Precursor Science Studies Needed

TPF needs to know where to point and what it might see when it does.

- **How many terrestrial planets can be expected?** Dynamical modeling of solar system formation and the influence of large planets can help.
- **Which stars are the best candidates?** Stars that have giant planets in their habitable zones would likely preclude the existence of habitable terrestrial planets.
- **What are the most important spectral lines and what can they tell us about the planets TPF will see?** Atmospheric modeling of planets from early to evolved states is required.

TPF needs the astronomical community to answer these questions and ask others.

Opportunities for Community Participation

The TPF science objectives were defined by the TPF Science Working Group, a team of astronomers selected from the community at large. With the formal definition of separate TPF missions, new teams have recently been established: the TPF-C Science and Technology Definition Team (STDT) and the TPF-I Science Working Group (SWG). The STDT will finalize the TPF-C science goals, integrating them with results from the instrument concept studies (see below) in preparation for the Phase A study. The SWG will continue to refine the TPF-I science program and review technological developments. These groups will hold public meetings a few times over the year.

On January 28, 2005, a NASA Research Announcement will be issued for TPF-C instrument concept studies, including planet imagers, spectrographs, and general astrophysics cameras. The studies may include integration of portions of the instrument hardware into the starlight suppression system. Results will be presented to NASA and the TPF-C STDT in early 2006. The Announcements of Opportunity for TPF-C flight instruments and the TPF-C science center will be issued shortly thereafter and selections made in late 2006. Phase A is currently expected to begin in 2007.

The TPF project has and will continue to fund technological development and precursor science studies at universities and in government and industry through competitive grants. Previous work has included deformable mirror development, occulting mask fabrication, computational modeling, and stellar information databases.

A number of TPF-related workshops and conferences will be held during 2005. For future meeting dates, please check the JPL TPF homepage at tpf.jpl.nasa.gov.

### Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TPF-C</th>
<th>TPF-I</th>
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<tbody>
<tr>
<td>Type</td>
<td>Coronograph</td>
<td>Interferometer</td>
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<tr>
<td>Wavelengths Required</td>
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<td>6.5 – 13 µm</td>
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<tr>
<td>Wavelengths Desired</td>
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<tr>
<td>Completeness Desired</td>
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<td>Completeness</td>
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<tr>
<td>Min albedo</td>
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<td>Characterization completeness</td>
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<td>Launch (est.)</td>
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The Terrestrial Planet Finder Program

The Search for Habitable Worlds

Are There Other Earths?

One of the most fundamental questions in science is if life exists on other worlds. We can now make use of recent technological advancements to identify extrasolar planets that may support life. The distant goal is to image another Earth, with blue oceans and green forests, where life exists, intelligent or not. While this is far outside of our current capabilities, we are now able to consider locating such Earths and determine whether they have the ability to support life.

The Goals of TPF

The NASA Terrestrial Planet Finder (TPF) project, using coronographic (TPF-C) and interferometric (TPF-I) imaging, will directly image the reflected and thermally-emitted light from terrestrial planets that orbit nearby, solar-type stars. It will spectroscopically determine their potential to harbor life by identifying atmospheric molecular lines. It will also characterize their solar systems by observing exozodiacal dust and large planets. A portion of TPF observing time will be dedicated to general astrophysical studies.

The Targets

TPF will search for terrestrial planets within the habitable zones (HZs) of nearby stars. Given our familiarity with the conditions for life in our own solar system, TPF will concentrate on stars like the Sun, specifically main sequence F, G, and K spectral types. The habitable zone of our solar system spans the range from Venus to Mars. From this, we can define an approximate HZ for other stars to be between 0.7 and 1.5 AU scaled by the square root of the stellar luminosities relative to the Sun. Habitable planets are expected to have orbital eccentricities of 0.0 – 0.35 within these zones.

Plants down to ½ the surface area of Earth and ½ of its albedo or infrared luminosity will be detected. Multiple visits to each target will be required to ensure that any detectable planet was not missed because it appeared too close to the star or it had an unfavorable illumination phase in the first visit.

Multimgravelength simulation of a TPF-C observation. The deformable mirrors create a dark, square hole in the center where optical aberration and amplitude errors have been corrected.

TPF-C will survey a minimum of 35 selected stars within two years. This provides a 90% chance of finding at least one planet assuming that 10% of the sampled stars have at least one in their habitable zones. The survey will be extended to an additional 130 stars of more diverse types but with lower completeness as mission constraints allow. TPF-I will survey 165 stars. The two will spectrally characterize at least 50% of the detected planets, identifying biomarker spectral lines with equivalent width accuracies of 20%. It will also determine their orbits and photometrically measure their rotation periods and seasonal changes.

In addition to terrestrial planets, TPF will search for and characterize Jovian planets within 5 AU (scaled by L_⊕) around 50% of the core sample.

It will also search for circumstellar dust down to 0.1 of the optical depth of the solar zodiacal cloud. TPF will be able to characterize the spatial and spectral properties of these dust disks.

The Need for Both Visible and Infrared Data

Observations in both visible and mid-infrared wavelengths are required to accurately characterize terrestrial planets. Broadband albedos and atmospheric
lines such as O$_2$ and H$_2$O can be measured in the visible, while mid-infrared observations are more sensitive to temperature indicators and can penetrate deeper into the atmospheres. Important infrared line sources include O$_3$, CO$_2$, N$_2$O, and CH$_4$.

The required resolution can be achieved at visible wavelengths with a single large telescope, but additional measures must be taken to provide the necessary contrast. A coronagraph can suppress the diffraction pattern of a star using focal plane and pupil masks, providing orders of magnitude contrast improvement. However, it does not reduce the light scattered by the optical surface and coating errors in the telescope. One way to correct these is by using one or more high-actuator-density deformable mirrors. These can be adjusted on-orbit using a variety of wavefront sensing and control algorithms. For best performance, an unobscured, nonsegmented telescope is required.

At infrared wavelengths apertures of $\approx 100$ m are needed. A single telescope this large in space is not currently practical, so instead multiple small ($\sim$3m) telescopes separated by tens of meters are used to achieve the same resolution, though with less light-gathering ability. With the telescopes pointed at the same target, the light from each interferes with that from the others in the beam combiner, hence creating an interferometer. The optical path lengths between the telescopes can be adjusted so that destructive interference nulls the light of the star (light from an off-axis source such as a planet is not nulled). Path length control is easier at longer wavelengths, so interferometers are currently best suited for infrared observations.

To meet its goals, TPF needs to be two missions: TPF-C, a visible-light coronagraphic telescope, and TPF-I, a mid-infrared interferometer. TPF-C is currently targeted for a 2015 launch and TPF-I in 2019.

The European Space Agency (ESA) is planning a terrestrial-planet-finding interferometry mission called Darwin for a launch around 2015. Discussions are currently underway on NASA and ESA collaboration between TPF-I and Darwin.

**Current Designs**

The current baseline design for TPF-C is an off-axis, unobstructed telescope with an 8m x 3.5 m elliptical, monolithic primary mirror. An elliptical mirror provides the largest diameter telescope that can fit within current launcher shrouds. To maintain thermal stability and reduce stray light, the telescope is surrounded by a multilayer, deployed shield. The telescope will orbit at the Lagrangian point L2, which provides a stable thermal environment and allows a high data transmission rate. Note that all of these parameters may change in response to the instrument studies and further community input.

Light from the telescope will pass through a starlight suppression system. This will include a coronagraph to suppress the diffraction pattern of the star. Wavefront aberrations caused by optical surface and coating errors will be corrected using one or more high-actuator-density deformable mirrors.

TPF-C will operate from $\lambda = 0.5 – 0.8$ µm, with a goal of extending out to 1.05 µm. A spectral resolution of R $\approx 70$ is required. The imaging camera and spectrograph will be competition-selected. These instruments would likely be used to determine the wavefront errors, so they might be partially integrated into the starlight suppression system.

The TPF-I design envisions three or four separate ~3 m telescopes and a beam combiner spacecraft flying in formation. Given the later launch date, a number of TPF-I design concepts are still being studied. Recently, structurally-connected systems were rejected due to the vibration and thermal stability control requirements. TPF-I will operate at $\lambda = 6.5 – 13$ µm, with a desired extended range up to 17 µm. A spectroscopic resolution of R = 5 is required.

**Technology Development**

When it launches, TPF will definitely represent the state-of-the-art in optical fabrication, large structure metrology, wavefront sensing and control, and integrated structural modeling. Through funding to universities, research institutions, and businesses, along with work at government laboratories, rapid progress has been made in all of these areas.

As an example, in the High Contrast Imaging Testbed at JPL, the combination of deformable mirrors and coronagraphs have achieved contrast ratios of $2 \times 10^{-9}$ (good enough to detect extrasolar Jupiters) in the relative regions of the image of interest to TPF. Work continues on the HCIT to improve the contrast levels, as well as to evaluate new light suppression techniques, including occulting mask designs recently developed at universities.

**Opportunities for General Astrophysics**

While TPF-C and TPF-I will be designed to meet the requirements for planet detection and characterization, they also will provide unparalleled facilities for more general astronomical observations. A portion (~25%) of TPF time will be devoted to such studies.

TPF-C will be the largest visible-wavelength telescope when it launches. In addition to the narrow-field planetary camera and spectrograph, which could be used for quasar, supernova, and young stellar object studies, it will have a competition-selected general-use...