of TPF and its critical technologies have been carefully studied since its initial review and endorsement by the 2000 NRC Decadal Review. Since that time, the scientific motivation for the mission has become ever more compelling with the discovery of almost 200 extra-solar planets with ever lower masses and ever increasing orbital radii. We are approaching the ability, through indirect means, of identifying true solar system analogs. The conclusion that earth-like planets must be common, i.e. more frequent than the minimum 10% assumed in scaling many of the key attributes of TPF-I, seems inescapable. In addition, enormous progress has been made in the key technology of interferometric nulling with laboratory testbeds at JPL and in Europe achieving stable, broadband nulls at the $10^{-4}$ - $10^{-5}$ level, within a factor of a few of the desired levels. Significant progress has also been made in the areas of operating interferometers on moving platforms and demonstrating formation flying using flight-like hardware and software with sophisticated robotic testbeds. Our European colleagues will be demonstrating critical aspects of formation flying on orbit in 2008 with a Swedish-led technology mission called Prisma. Depending on programmatic issues such as technical readiness and international agreements, TPF-I could be launched late in the next decade either before or after TPF-C.

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