NASA’s Terrestrial Planet Finder Missions

D. Coulter
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109

ABSTRACT

NASA has decided to move forward with two complementary Terrestrial Planet Finder (TPF) missions, a visible coronagraph and an infrared formation flying interferometer. These missions are major missions in the NASA Office of Space Science Origins Theme. The primary science objectives of the TPF missions are to search for, detect, and characterize planets and planetary systems beyond our own Solar System, including specifically Earth-like planets.

1. INTRODUCTION

One of the most profound questions of our time is whether or not Earth-like planets—habitable or already life-bearing—exist elsewhere in the universe. One of the elements of NASA’s New Vision for Space Exploration, articulated earlier this year, is to conduct advanced telescope searches for Earth-like planets and habitable environments around other stars. NASA’s Origins Theme1 in the Office of Space Science seeks to address this subject from a scientific perspective. The scientific motivation for such endeavors has been discussed in a series of reports over the past decade including: The Search for Life’s Origins2; TOPS: Toward Other Planetary Systems3; A Roadmap for Exploration of Neighboring Planetary Systems (ExNPS)4; HST and Beyond5; and, Terrestrial Planet Finder- Origins of Stars Planets and Life6.

The specific goal of the TPF missions is to search for and characterize Earth-like planets as well as explore and understand the formation and evolution of planetary systems and ultimately, of life beyond our Solar System. Their primary objective is to detect radiation from any Earth-like planets located in the habitable zones surrounding nearby stars. Following detection, they will characterize the orbital and physical properties of the detected planets to assess their habitability and characterize their atmospheres to search for potential biomarkers among the brightest Earth-like candidates. Having both visible data from the coronagraph and infrared data from the interferometer will enable scientists to develop a complete picture of the physical characteristics of detected planets and their atmospheres and will provide a robust assessment of biomarkers and the possibility of life.

A secondary, but very important objective of the TPF missions is to detect radiation from and characterize a variety of solar system constituents in addition to Earth-like planets. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, e.g., both gas giant and terrestrial planets, and debris disks. Some of this information, such as the properties of debris disks and the masses and orbital properties of gas-giant planets, will become available with currently planned space or ground-based facilities. However, the spectral characterization of most giant planets will require observations by the TPF missions. The ability to carry out a program of comparative planetology across a range of planetary masses and orbital locations in a large number of new solar systems is by itself an important scientific motivation for the mission.

Finally, the TPF missions will be able to collect data on a variety of targets of general astrophysics interest. Observatories with the power to detect an Earth-like planet orbiting a nearby star will provide an unprecedented capability for such ancillary science observations.

The search for Earth-like planets will not be easy. The targets are faint and located close to parent stars that are > 1 million times (in the infrared) to > 1 billion times (in the visible) brighter than the planets. However, the detection problem is well defined and can be solved using technologies currently being developed.

2. BIO-SIGNATURES AND PLANET CHARACTERIZATION
Early discussions by the TPF Science Working Group (TPF-SWG) led to the conclusion that observations in both the visible/near infrared or mid-infrared portions of the spectrum were scientifically important and technically feasible. A sub-committee of the TPF-SWG was established under the leadership of Dr. David Des Marais, an astrobiologist from the NASA Ames Research Center, to assess the two wavelength regimes with respect to their suitability for addressing TPF science requirements. Their report can be summarized briefly as follows:

- Photometry and spectroscopy in both the visible/near infrared or mid-infrared region of the spectrum will give compelling information on the physical properties of planets as well as on the presence and composition of an atmosphere.

- The presence of molecular oxygen (O₂) or its photolytic by-product ozone (O₃) are the most robust indicators of photosynthetic life on a planet.

- Even though H₂O is not a bio-indicator, its presence in liquid form on a planet’s surface is considered essential to life and is thus a good signpost of habitability.

- Species such as H₂O, CO, CH₄, and O₂ may be present in visible/near infrared spectra of Earth-like planets.

- Species such as H₂O, CO₂, CH₄, and O₃ may be present in mid-infrared spectra of Earth-like planets.

- The influence of clouds, surface properties, rotation, etc. can have profound effects on the photometric and spectroscopic appearance of planets and must be carefully addressed with theoretical studies in the coming years.

3. SCIENCE OBJECTIVES

The objectives of the TPF missions include direct detection and characterization of planets, including specifically Earth-like planets, around nearby stars. The ability of direct detection implies separating planet light from starlight. The ability to characterize implies determination of the type of a planet and characterization of its gross physical properties and its main atmospheric constituents, thereby allowing an assessment of the likelihood that life or habitable conditions exist there. On astrophysical grounds, Earth-like planets should be found around stars that are roughly similar to the sun. Therefore TPF target stars should include main sequence F, G, and K stars.

Considering the radii and albedos or effective temperatures of solar system planets, the TPF missions should be able to detect terrestrial planets different from our own, down to a minimum size defined as having half the Earth’s surface area and the Earth’s albedo.

TPF missions will search the most likely range as well as the complete range of temperatures within which life may be possible on a terrestrial type planet. In the Solar System, the most likely zone is near the present Earth, and the full zone is the range between Venus and Mars. The habitable zone (HZ) is defined as the range of semimajor axes from 0.7 to 1.5 AU scaled by the square root of stellar luminosity.

The occurrence and properties of giant planets may determine the environments of terrestrial planets. The TPF missions should achieve a field of view and sensitivity sufficient to detect a giant planet with the radius and geometric albedo or effective temperature of Jupiter at 5 AU (scaled by the square root of stellar luminosity).

Emission from exozodiacal dust is both a source of noise and a legitimate target of scientific interest. TPF missions should be able to detect planets in the presence of zodiacal clouds at levels up to a maximum of 10 times the brightness of the zodiacal cloud in the solar system. From a science standpoint, determining and understanding the properties of the zodiacal cloud is essential to understanding the formation, evolution, and habitability of planetary systems. TPF missions should be able to determine the spatial and spectral distribution of zodiacal clouds with at least 0.1 times the brightness of the solar system’s zodiacal cloud.
The required spectral range of TPF missions for characterization of extrasolar planets will emphasize the characterization of Earth-like planets and is therefore set to 0.5 to 0.8 micron in the visible and 6.5 to 13 microns in the infrared. The desired ranges are 0.5 to 1.05 microns and 6.5 to 17 microns respectively.

Colors distinguish planets from other objects. TPF missions will use color to characterize the type of planet and to measure its gross properties, including effective temperature at mid-IR wavelengths. Reference colors and relative magnitudes are those of Venus, Earth, Mars, and Jupiter. TPF should be able to measure planet color in 3 or more bands (wavelengths and bandwidth TBD), to an accuracy of 10%, for any detected planet.

The TPF missions will use the spectrum of a planet to characterize its surface and atmosphere. The spectrum of the present Earth, scaled for semi-major axis and star luminosity, will be used as a reference. The required spectral resolution is 70 in the visible and 20 in the infrared. TPF must measure \( \text{O}_2 \), \( \text{H}_2\text{O} \), and \( \text{O}_3 \) in the visible and \( \text{H}_2\text{O} \) and \( \text{O}_3 \) in the infrared. In this context, a measurement of a species is defined as the determination of the equivalent width of a spectral feature of that species to 20% accuracy. It is desirable that TPF missions also measure Rayleigh scattering, photosynthetic pigments, \( \text{CO}_2 \), and \( \text{CH}_4 \) in the visible and \( \text{CO}_2 \) as well as \( \text{CH}_4 \) in the infrared.

The TPF coronagraph mission must have the capability of searching at least 35 core stars, and additionally the goal of being able to search \( \approx 150 \) stars. The TPF interferometer mission must be capable of searching \( \approx 150 \) stars. It is desirable to search as many stars as possible. It is anticipated that any missions capable of satisfying these objectives will also be capable of searching many more stars if the overall requirements are relaxed. Therefore it is desirable that TPF missions be capable of searching an extended group of stars defined as those systems of any type in which all or part of the continuously habitable zone can be searched.

Search completeness is defined as that fraction of planets in the orbital phase space that could be found within instrumental and mission constraints. Each core star should be searched at the 90% completeness level. It will be difficult to obtain spectra of the fainter or less well positioned planets therefore the ratio of spectrally-characterized planets to all detected planets may not be unity.

Multiple visits per star may be required to achieve completeness or to study a planet along its orbit, to determine its orbit, distinguish it from background objects, and validate a measurement. Therefore TPF missions must make enough visits to meet the completeness and other requirements.

After the completion of the required number of visitations defined above, TPF missions should be able to characterize a planetary system as complex as our own with 3 terrestrial-sized planets assuming each planet is individually bright enough to be detected.

After the completion of the required number of visitations defined above, should be able to localize the position of a planet orbiting in the habitable zone with an accuracy of 10% of the semi-major axis of the planet’s orbit. This accuracy may degrade to 25% in the presence of multiple planets.

### 4. ARCHITECTURE STUDIES

Over the last quarter century, there have been a number of studies of the feasibility of space observatories for the detection of planets beyond our solar system\(^a\)^,\(^b\)^. In 1999, JPL published a description of a formation-flying, nulling infrared interferometer (the 'TPF Book design") consisting of four spacecraft each supporting a 3.5-m telescope, and a separate spacecraft for the beam combiner\(^6\). The TPF Book design is in many respects similar to early versions of ESA’s Darwin mission concepts\(^5\) which also used free-flying telescopes, but in a two-dimensional array that potentially has some advantages for the rejection of exo-zodiacal light.

In March, 2000, the TPF project at JPL solicited Pre-Phase A Architecture Studies from the community and selected four university/industry teams to examine a broad range of instrument architectures capable of directly detecting radiation from terrestrial planets orbiting nearby stars, characterizing their surfaces and atmospheres, and searching for
signs of life. Over the course of two years, the four teams incorporating more than 115 scientists from 50 institutions worked with more than 20 aerospace and engineering firms in support of the study.

In the first year, the study teams and the TPF-SWG examined approximately 60 wide-ranging ideas for planet detection. In January, 2001, four major architectural concepts with a number of variants were selected for more detailed study. These included the previously studied formation-flying infrared interferometer. Following a second year of study, in January, 2002, two broad architectural classes, infrared interferometers and visible/near infrared coronagraphs, were found to appear sufficiently realistic that further study and technological development was recommended to NASA. The primary conclusion from the TPF Pre-Phase A Architecture Study was that with suitable technology investment starting now, missions to detect terrestrial planets around nearby stars could be launched by the middle of the next decade (2010–2020).

4.1 Coronagraph Architectures

The TPF science could be accomplished at visible/near infrared wavelengths with a large telescope (5-10 meter diameter aperture) equipped with a selection of advanced optics to reject scattered and diffracted starlight (apodizing pupil masks, coronagraphic stops, and deformable mirrors, etc.). Such an instrument can make direct images of reflected light from Earth-like planets. While conceptually simple to operate at the system level, such an instrument offers significant technical challenges at the component/assembly/sub-system level, including construction of a very high surface quality primary mirror (approximately ∥/100), a very large (probably deployable) telescope and precise (approximately ∥/3,000), stable (approximately ∥/10,000) wavefront control. To achieve the required level of wavefront correction required, a deformable mirror of up to 10,000 actuators may be required.

The coronagraph teams investigated the prospects of their designs for general astrophysical observations, assuming it were possible with a low additional cost to the overall mission. A large, conventional telescope equipped with a visible coronagraph readily lends itself to a traditional suite of astronomical instrumentation.

4.2 Interferometer Architectures

Alternatively, the TPF science could be accomplished at mid-infrared wavelengths with nulling interferometer designs using from three to five 3-4 meter diameter telescopes—located either on individual spacecraft flying in formation separated by up to 20-200 meters or on a large 20-40 meter long structure. Such instruments could directly detect the thermal radiation emitted by Earth-like planets. While no single component/assembly/sub-system appears to be unusually challenging, this architectural class presents significant technical challenges at the system level, including passive cooling, nulling, beam transport, and formation flying or large precision deployable structures.

The interferometer teams also investigated the prospects of their designs for general astrophysical observations, assuming it were possible with a low additional cost to the overall mission. An infrared interferometer offers the possibility of dramatic gains in sensitivity and angular resolution particularly in the case of the formation flying version. Such an instrument could be utilized in specialized applications such as investigating star-forming disks or the cores of active galaxies.

5. PRE-PHASE A STUDIES

5.1 Overview

The architecture studies described earlier in this document provided a set of baseline concepts, technology needs and requirements that have been utilized to plan and implement a more extensive study and development effort. Design teams and technology teams have been established for both the coronagraph and interferometer architectures. JPL, with support from industry and university experts and the TPF-SWG, has performed detailed mission studies of point designs and associated error budgets/specifications for the coronagraphic and interferometric versions of TPF. The TPF-SWG has continued to define and refine the mission science objectives.
The bulk of TPF funding is targeted to demonstrate the key technologies needed for both architecture classes. The TPF Technology Plan [10] summarizes the top-level scope, approach, and metrics for development and acquisition of technology for during the Advanced Study Phase (Pre-Phase A) to establish feasibility of TPF architectures and support entry into Phase A.

Approximately 10% of the total TPF budget is allocated on an annual basis to support TPF foundation science investigations and fellowships with the goal of better understanding the nature and, if possible, the frequency of occurrence of Earth-like planets around other stars.

5.2 Architecture Concepts

During the past two years, the TPF design teams have performed extensive studies on three specific TPF mission point designs which have evolved out of the earlier studies. These include a visible coronagraph with an elliptical 4m x 6m primary mirror; a structurally connected infrared nulling interferometer with four 3.2m telescopes on a deployable 36m boom; and a formation flying infrared nulling interferometer consisting of four 4m telescopes on individual spacecraft along with a beam combiner on a fifth spacecraft all flying in precision formation with baselines of 60-100m. Artist conceptions of these concepts are shown in Figure 1.

![Figure 1: Artist conceptions of TPF point designs including A) visible coronagraph, B) structurally connected infrared nulling interferometer and C) formation flying infrared nulling interferometer.](image)

Careful study of the capabilities of these architectures led to the conclusion that because of its limited baseline, the structurally connected interferometer’s ability to image terrestrial planets near their parent stars and correctly deconvolve the signatures of multiple planets in one system is very limited. This led to the decision to eliminate this concept from further consideration for TPF. On the other hand, the capabilities of the visible coronagraph and formation flying interferometer indicate both can meet the TPF science objectives and that, in fact, data from them are complementary. Combining the data from both missions will enable a complete characterization of the physical properties of the planets and planetary systems detected as well as a robust assessment of potential habitability and the signatures of life that may exist.

5.3 Technology Development

Also during the past two years, there has been a substantial effort to develop key TPF technologies. Based on the architecture studies by the industry/academia teams, the TPF Project has identified technologies to be developed, and associated performance goals to demonstrate feasibility of the various architectures. The identified key technologies and performance goals are consistent with current understanding of the TPF technology and mission needs, as identified through several years of study of candidate architectures (mid-infrared interferometers and visible/near infrared coronagraphs). Development tasks have also been identified to address the key technologies within the TPF Project Work Breakdown Structure. The lists of currently technology development/demonstration are included below.
Technology efforts in support of the visible coronagraph architectures include:

- Technology Demonstration Mirror
- High Contrast Imaging Testbed
- Advanced Coronagraph Technologies
- Mask & Stops Technology
- Wavefront Sensing & Control Technology
- High Actuator density Deformable Mirror
- Integrated Modeling

Technology efforts in support of the infrared interferometer architectures include:

Core Technology
- Achromatic Nulling Testbeds (Room Temperature and Cryogenic)
- Advanced Nulling Technology
- Planet Detection Testbed
- Spatial Filters
- Cryogenic Delay Lines
- Cryocoolers

Structurally Connected Architecture
- Structurally Connected Interferometer Testbed
- Cryogenic Structures Modeling & Technology

Formation Flying Architecture
- Formation Interferometer Testbed
- Formation Algorithms & Simulation Testbed
- Formation Sensor Testbed
- Formation Control Testbed

Formation Algorithms & Simulation Testbed

The interested reader can refer to the TPF Technology Plan\textsuperscript{10} for more detailed descriptions of these efforts.

On area of emphasis has been on the critical sensing technologies for both the visible coronagraph and the nulling interferometers. The visible coronagraph requires better than a billion-to-one starlight rejection in the region where planets will be visible at the focal plane. The High Contrast Imaging Testbed (HCIT) has been developed at JPL to investigate the feasibility of achieving this demanding requirement. By manipulating the scattered and diffracted light from a simulated point source star image injected into the system with a high actuator density deformable mirror and a combination of coronagraphic masks and stops, a "dark hole" is created at the focal plane where planets can be imaged. As of this writing, average contrast ratios of $\approx 2 \times 10^9$ at the required inner working angle have been achieved at 800nm on the HCIT. A contrast map from the HCIT focal plane achieved with a linear sinc$^2$ occulting mask is shown in Figure 2.
Figure 2: HCIT contrast map showing the “dark hole” at the focal plane where planets could be imaged. The average contrast ratio relative to the injected point source is $\approx 2 \times 10^{-9}$ with localized regions achieving ratios of down to $\approx 3 \times 10^{-10}$.

The infrared interferometers require better than a million-to-one starlight rejection in the region where the planets will be visible. This is achieved by the nulling technique where the input beams from multiple collectors are phase shifted in such a manner as to destructively interfere on axis creating a null fringe on the star thus suppressing the starlight, while placing a bright fringe where the planets would be visible. The Achromatic Nulling testbed has been developed at JPL to demonstrate nulling to the required level. As of this writing, nulling to better than $1 \times 10^6$ has been achieved at 10 microns in the laboratory as shown in Figure 3.

Figure 3: Results from the Achromatic Nulling Testbed showing a stable null at 10 microns to better than one part per million.

5.4 Science Studies

Our understanding of planetary systems has undergone a profound shift in the past several years. Beginning with the remarkable discoveries of planets orbiting other stars like the sun by Mayor and Queloz$^{11}$ and Marcy and Butler$^{12}$, the field has been transformed from a situation in which speculation, educated guesses, and extrapolation from a single studied example (our own system) have been abruptly replaced by the empirical wealth of over 120 different planetary systems, with several new planets being discovered every month. Yet these discoveries just reveal the tip of the iceberg. If our solar system is a typical abode for planets, these giant planets would probably be accompanied by at least that many sibling terrestrial planets.

There is a need for TPF precursor science including both observational and theoretical programs focused on the issues of planetary formation and evolution, which can explain the observed variety of planets and provide a road map to the likely distribution of terrestrial worlds like our own. This information is critical to our growing understanding of how solar systems, terrestrial planets, and ultimately abodes of life like our own form and evolve. In addition, some of this information is directly relevant to the design of TPF.
A description of the relevant preparatory science for TPF can be found in the recently drafted Precursor Science for the Terrestrial Planet Finder Mission document\textsuperscript{3} which will be a companion document to the TPF Technology Plan.\textsuperscript{10} This document describes key scientific information needed to guide the development of the TPF missions as well as to lay the foundation for the next decade of research relevant to the search for life on other worlds. It presents a multidisciplinary approach to preparing the way for the TPF missions. It reflects the breadth and diversity of the growing field of the study of extrasolar planetary systems. For the TPF missions, we must be sure that we are posing the scientific questions correctly; and that we will be able to interpret the results that will be delivered. No single observing method or numerical model provides the whole story, so the approach proposes many interlocking, interdisciplinary studies. Taken together, they will lay the foundation for an entirely new field of scientific endeavor for the twenty-first century: the exploration of planetary systems in our solar neighborhood – their physical, chemical, and biological properties; and their formation and evolution.

6. CONCLUSION

One of mankind's longest standing questions is: "Are we alone in the universe?" The successful detection of an Earth-like planet with an environment suitable for life as we know it would have dramatic implications for humanity's view of our place in the universe. The scientific answer to this question builds not only on astronomy and space sciences, but draws on geophysics, atmospheric physics, biophysics and organic chemistry. Observations conducted from space over the next two decades will provide the key to understanding the origin of life and its evolution in the universe by allowing us to detect and study Earth-like planets and to characterize them as possible abodes of life. Although for centuries this question has been the topic of vigorous philosophical and religious debate, we have finally arrived at a time when our technology has advanced to a state that allows us to address this question with the tools of science.

Current and future ground and space-based observatories have taken and will continue to take the first small steps with the discoveries of additional planets via radial velocity studies, transits, and the imaging of hot young planets (or brown dwarfs). Within the next decade, approved NASA mission such as SIM, Kepler, and JWST will take the next important steps by carrying out a planetary census and imaging Jupiter-mass planets around the nearest stars. But it will only be with the launch of the TPF missions that we will be able to address the central questions of Earth-like planets, habitability and life beyond our solar system.

7. ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein 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.

8. REFERENCES


