

An Optical/UV Space Coronagraph Concept for the Terrestrial Planet Finder

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ABSTRACT

NASA's current strategic plan calls for the launching of a space observatory, The Terrestrial Planet Finder (TPF), by the middle of the next decade; it will search for terrestrial planets in the habitable zone of roughly 150 nearby stars and characterize them for the potential to harbor life. This paper describes a visible light concept for TPF developed by the Ball Aerospace led TPF study team. This concept consists of a 4 meter by 10 meter coronagraphic telescope in a deep space orbit. Imaging planets requires overcoming the problem of high contrast between the light from the parent star and from the planet, coupled with their small angular separation. For a coronagraph, the diffraction pattern of the telescope must be suppressed at the planet image location. The high contrast needed can be achieved using optimized pupil shapes that provide the needed 10 billion times suppression as close as $4\lambda/D$ to the center of the star. In addition, wavefront errors induced by the mirror deformities will be corrected using deformable mirrors in a novel active optics system that corrects both amplitude and phase errors. The paper describes the baseline design of a visible light telescope and instrument that will meet the mission requirements.

INTRODUCTION

NASA's Terrestrial Planet Finder (TPF) is expected to be launched in the 2015 time-frame and will be the first observatory with the ability to image extrasolar earthlike planets, that is, planets within the habitable zones of the nearest 200 stars. With TPF, astronomers will not only catalogue the nearest planetary systems—they will perform new science, searching for biomarkers in the spectrum of the atmosphere, analyzing planetary mass and albedo, studying extrasolar system dynamics, and measuring variability that might be produced by rotation, climate or weather.

The critical challenge to overcome is the high contrast between the planet and the star it orbits (on the order of 10 billion in the visible). The recent TPF architecture studies run by JPL examined numerous approaches to designing a high-contrast observatory. In the end, two techniques showed the most promise—visible light coronagraphy and infra-red nulling interferometry. The authors of this paper were all members of the Ball Aerospace led team that proposed a 4×10 m visible light observatory with a coronagraph. We summarize below the essential features of the proposed architecture, the novel approaches to coronagraphy developed, the critical technologies required to achieve the needed contrast, and the potential science achievable with such an observatory.

TPF SCIENCE

Before describing the proposed spacecraft, it helps to review the requirements and potential science to be gained by a visible light coronagraph. We note that in addition to planet finding, a large visible light telescope will provide enormous potential for additional astrophysics in a post-Hubble age. Because of space constraints, we refer the reader to other sources. Currently, NASA requires that TPF survey 150 F, G, and K stars for the existence of terrestrial planets within the habitable zones. This discovery mode includes determining quantities such as separation, position, orbital parameters, and perhaps even mass. TPF will also include a planet characterization mode where it is required to have the capability to search spectroscopically (with low and medium resolution) for signatures of biomarkers on the discovered planets. And it must accomplish this between 2015 and 2020 at reasonable cost.

Target Distribution and Aperture Requirements

The requirement that the full habitable zone be searchable for most stars within 20 pc quickly became the driving requirement on aperture size. Using the results of Kasting, et. al. (1993), the habitable zone can be computed for all nearby stars on the main sequence. Various geometric, photometric, temporal, and spectroscopic properties of possible planets can be inferred and a “search space” can be defined for TPF. Ebbets, et. al. (2002) describe the results of this target search and the implications on the observatory requirements and design. For example, Figure 1 shows the collection of 202 stars we discovered as viable candidates vs. distance. It is clear from this figure that to enable discovery of planets at the innermost edge of the habitable zone for the most difficult stars, TPF must be capable of resolving planets 30 milliarcsec from their host stars. This puts a strong requirement on the aperture size. For observations at 0.5 micron and the best coronagraph resolution of $4\lambda/D$, the longest dimension must be roughly 10 m. (It is worth noting that reducing the aperture size, even to 4 m, still results in significant science and only partial degradation in the observable habitable zone of many of the target stars—see Brown, et. al. (2002)).

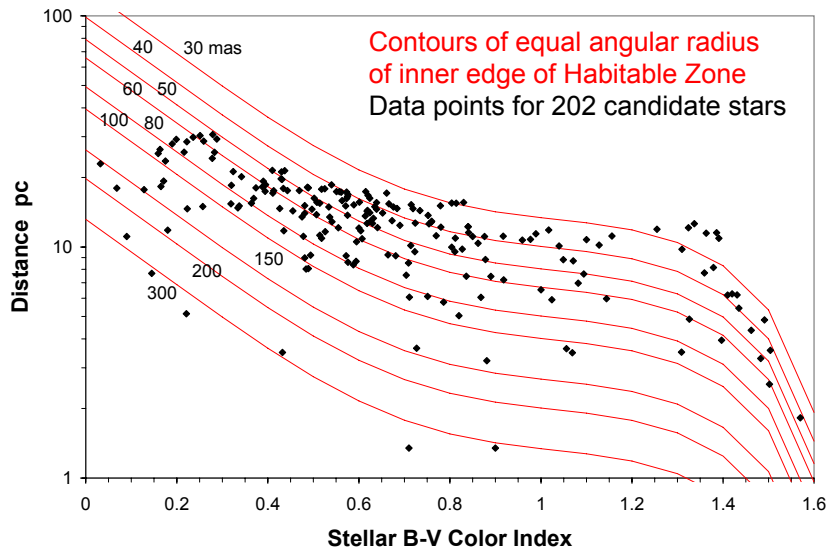


Fig. 1. Available stars arranged on contours of equal radius for the inner edge of the Habitable Zone.

Other considerations, such as integration time and spectroscopy, put requirements on total area. One innovation of the study was the realization that it is not necessary to make the pupil circular. Using an elliptical aperture allows for sufficient area (photon collection) with the needed resolution in the long axis and a PSF that satisfies the high contrast system requirements. This makes the total mass substantially less and greatly simplifies launch vehicle packaging. The final design incorporates a 10×4 m elliptical aperture.

Spectroscopy and Biomarkers

In addition to discovery, the TPF program requires the capability for low to medium resolution spectroscopy. These measurements provide a wealth of information (details can be found in Traub, et. al.

(2002) and Brown, et. al. (2002)). For example, mass can be inferred by comparing photometry in various bands, and, most importantly, atmospheric signatures can be searched for indications of biotic processes (Traub, et. al., 2002). Figure 2 shows measured spectra for the solar system. Clear distinctions among the planets is evident and easily determined by TPF. Of particular interest is the Earth spectrum, taken by measuring the Earthshine from the moon (Woolf, et. al., 2002). Important biomarkers, such as water, oxygen, ozone, and carbon dioxide are evident. Also measurable is the atmospheric Rayleigh scattering and the red-edge feature of chlorophyll containing plants.

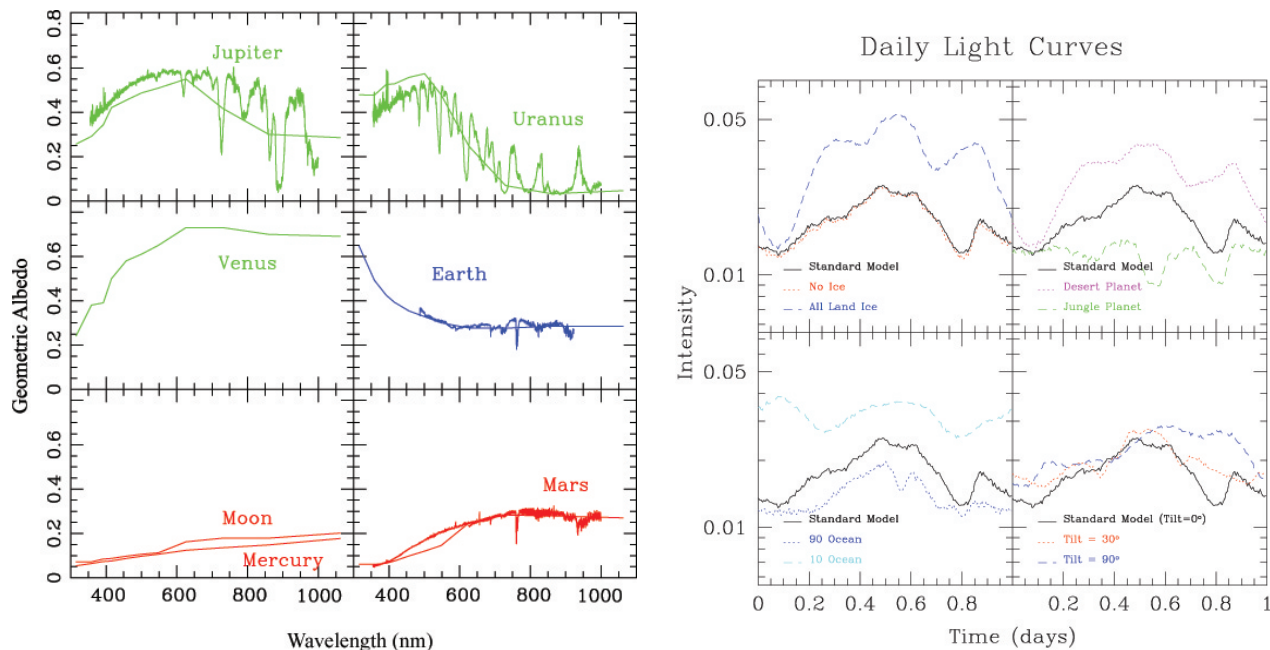


Fig. 2. (Left) Photometric data from the six Solar System planets (Brown, et. al., 2002). Earth data obtained from reflected Earthshine from Moon (Woolf, et. al., 2002). (Right) Daily Light Curves of Earth Model Spectrum under Various Conditions (Ford, et. al., 2002)

Photometric Variations

Even without spectroscopy, simple photometry can provide fascinating information on discovered planets. Beyond orbital parameter estimation, photometry at various times can be used to discern the diurnal variations of the planet's light curve. This can be used to infer such things as oceans, climate, and cloud cover. Ford, et. al. (2002) present results, performed during the TPF studies, on photometric variability of terrestrial planets. Figure 2 shows examples of the Earth's variability under various conditions. These are all measurable with TPF.

THE TPF CORONAGRAPH OBSERVATORY OVERVIEW

Figure 3 shows a schematic of the Ball visible light TPF concept. The observatory is an off-axis gregorian telescope with a 10×4 m monolithic elliptical primary. The observatory will be flown in a deep space orbit, either L2 or Earth-trailing, and be launched on a Delta IV H launch vehicle. While cryogenic operation is not required for a visible light telescope, thermal stability is of critical importance. Thermally induced distortions in the optics produce wavefront errors that can devastate performance, particularly if over short time scales. A passive thermal environment is created by going to deep space and controlled via an articulated sun shield. The spacecraft will be three axis stabilized and have a launch mass of roughly 6000 kg. It will be designed for 5 years of operation. Performance of the observatory has been confirmed through an integrated modeling effort at Ball, which includes a detailed optical prescription, structural flexibility, thermal distortion, and active pointing control. This observatory design meets all of the requirements described above.

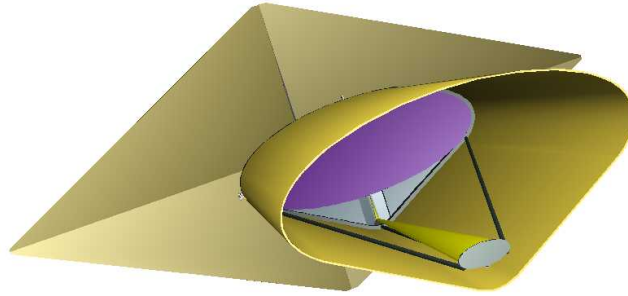


Fig. 3. Drawing of Proposed Elliptical Off-Axis Visible Light Observatory for TPF

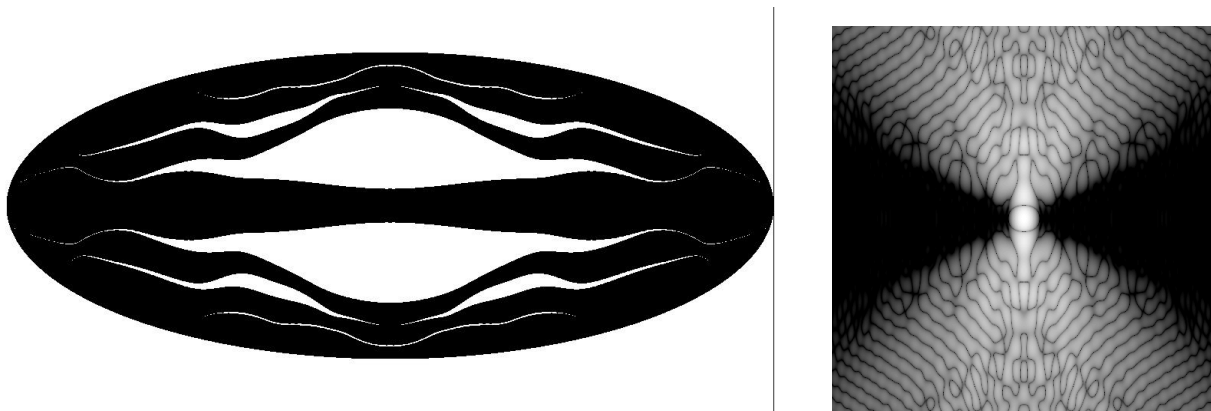


Fig. 4. Sample elliptical pupil and corresponding point spread function with inner working distance of $4\lambda/D$

ACHIEVING HIGH CONTRAST IN THE VISIBLE

As discussed, critical to the success of TPF is the ability to detect planets to within the inner edge of the habitable zone. This requires an optical system capable of extremely high contrast imaging (roughly 10^{-10} in the visible) within several Airy rings. The traditional coronagraph approach to this utilizes an image plane field stop (usually Gaussian) followed by a Lyot stop at a reimaged pupil. Kuchner and Traub (2002) present a novel coronagraph utilizing bandlimited masks. While the basic approach is the same, replacing the Gaussian field stop with a bandlimited function dramatically improves contrast and increases throughput. One of the advantages of this approach is its ability to search all azimuths at once. Its two main disadvantages are the difficulty manufacturing the field stops with the needed precision and the sensitivity to pointing error. (We point out that some of the difficulties in manufacturing can be mitigated by using notch filter masks as described in Kuchner & Spergel, 2002).

An alternative coronagraph approach was invented during the studies. This relies on apodization rather than field stops. However, rather than smoothly apodizing the entrance pupil (see, e.g., Slepian (1965)), we suggest instead to simply optimize the shape of the aperture. Specific shapes can be found that result in a PSF with the needed contrast at the desired inner working distance. The great simplicity of this approach is that these masks are binary—metal masks can easily be created inexpensively with existing technology. The potential limitation is that they provide discovery only over limited azimuths, requiring a rotation of the observatory (for an elliptical mirror this is necessary in any event to provide maximum sensitivity at all azimuths). Note that for characterization, where the planet position is known, very narrow discovery spaces can be used resulting in substantial improvements in integration times. Kasdin, et. al. (2003) provide details of the mask optimization process. Figure 4 shows an optimal elliptical pupil and the corresponding point spread function. The inner working distance for this pupil is $4\lambda/D$.

STATISTICAL AND SYSTEMATIC NOISE SOURCES

Everything discussed until now has been for an ideal optical system. Unfortunately, the limiting performance of TPF will be determined by the various error sources. Our capability to achieve high contrast is limited and there will always be a residual halo of scattered starlight near the planet. A common parameter for measuring this error is Q , the ratio of planet light to the residual background (Brown & Burrows, 1990). It is conceptually useful to divide the various error sources into two categories—statistical and systematic—both of which contribute separately to Q . Statistical errors are due to the random arrival of photons, diffracted background light, local and exo-zodi, stray light, and detector read noise. Systematic errors arise from wavefront phase and amplitude errors, scattered light, polarization, chromatic effects, and pointing error. It is beyond the scope of this paper to describe these all in detail. However, we will summarize the important ones and their impact on the design.

Statistical Noise and Integration Time

Of primary importance when considering statistical noise is integration time. A premium is placed on the time needed for discovery and characterization. Less time per observation means more science. It is generally agreed that a system operating at a $Q = 1$ provides the best compromise between integration time and design difficulty. Assuming a $Q = 1$ system allows various coronagraph approaches for achieving high contrast to be compared and optimized. Kasdin et. al. (2003) presents a thorough discussion of optimal shaped pupils and statistical noise considerations. We also point out that two of the advantages of a visible light TPF are the ability to resolve out the exo-zodiacal emission compared to IR approaches and the ability to use ambient temperature detectors.

Systematic Errors—Wavefront Sensing and Control

The biggest difficulty to overcome in order to achieve a $Q = 1$ system is the systematic error. While there are many sources, the most significant is wavefront distortion due to imperfect optics. Scattered light from ripples in the mirrors or amplitude changes due to reflectivity variations can be orders of magnitude larger than the planet in the mid-spatial frequency range where discovery takes place. Wavefront accuracy on the order of $\lambda/10,000$ is necessary to reduce the halo to acceptable levels.

A visible light TPF must be equipped with an active wavefront control system. The current plan utilizes a deformable mirror at a reimaged pupil (perhaps just following the shaped aperture mask) to correct the light. A variety of wavefront sensing algorithms are being examined for determining the needed correction (e.g., Redding, et. al. (2002), Shaklan, et. al. (2002), and Trauger, et. al. (2002)). Deformable mirror technology has progressed such that the needed stability and precision has been demonstrated in the laboratory (Trauger, et. al., 2002). Figure 5 shows the result of a deformable mirror test at JPL where the surface error was corrected to a residual error of 0.025 nm rms in the mid-spatial frequencies. This level of correction has been maintained for many hours in vacuum.

Of equal importance is amplitude error. While amplitude (reflectivity) errors on the mirrors can introduce scatter of intensity equal to the phase errors, there is far less experience correcting it. It is particularly difficult to do polychromatically. Littman et. al. (2002) presents a new concept for simultaneously correcting phase and amplitude using two deformable mirrors. Figure 6 presents a demonstration of amplitude adjustment using white light.

System Stability

The final critical issue related to systematic errors for a monolithic TPF is stability. Wavefront corrections will take many hours to perform. Single observations will require 1 to 2 hours for detection, longer for characterization. The corrected system must be stable at the $Q = 1$ level during these observations. This implies minimal elastic deformations and tight thermal control. Potential momentum wheels for attitude control have been examined and careful vibration isolation designed to minimize the coupling of imbalances into mirror vibrations. Simulations indicate that performance is well within requirements. A stable thermal environment is also needed to eliminate distortions in the optics due to varying thermal gradients. This is accomplished by placing the observatory in a deep-space orbit with a very benign thermal environment, using passive thermal shielding based on JWST technology, and, if necessary, active thermal control on critical components. We have performed detailed modeling and simulation of the thermal environment to

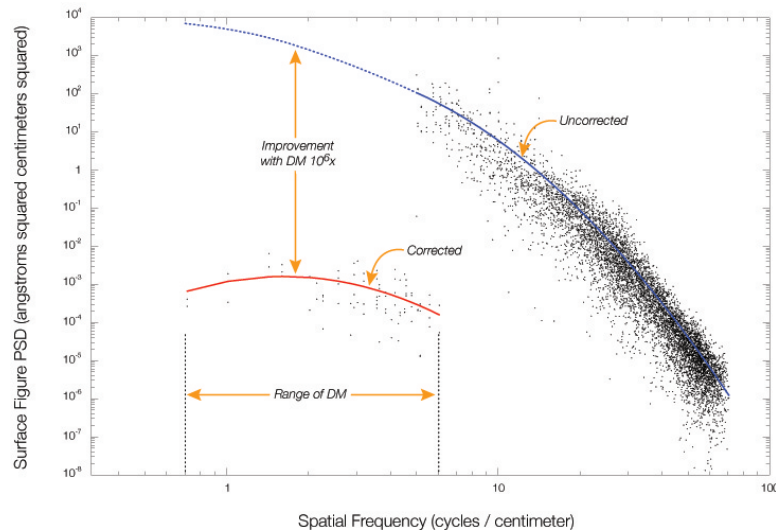


Fig. 5. Demonstration of deformable mirror capability at JPL. Mirror PSD has been corrected by a factor of 1 million within needed mid-spatial frequencies. (Trauger, et. al., 2002)

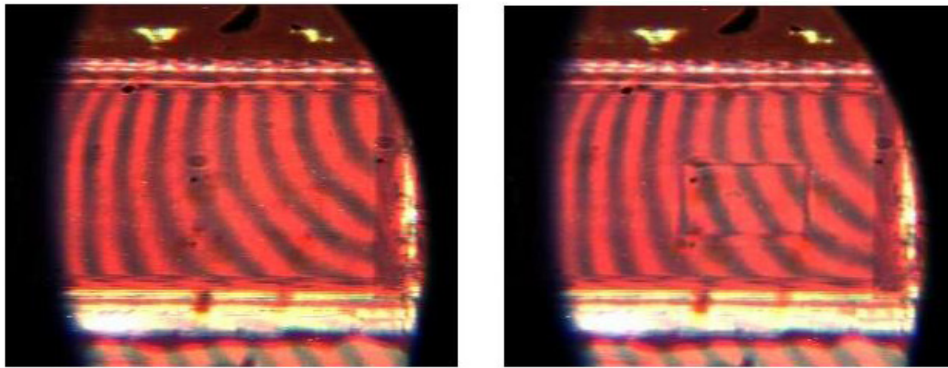


Fig. 6. Demonstration of amplitude control using a white light source and a Michelson interferometer. Left image is before adjustment and right image is after adjustment. (Littman, et. al., 2002)

verify performance. Thermal and vibration induced deformations (both static and dynamic) have been incorporated into an end-to-end integrated model including all optical elements to demonstrate system performance.

CONCLUSIONS

Undoubtedly one of the most exciting new frontiers of astronomy is the search for, and characterization of, extrasolar planetary systems. The knowledge to be gained and the implications for life here on Earth are profound. We don't expect that in the near future the capability will exist in ground telescopes to image the smaller terrestrial planets near the inner edges of the habitable zone. For this, a space observatory will be necessary. TPF (joined with the related European program, DARWIN) will be the flagship mission leading this effort. With the conclusion of the recent studies, NASA is well on its way to accomplishing this goal. We have presented in this paper a credible, cost effective, and exciting concept for a visible light coronagraph to detect terrestrial planets. We summarized the science to be gained, outlined the spacecraft engineering, demonstrated that high-contrast imaging is achievable, and presented the most important sources of errors and the plans for mitigating them. Laboratory work is underway at a number of institutions to perfect the wavefront control systems and demonstrate the required 10^{-10} contrast. Within 5 years development should begin on a flight observatory.

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