Executive Summary

SCIENCE GOALS

The Terrestrial Planet Finder (TPF) will revolutionize humanity's understanding of the origin and evolution of planetary systems. TPF will allow us to identify habitable planets like our own Earth around the nearest stars and to assess how common they might be. By combining the sensitivity of space-borne telescopes with the high spatial resolution of an interferometer, TPF will study planets beyond our own solar system in a variety of ways: from their formation and evolution in the disks of newly forming stars to the properties of planets orbiting the nearest stars; from their numbers, sizes, locations, and diversity to their suitability as abodes for life. Using the technique of interferometric nulling, TPF will be able to reduce the glare of parent stars by a factor of more than one hundred thousand to reveal planetary systems as far away as 15 parsec (pc), or nearly 50 light years. The characterization of the size, temperature, and orbital parameters of entire planetary families, including bodies as small as the Earth in regions where liquid water might be expected to be stable, i.e. the "habitable zones," will reveal the diversity of planetary systems in our galactic neighborhood.

TPF will also use spectroscopy to measure the relative proportions of gases like carbon dioxide, water, ozone, and methane in the atmospheres of detected planets, to assess whether they might support life. The measurement requirements for TPF have been developed and will continue to be refined through detailed discussions with atmospheric chemists and biologists, including scientists participating in NASA's newly formed Astrobiology Institute.

TPF will advance our understanding of how planets and their parent stars form. The 250 year old nebular hypothesis of Kant and Laplace holds that planets originate in a flattened disk of material resulting from the collapse of a rotating cloud of gas and dust. While this theory has been strengthened by observations of protostellar disks that span tens to hundreds of astronomical units (AU) across, the recent discoveries of extrasolar planets with diverse orbital properties suggest that planetary systems are dynamic and that planets may migrate from the sites of their birth. As yet, we know almost nothing about the inner regions of protostellar disks where planet formation and migration is thought to occur. By studying the emission from dust, ices of water and carbon dioxide, and gases such as carbon monoxide and molecular hydrogen, TPF will provide essential information on the mass and temperature distribution across the protoplanetary cradle. This in turn will yield important clues on physical processes that determine how and where rocky and gaseous planets form. In the nearest star formation regions, TPF will resolve disk structures on the scale of a few tenths of an AU to investigate in detail how gaseous and rocky planets form out of disk material. The comparison of planetary systems around stars with different masses and ages will provide additional clues to the frequency with which habitable planets occur, allowing an estimate of the frequency of Earth-like planets through the cosmos as a whole.

Finally, TPF can investigate many other astrophysical sources where observations of milli-arcsecond structures are critical to understanding the essential physical processes. Combining the sensitivity of the Next Generation Space Telescope (NGST) with milli-arcsecond imaging, TPF will be able to study such diverse topics as the winds from dying stars that enrich the interstellar medium with heavy elements or the nature of ultra-luminous objects at high redshift that may harbor black holes, enormous bursts of star formation, or other exotic phenomena.

ILLUSTRATIVE MISSION CONCEPT

This report reaffirms the conclusions of an earlier study (Exploration of Neighboring Planetary Systems (ExNPS) Report 1996) that an infrared interferometer represents the best approach to the challenge of detection and spectroscopic characterization of planets around nearby stars. The TPF configuration described in Table 1.1 was chosen to illuminate various technology, mission design, and cost issues and in no way represents a final mission design. The primary goal of planet detection and characterization will utilize core wavelengths of 7 to 20 µm and baselines of 75 to 200 m. Table 1.2 highlights how the sensitivity to Earth-like planets and the potential of spectroscopy to identify habitable planets and to find evidence for life itself increases dramatically with increasing aperture. The present TPF observatory concept (highlighted in purple) can address whether a planet harbors primitive life in just two weeks of observation, roughly the time expended on the deep fields observed with the Hubble Space Telescope.

TPF's properties can be enhanced relative to what is necessary for planet detection with only small changes to the facility. For example, broader wavelength and baseline coverage will enable high dynamic range imaging of complex astrophysical sources with the milli-arcsecond resolution previously available only with very-long-baseline radio interferometry. Spectral resolution of a few hundred will isolate the emission of key gases such as molecular hydrogen and carbon monoxide. Still higher spectral resolution, approaching 100,000, is an instrumental option for selected spectral lines that would allow TPF to probe the dynamics of protostellar disks.

The present concept assumes four 3.5 m diameter telescopes, each on its own spacecraft, and a central spacecraft that houses the beam com-

Table 1.1. Illustrative Properties of a TPF Observatory Concept	
Telescopes	Four × 3.5 m diameter Diffraction-limited at 2 µm operating at <40 K
Baseline	75-1,000 m (free-flying)
Angular Resolution (maximum)	0.75 milli-arcsec (3 µm @ 1,000 m baseline)
Field of View (determined by primary telescope beam)	0.25” at 3 µm 1.0” at 12 µm
Wavelength Range	7-20 µm for planet detection 3-30 µm for general imaging
Spectral Resolution	$R = \lambda/\Delta\lambda$~3-20 for planet detection and spectroscopy R~3-300 for continuum and spectral line imaging Very high resolution (R~10^5) is an option for specific lines
Sensitivity	0.35 µJy at 12 µm (5σ in 2 hr at R~3)
Orbit	Earth-trailing (SIRTF) or L2
Mission Duration	>5 years
Mission Launch	2010 (FY2011)
Launch Vehicle	Ariane 5, EELV, VentureStar

bining apparatus and astronomical instrumentation. TPF will orbit in an Earth-trailing, Space Infrared Telescope Facility (SIRTF)-like, orbit or at the Earth-Sun L2 point. Earlier designs, as described in the ExNPS report to NASA and the Darwin proposal to the European Space Agency (ESA), used 1-2 m telescopes on a connected truss operating in the low-background environment at 5 AU. The present concept leads to a robust systems-engineering and mission-design approach to TPF's challenges as well as enabling a broader range of scientific investigations. Other configurations involving four to six smaller telescopes, possibly 2-3 m segments identical to those developed by the Next Generation Space Telescope, are under active study by NASA and by ESA.

In the first year of its five-year mission, TPF will build on the astrometric results of the Space Interferometry Mission (SIM) to examine ~150 solitary stars within 15 pc, to characterize planets discovered by SIM, as well as to extend the SIM census of planets to include planets as small as the Earth. Combined SIM and TPF data will allow a very detailed physical characterization of planets ranging in mass from Jupiter to a few times the Earth's mass. In subsequent years, TPF will carry out a program of spectroscopic follow-up of the most promising targets to search for habitable or inhabited planets, as well as in mapping a broad range of astrophysical targets.

Table 1.2. Time Requirements For Various Configurations of TPF to Observe Terrestrial Planets

Science Goal	12 µm observation of an earth at 10 pc	4×2 m (5 AU)	4×0.85 m (1 AU)	4×2 m (1 AU)	4×2.7 m (1 AU)	4×3.5 m (1 AU)
Detect Planet	Spectral Resolution *(R)*=3 Signal to Noise *(SNR)*=5	1.4 hr	470 hr	15.3 hr	5.1 hr	2.0 hr
Detect Atmosphere CO_2, H_2O	*R*=20/*SNR*=10	2.4 day	–	18.1 day	5.9 day	2.3 day
Habitable? Life? O_3,CH_4	*R*=20/*SNR*=25	15.0 day	–	–	–	14.7 day

TECHNOLOGY

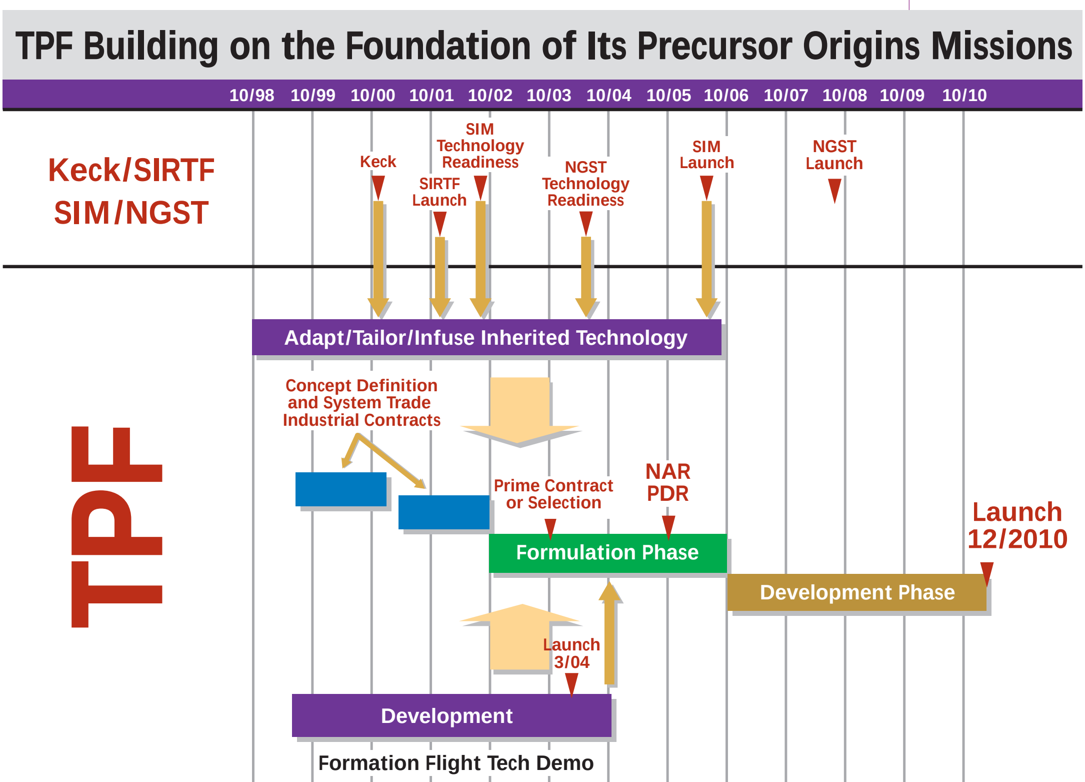
While TPF presents many challenges, the key technologies are being addressed by a variety of NASA programs in preparation for the launch of TPF at the end of the next decade. At the beginning of TPF's development phase around 2006, the missions listed below will have demonstrated almost all of the key technologies needed for TPF. A few TPF-specific technologies will have to be developed in a carefully planned technology program.

- NGST will fly a cooled, 8 m light-weight mirror (~15 kg m^{-2}) with cryogenic actuators and precision wavelength control. Smaller mirrors utilizing the same technology will be used by TPF.
- Ground-based interferometers such as the Keck Interferometer, the Large Binocular Telescope, and European Southern Observatories (ESO) Very Large Telescope Interferometer (VLTI) will develop hardware techniques, software packages, and a community that is ready to use TPF.
- The Space Interferometry Mission (SIM) will be a fully functional space-borne interferometer that will demonstrate all aspects of interferometry including starlight nulling. SIM will demonstrate the pathlength control needed for TPF.
- The Space Technology Three mission (formerly known as Deep Space Three, or DS3) will demonstrate precision formation flight and nanometer pathlength control over a 1 km separation.
- Laboratory investigations have already begun to address the demanding requirements for deep interferometric nulling. Nulls as deep as one part in 25,000 have already been achieved in the laboratory.

COMMUNITY INVOLVEMENT

There will be numerous opportunities for involvement in TPF by the astronomical community through normal peer-reviewed channels, including: technology and instrument development, theoretical investigations of the possible signatures of habitable planets (through NASA's Astrobiology Institute), development of target star lists along with preparatory ground-based observations, execution and analysis of observing programs to search for and characterize planets using TPF, and General Observer programs for astrophysical imaging. The relative proportion of time TPF will spend on surveys of nearby stars, making spectroscopic follow-up observations of promising targets, and on astrophysical imaging will be made by a combination of NASA officals, a TPF science team selected by peer review around the start of the TPF implementation phase, and a community-based time allocation committee.

Figure 1.1. The integrated development plan for the upcoming Origins missions leads to the technology needed for TPF by the start of the TPF implementation phase.



PROGRAMMATIC CONSIDERATIONS

The Terrestrial Planet Finder mission described in this report has evolved over almost two decades of discussions within the scientific community and with various space agencies, as described in the Committee on Planetary and Lunar Exploration (COMPLEX), Towards Other Planetary Systems (TOPS), Darwin, and ExNPS reports. TPF is presently being considered by NASA for a new start in 2007 after the successful completion of key technological milestones during the development of the Space Interferometry Mission (SIM) and the Next Generation Space Telescope (NGST). A schedule for the key contributors to the technology of TPF is given in Figure 1.1.

The European Space Agency is presently studying the Infrared Space Interferometer (IRSI, formerly known as Darwin) for possible inclusion as a cornerstone mission in its Horizon 2000+ program. IRSI shares many of the scientific goals and technological challenges of TPF. Astronomers and engineers from both projects have established the groundwork for a fruitful collaboration on a project of broad public interest.

Additional information on TPF can be found at http://TPF.jpl.nasa.gov/. The relationship of TPF to NASA's overall Origins program is described on the Origins Web site: http://Origins.jpl.nasa.gov/.