The Terrestrial Planet Finder[1][2]

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Abstract—The Terrestrial Planet Finder (TPF) is a space-based astronomical telescope that will combine high sensitivity and spatial resolution to detect and characterize ~150 planetary systems within 15 pc of our Sun. In a five-year mission, currently expected to commence in 2012, TPF will look for the atmospheric signatures of life using the methods of planetary spectroscopy. This is only possible if implemented within a telescope or interferometer whose spatial resolution is capable of resolving the planet as distinct from its parent star, and yet being able to suppress the starlight to a level of 10^{-6} or better.

The design of TPF that had been used to illustrate the feasibility of the mission was an interferometer composed of a four-element linear array of 3.5-m diameter telescopes situated in an orbit at L2 and observing over the spectral band of 3-30 microns. At these wavelengths an earth-like planet would be more easily detectable in the glare of the parent star, but the angular resolution required for planet detection implies telescope separations of between 75 and 200 m, and separations of up to 1000 m would be needed for general astrophysics. The interferometer had therefore been envisaged as an array of free-flying telescopes.

More recent design studies for TPF have also considered the possibility of having it built as a single-aperture optical telescope. The required angular resolution for planet detection could then be achieved with a mirror spanning 8 or 10 m in diameter. Possible designs include coronagraphs with circular, square, rectangular, or other shaped entry pupils, with tapered transmission across the pupil to suppress unwanted sidelobes in the diffraction pattern. Coronagraphs with phase masks have also been proposed to more efficiently suppress starlight. For these coronagraphs the principal challenges include not only the suppression of scattered light but the design of adaptive optics systems with sub-nm control.

The design requirements and the current status of research will be reviewed. TPF is a key element in NASA's Origins Program and is currently under study in its Pre-Project Phase.

TABLE OF CONTENTS

1. INTRODUCTION

As a part of its long-term goals, NASA has been investigating the feasibility of using space-borne infrared interferometers for the detection of neighboring planetary systems. The technology Road Map described in the ExNPS Report [1] was written specifically to support the development of such an interferometer, which in 1997 became known as the Terrestrial Planet Finder (TPF) [2]. This paper will describe the concepts that have been considered for the design of TPF and review its current status.

The quality of any astrophysical observation depends on both the sensitivity and resolution (spatial and spectral) that are obtainable through the observer's telescope of choice. The sensitivity is a function of the telescope's collecting area, the throughput of its optics, and the characteristics of the detector used to detect the light. The spatial resolution, which is to say the ability to see fine angular detail in the images, is proportional to the diameter of the telescope's main mirror. The motivation for building larger and larger telescopes is therefore easily understood: larger telescopes make fainter, more remote, and yet more exotic objects amenable to study. At some scale-size it becomes difficult or impossible to build single-aperture telescopes. (At radio wavelengths the most extreme example is the 1000-ft diameter wire-mesh Arecibo telescope which occupies a valley in Puerto Rico. At optical/infrared wavelengths the largest segmented mirror telescopes are currently the two 10-m Keck telescopes in Hawaii, with discussions underway for the construction elsewhere of telescopes with 100-m mirrors or larger.) Needless to say, even the largest single-aperture telescope will leave unresolved the objects of most

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scientific interest to astronomers. Further progress in high angular resolution astronomy can only be obtained through methods of interferometry.

When the light from an array of telescopes is combined in an interferometer, the attainable angular resolution is limited not by the diameter of the individual telescopes, but by the longest baseline spanning the array. Whereas astronomical interferometry has been well developed at radio wavelengths, only in the last ten or fifteen years has the technology advanced sufficiently to make it practical and productive at optical and infrared wavelengths. The theory of stellar interferometry will not be reviewed here in detail; its development is well described in the collection of selected reprints edited by Lawson [3] and in the tutorial papers from the 1999 Michelson Summer School [4]. Long-baseline stellar interferometry has also been described in the review by Shao and Colavita [5] and more recently by Quirrenbach [6]. Links to resources relating to stellar interferometry, including the websites of projects worldwide, published papers, lists of meetings, and tutorial material can be found in the Optical Long-Baseline Interferometry Newsletter, http://olbin.jpl.nasa.gov/

A notable milestone in the history of stellar interferometry was the work of the Mark III astrometric interferometer [7], which showed that the complex sequence of alignments necessary in an interferometer could be automated to observe 200 or more stars per night. Researchers at the National Aeronautics and Space Administration, building on the success of the Mark III and other projects, are planning interferometric arrays for observations in space, where the advantages of being above the earth's atmosphere and unbounded by constraints of terrain promise the ultimate in high angular resolution astrophysics. The unifying theme of this undertaking is the search for extra-solar planets and the necessary technology development towards a Terrestrial Planet Finder mission.

TPF has been envisaged as an infrared interferometer composed on an array of free-flying telescopes. Earth-like planets should be much easier to detect at infrared wavelengths than at optical wavelengths, because in the infrared the planet should appear much brighter in comparison with its parent star [8]. The telescope system in a planet finder mission must have an angular resolving power capable of distinguishing the planet as separate from its host star. This implies a telescope many tens of meters in diameter. At both the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) the designs of a planet finding missions have therefore emphasized interferometric techniques of combining light from (possibly) numerous smaller separated telescopes [2,9]. The trade studies that were conducted up until 1998 considered trades between architectures of interferometers only. The principal trade was an analysis of the relative merits of a fixed-structure array versus an array of free-flying telescopes. The disadvantages of a fixed-structure were principally its sensitivity to vibrations induced by thermal differences in the structure and its inability to provide a tuned spatial response for observations of planetary systems at greatly different distances. It was also perceived that the angular resolution of a fixed array would not permit studies of more general astrophysical problems. The trade studies then shifted to an analysis of the different free-flying arrays that were possible. For a good overview of such designs, the reader is encouraged to consult the papers by Mennesson and Mariotti [10], Karlson and Mennesson [11] and references therein.

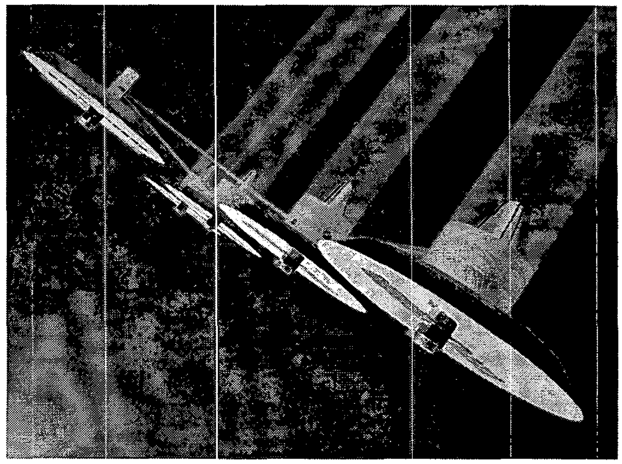

Figure 1. "Book" design of TPF showing light paths.

In 1998-99 the case for TPF was restated in the TPF Book [2], which included a description of the science objectives, a summary of our current knowledge of extra-solar planets, and a feasibility study of the mission. The purpose of the study was to explore the design requirements and outline the technology development necessary for this mission. For this exercise, the strawman design was a free-flying linear array of four telescopes, as illustrated in Figure 1. The completion of the study was timed to provide input to the Astronomy and Astrophysics Decadal Review Committee, whose conclusions influence the course of funding at the beginning of each decade. The report by the Decadal Review, published in May 2000, strongly endorsed technology development for TPF [12].

As a follow-up to the study in the TPF Book, it was desired to explore other perhaps more exotic architectures for TPF and have them analyzed and modeled by several of the major space contractors. It was intended that the principal parties interested in TPF from both academia and industry would collaborate to explore all viable designs for a planet detection mission that were compatible with the science objectives. In May 2000 contracts were let to Ball Aerospace, TRW, Lockheed Martin, and Boeing-SVS Industries.

The design used in the TPF book was intended simply to illustrate the feasibility of the mission, and was not intended to be a final or authoritative version of TPF; it was but one from a family of possible design solutions. The contractors were asked to take a fresh look at the design of a planet-finding mission and not be biased by designs presented in the book.

The initial period of the contract, up until December 2000, allowed a broad investigation of architectures prior to more directed studies. In this spirit, the contractors considered not only interferometers, but also designs for high performance coronagraphs for a space-based 8 to 10-m class optical telescope, such as the one illustrated in Figure 2. Whereas optical coronagraphs are unlike any of the designs used in the TPF book, initial investigations have suggested them to be also capable of detecting earth-like planets while meeting the other science goals of the program. Other designs for TPF that were considered include occulting screens, Fresnel lenses, and rotating arrays that use tethers. The relative merits of each design were judged based on an assessment of implementation risk (in terms of cost and development time), the projected reliability and robustness when implemented, the potential astrophysical studies that may be enabled, and the heritage or legacy that the technology would provide for subsequent missions. The ongoing studies in 2001 will serve to model and predict the performance of the most promising of these designs.

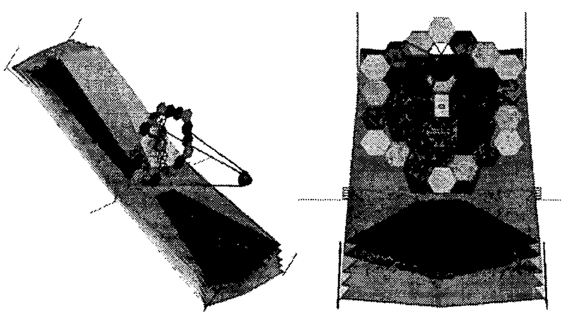

Figure 2. Coronagraph design suggested by TRW.

The Terrestrial Planet Finder is one of the key missions within NASA's Origins Program. The Origins Program, described at http://origins.jpl.nasa.gov/, seeks to find answers to fundamental questions such as "Where did we come from?" and "Are we alone?" through a series of missions including SIRTF, the Keck Interferometer, NGST, StarLight (previously known as ST-3), and the Space Interferometry Mission. Each of these missions builds on the scientific and technological foundations of previous missions and undertakes new technologies that will ensure the success of a Terrestrial Planet Finder. TPF provides a unifying theme for technology development throughout the Origins Program, and will in turn enable yet more ambitious future missions such as Life Finder and Planet Imager.

2. Scientific Objectives

Studies in support of the Terrestrial Planet Finder have described a mission capable of finding and characterizing Earth-like planets around stars within 15 parsecs of our Sun over the wavelength band of 7-17 μm. A mission capable of detecting planets should also be able to perform more general astrophysical observations. The goals for TPF have therefore been divided between that of planet finding and general astrophysics. Whereas it may be possible to construct TPF as an optical telescope, the goals described below are more specifically for a mid-infrared interferometer.

Planet Finding

The prime goal of TPF is to directly detect any earth-like planets in habitable zones around ~150 F, G, and K stars within 15 pc of our Sun. The desired sensitivity is to have the ability to detect an earth-like planet (1 earth-radius, at 1 AU from the host star, 10 parsecs away) in 2 hours, perform planetary spectroscopy and identify CO_2 and H_2O in two days of observations, and identify O_3 within two weeks.

As an additional goal, TPF should be able to establish the orbital properties and both physical and atmospheric characteristics of planetary systems, including Jovian planets around ~150 F, K, and G stars within 15 pc of our Sun.

General Astrophysics

The same mission should be capable of imaging a variety of astrophysical targets over the wavelength range of 3-30 μm, with a modest incremental cost to the mission. TPF should be able to carry out astrophysical initiatives that will expand our understanding of the formation and evolution of stars and planetary systems and explore subjects relevant to other NASA Origins missions. The desired performance is an angular resolution of ~0.75 mas (1 km baseline at 3 μm) and a spectral resolution of ~300-1000, with a resolution of $R \sim 10^5$ for specific lines.

If TPF were designed as an optical coronagraph with an 8 or 10-m primary mirror, its potential for general astrophysics would be remarkable; it would greatly surpass the capability of the Hubble Space Telescope with ~3 times greater angular resolution and ~9 times the collecting area.

3. Possible Architectures

Design Strategies for High Angular Resolution

A mission capable of detecting earth-like planets must be able to separate the light from the parent star from that of the planet. The telescope, or interferometric array, must therefore be able to resolve angular scales smaller than the planet-star separation. If we let the planet-star separation be the same as the earth-sun distance (1 AU), and if we look for planets as far away as 15 parsecs, we would need the ability to resolve angular scales as small as 67 milliarcseconds. The corresponding diameter of a single-aperture telescope is therefore straightforward to calculate. The angular resolution of a telescope is $1.2\lambda/D$, where λ is the wavelength and D is the diameter of the telescope's input aperture, and it follows that D must be $3.7 \times 10^6 \lambda$. An optical telescope (λ=0.550 μm) would have to be larger than 2.0 m in diameter, and a mid-infrared telescope (λ=20.0 μm) would have to be more than 70 m in diameter. These numbers underestimate the mirror requirements, because the desired resolution is 2 or 4 times greater than that implied by the Rayleigh criterion (described above) and the resulting mirror sizes are correspondingly larger.

Single-Aperture Optical Telescopes with Coronagraph

If TPF were designed to operate at optical wavelengths, it could be built as an 8 or 10-m class telescope equipped with a coronagraph. The coronagraph would require outstanding performance, and so its mask diameter would have to be large compared to the point-spread function of the telescope and also be matched with a suitable Lyot stop. The image of the star would require very accurate centering on the mask and the mask would need to cover ~5 Airy rings. The telescope aperture would have to be much larger than a conventional design, because the improved ability to reject light from the star would only be obtained at the expense of a degraded angular resolution. It follows that if earth-like planets were to be detected close in to a star, the telescope aperture would need to be 8 or 10 m in diameter. The surface and wavefront control provided by the mirror would also be vitally important so that scattered starlight would not obscure the planet. Simulations suggest that a ~8 m diameter optical telescope with wavefront control of $\lambda/2000$ rms and an advanced coronagraph might detect an Earth-like planet around a star 8 parsecs away [13]. Experiments suggest that the necessary wavefront control may be attainable with the next-generation adaptive optics systems. The use of phase masks in a coronagraph also promise substantial gains in performance, although their applicability may be restricted by chromatic effects [14, 15].

Mid-Infrared Nulling Interferometers

The motivation for observing at mid-infrared wavelengths is that the ratio of the star/planet light is about 1000 more favorable than at optical wavelengths. As noted above, this implies mirror diameters of 70 m or more, and so most effort in the design of a planet finding mission had previously been directed at interferometer designs with starlight nulling.

A long baseline interferometer composed of an array of telescopes can suppress the starlight if the phase of the wavefronts from each telescope is delayed in a controlled manner prior to combination. The far-field response pattern of the array is a set of interference fringes, whose variations are determined by the geometry of the array. A "null" is a location in the response where the combined wavefronts have canceled through destructive interference. By introducing achromatic phase shifts to the incoming beams, for example by applying phase-shifts through mirror reflections, it is possible to make the central fringe a broadband destructive fringe. Therefore, by pointing the central null onto the star, the starlight can be made to disappear. The breadth and depth of the null depend on the geometry of the array and the way in which the array is subdivided to form the null. The ability to attain deep nulls with starlight suppression better than 10^{-5} would seem unattainable, but has in fact been demonstrated in the lab through the use of spatial filters, as first suggested by Ollivier and Mariotti [16]. The various approaches to nulling interferometry, with examples from experiments and an extensive bibliography, are described by Serabyn [17].

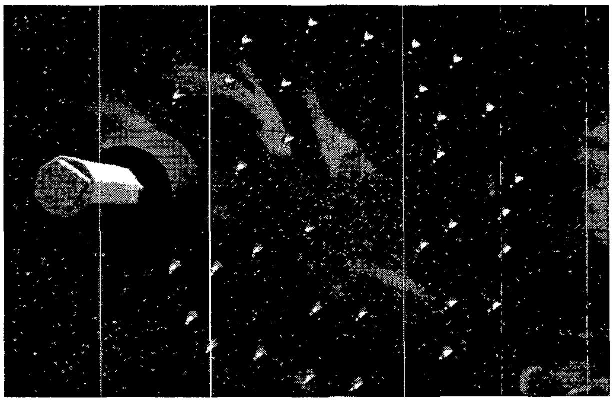

Figure 3. Hyper-telescope concept described by SVS.

A hybrid approach to starlight suppression is that of the Hyper-telescope concept, described by Labeyrie and co-workers [18] and illustrated in Figure 3. It comprises an interferometric array of numerous telescopes with the light relayed to a central location for imaging through a coronagraphic phase mask. Simulations have shown that starlight suppression to a level of $\sim 10^{-4}$ is possible if the telescope pupils are re-imaged and "densified" before the light is imaged onto the phase mask [18]. Another level of starlight suppression is then required to permit planet detection, possibly through the use of adaptive optics and the statistics of "dark" speckles in the image [19].

4. DESIGN REQUIREMENTS

Up until recently the assumption had been that TPF would be designed as a formation-flying interferometer. Whereas that assumption is now under question, the requirements presented here are restricted to interferometers only.

Formation Flying Requirements

If TPF is to be built as a interferometer comprised of numerous free-flying telescopes, the telescopes must all be controlled so that the starlight collected at each telescope can be relayed to a combiner spacecraft to form interference fringes.

When an incident wavefront of starlight is intercepted by the interferometer, the wavefront is sampled separately by two or more telescopes and then relayed to a central beam combiner. The relative delay of the wavefront segments when recombined must be the same to within a small fraction of a millimeter if fringes are to be detected. The tolerances depend on the observation wavelength λ and bandwidth $\Delta\lambda$; the relative delay Δl must be smaller than the coherence length of light for the observation, $\Delta l < \lambda^2/\Delta\lambda$. For example, observations using the full K band (λ=2.2 μm, $\Delta\lambda$ from 2.0 to 2.4 μm) require path equality to within 12μm.

Although this would seem to imply unduly tight tolerances in a free-flying interferometer, that is in fact not the case. Ground-based interferometers routinely provide delay compensation with control to about 10 nm rms [7], but use servo systems with three or more levels of control, each with different ranges and bandwidths. For example, delay lines often have a carriage that runs on rails whose position is monitored by laser metrology, and upon which is supported a cats-eye retroreflector with both a speaker coil and a piezo-transducer for fine adjustments of the delay. A similar delay line system would also be an important part of the combiner for a formation-flying array, and angle-tracking would also be subdivided into several levels of servo-control.

The requirements for control and knowledge of delay and delay-rates can be estimated if we assume TPF will have a functionality essentially similar to existing ground-based interferometers. The requirements for control and knowledge of delay and delay-rate then determine the requirements for inter-spacecraft range and bearing angle.

For TPF to be able to make efficient observations, it should be capable of finding fringes in a reasonable amount of time. The delay and delay-rate must therefore be controlled so that the fringes lie within the range of the delay line and are moving slowly enough that they can be found. Models suggest that formation flying should be able to provide delay control to within about 5 cms. Uncertainties in delay knowledge arise from uncertainties in range and bearing angle knowledge. Spacecraft range knowledge should be better than ~ 4 cms, and bearing angle knowledge better than ~ 5 arcminutes (giving rise to a delay of ~1 cm for telescope-combiner separations of 500 m).

The delay-rate should be controlled so that fringes are moving slowly enough so that they are not blurred so as to be undetectable. Let us suppose that the fringe tracker operates at λ=2.2 μm, and samples fringes with a sampling rate of 100 Hz, or 1 sample every 10 ms. These numbers are typical of a ground-based interferometer. Furthermore suppose that the fringe tracker scans in delay with steps of 1λ every sample, or in this case 220 μm/s. We would require that the delay rate be controlled to be no larger than about half the scan rate, which would be less than 110 μm/s.

The delay must however be known to better than the control values if fringes are to be found in a reasonable amount of time. Let us suppose that 10 minutes is the longest time we would allow the instrument to search for fringes. If the scan rate is at worst 110 μm/s, then the delay must be known to line within a range of delays spanning 6.6 cm. However, if fringes are to be found in less than 1 minute, the delay must be known to within 6.6 mm. This implies a corresponding range and bearing angle knowledge.

The telescope and combiner attitude control are estimated to be attainable at levels of 1 to 3 arcminutes. The telescope would probably be stearable over a range of 5 arcminutes, and calibrated with a star-tracker at the level of 10s of arcseconds. These parameters and those described above are listed in Table 1.

Table 1. Formation Flying Requirements for TPF

Thruster Firings	3 sec every 30 sec
Separation Range	70 – 1000 m
Range Control	4 cm
Range Knowledge	< Range Control
Range Rate Control	1mm/sec: acquisition 0.2 mm/sec: tracking
Bearing Control	5 arcmin
Bearing Knowledge	< Bearing Control
Bearing Rate Control	0.1 arcsec/sec
Combiner Attitude Control	3 arcmin
Telescope Attitude Control	3 arcmin
Combiner Attitude Know.	0.14 arcmin
Telescope Gimbal Range	5 arcmin
Star Tracker Resolution	10 arcsec

Nulling Requirements

If we assume that a null depth of 10^{-6} is required at a wavelength of λ=10 μm, Serabyn [2] has shown that the principal requirements are given as follows in Table 2:

Table 2. Nulling Requirements

Throughput asymmetries	0.4 %
Tip-tilt, rms error	10.0 mas
Path compensation error	3.2 nm
Polarization losses	
Delay	0.22 deg
Rotation	0.11 deg
Strehl Fluctuations	0.2 %

5. ENGINEERING CHALLENGES

Whether the design is to be a single-aperture optical telescope or a formation flying mid-infrared interferometer, there are clearly many common factors that must be taken into account in the design of the mission. Some of the design considerations that have been discussed as relevant to the Terrestrial Planet Finder include the definition of the following items, which have been included in the architecture studies that are now ongoing:

1) Overall observatory layout and geometry,
2) Development of end-to-end computer models including disturbances to demonstrate that the designs will meet the science requirements,
3) Point spread function or *(u,v)* plane coverage for imaging,
4) Life-cycle cost estimates,
5) Technology development roadmap,
6) Integration and test approaches,
7) End-to-end optical layout,
8) Detectors and coolers,
9) Contamination of optics,
10) Thermal control of surfaces,
11) Cryogenic component requirements,
12) Launch strategy,
13) Operations scenario, and
14) Other relevant aspects of observatory design.

Many aspects of the mission design will involve an extended research effort. Some aspects are more particular to interferometry, such as the engineering of cryogenic optical components, non-contaminating propulsion systems for formation flying, and the analysis of formation maneuvers. Other aspects are particular to coronagraphic systems, such as the effects of scattering due to phase and amplitude errors across state-of-the-art 10-m class monolithic or segmented optical mirrors. Work in these areas has only just commenced.

6. CURRENT STATUS

The architecture studies for TPF that were initiated in May 2000, involving Ball Aerospace, Lockheed-Martin, TRW, and Boeing-SVS, are still ongoing and are due to be completed in January 2002. The initial goal of the architecture study was for each contractor to initially explore as many concepts as possible, including non-interferometric options, and assess the potential of the most promising designs. A Preliminary Architecture Review (PAR) was held in December 2000 in San Diego where the contractors presented their preferred designs. TRW, Ball Aerospace, and Boeing-SVS all chose coronagraph designs as their first choice; Lockheed Martin chose interferometer designs, modified and intended for a potential precursor mission. Boeing-SVS included the Hyper-telescope concept in its presentation and was requested to retain that design for further study. The contractors are now devoting the remaining period of the contract to refining the analysis of their designs to determine the requirements for each and the available trade space. The analysis includes the development of integrated end-to-end models of the selected architectures so that trades can readily be assessed. The trades will involve an analysis of the predicted science performance, technology requirements, cost, risk, reliability, and future heritage, as mentioned in the previous section. The result of the studies will be a road-map of technology development for work in the coming years.

7. CONCLUSION

TPF is currently in its Pre-Project Phase. The four Pre-Project architecture studies that were initiated in May 2000 involve the most capable optical/infared interferometrists in both academia and industry. Although many of the engineering challenges appear formidable, the technology questions are being addressed in a staged program of study and systems analysis that will assure a successful mission. The ongoing research is being undertaken for an expected launch of TPF in September 2012.

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