Terrestrial Planet Finder, Planet Detection Test-bed: Latest results of planet light detection in the presence of starlight

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ABSTRACT

The Terrestrial Planet Finder, Planet Detection Test-bed is a lab based simulation of the optics and control systems for the Terrestrial Planet Finder Interferometer mission. The test-bed supports starlight nulling at 10um infrared wavelengths, with fringe tracking at 2um wavelengths and angle and shear tracking at visible wavelengths. It further allows injection of simulated planet light in the presence of the nulled star light, to allow testing of planet detection methods. We will describe the detailed construction and operation of the test-bed from an optical and control system perspective. We will also report the latest results for narrow band nulls, and the detection of broad band planet light in the presence of nulled starlight.
Keywords: Interferometry, nulling, infrared, exoplanets

1. INTRODUCTION

Over the last decade the subject of extra-solar planet studies has expanded enormously, starting from a handful of known planets with no direct light detections, to the present with nearly 300 detected planets and some studies of exoplanetary spectra underway. The bulk of exoplanet detections so far have come using radial velocity techniques, which are most sensitive to massive planets in close orbits around their parent star, and planetary spectra studies have relied on a few favorable cases of transiting exoplanets. The Terrestrial Planet Finder (TPF) missions aim to advance this field of study by directly detecting and characterizing rocky, approximately earth sized planets close to or in the habitable zone around nearby (closer than a few tens of parsecs) stars. Two proposed architectures for TPF are currently under study at the Jet Propulsion Laboratory (JPL): a coronagraph working in visible light (TPF-C), and an nulling interferometer working in the near infrared (TPF-I). This paper is concerned only with TPF-I, whose science goals are described in detail in Beichman et al[1].

The current concept for the TPF-I mission (Martin[2], Lay[3]) consists of four large telescopes in space engaged in formation flying to produce a nulling interferometer operating in a broad waveband centered at about 10um wavelength. The nulling effect will be used to suppress the starlight so that near infrared light from the planet can be directly detected. The 4 beams will be combined in pairs in two identical nullers, then the nulled outputs of these nullers will be further combined in a cross combiner before detection. In support of technology development for this mission concept, JPL has developed several testbeds: 1) a formation flying testbed, 2) a broad band infrared nulling testbed, and 3) a planet detection testbed (PDT). Lawson et al[4] describe progress to date on all these testbeds, and this paper gives details of recent developments and latest results for the PDT.

The PDT is an attempt to demonstrate in a laboratory setting, the technologies required to perform the TPF-I mission science goals. As such it reproduces as accurately as possible, given the limitations that it is in a room temperature environment, the optical and control aspects of the space mission. It will be used to generate data sets that can be analyzed to optimize planet signal extraction, and it will also be used to investigate various planet signal enhancement techniques and mission configurations.

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2. TESTBED DESCRIPTION

2.1 Testbed goals

In order to detect an earth like planet in an earth like orbit around a solar like star at a distance of about 10pc, the TPF-I will need to achieve a certain level of performance using a given set of techniques. The PDT is designed to demonstrate that performance using those techniques in a laboratory analogue of the full space mission.

TPF-I aims to isolate light from planets that have a contrast ratio of about 10^7 with their parent star at around 10um wavelength. In principle, the starlight could be nulled to this level, but in practice this does not achieve the desired detection due to the large thermal background which is dominated by local zodiacal light, and has possible contributions from exo-zodiacal light. It is expected that this background will be at about 10^{-4} of the stellar flux, so stable nulls at the 10^{-5} level will be sufficiently low. Further rejection of the background can be achieved by chopping, a common astronomical technique in the near infrared. In this case the chopping is interferometric rather than through pointing and is achieved as follows. The centers of the two sets of nuller fringes are placed at the star, so is to give the best nulls of the starlight, with planet light allowed to pass since in general it will not lie at a null. However, the fringes from the cross combiner are arranged so as to have an inflection point at about the position of the star, with a bright fringe on one side of the star and a destructive fringe on the other. Now, by shifting the cross combiner fringe by π, the bright and dark fringe positions are swapped giving an effective chop on the sky. In the case that the planet happens to lie at the peak of the cross combiner fringes, the differential of the flux at the two chop positions is a direct measure of the planet flux. Further reduction in the contribution of the background will be made by rotating the whole telescope array about the line of sight, thus rotating the fringe patterns on the sky causing all parts of the exoplanetary system to be alternately covered by a bright or dark fringe. Averaging over a whole rotation can thus map out the entire system. Use of these techniques should improve the signal to noise ratio (SNR) by a factor of about 100 over the background level, giving an SNR of unity at the 10^{-7} flux level. A further factor of ten improvement in the detection, allowing a useful SNR detection at the required flux ratio of 10^7 can be achieved by using the wavelength spectrum fitting technique (Lay[3]). See Martin et al[5] and Lay[3] for fuller descriptions of the proposed planet detection techniques.

PDT will demonstrate all the above TPF-I techniques except the wavelength spectrum fitting technique of Lay[3], which at present is beyond its capabilities since the stellar source is monochromatic at 10um (see below on sources). It will aim to show stable nulls at better than the 10^{-5} level over periods of several hours (the order of magnitude of the time required for a single array rotation). It will aim to demonstrate the SNR improvement due to phase chopping using the cross combiner. Lastly, it will aim to reproduce the effects of an array rotation and show the SNR improvement with averaging over whole rotations.

2.2 Basic testbed layout

Previous reports on the PDT (e.g. Martin et al[5]) have described the basic testbed layout. In brief, this consists of the following components. (Figure 1 shows a basic schematic of the layout, figures 2 and 3 show complete optical layouts and figure 4 is a photograph of the testbed).

In the source section there is: 1) A "stellar" source being a 10.6um CO_2 laser, plus a ceramic heater thermal source which are arranged to produce collinear collimated beams which are then focused onto a pinhole to produce a coherent source. 2) A "planet" source being another ceramic heater thermal source, filtered to produce only wavelengths >9um, which is also focused on to a separate pinhole. 3) A diode laser source operating at 850nm which is used for tip-tilt and shear tracking control.

In the beam production section the star sources are split in to 4 equal beams to represent the 4 collector telescopes of the TPF-I instrument. The planet source is also split into 4 beams and these are injected via beam splitters so as to be collinear with the 4 starlight beams.

In the beam combination section the 4 beams are combined pairwise on two nulling beams splitters, with one of each pair being phase shifted by π to produce the null. The nulled output (the other side is a bright output) from each of these nullers is further combined on a cross combiner beam splitter. One output from the cross combiner is then focused through a pinhole (to provide spatial filtering) onto the main LN2 cooled HgCdTe single pixel detector. It would be possible to also use the other output of the cross combiner to increase signal to noise in the fringe detection, but we do not currently do so.

Finally, laser metrology at about 1.5um is launched in both upstream and downstream directions from the mid point between the beam production and beam combination sections to measure beam train path length variations (see below on path length control using metrology).

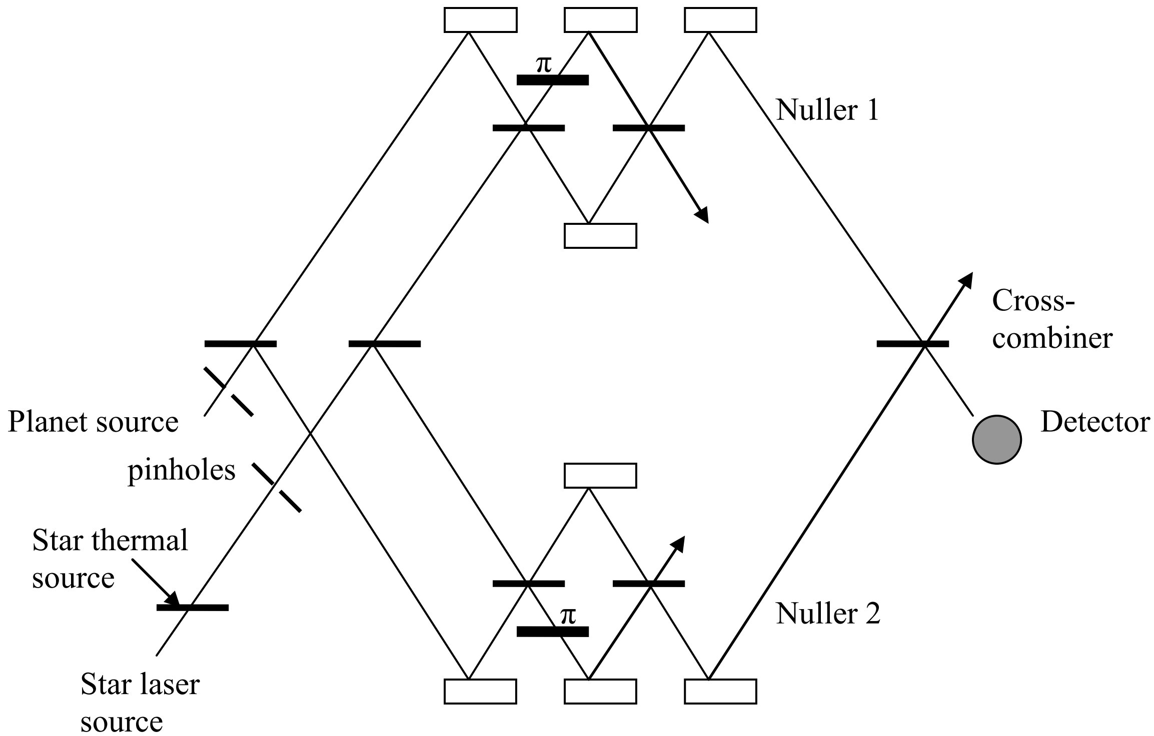

Fig 1. The basic schematic optical layout of the PDT showing the primary beam splitters and combiners

Detection at 10um is achieved using a chopper wheel running at about 500Hz, with lock in amplifiers measuring the detected flux. Both the planet and star beams have separate choppers that are synchronized. Obviously, this approach to signal detection cannot be used on the TPF-I in space since we cannot chop the sources! However, we have adopted this approach to simplify our detection technique in the lab, where, due to the much higher thermal backgrounds produced by the room temperature optics, we are forced to use sources that are some 8 orders of magnitude brighter than on sky sources. A comprehensive simulation of the spacecraft system using cryogenic optics in vacuum, with sources at appropriate flux levels for typical starlight and corresponding detector types would be much more expensive to produce and is not warranted at this stage of the technology development.

2.3 Recent upgrades to the testbed

Extensive optical and control system changes have been made to the testbed since we last reported on its status (Martin et al[5]), and we detail them here.

Most changes have occurred to the control system, which initially consisted of tilt and phase control achieved by dithering of the phase and tilt and doing a lock in detection of these dither signals on the 10um detector. We have now changed the nature of the control system to better mimic the type of control that would be required for a full up TFP-I mission, which will in addition allow us to maintain more stable nulls while detecting the planet signal. We next give a list of these control changes (with their required optical additions).

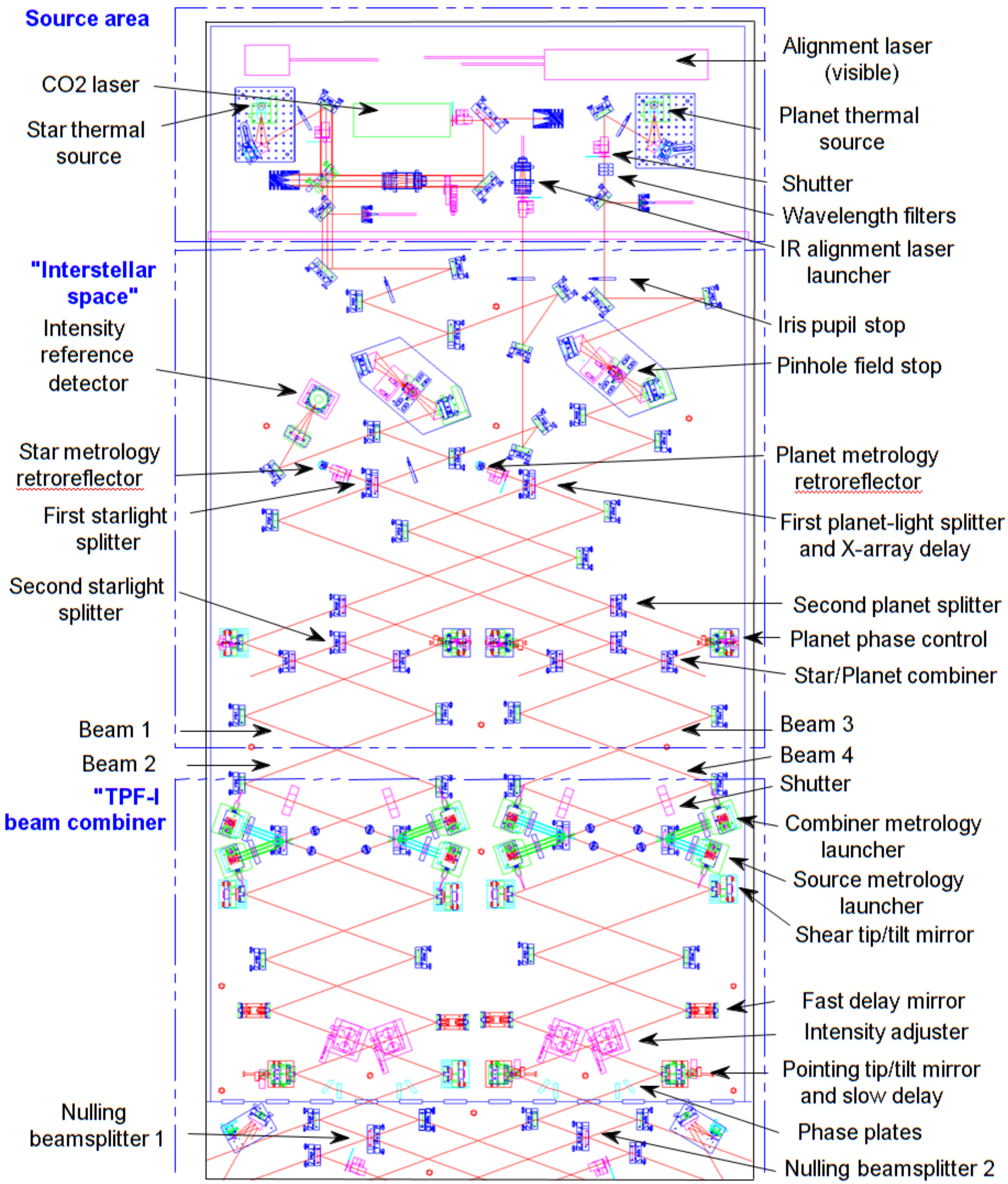

Fig. 2. Detailed PDT layout from the sources to the nulling beam combiners

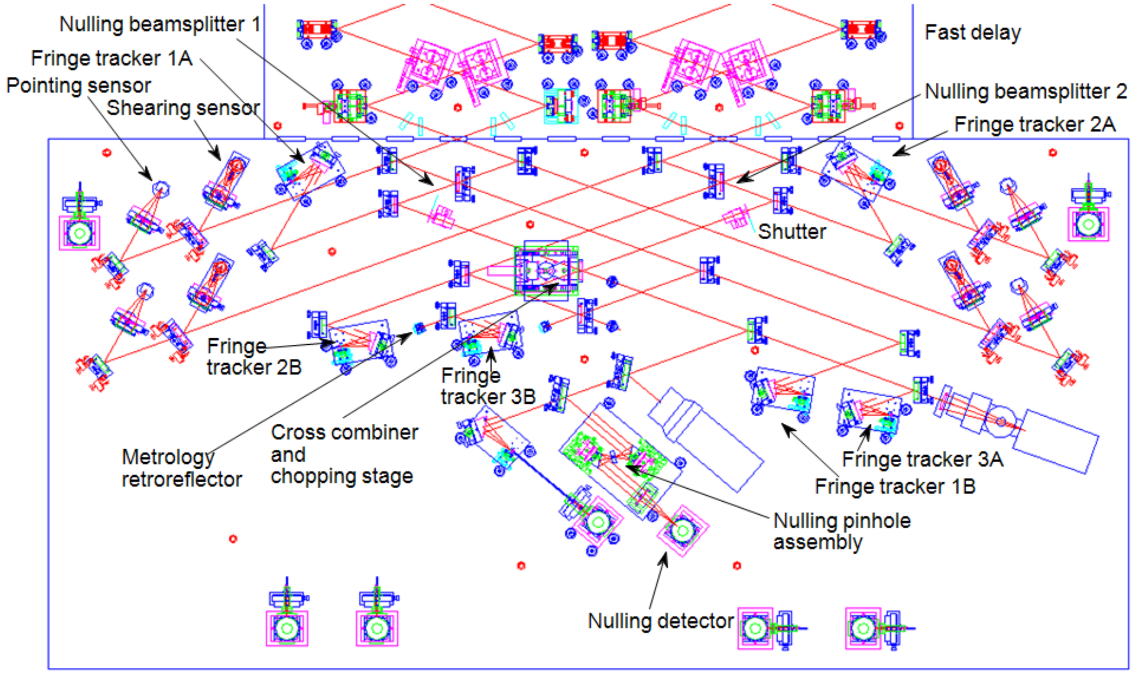

Fig. 3. Detailed PDT layout showing the cross combiner area and the detectors.

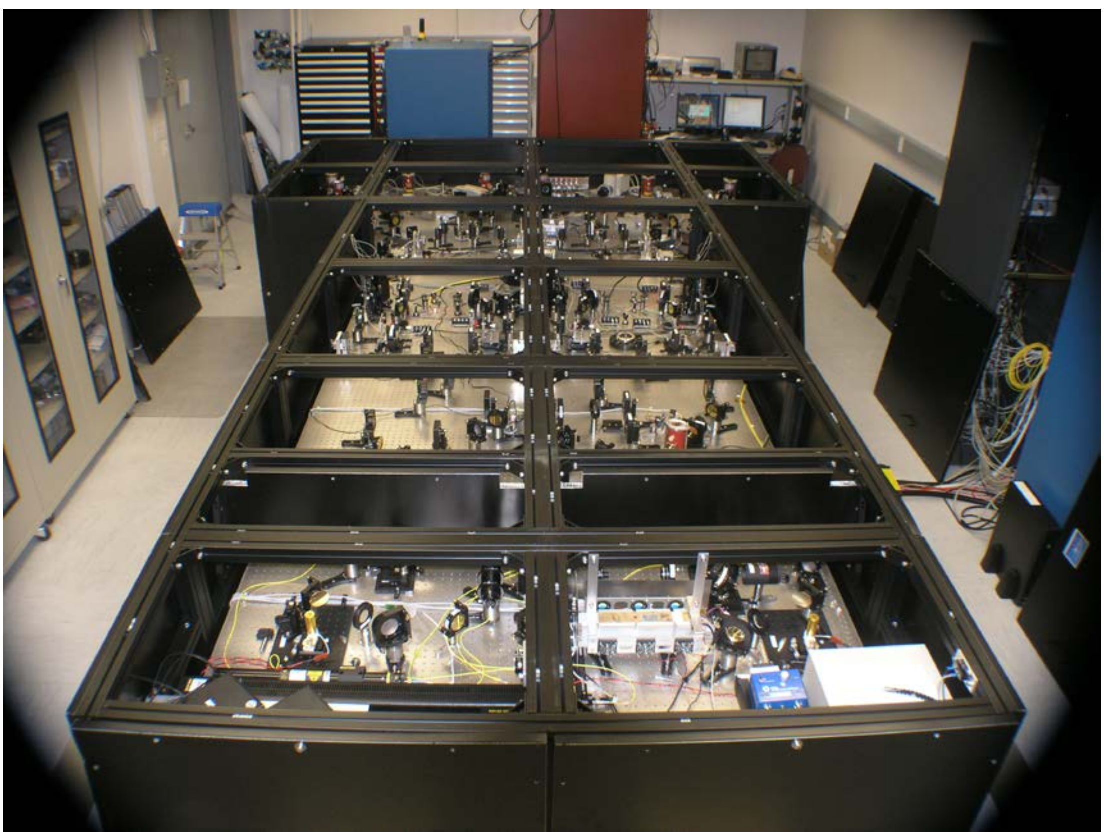

Fig.4. The PDT seen from the source end. The optical tables can be seen through the structure of the isolating enclosure (with its tops removed). In the background are the racks containing computers and electronics for the control system.

We have added separate tilt and shear sensors and control to the system (see figure 5). As mentioned above, a new laser diode source operating at 850nm has been added to the source set, and it is collimated and then injected in to the starlight beams from the back side of the first beam splitter, just down stream from the starlight pinhole. Detectors for this light have been placed behind the four last fold optics just upstream of the two nulling beam combiners, which have been converted to dichroic mirrors for this purpose. These detectors consist of a simple lens and quad cell detector for tilt detection and a four part lens and quad cell detector for shear detection. One of each of these is provided for each beam. Feed back from tilt detectors, with a bandwidth of a few tens of Hz, goes to simple tripod PZT controlled tilt mirrors just upstream of the pick off dichroics, again one for each beam. Feed back from the shearing detector, with a bandwidth of a few Hz, goes to a pure shear adjuster consisting of the tilt mirror acting in concert with a second tilt mirror just up stream from it. Tilt is still initially aligned by dithering the tilt mirror from each beam in both axes on the nulling detector and maximizing the throughput. Initial shearing alignment is achieved in the same way, but using the shear mirrors as the dither source.

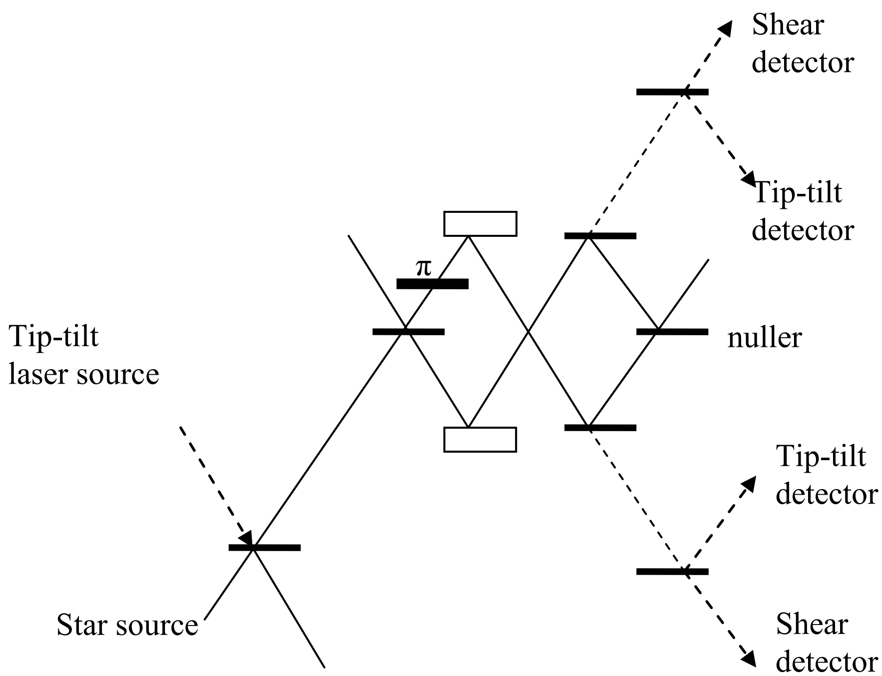

Fig 5. Schematic of the tip-tilt and shear control optical set up. Only one nuller (with 2 beams, star side only) shown for clarity. Solid lines show 10um light path, dotted lines, 850nm light path.

We have added fringe tracking using laser metrology tracking combined with fringe phase tracking working in the 2.2um to 2.53um wave band. As mentioned above, the metrology is launched from the mid point in the beam train between the beam production and the beam combination areas, in both the upstream and down stream directions. Up stream retro-reflectors are placed behind the beam combiners and down stream as close as possible to the star pinhole, allowing us to monitor and control higher frequency path length changes (due to vibrations, for example) over the whole beam train. Metrology control bandwidth is up to about 100Hz. Phase tracking at 2um is used to take out slower drifts in the absolute position of the metrology, with the phase tracking control bandwidth being a few Hz. The source for the phase tracking is the star thermal source mentioned above. Sensors for the phase trackers consist of 6 fiber fed LN2 cooled HgCdTe single pixel detectors, one each on both down stream sides of each of the two nulling and the cross combiner beam combiners. At present we use multimode fibers for the feed, but we have single mode fibers if we need to improve the 2um fringe contrast. The fringe sensors are used in pairs, taking the normalized difference of the measured flux on the two sides of a combiner as the error signal. Clearly, the most sensitive tracking is thus achieved at an inflection point of the fringes, close to the center of the group delay. Also, the error signal is insensitive the source intensity drifts. Feed back from the combined fringe and metrology control is to a pair of fast and slow delay lines which are located in each beam, and consist of a PZT driven mirror. The fast delay lines can be driven at the full rate required for metrology control, and have momentum compensation, but have a limited range of about 4um. The slow delay lines work at a few Hz bandwidth with a range about 80um, and are used to keep the fast delay lines desaturated. Fringe tracking for the two nullers feeds back to the delay lines one beam that contributes to the nulled light. Fringe tracking from the cross combiner feeds back to the delay lines in the two beams that feed one side of its beam splitter.

Optically, we have added a "phase plate" to each beam, consisting of a ZnSe plate about 10mm thick, that can be rotated to change its optical thickness. Using these we can match the 10um and 2um path such that the optimum fringe tracking condition mentioned above is met for the 2um fringes when we are close to a 10um null on the two nullers, and when we are close to a 10um fringe inflection point on the cross combiner. That way, given the wavelength difference, when we chop the cross combiner through half a 10um wave, we are moving two 2um fringes to another optimal 2um tracking point, so we can easily fringe track on both sides of the chop. Cross combiner shopping occurs at about 1Hz.

3. LATEST RESULTS

We have recently been able to start taking data with all the above mentioned improvements in place. In the next two sections we will describe the state of our nulling, and the first data showing a planet detection.

3.1 Null depths and null stability

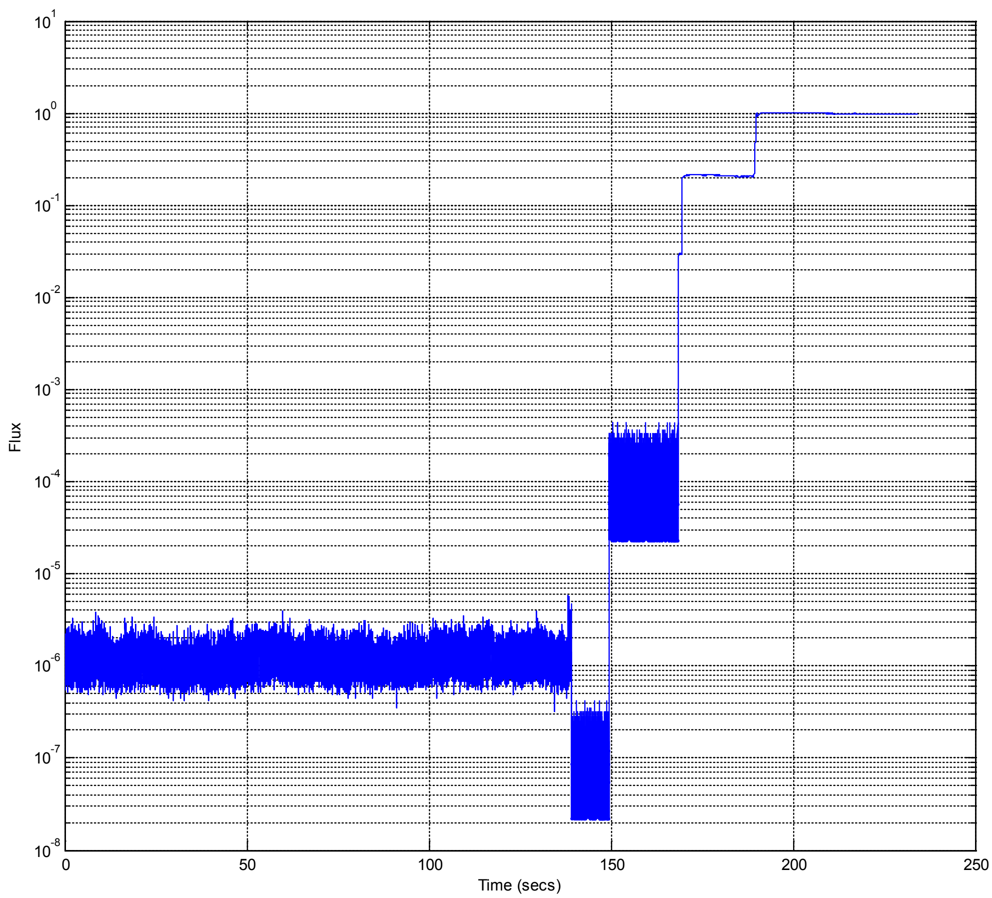

Fig. 6. Null depth on a single nuller with phase, tilt and shear tracking enabled. Times 0-140s, stabilized null; 140s-150s, laser shuttered off; >190s, bright fringe. Fluxes normalized to unity on bright fringe.

Figure 6 shows a typical measured null on one nuller (the other nuller produces comparable nulls) as a time series of flux measurements over a short time interval of about 100s. These data were gathered with all the appropriate control loops (tip-tilt, shear and phase) operating, and show the short term null stability. We have also measured longer term stability over thousands of seconds, and it is comparable with these short term data. The nulls show here were carefully optimized by matching the two beam intensities, the relative beam tilts, and the phase tracking zero point. The time series in the figure shows first nulled data, then a section with the CO_2 laser shuttered off to show the local background and detector noise. Clearly, the nulled light is well above this limit so represents true measured flux. In the final section the delay lines were moved to produce a fringe maximum (and a calibrated neutral density filter inserted in the source). All the fluxes shown in the figure were normalized so that this bright fringe flux was unity. Clearly, the minimum null depth lies at about 1.6×10^{6} to 1, which is will below our target level. The mean null depth for these data is 9×10^{5}, and the remaining null depth fluctuations are largely due to non-optimal tracking of the phase from the metrology sensors. We will be tuning this servo for better performance in the near future, and will be able to produce lower mean nulls, though even at the current level of fluctuations we are well below our target of stable 10^{5} nulls.

3.2 First planet detection result using the dual chopped linear Bracewell array configuration

As mentioned above, simulation of the TPF-I array rotation about the line of sight is implemented on the PDT by modulating the phase of the four planet beams before they are combined with the starlight beams using PZT controlled mirrors as delay lines. At the time of writing, we have not implemented the modulation needed to simulate the most likely TPF-I array configuration – the "stretched X-array" (Lay[3]), but we have implemented that needed to simulate the dual chopped linear Bracewell array configuration (Martin et al[5]). By changing the amplitude of the phase modulations we may simulate a planet at various distances from the star, and by changing their phase we may change the planet's location relative to the star with reference to the array zero rotation point.

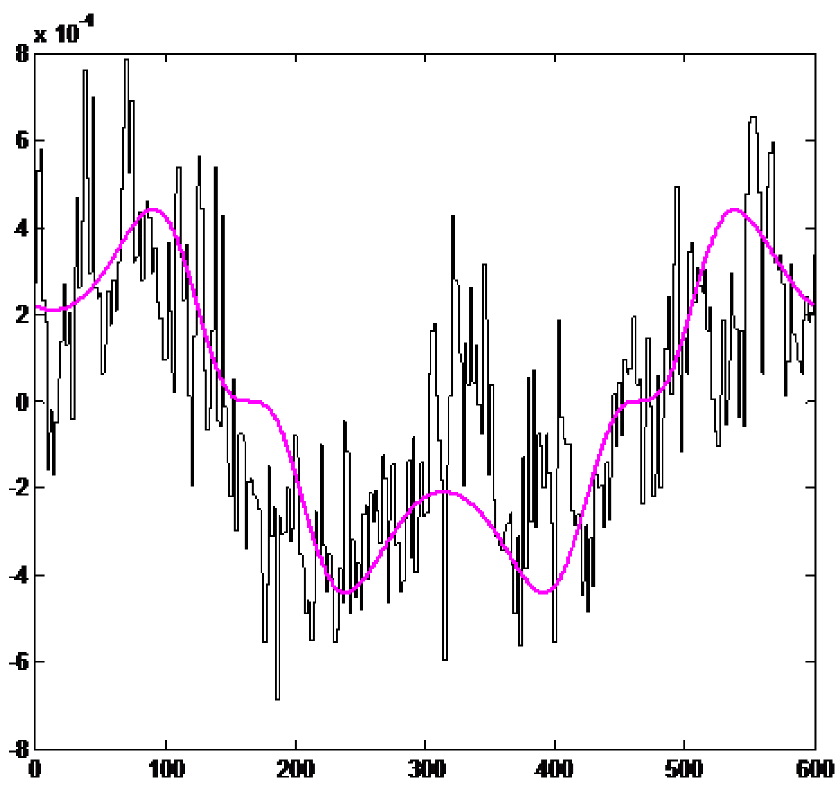

Fig. 7. Time trace (seconds) of chopped flux (arbitrary units) for planet light in the presence of nulled starlight. Noisy trace shows raw data, smooth line is a fit to these data.

Figure 7 shows a time trace of data taken over a single simulated array rotation lasting 10mins, which was our first attempt at detecting a "planet" signal from its thermal source in the presence of nulled "starlight" from the CO_2 laser. The figure shows the flux measured on the 10um detector as the difference of the flux on the two sides of the cross combiner chop, which ideally should therefore be centered on zero flux (when the planet lies on the peak of the cross combiner fringe at the "B" phase of the chop, the difference A-B will be negative). The fitted function is a template of the expected flux variation given the known array configuration, and a single point source planet.

Figure 8 shows a contour map of the likely planet position on the "sky" generated from fits to the data in figure 7. The position of the "star" is at the center of the plot. Also shown is the peak of the planet probability distribution, and the "actual" planet position from the known phasing and amplitude of the modulations to the planet beams. Note that the contours on the side away from the planet are negative (this symmetry results from the symmetry of the array with respect to a 180º rotation). For these data the simulation placed the planet some ~0.1urad from the star, which would represent ~1AU at ~50pc.

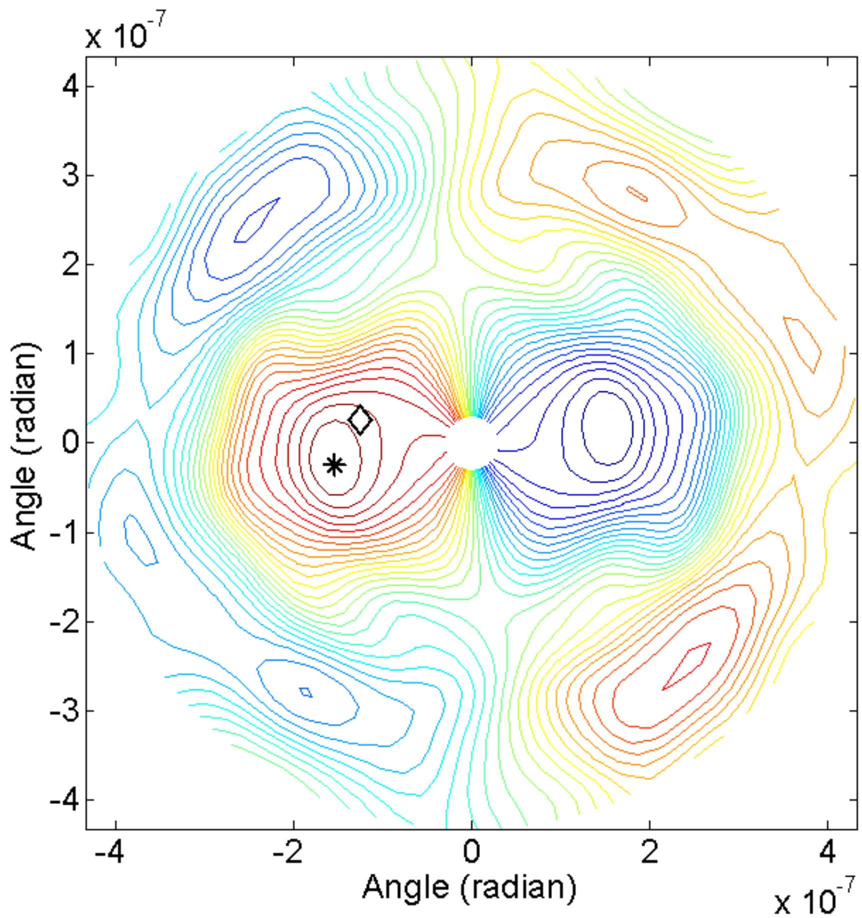

Fig 8. Contour map of probability of planet position generated from fit to data of figure 7. The star is at the center. * shows the peak probability position, the diamond shows the "actual" planet position (from known planet beam phases).

4. UPCOMING PLANS

We are currently implementing the planet beam modulations that will allow us to simulated the stretched X-array telescope configuration of TPF-I. In addition, we aim to improve the metrology fringe tracking control for the nullers and cross combiners. Once these improvements are made we will start a series of experiments demonstrating planet detections at the 10^6 contrast ratio level (note that, lacking a means to do spectral fitting, we cannot yet reach the 10^7 level of the full TPF-I), with a single array rotation taking some 2000s. This limit on the array rotation time is placed by the desire to do several rotations in the same observing session, and the ~10000s hold time of our detector cryogens. This should be compared to the expected 50,000s array rotation period for the TPF-I spacecraft.

Eventually we hope to replace the CO_2 laser with an argon arc source and the single pixel 10um detector with an array camera and spectrograph. With the inclusion of "adaptive nulling" techniques from the broad band nulling testbed (Lawson et al[4]), we will then be able to fully simulate the TPF-I optical and control architecture, including spectral fitting (Lay[3]).

5. SUMMARY

The PDT testbed has recently undergone extensive upgrades that make it a more accurate simulation of the expected TPF-I instrument. Using these upgrades we have demonstrated stable nulls at approximately the 10^6 level, and have shown a first planet detection in the presence of nulled star light.

ACKNOLEDGEMENTS

The authors wish to thank several people at JPL who have contributed to the development of the PDT: S. Fregoso, P. Lawson, O. Lay, K. Liewer, F. Loya, and M. Marcin.

The work reported here was conducted at Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology

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