Terrestrial Planet Finder: Technology Development Plans

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ABSTRACT

One of humanity's oldest questions is whether life exists elsewhere in the universe. The Terrestrial Planet Finder (TPF) mission will survey stars in our stellar neighborhood to search for planets and perform spectroscopic measurements to identify potential biomarkers in their atmospheres. In response to the recently published President's Plan for Space Exploration, TPF has plans to launch a visible-light coronagraph in 2014, and a separated-spacecraft infrared interferometer in 2016. Substantial funding has been committed to the development of the key technologies that are required to meet these goals for launch in the next decade. Efforts underway through industry and university contracts and at JPL include a number of system and subsystem testbeds, as well as components and numerical modeling capabilities. The science, technology, and design efforts are closely coupled to ensure that requirements and capabilities will be consistent and meet the science goals.

1. Introduction

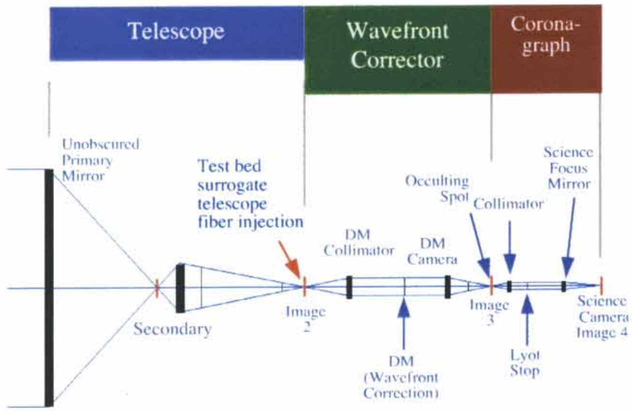
The Terrestrial Planet Finder (TPF) is among the most ambitious science missions ever proposed by NASA. TPF will search for earthlike planets around a statistically significant number of stars in our stellar neighborhood and characterize the atmospheres of detected planets to determine if they are capable of supporting life as we understand it. Subsequent missions, such as Life Finder and Planet Imager, will further refine our knowledge of extrasolar planetary systems.

The basic technical problem confronting TPF is to separate the light of a planet from the light of the star that it orbits. In the infrared portion of the spectrum, the star is $\sim 10^6$ times brighter than the planet's emitted radiation, and in the visible portion of the spectrum the star is $\sim 10^9$ times brighter than the reflected light of the planet. This situation is further complicated by the proximity of the planet to the star—given that the planet is likely to be on the order of 1 AU from its parent star, the angular separation will be very small—on the order of 0.1 arcsecond. Looking only at the required contrast, detecting planets in the infrared appears to be an easier task, but when the details of building a full space mission area taken into account, the preferred mission architecture is much less obvious; until recently, the TPF project was pursuing both paths, with the intent to narrow the focus of development to one in 2006. TPF is now planning to pursue both options, with the launch of a visible coronagraph on 2014, and an infrared interferometer in 2016.

1.1. Infrared vs. Visible

Scientifically, both the infrared and the visible are valuable, and indeed complementary, for detecting and characterizing habitable planets. Earlier studies [1] have determined that there are suitable biomarkers in both the visible (0.7 to 1.0 μm) and infrared (8.5 to 20 μm) portions of the electromagnetic spectrum, and that technical feasibility should be used to determine the best approach to the mission development. JPL commissioned a set of mission studies in 2000 to explore and refine the trade space for possible mission designs. Four teams, led by Ball Aerospace, Lockheed Martin, Boeing, and Northrop Grumman and composed of scientists, technologists, and engineers from academia and industry explored the possible trade space of missions capable of performing the TPF science. Two major classes of mission were identified in these studies as feasible for the TPF mission[2]: visible-light coronagraphs and infrared interferometers. The IR interferometers are further separated into subclasses of structurally connected interferometers and separated spacecraft interferometers

A visible light coronagraph would be based on a high-perfomance optical telescope, with a diameter, or at least one semi-major axis, of 4 to 8 meters, depending on the ultimate capabilities of the downstream optics. The coronagraphic instrument would use some combination of masks and stops to control diffracted light so as to block the light of the star and allow the light of the planet, at close angular separation, through the system. Because the system is very sensitive to scattered light, a high precision deformable mirror is also required. A schematic of this type of system is shown in Figure 1a.



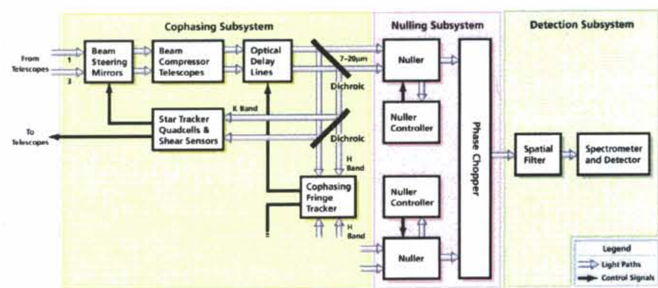
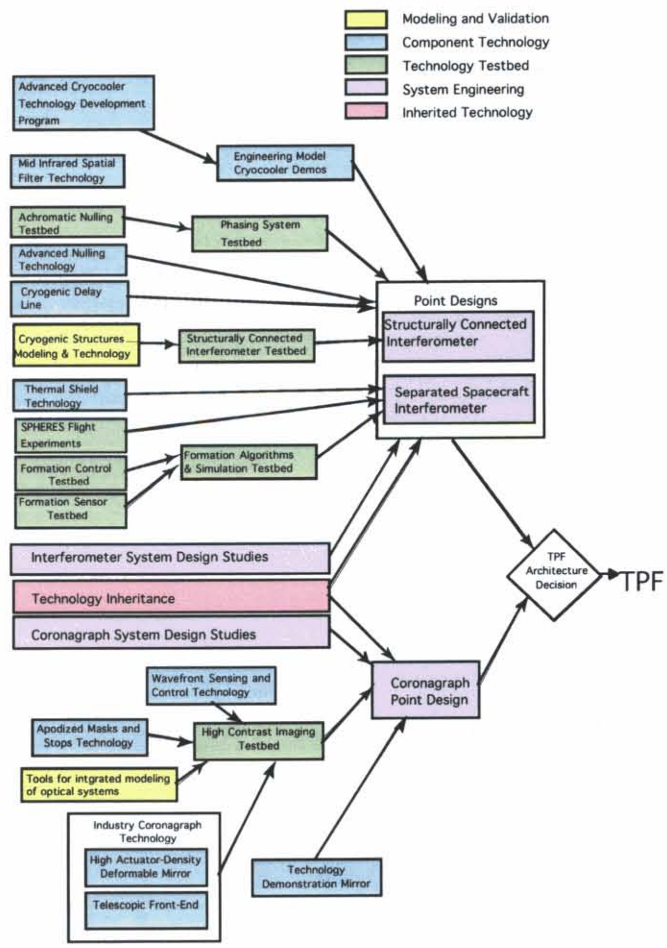


Figure 1. a) Schematic of a coronagraphic system. b) Schematic of an interferometer system.

An infrared interferometer would be based on a small number (four to six) of moderate sized (2 to 4 meter) infrared telescopes, with the entire optical system cooled to less than about 40 K. To obtain the angular resolution required to distinguish a planet from the central star, the telescopes would be arranged to create optical baselines of 30 to 70 meters, with longer baselines offering higher angular resolution. The positions of the telescopes could be maintained using a large deployable structure or by mounting each telescope on its own spacecraft. The interferometer would then combine the light from the telescopes in such a way that the on-axis light from the star is cancelled and the light from the nearby planet is transmitted to the focal plane. A schematic of a nulling interferometer is shown in Figure 1b.

Both the visible-light coronagraphs and the IR interferometers are challenging missions to build using available technology. Using results from the past studies, the TPF project at JPL has identified the key technologies required for each architecture and embarked on an intensive technology development program to demonstrate, by the end of 2006, sufficient capability to implement one or more of the mission concepts for launch around 2015.



2. Technology Development Approach

The coronagraph system must be capable of blocking out starlight that is as much as 10 billion times brighter than the orbiting planet. Masks and stops are used to block the starlight and control diffraction effects. Because there is so much more starlight than planet light coming into the optical system, the optical wavefront must also be very carefully controlled to prevent scattered light from appearing at the detectors and masking (or worse, mimicking) the planet light. For TPF, the main approaches to controlling the scattered light are an extremely high quality primary mirror, and a wavefront control system that uses a deformable mirror to correct wavefront errors that are introduced by other elements of the optical system.

2.1. Integrated Technology Planning

The TPF project approach closely couples the science goals, mission design, and technology development throughout the technology development period [3]. Science requirements were generated from inputs from a number of sources, including the TPF Science Working Group (SWG), prior industry studies, JPL studies, the inputs from multiple review panels, and newly published science results. These inputs, including technology development recommendations, were used to identify technology needs for the TPF architectures under study. Performance requirements for the technologies were determined from the industry/academia architecture studies and additional subsequent study efforts. The science requirements are being refined through regular meetings of the TPF SWG, leading to further refinements of the system design concepts and the resulting technology requirements.

The project is presently organized into separate teams for the interferometer and coronagraph that will develop the two concepts in parallel. Each architecture development teams is composed of mission design and technology development teams. The mission design teams develop and improve the mission designs to determine performance requirements and technology needs, and also perform trades and design changes based on inputs from the technology development teams. The technology development teams work to reduce mission risk by identifying key technologies for further development to meet mission needs, and then arranging to develop those technologies through a combination of JPL, NASA, and subcontracted industry and university efforts. Throughout the development program, the design and technology teams are closely coupled to ensure that the system designs are consistent with the available technologies.

The process described above led to the technology roadmap shown in Figure 2 and the published technology plan [3]. The technology roadmap shows the relationships among the various development tasks and how they integrate with the design studies to lead to at least one technically feasible design by 2006. The technology plan provides a full description of the requirements for each technology and the approach for achieving it. The technology plan was reviewed by the Navigator program Independent Review Team (IRT), which reports to NASA HQ, prior to publication. The technology plan is currently being revised to focus on the two architectures selected for further development. The remainder of this section describes the programmatic features of the technology plan, whereas the next section describes progress to date in particular key technologies.

2.2. Tracking Technology Development

A set of objective milestones and performance targets has been developed for each technology development task within the TPF project. The milestones represent specific work to be accomplished but do not include technical performance levels. The performance goals are quantitative estimates of the level of performance that is expected to be achieved with the corresponding milestone. Each technology is planned to be developed to NASA Technology Readiness Level ~5 by late 2006 (definitions of the NASA Technology Readiness Levels are provided in reference [3]). Progress against the plan is tracked in monthly management reviews and checked at least annually by an external technology review panel.

2.3. Industry and University Involvement

The TPF project is maintaining close involvement with universities and industry by incorporating them into the various teams. Design team members from both industry and academia have expertise in areas that are relevant to the system and instrument designs. The technology development efforts include several major components and testbeds that are being conducted under subcontract to industry and industry/university teams, as well as a number of smaller system and component development efforts that are being done primarily at universities. Among the larger efforts are the Technology Development Mirror, the Structurally Connected Interferometer Testbed, and the Telescope Front End. The individual component efforts include coronagraphic mask and stop development, deformable mirror development, and high-performance modeling software.

The entire technology development and system design program is connected as shown in Figure 2. Each technology effort feeds into other technology advances or testbeds, and ultimately into the system designs. Each task has a set of annual milestones and performance goals that are reviewed periodically to ensure they remain closely tied to the mission development as science requirements and mission concepts are refined.

2.4. Technology Inheritance

One key to a successful technology development program is recognition of other sources of technology development, whether they directly meet the technology need, provide a lower level of capability that can be enhanced with small additional investments, or provide a general knowledge and experience base that can be exploited to avoid repeating earlier basic research and development. Much of this inheritance comes through the expertise of experienced engineers who have done prior related work, such as wavefront sensing and control, or ground-based interferometer development. Because there is such a range of potential sources for technology, TPF has endeavored to identify and catalog sources of technology inheritance explicitly. Some examples of planned inheritance from within the Origins program are wavefront sensing and large cryogenic sunshields from JWST, as well as collaborative development of cryocoolers with JWST and Constellation-X. The formation flying technology program also derives substantial heritage from the former StarLight formation flying interferometer mission.

2.5. Technology Legacy

In addition to providing technologies to enable TPF, the TPF technology development program also considers the technology legacy that will be left by TPF. TPF is only the first of what will likely be a series of missions to detect and characterize extrasolar planets that may be capable of supporting life. Subsequent missions will require even higher spatial and spectral resolution, which leads to much larger collecting areas spread over much larger baselines or telescope diameters. In selecting technologies for development for TPF, the project seeks to ensure that the developments can be further extended to support these follow on missions.

3. Technology Development Progress

3.1. Coronagraph Technology

A paragraph or two here about coronagraph issues

3.1.1. High Contrast Imaging Testbed

HCIT Picture with half dark-hole inset

The high contrast imaging testbed (HCIT) is an adaptable testbed designed to demonstrate all the key technologies needed for a high contrast coronagraph in an integrated environment. It consists of a full-scale instrument in a temperature controlled vacuum chamber that is mechanically isolated from the laboratory. The HCIT simulates the input from the telescope with an optical fiber. The testbed includes a deformable mirror (see 3.1.2), locations for inserting occulting masks and Lyot stops, and can be easily reconfigured to switch from a Lyot coronagraph to an apodized pupil coronagraph [ref Spergel, Nisenson]. Wavefront sensing can be done at the science focal plane or at a wavefront sensing camera located after the deformable mirror and before the coronagraph optics. Recent results using the image at the science focal plane for wavefront correction have shown a contrast of $2\text{x}10^{-9}$ at $4\lambda/D$ with a laser source. A white-light source that is currently in development will allow extension of the high contrast results to white light in the next several months.

Xinetics DM picture

1.1.2. Deformable Mirror

In order to achieve the high contrast required for TPF, the wavefront of the signal through the instrument must be corrected to ~$\lambda/10^4$The wavefront control in the HCIT is currently being performed with a continuous face-sheet deformable mirror from Xinetics that can control the position of the mirror surface to better than 0.1 nm rms. The mirror is of modular construction so that multiple actuator modules can be integrated to create deformable mirrors of arbitrarily large size. Mirrors of up to 64x64 actuators (on 1 mm centers) have been received, with near term plans of 96x96 and the potential for even larger mirrors.

ANT Picture

A second MEMS-based mirror technology is also in development at Boston Micromachines, with delivery of a segmented face-sheet mirror expected in 200X. The MEMS based mirror uses an array of 660 μm hexagons with a 1 μm range and expected resolution of 0.1 nm. The segmented array is design so that each facet has three actuators and can be used to apply tip, tilt, and piston corrections. The same technology could be used to make continuous face-sheet deformable mirrors.

1.1.3. Technology Demonstration Mirror

A TPF coronagraph requires a much larger (4 to 8 m) and smoother (<7 nm rms surface error at 4 to 100 cycles per aperture) primary mirror than is typically built for visible wavelengths. Additionally, because the system is so sensitive to both diffracted and scattered light, an unobscured, off-axis telescope, is preferred over a more traditional on-axis telescope. To demonstrate that this is achievable, TPF is developing a 1.8 m, off-axis primary mirror with the surface quality necessary to achieve the low scatter required. Eastman Kodak was competitively selected to manufacture this mirror, and deliver it in [2006?] to the TPF project.

1.2. Formation Flying Interferometer Technology

Many of the component technologies for a TPF interferometer have been (or will be) demonstrated in ground and space based systems. Chief among these are the collector mirrors, which have requirements very similar to those of the James Webb Space Telescope, planned for launch in 2009. The main development focus for the TPF interferometer is on demonstrating the ability to produce a broad-band null in the infrared that is sufficiently deep and stable to detect planets. A number of component technologies are in development toward this end, but the primary work is now focused on testbeds to demonstrate the performance of a complete representative optical system.

Broadband ANT Data

In addition to the basic technology of nulling, the stable space platform to support the collector telescopes on a long (40 m or more) baseline must be developed. TPF is taking advantage of approximately $75M in investments that NASA made in the StarLight project over the last several years. StarLight has since been incorporated into the TPF project, with developments focusing on a small number of compenent technologies and the integration of the control algorithms into full three dimensional ground-based demonstrations.

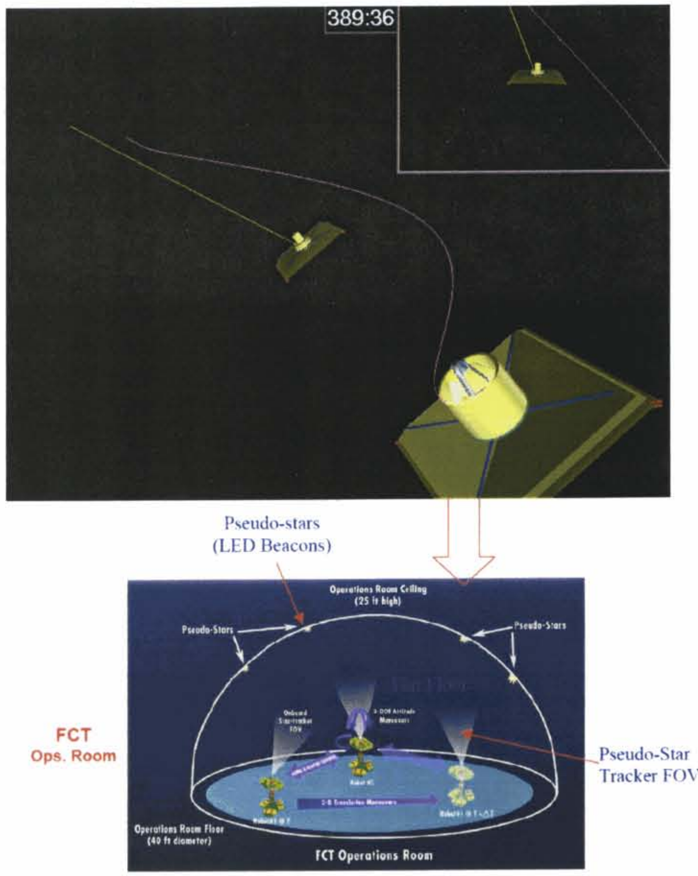
1.2.1. Infrared Nulling

The interferometry development efforts of TPF focus on two testbeds: the Achromatic Nulling Testbed and the Planet Detection Testbed. The two testbeds are designed to be complementary, so that progress can be made along multiple paths without having to address full system issues at the same time as individual technology advances.

The nulling testbed is aimed at demonstrating the basic technologies of nulling at performance levels that will meet or be traceable to the TPF requirements, but with only two input beams. So far it has demonstrated nulling to 10^{-6} with a

10 μm laser, and broadband nulling to 10^{-4} with a 30% bandwidth at 10 μm. Further demonstrations are planned to demonstrate broadband nulling with a 50% bandwidth (from 7 to 12 μm) to a contrast of 10^{-6} in a cryogenic environment.

The more complex Planet Detection Testbed will provide a system level demonstration with four input beams with features to suppress background noise and the ability to extract the planet light from a simulated star and planet system. The PDT will show operation of a nulling interferometer across multiple separate bands simultaneously, including a shorter wavelength metrology band to demonstrate use of stellar light at 2 μm (much shorter than the science band of 7 to 17 or more μm) to provide a bright beam for controlling the interferometer without reducing the light from the relatively dimmer science beam.



1.1.2. Formation Flying Sensors

Under the StarLight program, a Ka-band formation flying sensor was demonstrated to meet requirements close to those of the TPF formation flying system. On an outdoor test range, the Autonomous Formation Flying sensor was verified to meet range estimation requirements of 2 cm accuracy and 1 arcminute bearing-angle with a moderate field of view (+-70 degrees). The range and bearing performance is well within the TPF requirements, and further planned developments will extend the field of view to the full 4π steradians required for safe operation of a separated spacraft formation at the relatively close ranges required by TPF.

1.1.3. Formation Flying Algorithms and Controls

TPF is developing a full computer simulation of a separated spacecraft system that runs on a network of computers to model the full independent operation of the spacecraft, including appropriate delays for communication and demonstrations of anomalous formation operation (e.g. spacecraft losing relative orientation information). Thus far, this testbed has demonstrated formation flying of two autonomous simulated spacecraft with 5 cm range and 5 arcmin bearing control, which meets the basic TPF formation flying requirements. Subsequent demonstrations will include the addition of realistic error signals on the modeled sensors, as well as additional simulated spacecraft. Figure [collisionavoidance] shows the two simulated spacecraft autonomously avoiding a collision.

The algorithms developed in the simulated environment will be integrated into the Formation Control Testbed (FCT), that will use independent robots with a full 6 degrees of freedom, as well as sensors and actuators for the robot "spacecraft" to interact and move autonomously. The robots will move independently on a smooth floor using air-bearings. This hardware based demonstration will provide a realistic environment for demonstrating and debugging the dynamical spacecraft behavior and validate the formation flying control algorithms and software in on the ground.

4. Conclusions

The TPF project undertaking intensive technology development in anticipation of an architecture selection in late 2006. The technology development program is closely coupled to the science requirements and the system design activities to ensure that the technology developments are consistent with the system and science requirements. These activities will lead to the development of at least one viable mission concept to enter into Phase A around 2007. Further information, including current versions of the TPF Technology plan and Science Roadmap, is available in the library section of the TPF website [4].

Acknowledgement

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