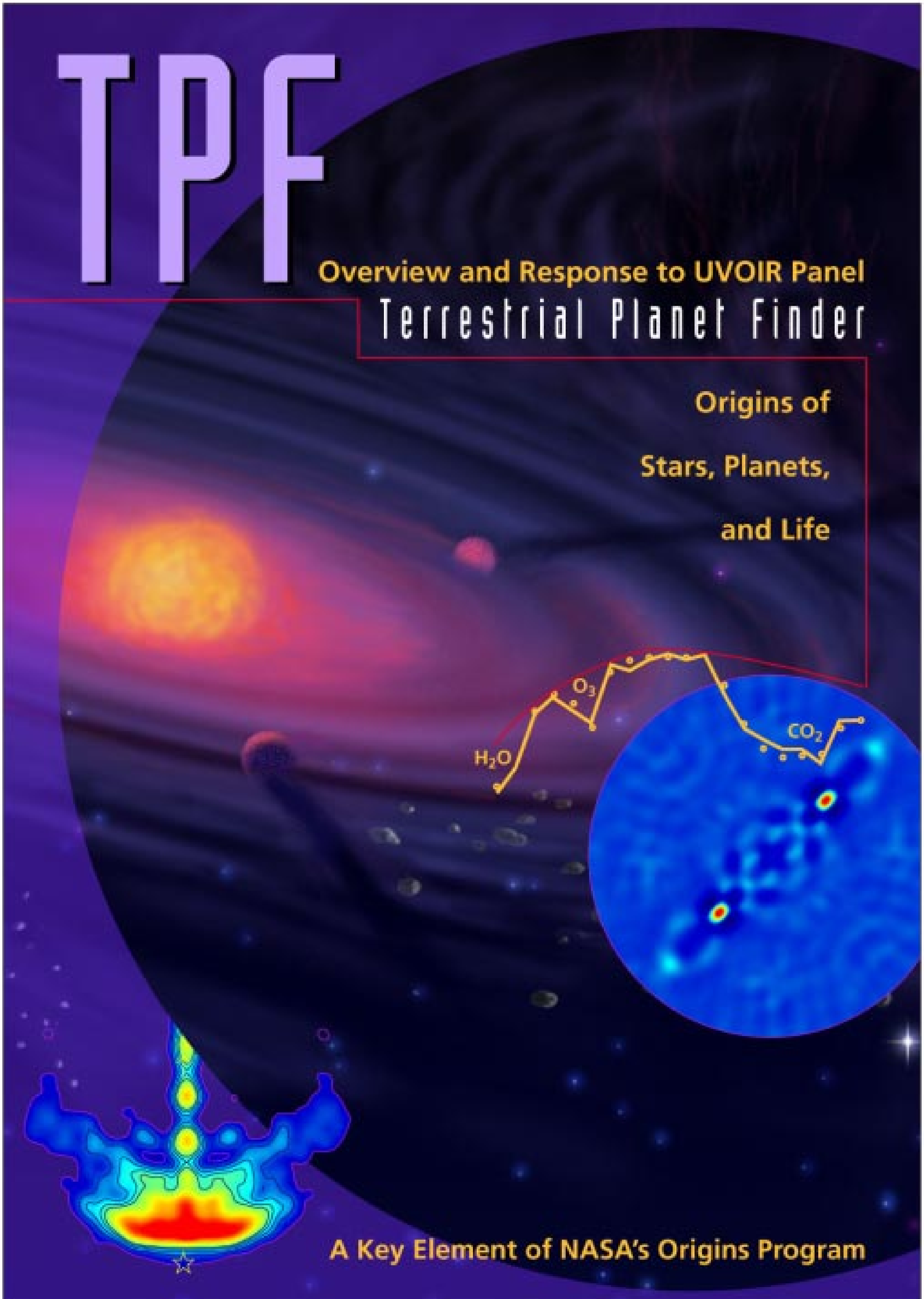
TPF

Overview and Response to UVOIR Panel

Terrestrial Planet Finder

Origins of Stars, Planets, and Life



A Key Element of NASA's Origins Program

Prepared by the TPF Science Working Group

Roger Angel, University of Arizona- Steward Observatory
Dana Backman, Franklin & Marshall College
Charles Beichman, Infrared Processing and Analysis Center,
Jet Propulsion Laboratory
Robert Brown, Space Telescope Science Institute
Alan Dressler, Carnegie Institution of Washington
Suzan Edwards, Smith College
Malcolm Fridlund, European Space Agency, ESTEC
Dan Gezari, NASA Goddard Space Flight Center
James Kasting, Pennsylvania State University
Doug Lin, University of California, Santa Cruz
Jonathan Lunine, Lunar Planetary Observatory
Geoffrey Marcy, University of California, Berkeley and San Francisco State University
Jean-Marie Mariotti (deceased), European Southern Observatory
Kenneth Nealson, Jet Propulsion Laboratory
Tobias Owen, University of Hawaii/Inst.of Astronomy
Anneila Sargent, California Institute of Technology
Cornelius Schalinski, Deutsches Zentrum fuer Luft- und
Raumfahrt (DLR)
Michael Shao, Jet Propulsion Laboratory
Frank Shu, University of California, Berkeley
Diane Wooden, NASA Ames Research Center
Neville Woolf, University of Arizona

Pre-Project Manager: Gary Parks
Pre-Project Scientist: Charles A. Beichman
Pre-Project Mission Scientist: Neville Woolf
System Engineer: Christian Lindensmith
Project Technologist: Daniel Coulter

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Overview of the Terrestrial Planet Finder (TPF)

A. Science Goals

The Terrestrial Planet Finder (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 number, sizes, and locations to their suitability as abodes for life. By combining the sensitivity of space-borne telescopes with the high spatial resolution of an interferometer, TPF will be able to reduce the glare of parent stars by a factor of more than 10^5 to reveal planetary systems as far away as 15 parsec. In addition to determining the size, temperature, and orbital location of planets as small as the Earth in the habitable zones of distant planetary systems, TPF's spectroscopic capabilities will allow atmospheric chemists and biologists to use the relative proportions of gases like carbon dioxide, water, ozone, and methane to assess whether a planet someday could, or even presently does, support life.

TPF will advance our understanding of how planets and their parent stars form. Current observations show that the disks of forming stars are tens to hundreds of few astronomical units (AU) across, but we know almost nothing about the inner regions of forming planetary systems where planets are thought to be born. TPF will resolve disk structures on the scale of a few tenths of an AU to investigate how gaseous and rocky planets form out of accreting disk material. By studying the emission from dust, ices of water and carbon dioxide, and gasses such as carbon monoxide and molecular hydrogen, TPF will investigate whether, as theory predicts, rocky planets form in warmer regions and gaseous planets in colder regions of a nascent planetary system.

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 will enable detailed studies of the winds from dying stars that enrich the interstellar medium with heavy elements, and the cores of active galaxies from our own Milky Way to ultra-luminous objects at high redshift.

Table 1. Illustrative TPF Properties

Telescopes	Four × 3.5 m diameter Diffraction-limited at 2 μm operating at 40 K
Baseline	75-1,000 m (free-flying)
Best Angular Resolution	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~3-20 for planet detection and spectroscopy R~3-300 for continuum and spectral line imaging Higher resolution (10^5) is an option for selected lines
Sensitivity	0.35 μJy at 12 μm (5σ in 2 hr at *R*~3)
Orbit	Earth-trailing (SIRTF) or L2
Launch Vehicle	Ariane-5, EELV, VentureStar
Mission Duration	>5 years
Mission Launch	2010 (FY2011)

B. Illustrative Mission Concept

The TPF Science Working Group reaffirms the conclusions of earlier studies 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 (and Figure 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 7-20 μm and baselines of 75 to 200 m. The present TPF observatory concept can address whether a planet may harbor primitive life in just two weeks of observation, roughly the time expended on the deep fields observed with the Hubble Space Telescope.

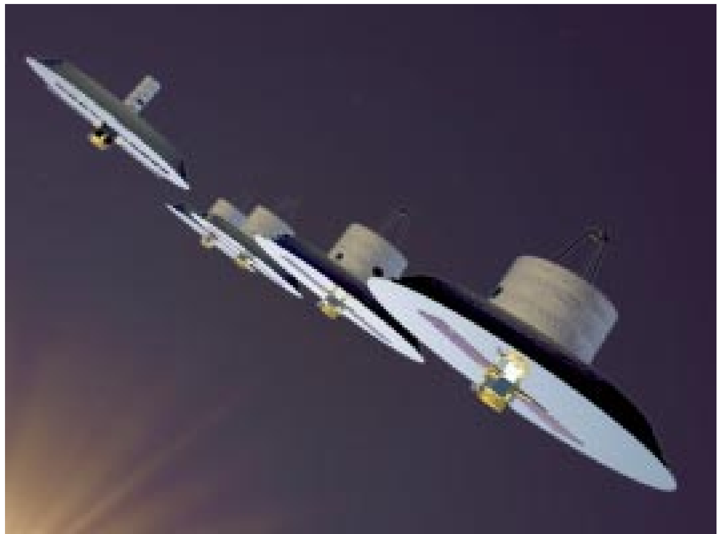

Figure 1. An artist's concept of the free-flying TPF constellation

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 (3-30 μm) and baseline (<1 km) 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 gasses such as molecular hydrogen and carbon monoxide. Still higher spectral resolution, approaching 100,000, is an instrument option for selected spectral lines that would allow TPF to probe the dynamics of protostellar disks.

The present concept utilizes four 3.5 m diameter telescopes each on its own spacecraft and a central spacecraft that houses the beam-combining apparatus and astronomical instrumentation. TPF will orbit in an Earth-trailing 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 to 2 m telescopes on a connected truss operating in the low background environment at 5 AU. The present concept leads to a more robust systems and mission engineering approach to the TPF's challenges as well as enabling a broader range of scientific investigations. Other configurations involving four to six smaller telescopes (possibly the 2 to 3 m segments developed for NGST) are possible and 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 single 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. The combination of SIM and TPF data for planets observed in common will allow a detailed physical characterization of planets ranging in mass from Jupiter to a few times the Earth 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.

C. Technology

While TPF presents many challenges, the key technologies are being developed by a variety of NASA programs in preparation for a new start in the next decade (Figure 2).

- NGST will fly a passively cooled, 8-m light-weight mirror (~15 kg m^{-2}) with cryogenic actuators and precision wavelength control.
- Ground-based interferometers such as the Keck Interferometer, the Large Binocular Telescope, and the Very Large Telescope Interferometer (VLTI) will develop hardware techniques, software packages, and a community ready to use TPF.
- The Space Interferometer Mission (SIM) will be a fully functional space-borne interferometer that will demonstrate all aspects of interferometry including star-light nulling.
- The Space Technology-3 mission (formerly Deep Space Three or DS-3) will demonstrate precision formation flight and nanometer pathlength control over a 1,000 m 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.

Thus, TPF will build on the substantial technology investments being made for a series of precursor missions to which NASA is strongly committed.

D. Programmatic Considerations

The Terrestrial Planet Finder mission described in this report is the outcome of over almost two decades of discussions within the scientific community and with various space agencies, as described in the COMPLEX, TOPS, Darwin and ExNPS reports. TPF is presently being

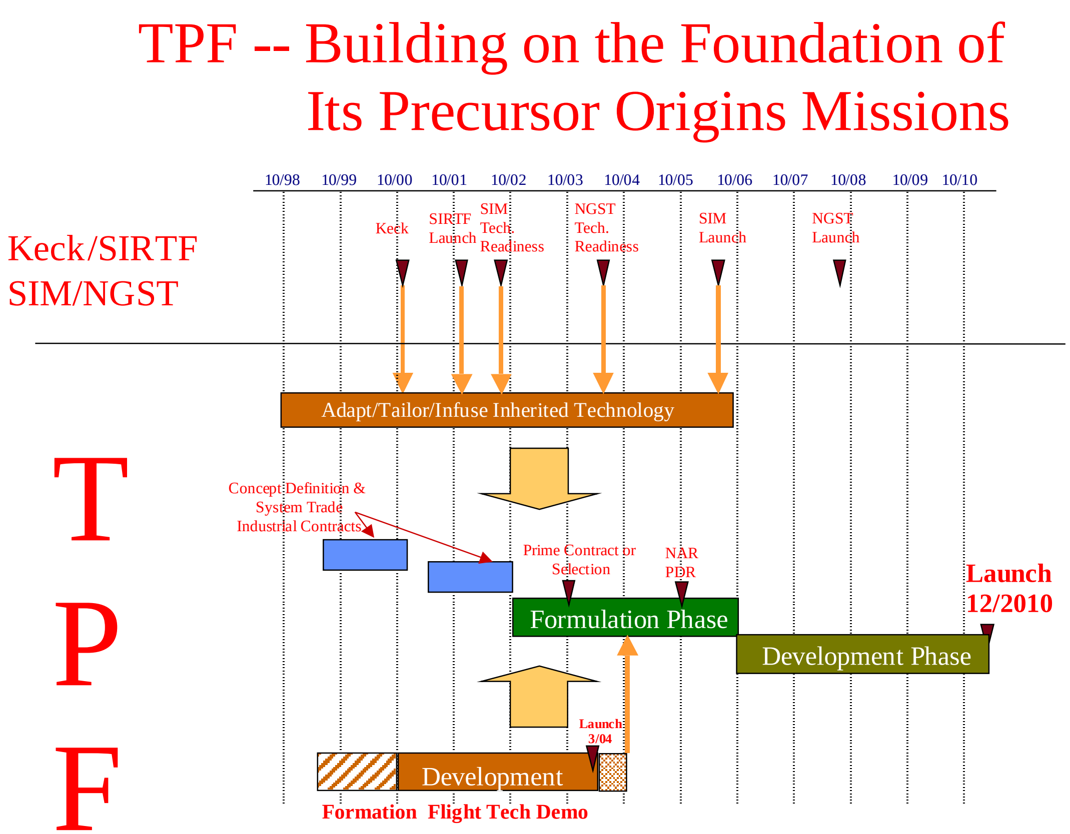

Figure 2. The integrated development plan for the upcoming Origins missions leads to the technology needed for TPF by the start of the TPF implementation phase.

considered by NASA for a new start around 2007 after the successful completion of key technological precursors such as Space Technology-3, the Space Interferometer Mission (SIM), and the Next Generation Space Telescope (NGST).

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.

E. 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 officials, a TPF science team selected by peer review around the start of the TPF implementation phase, and a community-based time allocation committee.

This remainder of this document addresses the 6 questions posed by the UVOIR panel of the NAS/NRC Decennial Survey Committee. Additional information on TPF can be found in the recently published report on TPF from the TPF Science Working Group and on the TPF website, http://TPF.jpl.nasa.gov.

Question 1) What are the primary astronomical problems that the mission will address?

Goal 1a: Complete a census of planets down to 1 $M_\oplus$.

Present status of planet searches: The search for other planetary systems is still in a very rudimentary stage. Fewer than four years ago Mayor and Queloz (1995) and subsequently Marcy and Butler (1996) found the first objects of approximately Jupiter-mass (M_J) orbiting nearby stars via Doppler measurements (Figure 3). As of this writing, more than a dozen companions of mass in the range (0.5-5)M_J/sin$i$, where i is the unknown inclination angle of the orbital plane to the line of sight, have been identified around nearby stars.

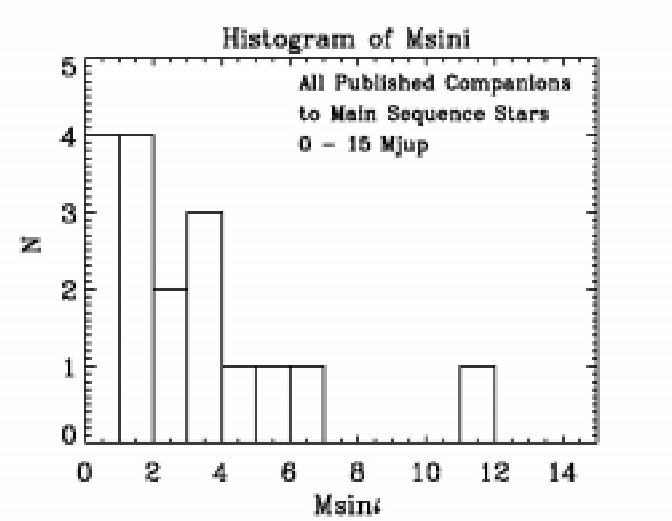

Figure 3. Distribution of planetary-mass companions found by radial velocity studies (Marcy and Butler 1998).

Preliminary data suggest that ~5% of solar type stars are accompanied by close companions in this mass range; nothing is yet known about objects of smaller mass. To date none of these systems have shown clear evidence for other companions revolving around the central star. Many of the companions detected so far are located very close to their parent stars. While this tendency is at least partially due to an observational bias of the Doppler technique, the present data may pose problems to our theoretical understanding of the formation and orbital dynamics of planets. Are these companions planets formed by agglomeration of material in a proto-planetary disk or are they failed stars (also known as brown dwarfs) formed in separate fragments of a proto-stellar core yet bound or captured into tight orbits? If these are planets, why are they located so close to their parent stars? These and other questions are at the forefront of the research into the nature of nearby planetary systems.

The exciting results of the past few years will be greatly enhanced in the next decade as Doppler observations of enhanced sensitivity and data from new observational techniques reveal more companions with a broader range of masses and orbital locations. The ground- and space-based observatories, in particular the Keck Interferometer and the Space Interferometry Mission (SIM), will set the stage for TPF by making a complete census of planets as small as 5 Earth-masses ($M_\oplus$) for stars within 10 pc and for planets as small as a few $M_\oplus$ around the nearest stars (<5 pc). *Although SIM may find a few terrestrial planets around the nearest stars, TPF will be the first observatory, on ground or in space, with the ability to detect and ultimately characterize Earth-sized planets around stars as far away as 15 pc.* TPF will build on the work of predecessor observatories to complete a census of planetary systems down to 1 $M_\oplus$ for stars out to 15 pc, before going on to study the physical properties of the terrestrial planets that SIM and TPF itself will discover. TPF's images will be very important in unraveling the astrometric and Doppler data for systems containing multiple objects, i.e. planetary systems. Given the limited time baseline of the indirect observations, a simple image of the planetary system from TPF will place immediate and fundamental constraints on possible orbital solutions.

Goal 1b: Expand comparative planetology to include planets beyond the Solar System.

Eventually, we want to probe the spatial distribution, mass and compositional gradient of the planets in other systems. The census of planets from SIM and the Keck Interferometer, augmented eventually by images and spectra from TPF, will expand the field of comparative planetology well beyond our Solar System:

- A broad range of orbital eccentricities and inclinations among planets within a system will provide important clues on the long term evolution of planetary systems.
- The distribution of zodiacal

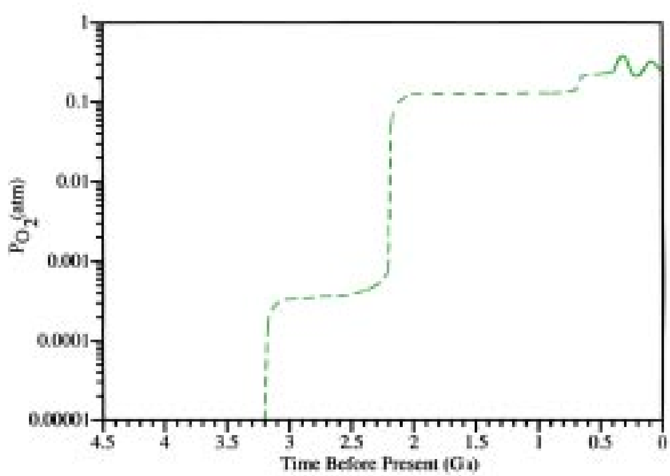

Figure 3. The development of photosynthetic life is thought to have increased the partial pressure of O_2 in the Earth's atmosphere approximately 3 billion years ago.

and Kuiper Belt dust may be related to the distribution of residual planetesimals and perhaps to the bombardment history of individual planets.

- Comparative atmospheric analysis for planets within a given system will provide clues to the importance of the greenhouse effect and volcanism.

TPF photometry will also yield information on the radius, temperature, and albedo of any detected objects. The combination of TPF data with mass information derived from the astrometric and Doppler data could provide a rough estimate of a planet's density and hence suggest whether its composition is rocky or gaseous. From this information it might be possible to infer the presence of a solid surface suitable, perhaps, for the development of life.

Goal 1c: Characterize the atmospheres of planets and search for life.

A fundamental goal of NASA's Origins program is to search for life on planets beyond the Earth to further our understanding of how life forms and subsequently evolves. Within the Solar System we will be able to study samples returned from the surface and sub-surface regions of Mars, as well as probe the oceans that may exist under Europa's ice-sheets. But beyond the planets and satellites of our Solar System, our choices are limited. We have to rely on the information brought to us by the light from distant planets to assess whether life is or might someday be present on those planets. Some of the conclusions of astrobiologists and atmospheric scientists working as part the TPF team are that:

- Life on earth is robust and thrives in a wide variety of environments.
- Given sufficient raw materials, such as cosmically abundant elements, liquid water, and free energy, life similar to what we find on Earth could arise elsewhere in the Universe.
- The environmental impact of life on its planet is sufficient to make life detectable on a planet located many light years away (Figure 4 shows how the presence of life affected the partial pressure of oxygen in the Earth's atmosphere).
- Trace gases such as ozone (Figure 5), methane, and nitrous oxide can tell us about the presence of life over billions of years of evolutionary development, particularly for planets within the "habitable zone" where liquid water might be found.
- The competition between biological and non-biological processes in a planetary atmosphere will have to be carefully understood before definitive statements about the presence of life will be possible for any particular planet.

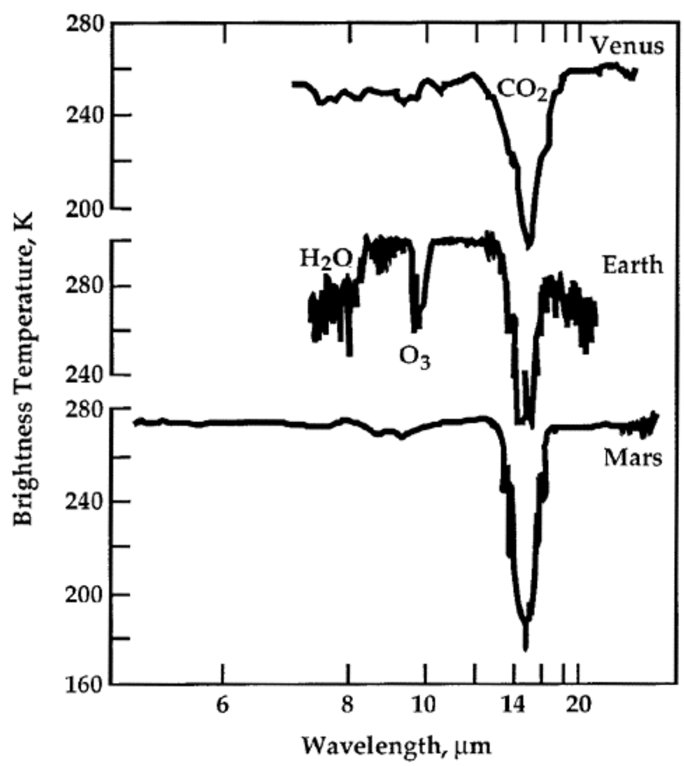

Figure 5. The mid-infrared band shows signatures of atmospheric gases in planets in the Solar System.

The TPF team (building on work of Lovelock, Margulis, and Sagan, among others) has identified the spectral region between 7 and 20 µm as offering strong lines of important atmospheric gases that could be detected with modest spectral resolution (*R*~20; as shown in Figure 5). These lines can be used to assess the presence of : a) an atmosphere (CO_2); b) a warm, wet atmosphere (CO_2, and H_2O); c) and ultimately, the presence of life (O_3 or CH_4). O_3 is a proxy for O_2,which exists (steady-state) in a warm, dense atmosphere as a result of photosynthetic activity. CH_4, though weak in the Earth's atmosphere, might be strongly present in a planet with pre-photosynthetic life. While there are only a few abiotic mechanisms that can produce O_3, there are many ways to produce CH_4 abiotically making this latter tracer an ambiguous marker of life.

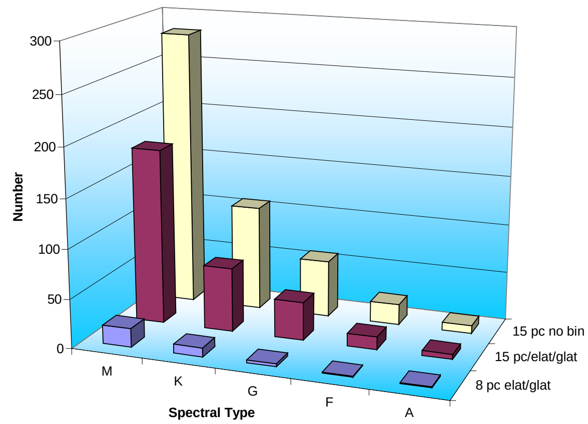

Figure 6. TPF will look at subsets of the closest stars chosen on the basis of criteria discussed in the text.

A scientifically meaningful search for habitable planets must be designed so that a negative result (no habitable planets found) is statistically significant. In other words, TPF must examine enough stars so that we can draw valid statistical conclusions about the prevalence and properties of planets found in other planetary systems. The initial failure to find extra-solar planets of Jupiter-mass was in no way a reflection on the radial velocity technique of the pioneering observers at the Canada-France-Hawaii telescope (Campbell *et al.* 1988). The roughly 25 stars the CFHT group examined simply didn't constitute a large enough sample given that we now know that the Jovian-mass planets that they could have detected appear to be present around only 5% of stars. To avoid a similar failure, TPF must have adequate sensitivity and operational lifetime to provide definitive answers to such questions as:

- How many stars of different spectral types, metallicity, and age have planets of various types?
- What is the range of orbital locations, eccentricities, and masses of detected planets?
- What is the range of planetary characteristics, including temperature, albedo, and atmospheric composition?
- How many planets are habitable, showing a dense, warm atmosphere with water and carbon dioxide?

Table 2. Observing 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)	4×2m (1 AU)	4×2.7m (1 AU)	4×3.5m (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 hr
Detect Atmosphere CO_2, H_2O	R=20/SNR=10	2.4 day	--	18 day	5.9 day	2.3 day
Habitable? Life? O_3,CH_4	R=20/SNR=25	15 day	--	--	--	15 day

- How many planets show signs of life via ozone or other tracers of biological activity?

The need to answer these questions with some degree of confidence suggests a minimum sample of at least 100-200 stars spanning a range of spectral types and other stellar properties. The failure to find habitable planets after studying only a handful of the nearest stars would raise questions about the relevance of the sample, not about the frequency of terrestrial planets. The sample size sets the minimum distance within which TPF must be able to detect and characterize terrestrial planets. Some of the constraints that affect the sample are: reject binary stars closer than 5-15" (nulling works only on single stars); exclude giant and white dwarf stars as unsuitable abodes for life; avoid |galactic latitudes| <10° (source confusion); avoid |ecliptic latitudes| > 45-60° (difficult for passive cooling of telescopes); ensure a broad range of spectral types (not just M stars); avoid stars with more than ~10x the level of zodiacal emission as in our Solar System (excess noise). After applying the above criteria (except for the unknown levels of exo-zodiacal emission) to the Gliese catalog, a distance of 15 pc yields about 150 stars concentrated in spectral types F5-K5 (Figure 6) that TPF could observe over a 5 year mission.

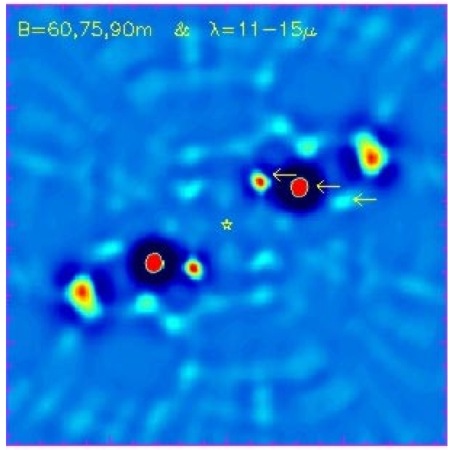

Figure 7. An image of a planetary system like our own 10 pc away, as reconstructed from simulated TPF data, shows Venus and Earth, while Mars is barely detectable. The symmetry of TPF observations results in two images of each planet and an echo at twice the orbital radius. More sophisticated image processing can remove these ambiguities.

TPF would carry out its primary program in three stages spread through a five-year mission:

- Complete survey of ~150 stars looking for planets (terrestrial and larger) around a large variety of stars.
- Spectroscopic follow-up of ~50 systems looking for broad, strong spectral lines of species such as CO_2 and H_2O.
- Very sensitive spectroscopic observations of ~5 most favorable systems looking for O_3.

Interleaved with the observations of planetary systems will be imaging observations of general astrophysical sources. These might start in the second year of the TPF mission, rising to occupy up to 40% of the observing time by the end of the mission.

The sensitivity calculations (Table 2, and addressed in response to question 2 below) indicate that a version of TPF using 3.5 m telescopes can detect an Earth-like planet in the habitable zone of a star 10 pc away in just 2 hours (*SNR*=5 at spectral resolution of 3). If we assume

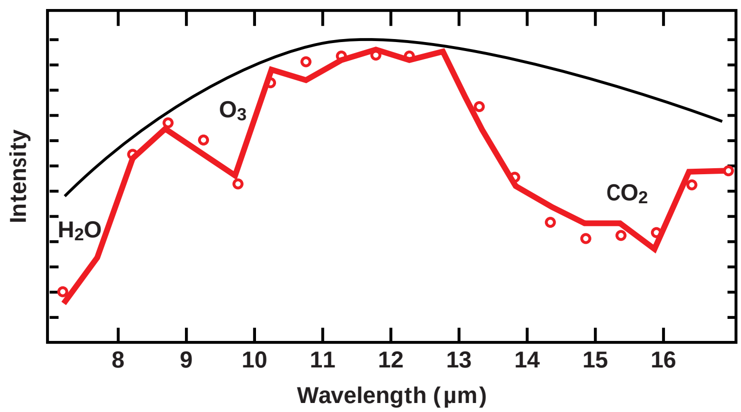

Figure 8. A spectrum of an Earth-like planet 10 pc away obtained after a million seconds of integration with TPF.

that the overhead for an observation is six hours for interferometer slewing and configuration, array rotation, etc., and add to that time an integration time of $2\times(\text{distance}/10\text{ pc})^4$ hours, then the wall-clock time to survey an illustrative sample of 141 stars is approximately 62 days, taking into account the actual distance to each star. If we observe each star three times per year for a total of 186 days per year, then the planet survey will require roughly 50% of the annual observing time. After two years we will have six sightings of each planetary system spread out over time so that we will see each planet sharing the proper motion and parallax of its parent star, as well as moving in orbit around its parent star (Figure 7). These observations will give definitive proof of the reality of the detected sources and of their association with the target star. All of these observations can be combined to improve the signal to noise to search for absorption lines from water and carbon dioxide.

The spectroscopic program will be divided into two parts: modest sensitivity observations requiring 1-2 days to obtain spectra adequate to deduce the presence of CO_2 and H_2O (including data obtained as part of the initial survey); and high quality spectra on the most promising sources to search for signs of life using O_3 and CH_4. The lower resolution observations will take 2.3 days, or approximately 3 days per star including nominal overheads. As the results of the survey accumulate during the first two years of the mission, TPF could spend up to 150 days per year observing up to 50 stars. These observations would probably be repeated at least twice, given their importance. Finally, TPF could spend up to two weeks per star making observations to the ultimate depth to search for spectral lines of O_3 and CH_4 (Figure 8). TPF might observe 5 stars per year with the higher level of sensitivity.

Goal 2: Study Formation of Low Mass Stars: Disks, Jets, and the Formation of Planetary Systems

The formation of planets is intimately linked to the birth of stars. From a wide array of space- and ground-based data, we know that protostars surrounded by protoplanetary disks emerge from the gravitational collapse of a rotating molecular cloud core. However, some of the most fundamental questions remain unanswered.

- What determines the mass of a star?
- What generates the ubiquitous collimated jets that are ejected from near-stellar regions in accretion disk systems?
- Do all disks evolve into planetary systems?
- When and how does the planet formation process begin?
- How do dynamical interactions between the disk, star, and evolving planets affect the emergent family of planets?
- What fraction of planetary systems form terrestrial and Jovian planets analogous to those in our own system?

The unprecedented imaging capability of TPF will offer the first direct look at the terrestrial planet formation regime in protoplanetary disks and resolve the region where jets emerge and become collimated. The ability to spatially resolve regions where the key physical processes occur that shape the formation and evolution of stars and planets take place will provide an extraordinary advancement in our understanding of our origins.

The power that TPF brings to bear on star and planet formation problems resides in its unparalleled angular resolution, its sensitivity, its wavelength coverage, and its spectral capabilities. The 4-element, free-flying configuration for TPF will enable the high angular resolution inherent in the interferometer to be applied in imaging mode, providing pictures of star forming systems at unprecedented resolution. With 3.5-m apertures TPF will provide a thousandfold improvement in sensitivity relative to ground-based telescopes at wavelengths longer than 3 µm, even if long baselines become available, because of thermal emission of the atmosphere and telescopes. The wavelength coverage and spectral imaging capability of TPF will probe gas and dust over a considerable range of temperatures and density, ideally matched to those expected in protoplanetary disks, accretion-powered jets, and Jovian and terrestrial planets.

The most dramatic gains will be made in imaging forming stars and their protoplanetary disks in the nearest star formation regions. At these distances, with a 1-km baseline, TPF will provide a spatial resolution on the order of 0.1 AU at 3 µm. Since disk and jet sizes are on the order of 10 to 100 AU, 0.1 AU resolution will yield images of exceptional quality. The scientific return will be very high since these nearest stellar nurseries harbor forming stars and planetary systems in three distinct evolutionary states, spanning an age range from 0.5 to 10 Myr. We discuss each of these in turn.

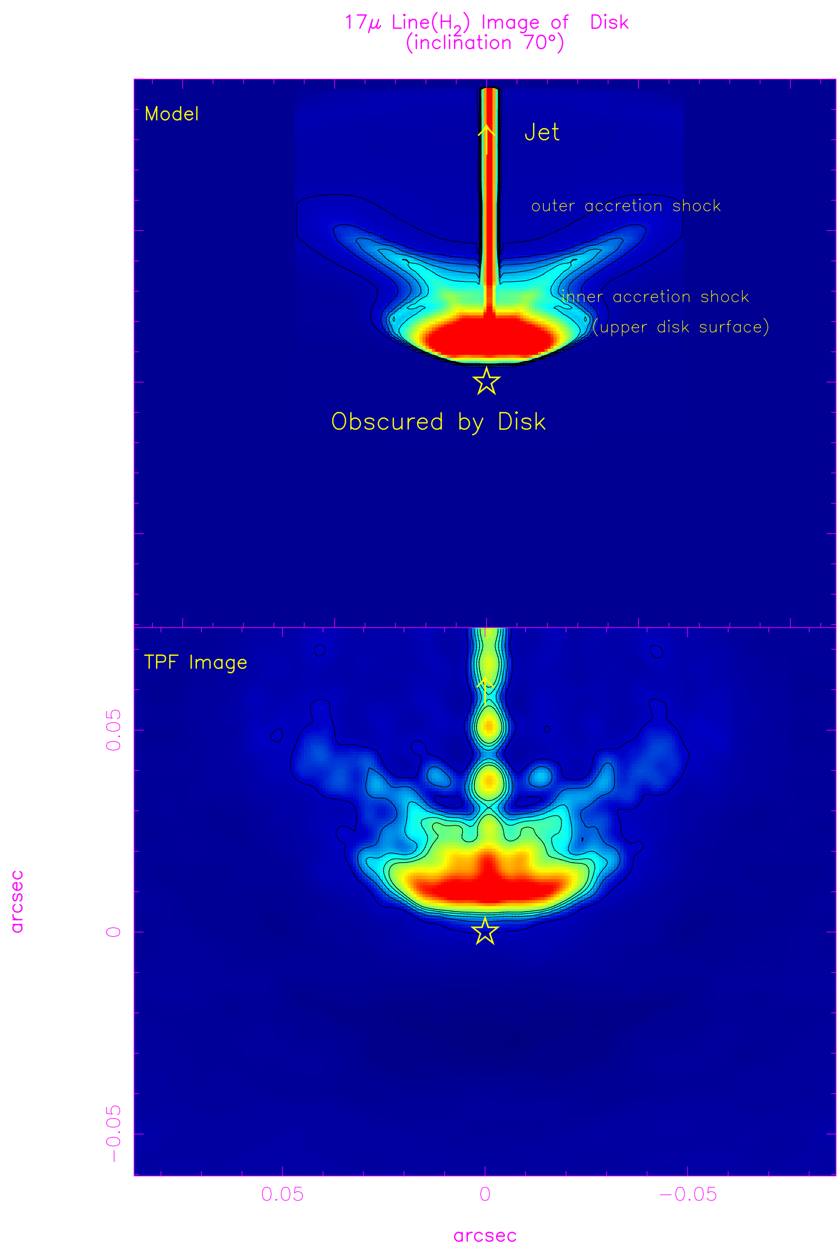

Figure 9. A model and a reconstructed image of the 17 µm H_2 line emission from the disk and jet associated with a protostar.

Embedded Accretion Disks and Core Infall: The youngest stars (0.5 Myr) and their accretion disks are still accumulating mass from remnants of the collapsing core. This natal material rains onto the disk over a range of radii determined by the angular momentum of the core, heating the disk and increasing its mass. During this phase the disks maintain a high accretion rate and can undergo instabilities that radically alter the disk structure and dump large quantities of material onto the star. It is likely that the material infalling from the core is dissipated by the winds generated in the near-stellar region of the disk, terminating the growth of the disk and possibly establishing the mass of the star as well. Observing the distribution of disk material might also help to explain the existence of giant planets recently found close to their parent stars since density waves in the disk have been suggested as one of the processes leading to an inward migration of giant planets. TPF images will clarify the morphology of the infalling material, the jet and the outflow cavity on 0.1 AU spatial scales (Figure 9). In addition, spectral line images at R~100 will provide spatial probes of the accretion shocks above the disk surface and of the interaction between the infalling envelope and the accretion-driven jet.

Revealed Accretion Disks and Planet Formation: After termination of infall of natal material from the core, at least half of the stars maintain active accretion disks for 1-10 Myr. These systems have low extinction from obscuring dust, allowing their accretion disks to be directly imaged. We anticipate that they will provide excellent laboratories to study the beginning phases of planet formation. Imaging at 0.1 AU resolution will reveal many important physical properties of young planetary systems, as described below.

Direct Determination Of The Temperature Structure. Determining the temperature structure of a protoplanetary disk is key to understanding its angular momentum transport and ability to form planets. Indirect methods of determining the temperature structure from spectral energy distributions have produced ambiguous results, since they depart significantly from theoretical expectations based on viscous accretion mechanisms. With TPF imaging at 3-30 μm, the surface brightness of the inner 10 AU of accretion disks will be mapped, revealing the location of warm dust ranging in temperature from 1000 K to a few 100 K, providing the first direct determination of the disk thermal profile.

Probes of the Planet Formation Process. The creation of protoplanets in an accretion disk is expected to propagate density waves through the disk and to clear gaps in the disk centered on the protoplanet's orbit. Protoplanetary bodies of Jovian mass can produce disk structure in the form of waves and gaps that can be resolved at the 0.1 AU resolution of TPF, providing extraordinary insight on the growth of planets, the timescale for their formation, and their effect on the evolution of the disk.

Direct detection of Giant Protoplanets. Young Jovian planets are anticipated to be very hot and luminous in their first 1 Myr. With TPF we will be able to identify the luminosity and temperature of giant protoplanets, providing crucial constraints on the formation of these bodies. TPF will also reveal their distance from the parent star, providing valuable insight on whether giant planets preferentially form at the ice condensation radius and how common orbital migration of planets might be.

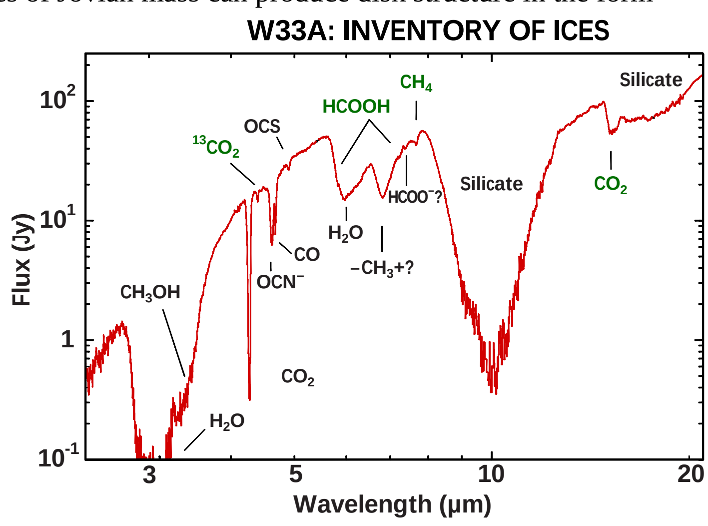

Figure 10. An ISO spectrum of the protostellar object W33A shows a wealth of mineral, ice and gas phase features. TPF will make images of disks around young stars in these and other spectral lines.

Probes of Disk Structure, Chemistry and Mineralogy. In spectral imaging mode, emission from abundant molecules such as CO, CO_2, H_2O, and solid particles such as silicates and water ice can be used to evaluate compositional gradients and non-equilibrium excitation conditions in protoplanetary disks. For example, trace amounts of material in gaps of dimension 0.1 AU can be illuminated by emission from molecular features such as CO, providing an alternate means of identifying tidally forced gaps. Figure 10 shows spectral features of a young stellar object, W33A, which are likely formed in its disk or immediate circumstellar environment. TPF will provide observations of the structure of disks in the lines of minerals, gases, and ices.

Disk Kinematics: An instrument option exists to obtain spectral images at very high spectral resolution (R=100,000). If this option were realized, it would prove to be a powerful probe of the kinematics of disks and accretion shocks, with a velocity resolution of a few km/sec. We could directly test whether inner disks are in Keplerian rotation, and thereby measure the mass distribution in the disk and of the protostar. We could also clarify where emission in spatially unresolved features was arising, by using the velocity profile to infer location in the disk. This would be an excellent means of finding small gaps in a disk where forming terrestrial planets have cleared out a narrow ring.

The Origin And Collimation Of Jets. In spectral imaging mode, emission from lines such as H_2 or low excitation forbidden lines will trace the outflowing gas emerging from near-stellar regions on unprecedented spatial scales. Such images should clarify the zone of origin and the means of collimating these extraordinary flows.

Probes Of The Star-Disk Interface. Pushing the spectral imaging capability to shorter wavelengths will provide the ability to study the complex star-disk interface region inside a few tenths of an AU. Imaging at 2-5 μm will bring both higher angular resolution and the ability to spatially resolve emission from lines that arise in magnetospheric funnel flows where the star couples to the accretion disk, the innermost regions of the disk, and the base of the wind. These will include features such as the Br series of hydrogen and the CO fundamental.

Goal 3: Starburst Galaxies and Buried AGN at the Epoch of Peak Star Formation.

Starburst galaxies: The recent detections of far-infrared sources using the ISO satellite (Clements *et al.* 1997) and of powerful sub-mm sources (Smail *et al.* 1998; Barger *et al.* 1998) using the SCUBA bolometer array (Holland *et al.* 1997) raises the interesting possibility that these bright sources correspond to the building of the cores of galaxies near the epoch of peak star formation (z~1-4). It is important to emphasize that the optical identifications of these sources, and hence their redshifts and luminosities, are not secure. Nevertheless, several studies find that the integrated luminosity from these sources would, with modest extrapolations to slightly fainter flux levels and shorter wavelengths, represent the majority of extragalactic background light at far-infrared and sub-mm wavelengths (Clements *et al.* 1997; Hauser *et al.* 1998; Fixsen *et al.* 1998). This background is almost certainly due to the reprocessing of ultraviolet flux into mid-IR, far-IR, and sub-mm radiation. Hot, young stars are the most likely source of the ultraviolet radiation, with AGN a close second. That SCUBA finds relatively few sources responsible for much of the background points to extraordinarily high star formation rates, hundreds of solar masses converted to stars per year (brighter than Arp 220) or bright AGN ($> 10^{46}$ erg/s). In either case, ISO and SCUBA are detecting a major epoch of formation: bulge formation in early galaxies or the growing of massive black holes (Richstone *et al.* 1998.) Distinguishing between these scenarios will be a task for future observatories: NGST (the most sensitive with sub-arcsecond resolution), SIRTF/FIRST (arcminute resolution but best sensitivity at the peak of the spectral energy distribution or SED), and the Millimeter Array (MMA)

TPF will play an important role in resolving the mid-infrared radiation in these SCUBA sources. From 3-30 μm TPF will be observing the radiation from warm dust (PAH emission) in the photo-dissociation regions surrounding the compact sites of star formation or heavily obscured active nuclei at redshifts z~1-2. TPF resolution with a 200 m baseline will be ~20 mas , with <0.1 μJy sensitivity for a 1 day observation in a broad spectral band (R~5). This sensitivity is more than sufficient to detect and image an Arp 220-like source at a redshift of z ~ 1, (F_ν(15μm) ~ 0.2 μJy). The angular resolution corresponds to a physical scale of 170 parsec, comparable to the 364 pc separation of the two nuclei/regions in Arp 220 (Scoville *et al.* 1998). Thus, TPF will be capable of either resolving the star-forming region or discovering the point-like source, << 100 pc, expected in a buried AGN. It is important to note that some of the tentative identifications of SCUBA sources suggest luminosities 3-5 times greater than Arp 220. Such sources will be observed and imaged with TPF to higher redshifts and at longer wavelengths. TPF will provide a unique combination of resolution and sensitivity, unmatched by NGST (~8 m baseline) or the VLT (10^6 more background). Thus, it will uniquely be capable of imaging the luminous nuclei and structures in these bright SCUBA sources, close to the peak wavelength of their SED.

IR Interferometry of AGNs: Research on active galactic nuclei (AGNs) and the host galaxies surrounding them has reached an exciting threshold. As evidence for supermassive black holes at the centers of galaxies continues to roll in (e.g. Richstone *et al.* 1998), demonstrating that these objects are the norm for galaxies, rather than the exception, studies of quasars and other AGNs are beginning to mesh with studies of galaxy evolution in general. Questions about how giant black holes form and grow now appear intimately related to questions about how galaxies themselves form. Yet, we remain largely ignorant about how quasars and other AGNs interact with their hosts. Infrared interferometers operating at 3-30 μm over ~100-1,000 m baselines will be very useful for clarifying these issues because they will be ideal for probing the interfaces between active galactic nuclei and their hosts.

Nuclear activity in galaxies occurs when a supermassive black hole is actively accreting interstellar gas. Exactly how galaxies manage to channel enough gas into such a small volume remains unclear; however, it seems unlikely that a galaxy could accumulate enough dense gaseous fuel at its center without igniting a burst of star formation as well. Disentangling the phenomena associated with a starburst from those associated with an AGN is tricky because the interface zone between an AGN and its host is only tens of parsecs in size, subtending an angle of less than 100 milli-arcseconds (mas). But if we are to determine how AGNs are fuelled or to learn whether an AGN predates a central starburst or vice versa, this is the crucial region to study.

The 1 mas beam size of a ~1,000-m mid-IR interferometer is well suited for studying the ~100 mas interface regions of the brightest AGNs (e.g. Voit 1997a), and a larger interferometer could perform similar studies of distant quasars. Thermal emission from AGN-heated dust in the interface region peaks in the mid-IR, and numerous emission features from fine-structure emission lines (e.g.[Ne II] 12.8 μm, [Ne III] 15.6 μm , [Ne V] 14.2 μm) and small carbonaceous particles (e.g. 3.3 μm , 11.3 μm) are also present. Mapping the thermal emission will reveal the spatial distribution of the fueling gas clouds on the crucial scale between HST (100 mas) and VLBA (1 mas) and will establish the relative contributions of the starburst and the accretion engine to the nuclear activity. Imaging the mid-IR emission features will provide information on the density, velocity, and obscuration structure of the interface gas and will also reflect the anisotropy of the AGN emission. Finally, nulling interferometry of the broad line emission from the nucleus could help to establish the mass of the central black hole (Voit 1997b).

Question 2) What are the performance specifications of the mission, and how do they address these astronomical problems?

Thermal Infrared Observations with an Interferometer: The longer wavelengths of mid-infrared radiation necessitate the use of very large apertures or long baselines to resolve the 0.1 arcsec separation of the habitable zone at 10 pc. For example, a coronagraph on a filled aperture telescope typically needs an occulting spot >3 Airy rings in radius for effective operation. Thus, a filled aperture telescope with a coronagraph would have to be >> 25 m in diameter to resolve an Earth analog in the presence of a bright parent star. Such aperture sizes are well beyond extrapolations of NGST technology for filled apertures. On the other hand, interferometers consisting of modest sized telescopes with baselines ~100 m are already under construction or in operation on the ground so that there is a clear technological path to a similar space-based instrument

Bracewell and MacPhie (1979) were the first to suggest that a space-based infrared interferometer could suppress the starlight by pointing a null in an interference pattern onto the star while simultaneously detecting the planet through an adjacent bright fringe. To allow the signal from the planet to be distinguished from noise and background sources, they further proposed rotating the array so that the planet signal would be modulated through the fringe pattern at a predictable frequency. Bracewell originally envisaged a rotating two-element interferometer on a rigid structure. Subsequent studies have pointed out that greatly improved sensitivity would be possible using four or more elements with adjustable separations (Angel 1990; Leger *et al.* 1996; the *ExNPS* report, 1996; Angel and Woolf 1997). The primary motivation for using more elements is to provide greater starlight suppression. The null should be as broad and deep as possible, but have an angular extent no larger than the orbit of the innermost planet. An interferometer array with more than two elements also offers the potential of fringe patterns with more complicated symmetry to help overcome ambiguities in the image reconstruction. Moreover, if the telescope separations are adjustable, as would be the case in a free-flyer configuration, the restrictions on the shape and width of the null could be relaxed, because the fringe pattern of the array could then be tuned to each candidate star.

Images of planetary systems are not formed by direct-imaging, but are reconstructed after measurements have been made with the array in multiple configurations. The array is rotated in a plane perpendicular to the line of sight to the star with measurements made at successive position angles. The data consist of a time series of the planet's signal as it rises and falls through the fringe pattern of the rotating array. The time series can be processed to give an image of the planetary system (Figure 7) with a spectrum at each point in the image (Figure 8).

Table 3. Signal and Noise Sources (photo-electrons)		
Resolution(R)=20, $\tau=10^5$ s @ 12 μm	2 m telescopes at 5 AU	3.5 m telescopes at 1 AU
Earth at 10 pc	0.008×10^6	0.025×10^6
Exo Zodiacal Emission	0.71×10^6	2.15×10^6
Local Zodi Emission	0.10×10^6	8.56×10^6
Nulled star leakage	0.04×10^6	1.16×10^6
Dark current	0.50×10^6	0.50×10^6
Total	1.35×10^6	12.39×10^6
Noise=(Counts)$^{0.5}$	1.17×10^3	3.52×10^3
SNR	6.9	7.1

The illustrative TPF concept is introduced in Table 1 and Figure 1. The system consists of four 3.5 m telescopes, each on its own spacecraft, and a beam combiner and instrument module on a fifth spacecraft. Light from the individual telescopes are combined and brought together in the beam combiner spacecraft. There are actually two beam combiner modules that can be thought of as instruments in a conventional telescope. The first is the nulling beam combiner that is used for the planet detection program. The second is an imaging beam combiner used for conventional interferometric imaging between four telescopes. Prototypes for these beam combiners are being developed for a variety of ground-based interferometers, particularly the Keck Interferometer.

The sensitivity of the interferometer in the nulling mode is described in Table 3 and Figure 11 which show signal strengths and noise sources for an observation of a planet 10 pc away using the 3.5 m telescope system. The table also gives values for a system using smaller telescopes operating in a low background 5 AU orbit. TPF can detect an Earth at 10 pc with SNR~7 at a resolution R~20 in 10^5 sec of integration. Sensitivity for other observations and for other configurations of TPF are given in Table 2.

For imaging observations, the major issue is building up uv-plane coverage to make detailed images. TPF will do this by using a series of rectilinear motions of the space craft to simulate the full rotation of the array. For free flying spacecraft, rotations which require constant thrusting are expensive in terms of fuel, while thrust and coast manuvers are inexpensive and can provide good uv-plane coverage. The sensitivity of TPF for imaging is illustrated in Figure 12, which shows a model for a

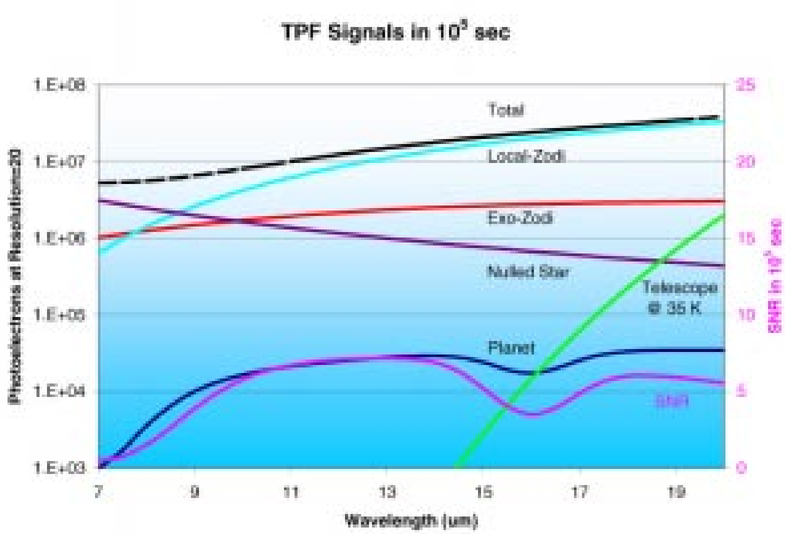

Figure 11. The strength of various signal and noise sources for a TPF observation of an earth-like planet at 10 pc.

YSO disk and the resultant SNR/per pixel (right axis) for a 10^5 sec observation at a resolving power of *R*~100 suitable for line imaging. The number of pixels in the resultant image (right axis) and the background from local zodiacal emission and the 35 K telescope are also shown (left axis).

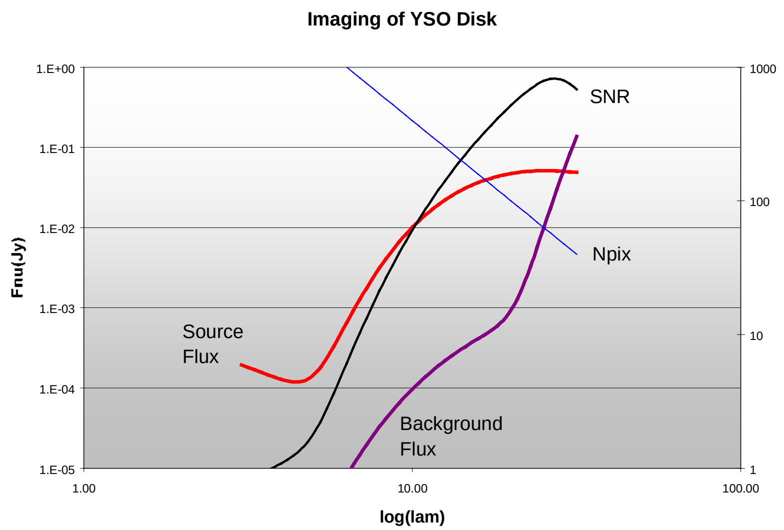

Figure 12. The sensitivity of TPF for imaging is shown for a model protostellar disk. The SNR and number of pixels use the scale on the right.

Question 3) What were the key decision-nodes and trade-offs in defining those specifications?

Earlier studies (*ExNPS Report*, 1996) identified a two-by-two matrix of top-level mission choices: separated-spacecraft vs. single-structure and orbiting the sun at 1 AU vs. 5 AU. These options were examined by three industrial contractors (Ball, Lockheed Martin, and TRW) and at JPL. The benefits and drawbacks of each of these mission classes are summarized in Table 4. A tethered-spacecraft option was also considered, but was determined to be more expensive and higher risk, due to increased complexity, than the other two spacecraft options.

The TPF science working group determined that the greatest scientific return would be provided by a separated-spacecraft mission operating at 1 AU. Foremost among the benefits offered by the separated spacecraft option is the ability to perform the milli-arcsecond resolution imaging; a single structure would seriously limit the possible resolution and the uv-plane coverage. The ability to vary the system baseline over a wide range would also improve TPF's capabilities for planet searching since observations could be carefully tuned for each star. The advances in large cryogenic optics promised by the NGST program allow a mission at 1 AU to match the signal-to-noise of the previously studied 5 AU mission while simplifying many aspects of the mission design.

The remaining trade-offs that remain to be made concern the exact TPF configuration, e.g. the number and geometrical configuration of telescopes, or deep stable nulls vs. shallower nulls with rapid chopping. The size of the TPF optics determines the distance to which one can detect planets and carry out spectroscopy on them (see Table 2). It is important to note that TPF cannot drop much below 3 m apertures without giving up a core scientific goal of characterizing planetary atmospheres in a reasonable sample of stars.

Question 4) What is the discovery potential?

With almost the same collecting area as NGST, but with 10 to 100 times the baseline of a single 8 m telescope, the discovery space for TPF is enormous. TPF will open a new realm in angular resolution at a sensitivity level impossible for an interferometer operating through the high backgrounds and turbulence of the Earth's atmosphere. Thus for general astrophysical imaging, TPF will be able to map the central ~1 arcsecond of sources with milli-arcsecond angular resolution and with a spectral resolutions of a few hundred (and possibly much higher for certain instrumental configurations). There are many objects where the structure within a small area is of particular interest, e.g. the disks around forming solar mass stars, the dense cores of molecular clouds where clusters of high-mass stars are forming, AGB stars and their associated outflows, the cores of globular clusters, the dusty cores of AGN with their broad and narrow line regions and energetic jets, and even star forming regions located within very distant (z~4) galaxies. Surprises are certain with high-sensitivity images on the milli-arcsecond scale.

In the nulling mode, TPF will be a unique and focused instrument working to understand the nature of nearby planetary systems. Surprises are inevitable, particularly when you consider that the first detection of planets around nearby stars has confounded theoretical expectation. What will we find when we can search for terrestrial planets for the first time? Consider the variety of bodies within our own Solar System: an inferno heated by a run-away greenhouse effect; a warm, wet planet on which reducing and oxidizing gases coexist in apparent violation of thermodynamic principles; an arctic desert that may be the remnant of a warm, wet planet; moons with tidally-driven volcanoes, a tidally-melted ocean under a glaciated surface, or a organic-rich, low temperature atmosphere. TPF offers the prospect for remarkable discoveries as we explore the nearest planetary systems.

Table 4. Trade-offs in the Design of TPF

	Advantages	**Disadvantages**
Separated Spacecraft	• Tunable baseline for planet finding. • Astrophysics imaging capability. • Legacy for future separated spacecraft missions. • Less structural mass • Multiple launch is possible • Simpler Integration and test	• Multiple spacecraft • Needs precise formation flying • Contamination from neighboring spacecraft • More propellant mass.
Single Spacecraft	• Single set of spacecraft subsystems. • Less propellant mass.	• Complex, high-risk deployment. • More structural mass • Stability issues of large structure.
1 AU	• Large amounts of available solar power. • Good sky accessibility • Easier communications • Larger launch capacity or multiple launches	• Larger apertures needed to compensate for increased zodiacal emission • Passive cooling harder
5 AU	• Smaller, less demanding collectors needed • Less zodiacal dust • Passive cooling easier	• Long delay between launch and arrival on station. • Difficult power and communication problems • 11-year orbit period decreases sky accessibility • More autonomy required. • More stringent nulling and detector requirements

Question 5) What are the technological hurdles to achieve success, with a status report and prognosis for solutions?

Studies over the past three years have identified the technologies that are essential to the success of TPF. This section addresses the key TPF issues and how other NASA programs as well as a specific TPF technology program will meet these challenges. Table 5 summarizes the required technologies and shows that a number of ground and space-based telescopes and interferometers currently in operation or under development will provide a rich technology heritage on which TPF will build. Figure 2 shows an integrated plan for Origins missions leading to the development of TPF technologies. *The most important thing to remember from the response to this question is that seven or eight years from now, when TPF enters its development phase, almost all of the key technological challenges for TPF will have been demonstrated by the combination of ST-3, SIM, NGST, and the Keck Interferometer.*

To address those TPF technologies not directly dealt with by the other programs, NASA initiated a TPF-unique technology development program in FY1998. The present focus of the program is interferometric nulling, but the program will be expanded over the next few years, both in scope and resources, to help adapt the technology from other programs into TPF-specific needs. The following two sub-sections address the mission-technology matrix given in Table 5, first discussing the missions and then the individual technologies.

Technology Precursor Missions

Ground-Based Infrared Interferometers

A. Palomar Testbed Interferometer. The Palomar Testbed Interferometer (PTI) is a long-baseline near-infrared interferometer operated by JPL at Palomar Observatory. PTI was designed as a testbed for interferometric. techniques. It is highly automated with a number of active subsystems similar to those needed by TPF, including fringe trackers, star trackers, and active delay lines. PTI includes extensive laser metrology of both the delay lines for servo control as well as of the entire optical path.

B. Keck Interferometer. The Keck Interferometer (Keck-I) is a long-baseline infrared interferometer that will combine the two 10 m Keck telescopes on Mauna Kea, Hawaii, with four 1.8 m outrigger telescopes. The Keck-I science will include direct detection of hot Jupiter-sized planets, synthesis imaging, precision narrow-angle astrometry, and detection of exo-zodiacal dust around nearby stars. This last objective, accomplished through nulling interferometry with the two Keck telescopes, is directed primarily at TPF mission development and planning. Keck-I includes many of the active subsystems required for TPF, including laser metrology, automation, and a cryogenic nulling interferometer back end. The implementation of the Keck-I nuller is similar to one of the TPF approaches using rooftop prisms or cat’s eye mirrors. Practical application of the nuller architecture to science observations, which will require development of the requisite alignment, calibration, and observing plans, will provide insight into TPF nuller architecture and efficient mission design and planning.

C. Large Binocular Telescope. The University of Arizona’s Large Binocular Telescope (LBT) will consist of two 8.4 m mirrors on a beam, mounted as a single telescope. NASA is assisting in the development of the LBT in part as a testbed for TPF. LBT will have a cryogenic IR nulling beam-combining station. The implementation of the LBT’s nuller is similar to a second of the TPF approaches using achromatic dielectric plates for nulling phase control. LBT will observe exo-planetary dust, and will demonstrate cryogenic path length control, and performance of nulling optics at cryogenic temperatures.

Space Missions

A. Space Infrared Telescope Facility (SIRTF). The Space Infrared Telescope Facility (SIRTF) is a cryogenic infrared telescope that will provide unprecedented sensitivity and is planned for launch in late 2001. It will provide important component- and system-level technologies needed for TPF. It will be the first mission to use high-efficiency passive cooling techniques on a large scale to minimize the use of stored cryogen; the passive cooling is expected to achieve temperatures of less than 40 K. The SIRTF instruments will have InSb and Si:As arrays as near IR and thermal IR detectors respectively, with sufficient sensitivity for TPF. SIRTF will also provide important experience in the design, development, integration, and testing of a complex cryogenic space optical system.

B. Space Technology-3. The Space Technology-3 (ST-3) mission, formerly known as Deep Space Three (DS-3), is a TPF flight validation mission which will demonstrate and validate separated spacecraft interferometry and precision formation flying. ST-3 is expected to launch into an Earth-trailing heliocentric orbit in 2004. It will start observations as a short-baseline monolithic interferometer operating at visible wavelengths and will separate into two independent platforms after verification in this mode. The multi-element system will have one collector

Table 5. Technologies Required by TPF

Science and Technology Precursors	**Nulling**	**Separated Spacecraft Formation Flying**	**Large Cold Optics**	**Interfer-ometer Technology & Metrology**	**IR Detec-tors**	**Active Optics**	**Passive Cooling**	**Pointing, Stabiliza-tion & Vibration Control**
Palomar Testbed Interferometer (PTI)				X		X		X
Keck Interferometer (Keck-I)	X			X		X		X
Large Binocular Telescope (LBT)	X			X		X		X
SIRTF			X		X		X	
Space Technology-3 (Deep Space-3)		X		X		X		X
Space Interferometer Mission (SIM)	X			X		X		X
Next Generation Space Telescope (NGST)			X		X	X	X	X

spacecraft and one that doubles as a combiner and collector. ST-3 will validate laser metrology and interferometric phase-control in space at a level of <5 nm, which is nearly adequate for TPF. Its precision formation flying and variable baseline interferometry will be key tests for TPF. ST-3 spacecraft will be operated at separations of up to 1 km. The constellation will be controlled to the level of a few millimeters in pathlength and ~1 arcminute in angle. ST-3 will explore the full range of separations planned for TPF and demonstrate the required level of control. Additionally, ST-3 will demonstrate system-level integration of separated spacecraft control with interferometer control systems. Integration and test of ST-3 will provide valuable experience with formation-flying spacecraft.

C. Space Interferometry Mission. The Space Interferometry Mission (SIM) is planned for launch in 2005 into an Earth-trailing solar orbit and will be the first implementation of a stellar interferometer in space for science applications. It is an important technology precursor for TPF in a variety of ways. SIM will demonstrate the use of a complex space-based interferometer to gather high-quality science data. It will perform nulling and synthetic imaging observations, two key elements of the TPF mission. SIM's 5 to 7 year lifetime will probe a range of issues, including the operational reliability of an interferometer in space and developing methods for processing the data. SIM will also serve as a pathfinder for TPF's system integration, test processes, and flight and ground operations. At the component level, SIM will demonstrate space-qualified pointing and pathlength control hardware and software used to acquire, track, and make measurements on science targets. It will also demonstrate sub-nanometer metrology systems needed to sense critical dimensions and vibration isolation systems that will minimize onboard disturbances imparted by the avionics to the optical system. Imaging with SIM will involve taking highly accurate phase and visibility data with a number of baseline lengths and orientations and synthesizing an image. This technique is similar to that envisioned for TPF's astrophysical studies. The nulling beam combiner will have to control the differential optical paths between two arms of the interferometer to about 1 nm rms and the pointing error to less than 3 mas. Both requirements are consistent with the TPF architecture concepts.

D. Next Generation Space Telescope. The Next Generation Space Telescope (NGST), planned for launch in 2007, will be a passively cooled IR telescope designed for performing observations of the early universe including the earliest galaxy formation in the 0.6-10+ μm band. Like SIM, NGST represents a major step towards TPF. Its primary aperture will be an 8 m diameter, ultra-lightweight, segmented, deployable mirror using an active optical control system The NGST instruments will include very high sensitivity IR detectors. NGST will cool its telescope passively to ~35 K by using a large, lightweight, deployable or inflatable sunshade. The cold optical telescope assembly will be isolated from the vibrations associated with the avionics systems on the spacecraft through a combination of passive and active vibration control systems. Beyond simply providing component and subsystem technologies useful to TPF, NGST will provide experience in system-level issues for very large, complex cryo-optical space systems. Lessons learned during the NGST technology development program and architecture studies will provide much of the basis for a successful development phase for TPF. Detailed integrated models relating optical performance to environmental parameters and observatory system performance will be developed and validated against laboratory and flight data. Techniques to integrate and test large, cryogenic optical systems will be developed and validated. Highly efficient ground and flight operations methodologies will be implemented including significant levels of onboard autonomy. These system-level technologies, along with those developed for SIM and ST-3, will guide the implementation of TPF as NASA's first, cryogenic separated-spacecraft interferometer mission.

TPF Technologies

A. Nulling Perhaps the most difficult challenge of finding planets around nearby stars is that of rejecting the light of the parent star. The approach that appears technologically most feasible is an interferometer using nulling to remove the on-axis light from a parent star. Nulling is no more complex than standard Michelson interferometry, but with a phase shift of π radians introduced into one beam resulting in destructive rather than constructive interference at zero path difference for a source located on the optical axis. The challenge of nulling for TPF involves making the null sufficiently deep and achromatic that a broad range of wavelengths can be passed to enable detection of any weak off-axis sources such as a planet. Three experiments made in the last year have demonstrated the underlying principles of nulling interferometry:

- Nulling was first used astronomically at the Multiple Mirror Telescope to observe circumstellar envelopes around red giant and supergiant stars. Images of the dust cloud around Betelgeuse (α Ori) were made by nulling the central star by 24:1 in a R~10 spectral bandwidth, a modest but important milestone on the route to TPF (Figure 13b).

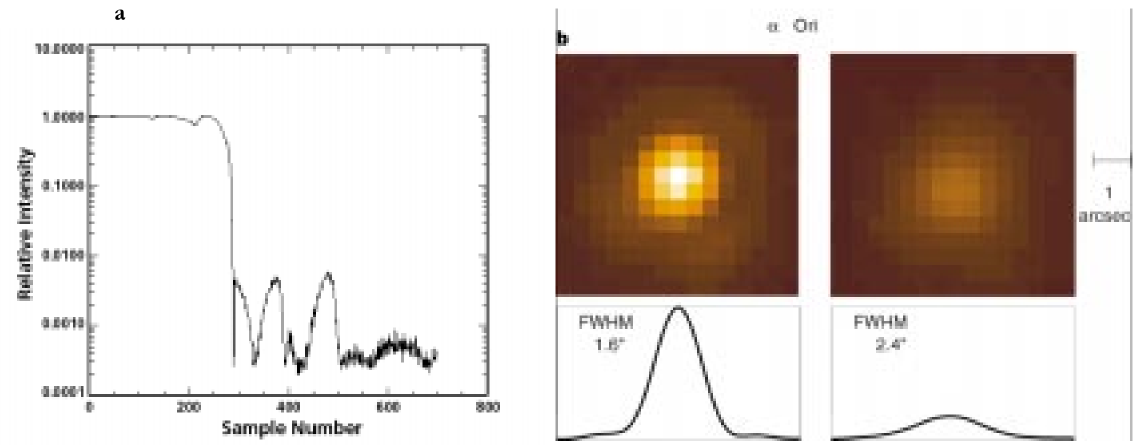

Figure 13. a) A JPL group has demonstrated a 25,000:1 visible light null in the laboratory. b) A University of Arizona group has demonstrated a 25:1 broad null infrared on the star α Ori using an interferometer on the MMT.

- An interferometer at JPL recently achieved a null depth of a part in 25,000 on a visible-light diode laser with a 0.5% (R=200) bandwidth as shown in Figure 13a.

- The first attempt at white light nulling using the JPL apparatus resulted in a null depth of a part in 900 with visible light in a 5% (R=20) bandwidth and in a single polarization. Improvements in this apparatus in the next two years, including vibration-isolation, operation in a vacuum, implementation of a control loop are expected to allow deep nulls to be obtained in broad-band visible light.

TPF's ultimate goal requires nulling starlight to 10^{-5}-10^{-6} across the 7-20 μm region (in a series of spectral bands with $R = \lambda/\Delta\lambda \sim 20$). The most stringent requirements for TPF nulling operation is at 7 μm. The nulling requirement at 20μm is less stringent due to the more favorable planet-star ratio and easier to achieve because of the longer wavelength. Table 6 describes some of the factors that must be controlled to achieve the desired null depth. By way of comparison with laboratory experiments, it is interesting to note that the few nanometer control needed for a 10^{-6} null at 7 μm is easier to achieve than the recently achieved null depth of 10^{-4} at visible wavelengths.

Table 7. Nulling Development for TPF			
Activity	Date	Mid-IR	Visible Light
Telescope Demonstration	3/98	25:1 (UofA)	
Passive, open-air, Laboratory Nuller (laser)	2/99		25,000:1 (JPL) 6,000:1 (UofA)
Passive, open-air, Laboratory Nuller (white light)	3/99		300:1 (JPL)
Keck Mid-IR Nuller (active, cryogenic)	2001	10,000:1 (JPL)	
Active, vacuum, Laboratory Nuller (white light), SIM prototype	2001		10,000:1 (UofA, JPL/Lockheed Martin)
Large Binocular Telescope-MMT Mid-IR Nuller	2003	10,000:1 (UofA)	
TPF Laboratory Prototype (cryogenic, vacuum)	2005	100,000:1 (requirement) 1,000,000:1 (goal)	
SIM Nulling Experiment (vacuum, white light, in space)	2005		10,000:1

To achieve TPF's ultimate goal will require significant technological progress that will be demonstrated through a series of laboratory testbeds coupled with astronomical experiments on ground-based and space-based telescopes (Table 7). While there are no insurmountable technical obstacles, extremely careful attention to experimental detail will be required, including increased refinement in areas such as optical coatings and pathlength control, infrared polarization devices, infrared spatial filters, beamsplitters, etc.

The first step toward deep nulling involves experiments aimed at mid-infrared interferometry on large ground-based pairs of telescopes, such as with Keck-I and the LBT. From the ground, residual atmospheric wavefront distortions will likely limit the null depths attainable in these experiments to 10^{-3}-10^{-4}. However, these experiments will provide initial guidance in several key areas, including intensity, polarization, and pathlength control, and a host of subsidiary issues such as beamsplitter reflection/transmission ratios and spatial filter (pinhole, waveguide, or fiber) efficiencies. The ground-based, cryogenic mid-infrared experiments will be followed by a nulling experiment on SIM at optical wavelengths, the goal of which will be to demonstrate in space the requisite level of pathlength control that TPF will eventually need. This corresponds to a null depth of 10^{-4} at a wavelength of 1 μm, and so will necessitate correspondingly tighter constraints on polarization and intensity control as well. By following the technology development program outlined above with laboratory testbeds as well as instruments on Keck, LBT, and SIM, the nulling capability needed for the full range of TPF requirements will be in place to support a start for TPF sometime in the next decade.

Table 6. Control Requirements for TPF Nulling	
Error Sources	**Requirements for Null $<10^{-6}$@ 7μm $<5\times10^{-5}$@ 20μm**
Optical Path Errors	3.5 nm 70 nm
Transmission Asymmetries between Beams	<0.2% <1.4%
Pointing Jitter	10 milli-arcsec 75 milli-arcsec
Differential Polarization Rotation	0.1 deg 0.7 deg
Differential polarization (s-p Waves) Delay	0.2 deg 1.4 deg

B. Separated Spacecraft Precision Formation Flying. Current TPF concepts include multiple (~5) separated spacecraft maneuvering in formation to form a variable baseline interferometer incorporating an optically-linked virtual truss with multiple collectors and one combiner spacecraft. Science observations will require rotating the five-spacecraft formation about the line-of-sight of a target star at approximately one revolution per 8 hr. Re-targeting maneuvers will be executed by the combiner and will be repeated by the collectors which are slaved to guide on the combiner and reference each other by the formation flying system and the optical metrology system.

As described above, much of the technology required for TPF precision formation flying will be developed and demonstrated on the ST-3 mission. Following launch and deployment of the collector and combiner spacecraft, the acquisition of the initial formation and precision formation flying will be accomplished using relative 3-D position sensing accurate to ~0.5 cm and the relative angles to ~1-2 arcminutes. Spacecraft position and attitude information will be exchanged through the on-board RF links so that constellation internal geometry, relative orientation, and integrity can be autonomously monitored, and maneuvers can be automatically sequenced and executed. Fast steering mirrors and optical delay lines on the combiner spacecraft will provide the nanometer control needed for interferometry.

C. Large Lightweight Cryogenic Optics Technology. The current concept for TPF incorporates telescopes with monolithic primary mirrors each 3.5 m in diameter, operating at < 40 K with diffraction-limited performance at 2 µm. Logical extensions of current lightweight cryogenic mirror technology developing for SIRTF and NGST will be adequate to build the TPF collector telescope mirrors. The NGST mirror will operate in the same region of the spectrum and at the same temperature as TPF. The individual NGST mirror segments are likely to be at the low end of the size range for TPF primaries. They will have the same low areal density of ~15 kg m^{-2} that is planned for TPF.

D. Cryogenic Active Optical System Technology. TPF, like many of its precursors, will utilize a number of active optical control elements. The optical deployment and control systems on NGST will utilize low-power, low-mass, precision cryogenic mechanisms including hinges, latches, actuators, drive mechanisms, fast steering mirrors, deformable mirrors, etc. They are expected to include examples of nearly all the cryogenic devices required by TPF, except those required for path length adjustment and thus cryogenic optical control-component technology developed by and for NGST is anticipated to meet most of TPF’s needs in this area.

E. Pathlength Control. One of the key active optical systems in an interferometer is the pathlength control system. Pathlength control in TPF will be accomplished by a multi-stage scheme. Large pathlength errors are reduced by moving the telescopes. Small pathlength errors are reduced by an optical delay line (ODL) to the required nanometer levels. A three-tiered actuation scheme has been devised for SIM, which works in concert with the optical architecture of a parabola-flat retro-reflector or cat’s eye, to provide a high bandwidth actuator that will accommodate its dynamic range. There is a great deal of history with this architecture, from early experiments on the Mount Wilson interferometer to PTI and the JPL Interferometry Technology Program (ITP), that prove the disturbance rejection and tracking capability of these devices. In addition, the ITP ODL was designed as a flight-qualifiable brassboard, and has survived flight-level environmental testing in random vibration, shock, and thermal/vacuum.

F. Detector Technology. TPF will require both visible/near IR (0.5-2 µm) detectors for alignment and metrology and thermal IR (3-30 µm) detectors for the science payload. The current detector development activities for SIRTF and NGST will produce arrays that meet or exceed anticipated

TPF requirements. For the required performance, the thermal IR detectors must be cooled to 5 K, which requires active cooling. Approximately 2 mW of cooling power will be required at 5 K. Additionally, the cooler must be reliable over the lifetime of the mission, and must not vibrate appreciably. The miniature Turbo-Brayton cooler, considered for development for NGST, or a sorption cooler, under development for the Planck and Far Infrared and Submillimeter Telescope (FIRST) missions, are good candidates that are expected to be available in the TPF timeframe and meet the TPF requirements.

G. Metrology Technology. TPF metrology is required to work in two very different regimes. For planet studies, there will be a bright star to serve as a phase reference source by its short wavelength IR emission (1-2 μm). Internal referencing is also possible with visible laser beams. The one motion not directly sensed is the motion along the line of sight to the star. Accelerometers can provide the short timescale information to link to the stellar phase reference. For astrophysical observations, the available phase reference is over 100 times coarser, and alternate metrology systems are likely to be needed. The components for such alternate metrology systems are currently in various stages of development for SIM and ST-3 and will be sufficient for TPF.

H. Interferometer System Technologies. TPF will be a very complex system involving multiple optical, electrical, structural, thermal, mechanical, and control elements, many of which will operate in a highly integrated manner. Every subsystem will have ambitious requirements contributing directly to the overall performance of the mission. The questions then arise: What architecture or mission will most effectively use existing and emerging technologies to provide the maximum science return? How will we validate and qualify key technologies, and integrate and test TPF components, systems and subsystems to reduce the risk of failure?

In the past few years, industry and NASA have developed integrated computational modeling capabilities for complex systems. These tools are currently being used by the NGST project to demonstrate the feasibility of an eight-meter aperture in space. In addition, a number of system and subsystem testbeds are planned for TPF technology demonstrations and validation purposes. These testbeds will demonstrate in the laboratory environment how the various functional elements of the TPF system will operate together. The modeling of testbeds and the comparison of predicted results to actual performance is one key element of the TPF validation process for technological readiness. A system testbed will be developed --- a virtual TPF --- which will incorporate models, software and hardware representing all critical functions, from science investigations and flight systems to operations. These capabilities and facilities will support mission architecture development, as well as integration, test, and operation, during later stages of the program.

I. Passive Cooling Technology. The TPF optics, like those of NGST, are expected to cool passively to <40 K by radiating to cold space. This will require lightweight sunshades shielding the collector telescopes and beam combiner/instrument module from solar radiation and radiation from the warm parts of the other spacecraft in the constellation. NGST is developing an inflation-deployed shade and has recently completed a ground demonstration of a 1/2 scale test article. The first NGST Pathfinder Flight Experiment, the Inflatable Shield In Space (ISIS) planned for launch in 2000, will demonstrate and validate this concept in the space environment. TPF will inherit the technology for such large, deployable sunshields from NGST and benefit from the experiences of SIRTF and NGST thermal design.

J. Pointing, Stabilization and Vibration Control Technology. Most of the pointing, stabilization, and vibration control technology necessary for TPF will be available and validated by precursor missions including NGST, SIM, and ST-3. Pointing control will be largely based on the mid-IR diffraction disk of stars seen through the telescope apertures. Control to ~1/100 of the diffraction disk diameter at 1 µm, corresponds to control to 1/1000 of the diffraction disk at 10 µm and will be adequate for planet studies. Star images in the combiner telescope cold focal planes can serve as the fine pointing reference. This fine pointing control function can track a star image on the detector array and provides error signals to control a two-axis fast steering mirror (FSM). Such a the system is currently under development for NGST.

Question 6) What is the future potential of the technology developed for this mission? What is the expected growth path?

As part of NASA's Origins program, TPF will build on projects like Keck, SIRTF, SIM, Space Technology-3, and NGST and must itself leave a legacy of scientific results and technological capabilities for subsequent missions. Thus, it is important to ensure that in addition to accomplishing its own aims, TPF lead toward more long-term goals of the Origins program and other areas of space research. What Origins-related missions might we want to carry out in the decades after TPF? Are there choices for TPF's architecture that are likely to open new technological vistas? These questions must be considered carefully as we place TPF within the context of an integrated program lasting 25 years or more.

The design choices described in this report can be extrapolated to future observatories that will improve on TPF's ability to search for life on other planets. After TPF has finished its initial characterization of neighboring planets, one can imagine areas of performance that might be enhanced:

- Increasing sensitivity to enable the comparative study of the atmospheres of planets orbiting thousands of stars, rather than just a few hundred.
- Improving spectroscopic resolution to probe atmospheric conditions using the profiles of strong lines, and to search for weak lines of gases that either singly or in combination with others might offer unambiguous markers of biological activity.
- Operating at visible and near-IR wavelengths to look for additional tracers of life
- Making the first resolved images of the nearest planets to look for moons and even gross features on the surfaces of planets themselves.

Observatories capable of addressing these expanded goals would require apertures as large as 10-50 m with interferometric baselines from 100's of meters for spectroscopy to hundreds of kilometers for imaging. What technologies will ultimately be developed to implement such capabilities are of course unknown, but those projects will build on the techniques developed for TPF.

As one example of how TPF will pioneer techniques for later missions not associated with planet finding, consider that a separated spacecraft interferometer dramatically breaks the linkage between telescope aperture and maximum baseline. While SIM will take the first steps in interferometry, using numerous small telescopes on a 10 m baseline, TPF will extend its baseline to hundreds and even thousands of meters, revolutionizing high resolution imaging in a way that can be of use for astronomy missions operating anywhere from the submillimeter to X-rays. Observatories with sub-milli-arcsecond resolution and nano-Jansky sensitivity offer remarkable capabilities for all facets of astronomy, not to mention applications looking at objects in our own Solar System, or back at our own planet. A precisely controlled constellation of spacecraft operating as an interferometer is also an enabling technology for space-based gravitational wave astronomy. Finally, TPF will require four or more 3-4 m class telescopes diffraction-limited at 2 μm that must be developed at low cost. The ability to build and launch these telescopes economically, perhaps to send one to the low background environment found at 3 AU from the sun, would be a lasting legacy of TPF.

TPF will lay a technological foundation for future generations who will raise questions that are presently beyond our grasp or even beyond our imaginations. The Terrestrial Planet Finder is not an end-point of the Origins program, but rather TPF will be a vital way-station in humanity's long quest to discover the origins of life, to learn whether or not the Universe teems with life, and ultimately to deepen and broaden our understanding of ourselves and of our place in the Universe.

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