

Recommended Architectures for The Terrestrial Planet Finder

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Abstract.

The primary conclusion from an intensive, two year period of study is that with suitable technology investment, starting now, a mission to detect terrestrial planets around nearby stars could be launched within a decade. A visible light coronagraph using an 8-10 m telescope, or an infrared nulling interferometer, operated on either a ~ 40 m structure or separated spacecraft, could survey over 150 stars, looking for habitable planets and signs of primitive life.

1. Introduction

In March, 2000, the Terrestrial Planet Finder (TPF) project at JPL selected four university-industry teams to examine a broad range of instrument architectures capable of directly detecting radiation from terrestrial planets orbiting nearby stars, characterizing their surfaces and atmospheres, and searching for signs of life. Over the course of two years the four teams, incorporating more than 115 scientists from 50 institutions worked with more than 20 aerospace and engineering firms. In the first year of study, the contractors and the TPF Science Working Group (TPF-SWG) examined over 60 different ideas for planet detection. Four main concepts, including a number of variants, were selected for more detailed study. Of these concepts, two broad architectural classes appear sufficiently realistic to the TPF-SWG, to an independent Technology Review Board, and to the TPF project that further technological development is warranted in support of a new start around 2010. *The primary conclusion from the effort of the past two years is that with suitable technology investment, starting now, a mission to detect terrestrial planets around nearby stars could be launched within a decade.*

The detection of Earth-like planets will not be easy. The targets are faint and located close to parent stars that are >1 million (in the infrared) to >1 billion times (in the visible) brighter than the planets. However, the detection problem is well defined and can be solved using technologies that can be developed within the next decade. We have identified two paths to the TPF goal of finding and characterizing planets around 150 stars out to distances of about 15 pc:

- At visible wavelengths, a large telescope (a 4x10 m elliptical aperture in one design and an 8x8 m square aperture in another) equipped with a selection of advanced optics to reject scattered and diffracted starlight (apodizing

pupil masks, coronagraphic stops, and deformable mirrors) offers the prospect of directly detecting reflected light from Earths.

- At mid-IR wavelengths, nulling interferometer designs utilizing from three to five 3~4 m telescopes located on either separated spacecraft or a large, 40 m boom can directly detect the thermal radiation emitted by Earths.

The TPF-SWG established that observations in either the optical/near-infrared or thermal infrared wavelength region would provide important information on the physical characteristics of any detected planets, including credible signposts of life. In fact, the two wavelengths provide complementary information so that in the long run, both would be desirable. The choice of wavelength regime for TPF will, in the estimation of the TPF-SWG, be driven by the technological readiness of a particular technique.

2. Science Goals for The Terrestrial Planet Finder

The TPF Science Working Group (TPF-SWG) established a Design Reference Program to give broad guidelines for defining architectures for TPF. The goals for TPF were set out at the December, 2000, meeting of the TPF-SWG:

Primary Goal for the Terrestrial Planet Finder (TPF): TPF must detect radiation from any Earth-like planets located in the habitable zones surrounding 150 solar type (spectral types F, G, and K) stars. TPF must: 1) characterize the orbital and physical properties of all detected planets to assess their habitability; and 2) characterize the atmospheres and search for potential biomarkers among the brightest Earth-like candidates.

The Broader Scientific Context: Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, e.g. both gas giant and terrestrial planets, and debris disks. Some of this information, such as the properties of debris disks and the masses and orbital properties of gas giant planets, will become available with currently planned space or ground-based facilities. However, the spectral characterization of most giant planets will require observations with TPF. TPF's ability to carry out a program of comparative planetology across a range of planetary masses and orbital locations in a large number of new solar systems is by itself an important scientific motivation for the mission.

Astrophysics with TPF: An observatory with the power to detect an Earth orbiting a nearby star will be able to collect important new data on many targets of general astrophysical interest. Architectural studies should address both the range of problems and the fundamental new insights that would be enabled with a particular design.

3. Biomarkers for TPF

Early TPF-SWG discussions made it apparent that observations in either the visible or mid-infrared portions of the spectrum were technically feasible and scientifically important. A sub-committee of the TPF-SWG was established under the leadership of Dr. Dave Des Marais to address the wavelength regimes

for TPF. The conclusions of their report (Des Marais *et al.* 2002) can be summarized briefly as follows:

- Photometry and spectroscopy in either the visible or mid-IR region would give compelling information on the physical properties of planets as well as on the presence and composition of an atmosphere.
- The presence of molecular oxygen (O_2) or its photolytic by-product ozone (O_3) are the most robust indicators of photosynthetic life on a planet. Even though H_2O is not a bio-indicator, its presence in liquid form on a planet's surface is considered essential to life and is thus a good signpost of habitability.
- Species such as H_2O , CO , CH_4 , and O_2 may be present in visible-light spectra (0.7 to 1.0 μm minimum and 0.5 to 1.1 μm preferred) of Earth-like planets.
- Species such as H_2O , CO_2 , CH_4 , and O_3 may be present in mid-infrared spectra of Earth-like planets (8.5 to 20 μm minimum and 7 to 25 μm preferred).
- The influence of clouds, surface properties, rotation, etc. can have profound effects on the photometric and spectroscopic appearance of planets and must be carefully addressed with theoretical studies in the coming years (e.g. Ford, Seager, and Turner 2001).

In conclusion, the TPF-SWG agreed that either wavelength region would provide important information on the nature of detected planets and that the choice between wavelengths should be driven by technical considerations.

4. TPF Architectural Studies

After an initial year during which the four study teams investigated more than 60 designs, the teams plus JPL identified four architectural classes (with a number of variants) worthy of more intensive study (Table 1). High level descriptions of these architectures are given below; more detailed information is available in the summary of the recent architecture studies (Beichman *et al.* 2002), the final reports from the teams, and, for the separated spacecraft interferometer, the TPF Book (1999).

Table 1. *Phase II Architecture Studies*

<i>Study Team</i>	<i>Architecture Class</i>	<i>Time to Survey 150 Stars, Days Single Epoch</i>
Ball Aerospace	Shaped Pupil Coronagraph (Vis.)	50
	Classical Coronagraph (Vis.)	15
Boeing-SVS	Non-Redundant Linear Array (IR)	55
	Apodized Square Aperture (Vis.)	262
Lockheed-Martin	Structurally Connected IR Interferometer	40
	Separated Spacecraft & JPL IR Interferometer	106
TRW	28 m IR Coronagraph	N/A

4.1. Visible Light Coronagraphs

Two groups (Ball and Boeing-SVS) investigated the potential for a visible light coronagraph to satisfy TPF's goals. While there are differences between the designs, there are major similarities: 1) a large optical surface (4×10 m for Ball, 8×8 m for Boeing-SVS); 2) a highly precise, lightweight primary mirror equipped with actuators for figure control with surface quality of order 1-5 nm depending on spatial frequency; and 3) a variety of pupil masks (square, Gaussian, or other (Spergel and Kasdin 2001) and/or Lyot stops) to suppress diffracted starlight. In the case of the Ball designs, a key component was a small deformable mirror with $\sim 100 \times 100 = 10^4$ elements capable of correcting residual mid-spatial frequency errors to $\lambda/3,000$ and stable to $\lambda/10,000$. In the Ball design, the combination of pupil masks and the deformable mirror reduces the ratio of starlight (scattered or diffracted) to planet light to approximately unity over an angular extent between $\sim 5\lambda/D$ and $100\lambda/D$.

With these features, the Ball systems are able to conduct a survey of 150 stars with images taken at 3 epochs for confirmation and orbital determination in less than half a year (Table 1). The Boeing-SVS system, as proposed, takes more time to complete such a survey because without a deformable mirror the ratio of starlight to planet light is about 100 times worse than in the Ball design; addition of a deformable mirror would result in comparable performance for the two telescopes. In under a day per star, the Ball system could detect (SNR=5 at spectral resolution $R = \lambda/\Delta\lambda \sim 25 - 75$) various atmospheric tracers, including O_2 , a critical signpost for the presence of photosynthetic life.

The study teams pointed out that the potential for ancillary science was particularly impressive for the visible systems, since it would be straight-forward to add a complement of traditional astronomical instruments, e.g. UV-optical imagers and spectrographs. Operated on an 8-10 m telescope, such instruments would represent a giant advance over the present UV-optical performance of the Hubble Space Telescope. Of particular interest would be the ability to make diffraction limited images at UV-wavelengths with < 5 milli-arcsec resolution.

Future studies will have to assess whether the specialized requirements of a planet finding, e.g. an off-axis secondary, might compromise the general astrophysics potential of a visible system. Conversely, NASA will have to weigh whether specialized needs such as high UV throughput requiring special coatings and careful attention to contamination issues might significantly increase the cost of the observatory or compromise its planet-finding performance.

The greatest technical risk for the visible coronagraph is in the development, manufacturing and implementation of a large primary mirror with ultra-low wavefront errors as well as components associated with starlight suppression. The coronagraphs themselves functionally simple and although the demands for system performance are challenging, none are thought to be insurmountable. However, the problem of fabricating and launching a large (8-10 m) mirror cannot be overemphasized. The TPF Project's independent Technology Review Board noted that there exists no capability to fabricate such a high precision (3-5 times better than Hubble's mirror, 5-10 times better than NGST's mirror), lightweight optical element for ground or space. But even if a 8-10 m system proves to be too difficult to implement on the TPF timetable, a 2-4 m class telescope could demonstrate high dynamic range coronagraphic imaging and carry

out an exciting scientific program. Such a system could find Earths only around the closest dozen stars because of its degraded angular resolution, but it could find and characterize Jupiters around many more distant stars. A telescope of this scale might fit into budget of a Discovery mission.

4.2. Nulling Infrared Interferometers

Lockheed Martin and JPL examined two versions of the infrared nulling interferometer: structurally connected and separated spacecraft. The Lockheed Martin study concluded that a structurally connected infrared interferometer with four 3.5 m diameter telescopes on a fixed 40 m baseline comes close to achieving TPF's goals. The system uses four collinear telescopes arranged as two interleaved Bracewell nulling interferometers to reject star light adequately so that stellar leakage does not compromise the overall system noise. The array would be rotated around the line of sight to the star over a 6-8 hour period. The telescopes can be combined in different pairs to achieve the short and long baselines needed to observe distant or nearby stars. The nulled outputs of the combined pairs are combined again to yield a θ^4 null or an effective θ^3 null with phase chopping.

The separated spacecraft version of the nulling interferometer was described in the 1999 TPF report (Beichman *et al.* 1999; also, see Woolf and Angel 1998). It uses a different arrangement of telescopes to produce a deeper, θ^6 , null that can be tuned to resolve most effectively the habitable zone around each target. Because the stellar leakage is reduced in this design, the stability requirements are relaxed relative to the structurally connected interferometer. The θ^6 null is, however, less efficient in its use of baseline, requiring roughly 1.5-2 times longer baselines than the structurally connected system. Providing a 80-100 m baseline leads, in turn, to the likely requirement for a more complex separated spacecraft system. Thus, a near-term study must investigate whether a 40 m system can satisfy TPF's goals. If not, then NASA should pursue aggressively the development of a separated spacecraft nulling interferometer.

The infrared system is somewhat more susceptible to the effects of zodiacal emission than visible light coronagraphs. Figure 1 compares the relative time needed to detect an Earth as a function of the brightness of the zodiacal emission around the target star (in units of our own zodiacal cloud). At ten times the brightness of our zodiacal cloud, both the visible and infrared systems are adversely affected, the infrared system by a factor of 3-4, the visible system by a factor of 2-3.

Figure 1. The effect of zodiacal emission around target stars at two distances on the integration time to detect an Earth for the Lockheed-Martin nulling interferometer and the Ball coronagraph.

It should be mentioned that the European Space Agency (ESA) has studied a two dimensional, separated spacecraft array of infrared telescopes for its Darwin mission. An industrial study by Alcatel found that this version of a planet-finding mission was technically feasible.

The ancillary science possible with an interferometer is likely to be more specialized than for a 8-10 m visible telescope equipped with general purpose instruments. However, the prospect of a telescope with NGST-like sensitivity, but with $10 \times$ better angular resolution, imaging the cores of protostars, active galaxies, and high redshift quasars is an exciting one.

The largest area of technical risk for the infrared interferometers is not in the performance of the individual components but in the operation of the various elements as a complete system. Most of the required elements are either under development and making good progress, or are reasonable extensions of technology being developed for missions and ground observatories that will be in place well before TPF needs them. However, the system complexity of the separated spacecraft system cannot be overemphasized. Such a system would demand at least one precursor space mission: a formation flying interferometer, such as the Starlight project, to validate the complex control algorithms and beam transport needed for this version of TPF.

5. Other Concepts

TRW and Boeing-SVS investigated two architectures that in the opinion of the TPF project and the independent Technology Review Board were less promising in the near term than the IR interferometer and the visible coronagraph.

- TRW studied a cooled, 28 m, telescope operating in the mid-IR. The major drawback of this system is its relatively poor angular resolution, $\lambda/D \sim 90$ mas at $10 \mu\text{m}$, which would allow it to observe only the closest stars. This restriction becomes even more severe if one requires a typical inner working distance of $3 \sim 5 \times \lambda/D > 250$ mas. Interior to this separation, the ratio of planet light to diffracted starlight is very unfavorable ($< 10^{-3} \sim 10^{-4}$), demanding great stability for a large structure over many hours.

- Boeing-SVS studied a sparse aperture imaging system called the Non-Redundant Linear Array (NRLA). Working in the mid-infrared wavelengths, the NRLA, or hyper-telescope, consists of an array of seven, passively cooled, 3 m meter telescopes distributed along a 100 m long structure. The system uses “densification” to rearrange the location of the apertures in the pupil to produce a compact, clean point spread function. A coronagraph consisting of a phase mask in the image plane rejects stellar light. The observatory, located at L2, rotates to collect data suitable for planet detection and characterization. The project and the Technology Review Board regarded the launch and on-orbit assembly of the required 100 m structure as potentially very expensive compared with some of the other systems.

6. Conclusions

The recently completed architectural studies have identified two plausible paths to TPF. With a substantial investment in technology over the next few years, the choice between a nulling infrared interferometer and a visible coronagraph will become clearer from the standpoint of technological maturity, cost, and risk. At the same time, a number of missions will have important scientific input into the design of TPF. By 2006, SIRTF, as well as the Keck, VLT, and LBT Interferometers will have measured zodiacal clouds around hundreds of TPF targets, giving us valuable information on the significance of this noise source. Thus by 2006, it should be possible to choose between the visible and infrared systems on both scientific and technical grounds. Another scientific milestone comes around 2010 when the Kepler mission (Borucki *et al.* 2001) will have measured the frequency of Earths around solar type stars, η_{\oplus} (Beichman 2000). This information will help to set the size of the TPF apertures and the required angular resolution by telling us whether we need to look out to 5, 8, or 15 pc to ensure a high probability of finding planets.

As the technology matures and the opportunity to start the mission approaches, NASA and the science community will have to reach a consensus on the scientific performance in the areas of planet finding and general astrophysics needed to justify the mission. Some of TPF's observational capabilities will be affordable; others will have to be deferred to subsequent, still more capable missions. At the end of TPF's pre-formulation phase, NASA, together with its

potential international partners, will be prepared to address the challenge of looking for habitable planets and seeking signs of life beyond the Solar System.

7. Acknowledgements

The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was supported by the TPF project. The author acknowledges valuable contributions from TPF Science Working Group and the contractor teams, as well as the dedication and hard work of Dan Coulter and Chris Lindensmith at JPL.

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