12

Technology for the Terrestrial Planet Finder

INTRODUCTION

TPF is a scientifically and technologically challenging undertaking. Mission studies by JPL, industry, and academia have identified technologies that are essential to TPF success and baseline performance requirements for many of the subsystems. Fortunately, the TPF project will not have to begin from scratch; a number of advanced ground and space-based telescopes and interferometers currently in operation or under development will provide a rich technology heritage on which TPF will build. Two main items require development: interferometric nulling and control of spacecraft flying in formation. Both are under development for ground observations or precursor missions, but will also require some TPF-specific development. NASA is already investing in TPF technology and plans a substantial investment prior to the start of the implementation phase. A well-planned, adequately funded technology development and validation program that builds on successful prior missions will provide the necessary ingredients for an exciting, affordable TPF mission.

The first section of this chapter describes a technology development roadmap showing the various development and validation activities leading to technology readiness. The next section provides brief descriptions of important science and technology precursors to TPF and highlights how they will contribute to the key technology needs identified during the TPF mission studies summarized in Table 12.1. The focus is on a suite of technologies that will enable the optimum TPF architecture. One defining assumption at this time is that the TPF baseline architecture will be a separated-spacecraft interferometer, which was determined by the science working group as capable of greater science return than a single, connected structure. Moreover, in the future, very long baseline interferometers are expected, and TPF will provide valuable experience in the development and operation of such instruments. Thus, technology relevant to large (~100 m) precision deployable structures is not addressed in this chapter. It should be noted, however, that if future architecture studies conclude that such a structure is desirable, many of the necessary technologies are incorporated in the plans of other precursor missions, and additional TPF resources could be applied at that time. This chapter concludes with detailed discussion of the critical technologies, except for broad-

Table 12.1. TPF Precursors will Make Significant Contributions to Key TPF Technologies

	Technologies Required by TPF							
Science and Technology Precursors	Active Optics	Interferometer Technology and Metrology	IR Detectors	Large Cold Optics	Separated Spacecraft	Nulling	Passive Cooling	Pointing, Stabilization and Vibration Control
PTI	*	*						*
Keck-I	*	*				*		*
LBT	*	*				*		*
SIRTF			*	*			*	
ST-3	*	*			*			*
SIM	*	*				*		*
NGST	*		*	*			*	*

band achromatic nulling, their requirements, and how these needs will be met in time to make TPF feasible. Nulling technology requirements and the requisite development program were discussed earlier in Chapter 10.

TPF TECHNOLOGY ROADMAP

The TPF technology development roadmap is depicted graphically in Figure 12.1. The important ground-based systems and precursor missions are shown on the left of the figure. The critical technologies provided by these precursors flow into the TPF development activities. Validation of critical TPF technologies comes by way of a series of testbeds and culminates in a TPF system testbed.

A TPF technology development program was initiated in FY'98 to address nulling, considered by many to be the tallest technology tent pole. The program will be expanded over the next few years, both in scope and resources, culminating in a successful start of the TPF implementation phase around 2007. The emphasis will be on hardware and software products, and the efforts will be guided by the progress and results of the TPF architecture studies and modeling activity. Critical technology performance goals and priorities will be established and reviewed as the mission architectures mature. The technology program will, in turn, provide performance data from real hardware for incorporation in mission and subsystem models.

We anticipate that the technologies, testbeds, and models in this program will be developed primarily by those who will actually design, build, and operate TPF. This simplifies or eliminates the need for technology transfer and maximizes the technology's value to the mission. There must also be an effective technology transfer mechanism between SIRTF, NGST, SIM, ST-3, Keck, and PTI. Regular interaction

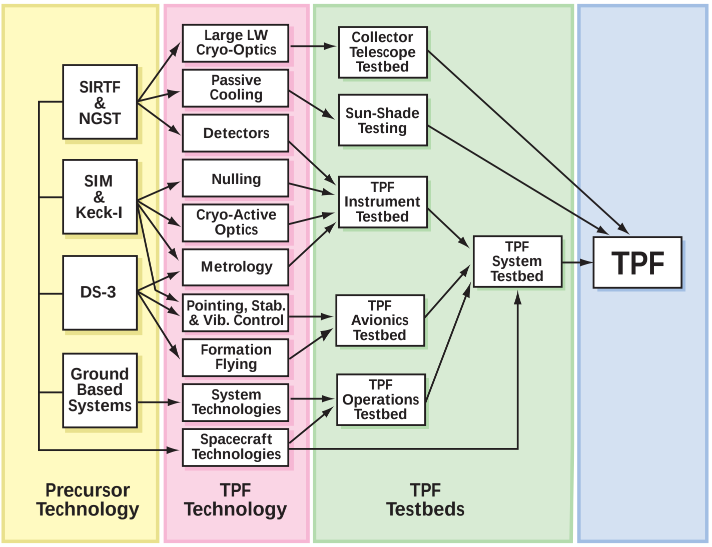


Figure 12.1. TPF Technology Development Roadmap.

and collaboration with the science community, industry, and other technology developers will be a key element of the program, as will regular progress workshops and reviews. With adequate support, dedicated effort, and timely development, these technologies will result in a highly capable, cost-effective TPF mission. NASA plans to spend ~$300M on the TPF technology development effort over the next decade, not including costs associated with technology development by and for precursor missions.

TECHNOLOGY PRECURSORS FOR TPF

Ground-Based Infrared Interferometers

Palomar Testbed Interferometer. The Palomar Testbed Interferometer (PTI) is a long-baseline infrared interferometer operated by JPL at Palomar Observatory in California. It is an outgrowth of earlier, smaller interferometers developed by JPL and others on Mount Wilson in the San Gabriel Mountains above Pasadena, California. PTI was designed as a testbed for interferometric techniques specifically applicable to the Keck Interferometer, and more generally applicable to ground and space interferometers.

PTI is highly automated with a number of active subsystems similar to those needed by the space interferometers SIM and 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 monitoring of the entire optical path. As a precursor to future interferometry missions, PTI also provides system-level experience in end-to-end interferometer operations, from the development of an observing plan through automated observations and data recording, as well as back-end data reduction and analysis.

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. An artist's conception of the Keck-I in its final configuration is shown in Figure 12.2. 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.

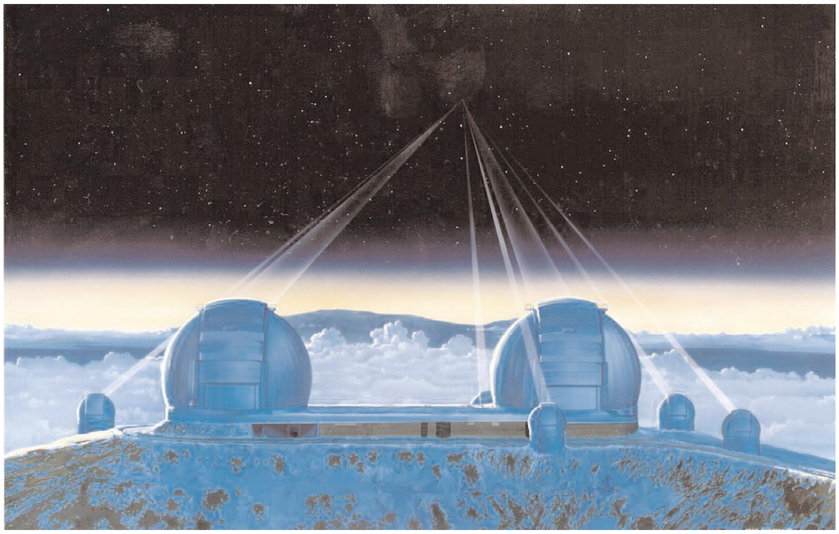


Figure 12.2. The Keck Interferometer in its final configuration, including the two 10 m Keck telescopes and the associated 1.8 m outrigger telescopes on Mauna Kea, Hawaii.

As a technology precursor, the Keck-I includes many of the active subsystems that are likely to be required on TPF, including laser metrology, automation, and a cryogenic nulling interferometer back end for the exo-zodiacal measurements. The implementation of the Keck-I nuller is similar to one of the TPF approaches using rooftop prisms or cat's eye mirrors. The Keck-I uses cascaded achromatic nulling interferometers to null the central star or the star plus the zodiacal cloud. By modulating the nulls, the Keck-I implements interferometric chopping to produce ac signals for robust detection despite expected slow background variability. Practical application of the nuller architecture to a science observation, 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.

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 supporting the development of the LBT, in part, as a testbed for TPF. In many respects, because of its different strengths and limitations, it will be complementary to the Keck-I described above. LBT will have just three warm mirrors leading to a cryogenic IR nulling beam-combining station. This study will explore the use of achromatic dielectric plates for nulling phase control. The telescope will be used to observe exo-planetary dust, and will demonstrate cryogenic path length control, and performance of nulling optics at cryogenic temperatures; both are required for TPF. LBT will demonstrate a null that is 35 times deeper than that of Keck-I, an important milestone toward meeting TPF requirements.

Very Large Telescope Interferometer and Magellan Interferometer. In addition to the specific TPF development activities above, additional interferometers, at both infrared and visible wavelengths, will be developing a community of experienced users. In the southern hemisphere, two infrared interferometers are of special note. The Very Large Telescope Interferometer is a European project in Chile, under construction and funded for interferometric studies that will include studies related to extrasolar planets. The Magellan Project, a U.S. project also based in Chile, is a pair of 6.5 m telescopes arranged like a smaller version of the Keck I and II telescopes. Magellan is therefore capable of continuing the Keck survey for exo-zodiacal dust into the southern hemisphere.

Space Missions

Space Infrared Telescope Facility. The Space Infrared Telescope Facility (SIRTF), shown in Figure 12.3, is the last of NASA's Great Observatory series of missions. SIRTF is a cryogenic infrared telescope that will provide unprecedented sensitivity and is planned for launch in late 2001. SIRTF 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. The payload will include components and mechanisms that must operate at liquid helium temperature. SIRTF will also provide important experience in the design, development, integration, and testing of a complex cryogenic space optical system. Building on the successes of the Infrared Astronomical Satellite (IRAS) and the Infrared Space Observatory (ISO), SIRTF will provide experience and technology for future space infrared observatories such as NGST and TPF.

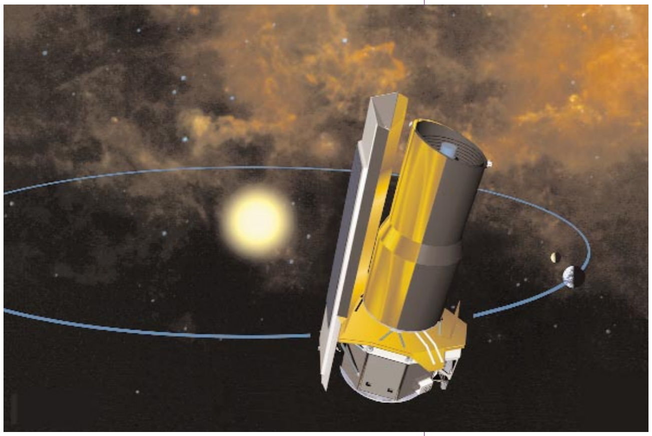


Figure 12.3. NASA's Space Infrared Telescope Facility (SIRTF).

Space Technology-3. The New Millennium Program's Space Technology-3 (ST-3) mission, formerly known as Deep Space Three (DS3), will demonstrate and validate key technologies for TPF and SIM. ST-3 is expected to launch into an Earth-trailing heliocentric orbit in 2003. 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 two-element system will have one collector 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 and SIM. Its precision formation flying and variable baseline interferometry will be key tests for TPF. The two spacecraft of ST-3 will be used at separations of up to 1 km, and will therefore explore the full range of separations planned for TPF. An artist's concept of one potential ST-3 mission architecture is shown in Figure 12.4.

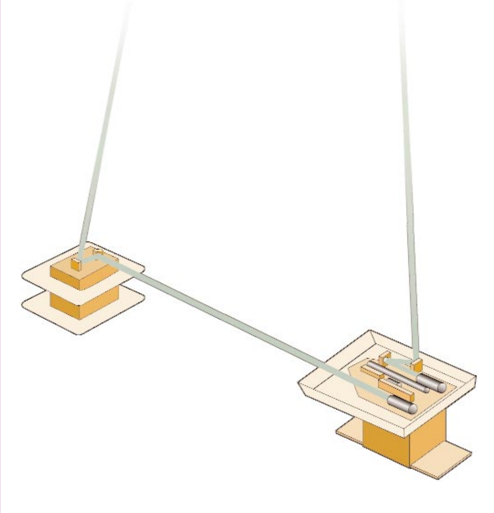


Figure 12.4. NASA's Space Technology-3 (ST-3), formerly known as Deep Space Three (DS3).

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 testbeds.

Space Interferometry Mission. The Space Interferometry Mission (SIM), shown in Figure 12.5, is planned for launch in 2005 into an Earth-trailing solar orbit. SIM 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. As a science instrument, SIM will demonstrate the use of a complex space-based interferometer to gather high-quality astrometric data. SIM's 5 to 7 year lifetime will flesh out 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 interferometer 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.

In addition to SIM's main use as an astrometric device, it will also perform nulling and synthetic imaging observations, two key elements of the TPF mission. Imaging with SIM will involve taking highly accurate

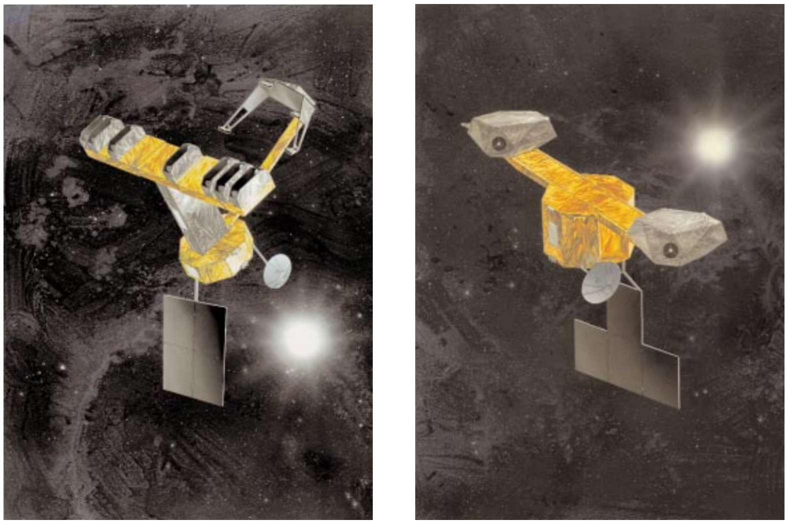


Figure 12.5. Two possible design variations for the SIM flight system, one with, and one without, an external metrology boom. The SIM project will select one of the designs in 1999.

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.

Next Generation Space Telescope. The Next Generation Space Telescope (NGST) is one of the major missions in the NASA Origins Program. Due to launch in 2007, it will be a passively cooled IR telescope designed for performing observations of the early universe including the earliest galaxy formation in the 0.5–20.0 µm IR band. Its primary will be an 8 m diameter, ultra-lightweight, segmented, deployable mirror using an active optical control system. One concept for NGST, developed by the Goddard Space Flight Center is shown in Figure 12.6. Like SIM, NGST, and especially its technology development program, represents a major step towards TPF.

The NGST instruments will include very high sensitivity IR detectors that require active cooling with long life, high-reliability, low-vibration cryo-coolers to give the required ~5 K temperatures. TPF will use a similar cooler. NGST will cool its telescope passively to ~35 K by using a large, lightweight, deployable or inflatable sunshade, roughly the size of a tennis court! The shade concept is an outgrowth of the SIRTF fixed shade design and will consist of multiple polymeric membranes similar to the familiar multi-layer insulation (MLI) supported by a deployed or inflated and rigidified structure.

The NGST spacecraft will be positioned on the warm side of the sunshade and connected to the telescope and instruments via a deployable thermal isolation truss. 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 large cryogenic separated spacecraft interferometer mission.

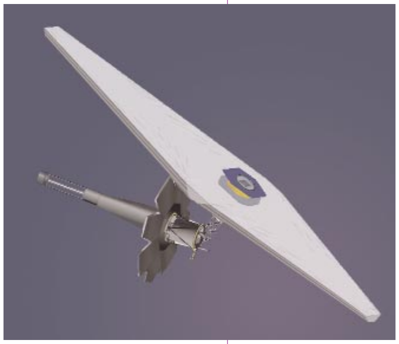


Figure 12.6. One concept for NASA's Next Generation Space Telescope Mission (NGST).

TPF TECHNOLOGIES

Large Lightweight Cryogenic Optics Technology. The current concept for TPF incorporates four collector telescopes with monolithic primary mirrors each 3 to 4 m in diameter (or similar collecting area with an elliptical shape), operating at < 40 K with diffraction-limited performance at 1-2 µm. Logical extensions of current lightweight cryogenic mirror technology developing for SIRTF and NGST will be adequate to build the TPF collector telescope mirrors. Several examples of emerging mirror technology are shown in Figure 12.7.

The NGST mirror will operate in the same region of the spectrum as TPF. It, too, will be background-limited, and, depending on wavelengths chosen for NGST instruments, may require the telescope structure and optics to be cooled as low as 35 K. NGST is intended to provide diffraction-limited performance at 1 to 2 µm, similar to the TPF needs. The lightweight optical telescope assembly (OTA) will be much larger than the collecting telescopes for TPF. The individual 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. The optical deployment and control systems will utilize low-power, low-mass, precision cryogenic mechanisms. These include hinges, latches, actuators, drive mechanisms, fast steering mirrors, etc. They are expected to include all the cryogenic devices required by TPF, except those required for path length adjustment.

Technology readiness for the TPF large lightweight cryogenic optics will be evaluated based on the success of the NGST telescope development efforts and ultimately demonstrated by bringing the various TPF specific component technologies together in a TPF collector telescope testbed.

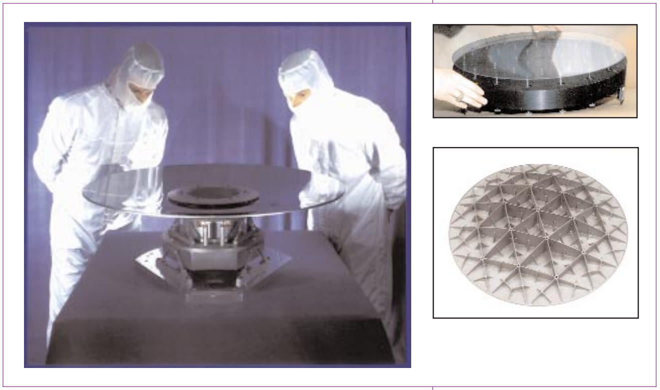


Figure 12.7. Clockwise from left: a) Lightweight 0.85 m cryogenic beryllium mirror for SIRTF; b). Lightweight 0.5 m thin shell glass mirror demonstrator for NGST (University of Arizona); c) Lightweight 0.5 m C-SiC mirror demonstrator for NGST (IABG/BDM).

Cryogenic Active Optical System Technology. TPF, like many of its precursors, will utilize a number of active optical control elements. Nearly all of the requirements for these systems are approximately within the current state of the art except that some are not presently available for operation at cryogenic temperatures. Cryogenic optical control-component technology developed by and for NGST is anticipated to meet TPF's needs in this area.

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 needs (see Figure 12.8).

There is a great deal of history with this ODL 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.

TPF will likely use just the last two stages of this device, to remove errors of at most a few cm. These stages are: 1) a mid-range tier consisting of a parallel motion flexure stage (with a low break-frequency for passive vibration attenuation) holding the entire cat's eye driven by a voice coil; and 2) a fine tier consisting of a parallel motion flexure stage holding the flat mirror driven by a piezo (PZT) stack. This construction provides high bandwidth with good dynamic range overlap between stages and minimum device power consumption. Several improvements will be required to enable and enhance low-temperature performance. The existing piezoelectric actuators, for example, will be replaced with suitable cryogenic actuators (possibly magnetostrictive) and the voice coil motor will likely be changed out (or superconducting coils used) to decrease power consumption down to the ten-to-hundred milliwatt level. Some development of high-temperature

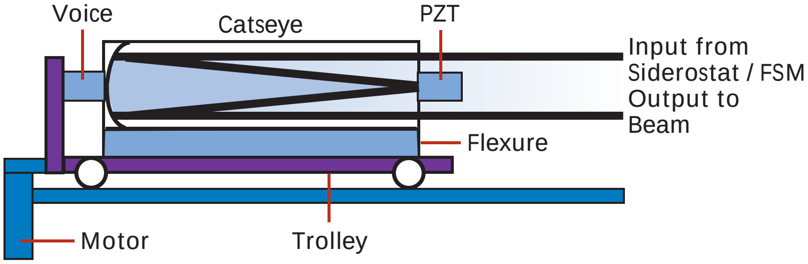


Figure 12.8. Schematic of high dynamic range optical delay line architecture.

superconducting coils and magnetostrictive actuators is already being supported for NGST. The TPF ODL will ultimately be validated on the TPF instrument and system testbeds.

Detector Technology. TPF will require both visible/near IR (0.5-5 µm) detectors for alignment and metrology and thermal IR (3-30 µm) detectors for the science payload. The detector requirements for TPF are not believed to be especially challenging. 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, currently under 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.

The detector and cryocooler readiness will be demonstrated and validated in a TPF instrument testbed that will include prototype TPF instruments. The prototypes will be evaluated first in the laboratory and potentially later at astronomical observatories.

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). Much 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 are expected to be sufficient for TPF. The specific TPF metrology systems will be validated on the TPF instrument testbed and ultimately on the TPF system testbed.

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? Also, how will we operate TPF to achieve the best performance and maximum science return in a cost-effective, low-risk environment?

In the past few years, industry and NASA have developed integrated computational modeling capabilities for complex systems. They can help answer the questions posed above. For instance, the Integrated Modeling of Optical Systems (IMOS) and Modeling Analysis for Controlled Optical Systems (MACOS) tools developed at JPL can combine structural, thermal, control, and disturbance models of a complex system, and predict the overall performance in terms of simulated science data products. This approach has been validated by its application to a wide range of projects including the Hubble Space Telescope and a variety of system testbeds. These tools are currently used by the NGST project to demonstrate the feasibility of an eight-meter aperture in space. The particular emphasis of the NGST studies is on wavefront sensing and control.

Using IMOS and MACOS, a model of TPF can be built that shows the scientific impact of design decisions. For example, Figure 12.9 is a simulated reconstruction of planet image data generated from a nulling interferometer. The interferometer considered is a linear, four-element array, arranged in a θ^2 nulling, chopping Bracewell configuration. The optics are a simplified implementation of the TPF interferometer concept described in Chapter 11.

Each arm of the interferometer is specified with a separate optical prescription. MACOS traces the ray path through the optical model of each interferometer arm to a common spatial plane, at which the wave fronts from each are added to produce the interference fringe. In this simulation, the wavelength is 10 μm, the ratio of planet-to-star brightness is 10^{-6}, the apparent separation of the planet from the star is 0.2 arc-seconds, and the interferometer baseline is 30 m. A zero-mean random piston perturbation, with a standard deviation of 1 nm, is applied to the primary mirror of each interferometer arm at each step in a simulated time sequence. The interferometer is allowed to rotate once (360°). The interferometer response is simulated for 1024 equally spaced steps. Tools such as IMOS and MACOS will enable mission designers to optimize the TPF architecture and will be part of the testing and actual operations of the observatory.

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.

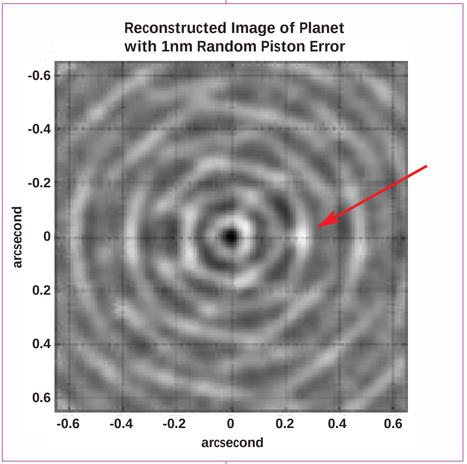


Figure 12.9. Simulated reconstructed image data from one rotation of a four-element, 30 m baseline nulling interferometer. Light from the central star is effectively nulled and the existence of a planet is indicated as a bright spot 0.2 arcseconds off axis.

An important aspect of the TPF systems technology is its evolutionary nature. Models of the type just described will be used to guide technology development. Existing technologies will be combined with key innovative developments and tested in incremental steps to build confidence in the underlying concepts, components, software and integrated systems. The technology programs will emphasize development of hardware and software products, not paper studies. Subsystem testbeds will be developed to validate the integrated performance of key sub-system elements. At least one major flight demonstration (ST-3) will be used to validate technology where ground testing is not possible or practical. 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.

The goals of TPF imply a significant level of spacecraft autonomy, a highly streamlined approach to ground operations and a well-designed architecture of protocols and tools to aid the planner and the scientific user at all phases of an observation from proposal to archival research.

TPF will require a significant level of flight system autonomy, in order to coordinate the actions of the participating spacecraft attitude controllers, spacecraft translation controllers, starlight mirror controllers, and optical path length controllers. Employing a “smart executive” that understands the sequence of parallel and serial tasks that comprise an observation, TPF will be able to tolerate the inevitable variances in the system performance and the resultant variances in the times required to complete each of the steps of an observation. The TPF “smart executive” will incorporate the autonomous interferometer sequencing capabilities that are already being developed for ST-3, Keck, and SIM.

TPF operators will only need to communicate with the flight when the list of observing targets, sequence, or time assigned is changed. TPF will employ a “formation commander” that will translate the ground-provided observing goals into an integrated set of control goals for each of the formation members. If necessary, TPF will be able to autonomously transition the entire flight system to a safe configuration, in which it telemeters diagnostic information to the ground and waits for further instructions.

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.

Figure 11.10 shows a half-scale, inflation-deployed NGST shade test article during a ground demonstration. 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.

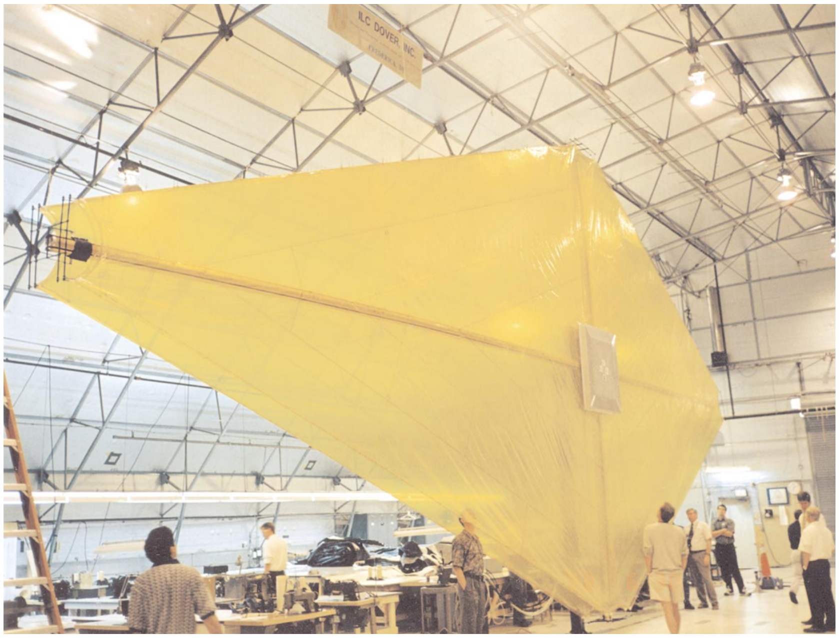
Precision Formation Flying. Much of the technology required for TPF precision formation flying will be developed and demonstrated on the ST-3 mission. Precision formation flying will be accomplished by ST-3 using relative three-dimensional position sensing provided by an Autonomous Formation Flying (AFF) system on each spacecraft; the AFF system will also include an RF transceiver to handle necessary spacecraft-to-spacecraft communications. It will sense the range between spacecraft to ~0.5 cm and the relative angles to ~1-2 arcminutes, allowing control at a level ~2 times larger.

Technology development for a ST-3 version of the AFF system is currently underway at Raytheon E-O Systems to add necessary transmit capability and the software to support the spacecraft control subsystem. No ground commands will be needed for system operation.

Advanced data processing and real-time estimation technology will be a TPF-unique development based on a well-proven estimation theory and advanced sensor fusion techniques under development in government and industry avionics and robotic systems technology centers. Hardware and software systems for collision avoidance in the event of a failure of the AFF system will also require TPF-specific development.

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

Figure 12.10. Half-scale NGST sunshade deployment demonstration at ILC Dover.



this 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) assembly. An expected minimum capability for the FSM, based on the reference mission, will be a closed-loop bandwidth of ~200 Hz and control to 2 milli-arcseconds (10 nanoradians) over a range of ±10 arc-seconds. Such a system is currently under development by the NGST project. Star-trackers and gyros developed under the X2000 program are anticipated to be available for TPF.

Pointing requirements for astrophysics will be much looser than for nulling, and most targets will provide a point source on which such pointing can be achieved. The anticipated TPF orbital options are largely free from non-constant external forces, and consequently only the spacecraft systems themselves will contribute high-frequency disturbance sources of concern for pointing jitter or stability. Spacecraft and instrument pointing and stabilization are treated as an integrated technology and architecture. The spacecraft and its control systems provide a “relatively coarse” control loop that operates in conjunction with a multistage interferometer pointing system.

Attitude sensing will be provided by a 3-axis attitude reference sensing system utilizing miniaturized CCD or Active Pixel Sensing (APS) star trackers, and either solid-state Interferometric Fiberoptic-Gyros (IFOG) or Hemispherical Resonator Gyros (HRG). The gyros will propagate the attitude states and provide extremely precise attitude rate for the real-time state estimation processing. This advanced celestial-inertial sensor technology is available today from the space industry.

Magnetic-bearing reaction wheels will provide the precision attitude control for all spacecraft. Commercially available magnetic-bearing reaction wheels have over 100 times lower vibration than conventional wheels, eliminating the need to support them on a hexapod isolator. They are also free from mechanical wear and can be electrically internally redundant.

Sources of vibration will include active cryo-cooling systems, structural-thermal gradient “crinkling”, and structural microphonics excited by the translation micro-thruster(s) impulses. Presently available hexapod isolation of the active cryocoolers, which also have internal disturbance suppression mechanisms themselves, is expected to sufficiently attenuate the remaining high frequency fundamentals and harmonics. Vibration-free sorption cryocoolers may also be available in the TPF time frame. The instrument fine pointing/stabilization loops can eliminate residual lower-frequency disturbances of the bus and telescope structure and response to micro-thrusters and thermal noise.

The TPF fine pointing and LOS stabilization/vibration control approach will use a multi-stage system to achieve ~2 milli-arcseconds (10 nanoradian) fine pointing jitter performance. The first stage will mitigate solar radiation torques which may be managed by electrically controlling the reflectivity of large portions of the sunshades, thus canceling the buildup of pitch and yaw reaction-wheel momentum storage, and limiting the need for eventual thruster firings to unload the wheels. The radiation pressure from a reflective surface is greater than that from an absorbing and re-radiating surface. Moreover, by deforming the sunshield, using controllable struts or electrostatic bimorph actuation, the buildup of roll (spin) momentum can also be mitigated. Such technology is currently under investigation and development by the NGST Project.

The second stage includes the previously described 3-axis attitude sensors (star tracker and gyros) and three magnetic-bearing reaction wheels that will provide 2 to 5 arc-second pointing knowledge, 15 arc-seconds pointing control, and jitter or stability of < 1 arc-second. Startrackers and gyros developed under the X2000 program are anticipated to be available for TPF.

The third stage includes vibration isolation of the combiner optics and detector from the spacecraft section and active cooler, which may be provided by a hexapod isolator employing active damping control technology. Hexapod technology is currently available and will have substantial flight heritage on SIM, ST-3 and NGST by the time TPF needs it.

In the fourth and final stage, star field images in the collector and combiner telescope cold focal planes will serve as the fine pointing reference. This fine pointing control function will track a star image on the detector array and provide error signals to control a two-axis flexure-pivot mounted, center-of-mass balanced, fast steering mirror

(FSM) assembly. An expected minimum capability for the FSM will be a closed-loop bandwidth of ~200 Hz and control to 2 milli-arcseconds (10 nanoradians) over a range of ±10 arc-seconds. Such a system is currently under development by the NGST project.

Orbit. Current orbital options for TPF include a heliocentric Earth drift-away orbit and an L2 orbit. Fundamental astrodynamic technology development will be required to assess the feasibility and enable the implementation of a TPF L2 orbit option. This option offers many advantages over the drift-away orbit. The recent discovery of quasi-halo orbits and the construction of the first quasi-halo demonstrate that formation flying near L2 is indeed possible. The missing key for selecting between the two options is the propulsion requirement. This cannot currently be estimated due to the lack of understanding of the orbital dynamics and control of formation flying near L2. Both theoretical and computational tools are required; an approach has been developed by JPL to combine dynamical systems theory with geometric control theory. A feasibility study may be performed within the next few years to determine the technical viability of the L2 option and provide a complete comparison of the two orbit options and a plan for the development of the astrodynamic technology for formation flying near L2.