TPF Planet Detection Testbed: demonstrating deep, stable nulling and planet detection[1,2].

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Abstract— The design of a testbed being built at the Jet Propulsion Laboratory is described. Simulatiung a dual chopped Bracewell interferometer, the testbed comprises a four beam star and planet source and nulling beam combiner. Since achieving a stable null is of great concern the testbed has many control systems designed to achieve stability of alignment and optical path difference over long periods of time. Comparisons between the testbed and the flight system are drawn and key performance parameters are discussed. The interaction between designs for phaseplate systems that achromatically invert the electric field of one of each pair of the incoming beams to achieve the null and the choice of fringe tracking schemes is also discussed.

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1. INTRODUCTION

Direct optical detection of earth-like planets orbiting nearby stars is the challenging technical problem being addressed by the Terrestrial Planet Finder project (TPF). At the Jet Propulsion Laboratory, testbeds are being built to test different aspects of planet detection for both a coronagraphic approach (TPFC) and an interferometric approach (TPFI). For both these approaches, a key technology is the reduction of the parent star's photon flux so that the faint planet flux can be sensed. In the case of the TPF interferometer, this is achieved by destructive interference (known as 'nulling') of the starlight with simultaneous constructive interference of the planet light. The current baseline TPF interferometer is a linear array of four independent 4 meter diameter infrared telescopes that collect and transfer light to a fifth beam combiner spacecraft, but other array configurations are possible [1]. The four beams of light are nulled in pairs and combined in such a way as to modulate the planet signal on and off; a process known as phase chopping. Typically the planet will contribute a single photon every few seconds, while the background of light from the instrument, star, zodiacal and exo-zodiacal light will be hundreds of photons per second. The interferometric telescope array also rotates around the line of sight to the star, a process that takes many hours. A key requirement therefore for successful planet detection is a highly stable interferometric beam combiner. The basic flight requirements are: optical path difference (OPD) control to about the 2 nm rms level, and beam amplitude control to about the 0.1% rms level. Moreover, these requirements must be met across the science waveband of 7 to 17 micrometers, and the instrument must be stable at all timescales from the short timescales associated with spacecraft vibrations to the timescales of many hours.

[1] 0-7803-8155-6/04/$17.00© 2004 IEEE
[2] IEEEAC paper #1315, Version 1, Updated October 20, 2004

Table 1: Selected performance and configuration requirements compared for a TPF flight system and for the Planet Detection Testbed

		Flight Value	PDT Value
Performance requirements			
	Star-Planet contrast	5.00E-08	1.00E-06
	Detection SNR	5	5
	Simulated rotation time	50000 s	5000 s
	Science wavelength	7-17 μm	10.6 μm
	Simulated planet offset	0.07 arc sec	0.1 arc sec
Major configuration requirements			
	# beams	4	4
	phase chopping	Yes	yes
	Array configuration	Dual Bracewell?	Dual Bracewell
	Simulate array rotation	Yes	yes
	Controls & cal scalable to flight	-	yes
Major derived requirements			
	Null stability	2.00E-08	6.00E-08
	Null depth	1.00E-06	1.00E-06
	OPD closed loop rms	2 nm	2 nm
	Amplitude closed loop rms	0.12 %	0.12 %

The TPF Planet Detection Testbed is being used at JPL to demonstrate this kind of instrument stability at near flight-like levels of performance. Initial requirements include planet detection against a star 10^5 times brighter and the goal is planet detection against a star 10^6 times brighter. The in-flight requirement will be about an order of magnitude greater. Configured as a chopping dual Bracewell interferometer, the testbed has a four-beam source simulating a star and planet and is capable of simulating an array rotation lasting 5000 s. Table 1 shows some selected performance requirements. The 10^{-6} null depth required has previously been achieved in experiments conducted at JPL [2]; the principal new goal in this area is that the null is to be maintained stably and the output phase-chopped accurately over a long period of time. Sensors and control systems are in place to control vibrations and thermal and environmental drifting which affect OPD. These systems cover frequency bands from a few hundred Hertz to milli-Hertz. In addition there are sensors and actuators monitoring and controlling beam tilt and beam shear, which vary on similar timescales, and affect the amplitude of a light coupled into the detector. By controlling the OPD and the optical alignment very accurately these systems will allow the extremely stable, deep nulling and phase chopping required.

An important difference between the testbed and the flight system is evident in the area of flux levels. Figure 1 illustrates the relative flux levels between the testbed and the flight system. While we expect to receive approximately 10^6 photons per second from the star, the photon flux from the laser will be nine orders of magnitude greater. This reflects the difference in the background photon flux. In space the background will come from the surfaces of the optical system and the local zodiacal flux. The flight instrument will be cooled to low temperatures to reduce the background flux levels produced by the optical system. On the other hand, the testbed will be operated at room temperature and the optics within the beam train will produce large numbers of thermal photons. To overcome the large thermal background the testbed uses a CO_2 laser to form the artificial starlight which is to be nulled. Since the photon flux in the testbed will be very high, there exists therefore a significant difference in the signal to noise characteristics of the testbed compared with the flight system.

Coupled to the issue of photon noise statistics is the effect of small variations in phase and amplitude of the light entering the beam combiner. These variations cause small changes in the null depth, thus transmitting more or fewer stellar photons to the science detector and generating a noise signal. Since the planet signal is so weak, most likely less than one photon per second, this noise signal must be carefully controlled to reduce the possibility of false planet detections[3]. One important goal of the testbed is to demonstrate the degree of control of the interferometer required by Terrestrial Planet Finder mission. A second goal is to be able to make measurements under signal to noise conditions that are representative of those expected to be experienced in space. A third goal is to demonstrate a fringe tracking system similar to that envisioned for the space system. This fringe tracking system would utilize the more numerous and shorter wavelength photons from the star of about 2 micron wavelength to phase the interferometer.

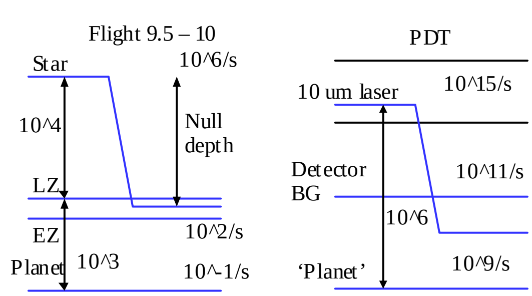

Figure 1: Relative flux levels for the TPF flight system and the Planet Detection Testbed.

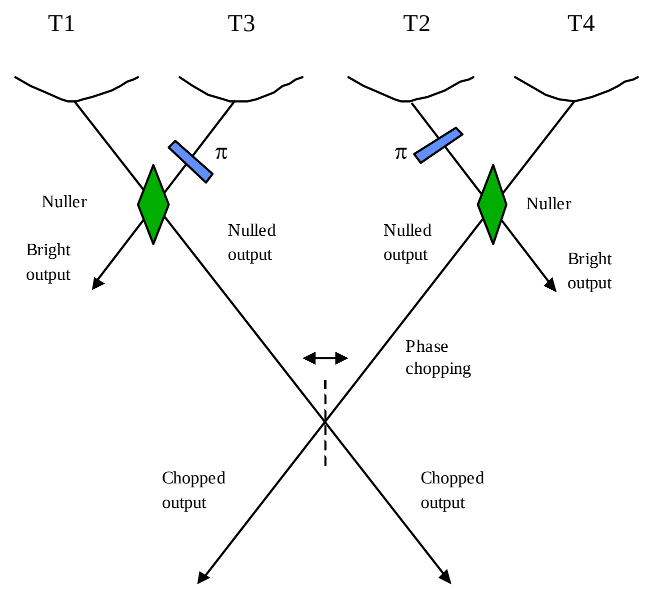

Figure 2: General layout of the beamcombiner showing the four telescopes, the two nullers and the cross-combiner.

2. Testbed Architecture

Overall concept

The testbed consists of two main parts; the light sources and the optics to produce the four star and four planet beams, and the optics and detectors that are representative of the TPF beam combiner. Therefore in the sense of requiring its own star and planet source, it is more complex than the flight beam combiner and it is architected somewhat differently, but in a way that is traceable to flight. In the flight system the beam combiner will be folded [4] into a compact shape with various focal plane array detectors performing functions such as science light detection, and fringe tracking. In the testbed the beam combiner is built on a flat optical table with individual single pixel detectors. This arrangement allows for greater flexibility in the testbed phase. A number of different layouts, for example fringe tracking layouts, can be tried and different optical components can readily be substituted. Figure 2 shows the general layout of the beamcombiner to combine the four beams by nulling in pairs, and then cross-combining.

Another significant difference between the testbed and the flight system is the use of a simpler nulling beam combiner, that is a single beamsplitter, rather than the modified Mach-Zehnder nuller (MMZ) [5] which uses pairs of beamsplitters. This reduces the complexity somewhat by reducing the number of output beams to just two rather than four at the expense of some asymmetry in the beam combiner. This asymmetry arises from the use of a simple null symmetrical beamsplitter. The asymmetry is compensated in the testbed by an opposite asymmetry in the star and planet source. The two asymmetries cancel each other, producing an equivalent result to the MMZ beam combiner. It is hoped that in the future beamsplitters with a high intrinsic degree of symmetry will be developed, allowing the simple beam combiner to be used in the flight system, resulting in reduced complexity. Currently the JPL baseline for flight utilizes an MMZ beam combiner, and there are significant differences in the ways that such a beam combiner can be architected for nulling. For example, to null the starlight beams a 180° achromatic phase shift must be introduced across the science band to one beam in each beam pair. Various methods exist to produce this phase shift such as field inversion through a focus [6], field inversion by reflections, and field inversion using glass plates known as phase plates [7]. The latter method can be used in the simple beam combiner as well as in the MMZ beam combiner, while the through-focus and reflection methods would not prove useful for a conventional dielectric beamsplitter used in a simple beamsplitter configuration. This is because the simple beam combiner requires only a 90° phase shift to achieve the null because the dielectric beamsplitter introduces its own 90° phase shift (assuming zero absorption) resulting in a total 180° phase shift. In the MMZ by contrast, any phase shift introduced by the first dielectric beamsplitter will be compensated by the second, resulting in a net zero phase shift regardless of the beamsplitter properties. So the simple beam combiner is a good representation

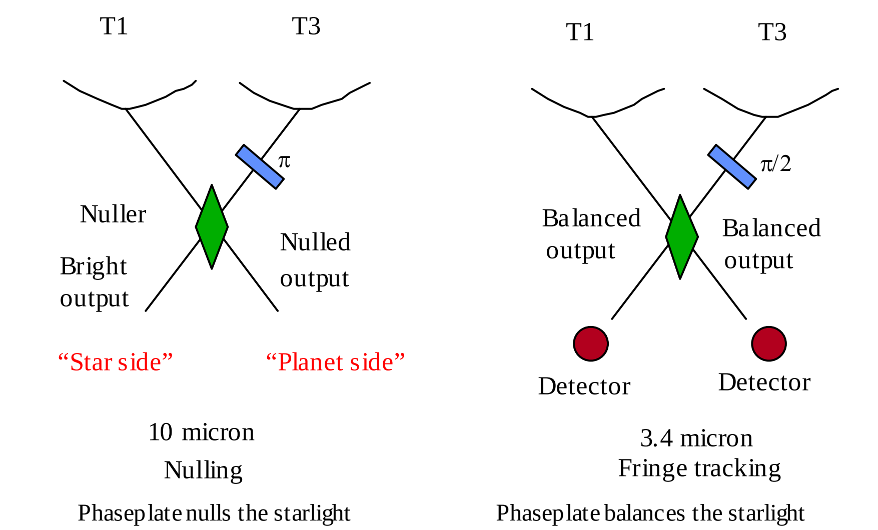

Figure 3: Showing the nomenclature for star side and planet side fringe tracking and the use of phaseplates to produce balanced outputs for fringe tracking.

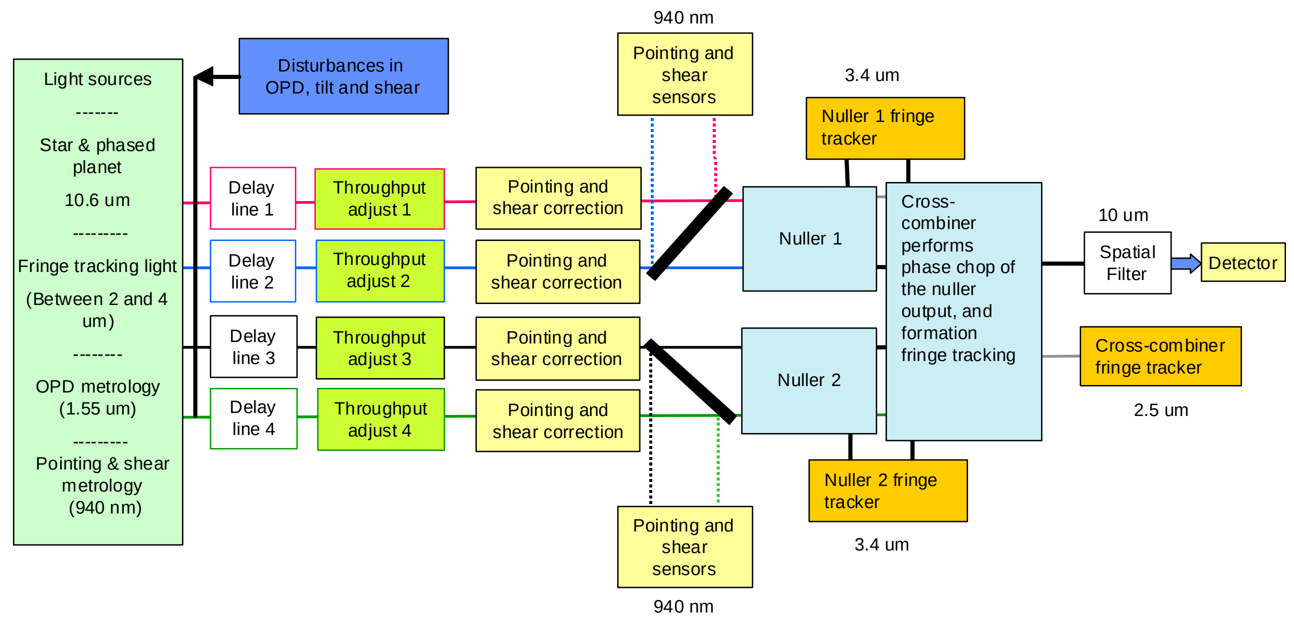

Figure 4: Testbed block diagram.

of flight if we assume that the flight system will use phase plates for the field inversion function. The phaseplates will be different in terms of thickness, but the principle of operation remains the same.

There remains an additional difference between the testbed and the flight system in this case and that is in the area of tracking the stellar fringe. In the baseline flight design utilized by JPL and also reflected in the work of the University of Arizona's TPF Common Path Phase Sensing Testbed [8], the phase plates introduce a phase dispersion at shorter wavelengths. This phase dispersion is useful for fringe tracking because whilst the star light is nulled at 10 microns because of the 180 degree phase shift, at shorter wavelengths the phase shift might be a multiple of 90° resulting in a more or less even balance of light passing either side of the nulling beamsplitter. The fringe tracking function can be performed by measuring the balance of the light and maintaining it at some fixed calibrated level. If phase plates are used for the MMZ nuller, thicker plates will be needed to produce the 180° phase shift, resulting in additional phase dispersion at shorter wavelengths. This means that the fringe tracking wavelengths at which 90° of phase occurs may be different. While this is true, we can still build a simple beam combiner with the same form and function as an MMZ beam combiner and make comparisons to relate fringe tracking performance between the two systems. The phase shift effects are illustrated schematically in Figure 3.

3. TESTBED LAYOUT

Figure 4 illustrates in a block diagram form the layout of the planet detection testbed. On the left a CO_2 laser provides the 10 micron thermal radiation from the star which is to be nulled, and a ceramic heater produces broadband thermal radiation providing the radiation from the star which is to be used for fringe tracking. A second ceramic heater also produces broadband thermal radiation providing the light from the planet; at the point of detection the planet light is band limited to a passband about 1 micron wide centered at 10 micron. Also on the left, a solid-state laser produces a beam of light at 940 nm which is to be used for alignment purposes. Four output beams are produced combining star light and planet light with the correct phases. Disturbances can be introduced between the star and planet source and the beam combiner that affect the OPD and the alignment of beams. In the beamcombiner, the starlight beams are nulled in pairs and then cross-combined before the science light passes through a single mode spatial filter prior to collection on the science detector. Any optical path and beam tilt and shear disturbances which had been introduced are removed using optical delay lines and tilting mirrors before the light enters the nullers using the feedback from the alignment sensors. Also, small adjustments to the throughput are made so that each beam has the same intensity. The optical delay lines are controlled by the three fringe trackers and eight metrology gauges, while the tip/tilt and shear mirrors are controlled using the alignment light introduced in the star source. In the flight beam combiner this alignment light would be introduced at the collector telescopes and coaligned with the star light by introducing it upstream of the fine guidance sensor which points the telescope at the

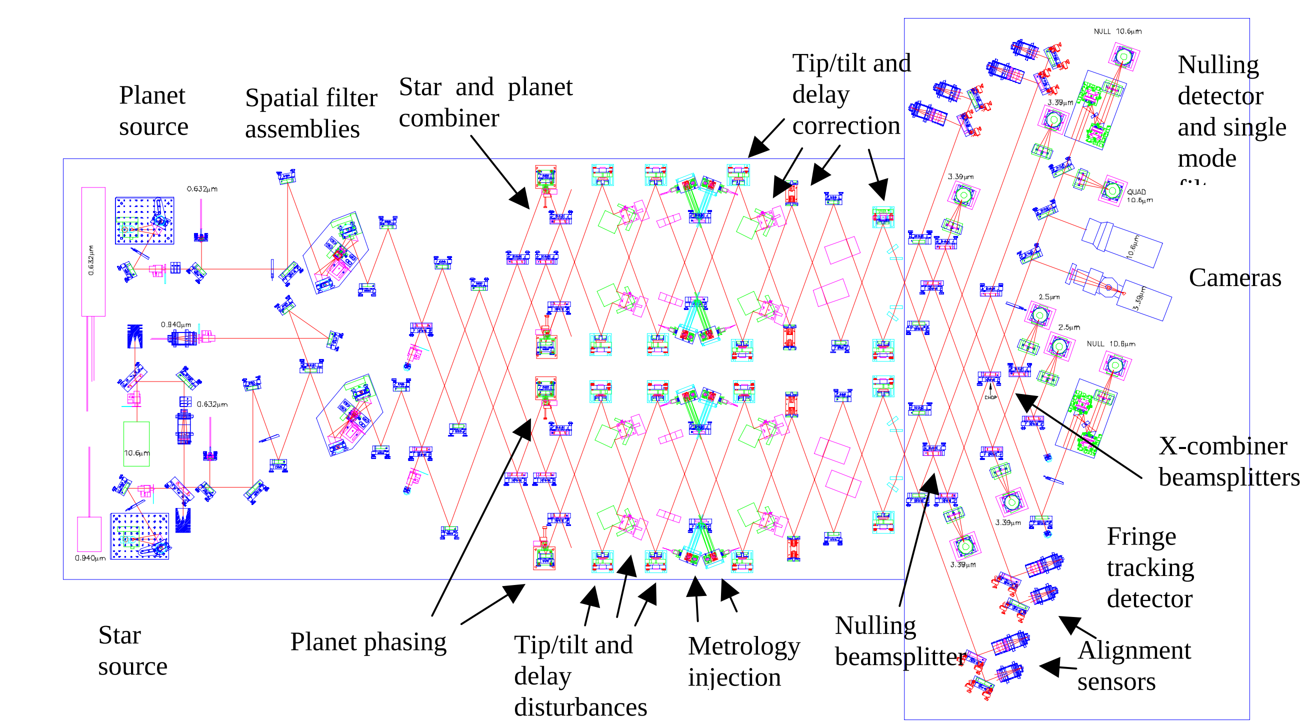

Figure 5: Optomechanical layout of the Planet Detection Testbed

star. The alignment light would be relatively bright allowing high-speed correction of the optical system alignment downstream of the collector telescopes. Similarly, the metrology beam is very bright compared to the fringe tracking light and also has a shorter wavelength, allowing high-speed correction of the optical path differences within the beam combiner and telescope array. Thus the fine guidance sensor and the fringe tracking sensors operate at comparatively low bandwidth and allow phasing and pointing of the formation as it drifts in space. The alignment beam and the metrology beam allow phasing and pointing corrections to compensate for internal vibrations of the structures and systems comprising the telescope which generally occur at higher frequencies. This is an area where the testbed can be adjusted to make its performance more comparable with the performance of the flight beam combiner. For example, the testbed fringe trackers might be noisier than the flight fringe trackers either because the detectors and the associated electronics are intrinsically noisier, or because the background light levels are higher. The testbed itself may have a higher level of vibration caused by the environment than the flight system. By adjusting the bandwidth of the fringe tracker's detection system and the bandwidth of the metrology system we may be able to create signal to noise ratios similar to those expected in flight, despite the very large differences in signal strength. This possibility will be investigated more thoroughly as the testbed development continues.

Figure 5 shows the optomechanical layout of the testbed. At the left are the sources, followed by the beam combination and phasing optics, followed by the disturbance-producing components. At the metrology input point, the model TPF beamcombiner begins. The amplitude, tip/tilt, optical delay and shear correcting components follow, then the nulling beamsplitters and cross-combiner. The configuration shown is the star-side fringe-tracking system described in more detail below. The array of 8 alignment sensors can be seen, and the 6 fringe tracking detectors. Also shown are two null detectors and alignment cameras.

In the flight system the metrology will originate somewhere on the collector telescope, as close as possible to the primary mirror. The only metrology extending out the star is the incoming 2 micron light detected by the fringe trackers. Assuming for the moment that there is minimal vibration between the telescope primary and the point of introduction of the metrology beam, then the metrology can be used to compensate all vibrations internal to the spacecraft array (ideally the laser metrology would originate at the primary mirror although even this arrangement does not guarantee the measurement of all disturbances). On the other hand, in the testbed, there is internal vibration between the point of introduction of metrology and the source light. Therefore the testbed has an additional metrology system pointing out towards the source and this is used solely for the purpose of compensating the high-speed vibrations encountered on the testbed that are introduced from the environment of the laboratory. In other words this metrology beam is high pass filtered so that it cannot be used for fringe tracking *per se*. Thus the testbed maintains the architecture of the TPF beam combiner while being able to compensate for the extraneous vibrations introduced by the artificial star and planet source.

Alignment sensors

There are two alignment sensors on each incoming beam placed as near the nulling beamsplitter as possible. One sensor measures tip and tilt of the alignment laser beam and the other sensor measures the shear. Both sensors utilize a quad cell and have identical electronics. The shear sensor measures the beam shear by dividing the beam into four quadrants and measuring the power in each quadrant. By maintaining constant power balance at some set point determined by calibration the beam shear can be maintained at a constant value. Since the sensors are placed very close to the nulling beamsplitter they have only a small error caused by the few optical components which are not shared by the incoming star light. Alignment sensors built for test before installation on the testbed have shown tilt sensitivities of 0.4 μradian and shear sensitivities of the order of 10 micron. The testbed error budget predicts overall performance at the 2 μradian rms and 60 μm rms level. This is adequate for control of the testbed to the desired null stability level.

Optical delay lines

There are three sets of optical delay lines in each beam on the combiner side of the testbed covering three different regimes. A long delay line capable of moving three millimeters is included to remove the simulated formation drifting disturbance imposed upstream of the beam combiner. A portion of the travel range of a pair of tip/tilt mirrors which are used to control beam tilt and shear is also used as an intermediate delay line with a travel of 15 micron. The third delay line is a high-speed delay line with a travel of 3 micron. but capable of operating at more than two kilohertz. Under the control system the high-speed delay line is used to remove the OPD variations caused by mechanical vibrations and thermal drifting of the testbed. The high-speed delay line is desaturated, in other words recentered to its rest position, using the intermediate delay line, and in turn the intermediate delay line is desaturated using the long delay line. A similar cascade of delay lines is envisaged for the flight system but with different operating ranges and speeds. The testbed goal is to achieve better 2 nm rms fringe tracking error and the error budget currently predicts (combining the fringe trackers and the laser metrology system) performance of 1.3 nm rms.

To create the disturbances on the star and planet side of the testbed a similar set of delay lines is installed. These delay lines do not however operate closed-loop.

Alignment control

As noted above two sets of tip and tilt mirrors are installed to control the alignment of the science beams at the nulling beamsplitter. It is important for high nulling performance that the beam tilt and beam shear are very small. In the star and planet source section of the testbed a similar pair of tip/tilt mirrors are installed which can create tip and tilt disturbances and beam shear disturbances. When these disturbances are sensed by the alignment sensors, the control system acts upon the tip/tilt mirrors on the beam combiner side to realign the incoming beams.

Beam conditioning

The science beam is initially conditioned by passing through a spatial filter assembly consisting of a pinhole 40 μm in diameter. This removes any stray reflections introduced in the source where there are a number of windows and filters which can introduce stray light. At the science detector the plan is to install single mode spatial filters for 10 μm radiation. These filters (single mode fibers) are not yet available but they are being developed and in the meantime the testbed plans involve using an 8 μm pinhole which should serve the same purpose. Modeling by the University of Arizona [9] predicts that this 8 micron pin hole will act like a fundamental mode circular waveguide at a wavelength of 11.8 μm with 30% bandwidth. Higher order mode rejection is expected to be greater than 25 dB. The total throughput when coupled to an f#1.5 optical system is expected to be ~45%.

In the previous deep infrared nulling experiments at JPL pinholes were used as conventional simple spatial filters to mitigate possible stray light problems. However there are large advantages to be gained from using true single mode spatial filters; not only do they spatially filter high spatial frequency wavefront error from the incoming beams, eliminating the need for near-perfect optics, but they also alleviate to a great degree the requirements for precise shear and tip/tilt control. For example without a single mode filter to obtain a 10^{-6} null, beam shear would have to be controlled at the 0.1% level. However with a single mode filter, models show that this requirements relaxes to the 1% level. Once these filters become available they should greatly improve our ability to achieve deep nulls and also to achieve high instrument stability.

Amplitude control

Gross amplitude, (or intensity) equality between the four incoming beams, as observed at the nulling detector, is achieved by building carefully matched sets of beamsplitters and installing them in the testbed so that each beam experiences an identical number of reflections and transmissions through the beamsplitters and other optics. Finer, quasi-static amplitude adjustments are then made using a fine wire or cross-hair which can be introduced into each beam to reduce its intensity up to 1%. The finest level

Table 2: Selected models for phase plate designs showing the thicknesses of the plates and air gap required, the wavelengths and width of the null, the mean null depth over this band and the wavelengths of operation of the fringe trackers. XCPS refers to the cross-combiner fringe tracker using planet side light, XCSS that using star side light, and XCChopper that for fringe tracking on the chopping beamsplitter.

		mm	mm	mm	micron				Wavelengths (micron)			
Model ID	# of glasses	TZnSe	TZnS	Tair	λ min	λ max	BW %	Mean null depth	FT Nuller	XCPS	XCSS	XC Chopper
B	0	0	0	-0.005					2.35	2.65	2.12	
									3.03			
D	1	-0.21	0	0.518	10	13	26		2.35	2.8	3.7	
									3.2			
H	2	-0.058	0.060	0.002	10.4	10.8	3.8	5E-07	2.7	3.4	2.26	(3.4)
K	2	-0.106	0.083	0.066	10.4	10.8	3.8	5E-08	2.15	3.53	2.44	3.53
									2.86			

of amplitude control is via the beam alignment system. By making small adjustments to the tip/tilt or shear of the beam its amplitude can be finely adjusted in a dynamic fashion under the control of the alignment sensors and actuators system.

Metrology system

The testbed employs a set of 12 metrology gauges to measure all the optical paths on the system. Eight gauges (internal metrology) point towards the beam combiner and four point (external metrology) towards the star. The four external metrology beams can also be used to verify the phase of the planet by closing and opening a pair of shutters. This is useful during formation rotation simulations. Four of the internal gauges measure the beam paths to the chopping beamsplitter, and the other four measure the beam paths to the cross combiner fringe tracking beamsplitter. The metrology laser beams are introduced at dichroic beamsplitters placed between the star and planet source and the beam combiner. The configuration is very similar to that which will be used on the TPF flight interferometer. In that design the external metrology beams travel from the beam combiner spacecraft to the telescope spacecraft. For use with an MMZ beam combiner additional metrology gauges would be needed.

The metrology system utilizes three lasers, one for each set of four gauges, with slightly different wavelengths near 1.55 micron. The two metrology retroreflectors have narrowband dichroic filters placed in front of them allowing them to reflect only one of the laser wavelengths. The beam from each telescope is also marked with its own heterodyne frequency so that each return signal from the metrology retroreflectors can be individually identified.

Testbed optical system

The testbed currently has more than 100 optical components installed. The mirrors all have bare gold coatings which have very high reflectivity for all wavelengths above 700 nanometres. The testbed utilizes many dichroic filters to combine and extract metrology beams and to separate fringe tracking light from science light. Other filters are used to limit the fringe tracking band pass and nulling band pass. Neutral density filters are used to control light intensities coming from the star and planet sources.

The metrology dichroics are composite optics consisting of a dichroic mirror which reflects the long wavelength radiation, backed by a truncated retroreflector which is bonded to the dichroic substrate. This allows precise metrology metering of the optical path referenced to an optic in the beam train thus ensuring no ‘uncommon path’ error, an error which is caused by measuring optical path external to the actual science beam path.

Testbed control system

With so many moving elements the testbed requires a large control system. The control system is based on a dual processor PC which runs Windows software on one processor and RTX on a second processor. RTX is a real-time operating system which is running the instrument software. A set of I/O boards brings in up to 32 analog signals and sends out up to 64 analog signals. An additional digital interface brings in 24 digitized metrology signals. The metrology signals are processed using microprocessors implemented on an FPGA card installed inside the PC. The entire I/O system is a run off a single clock and I/O events occur on a 10kHz cycle. This creates a system in which the timing issues which could be caused by running multiple clocks are minimized and appropriate digital filters in the control software take care of filtering requirements.

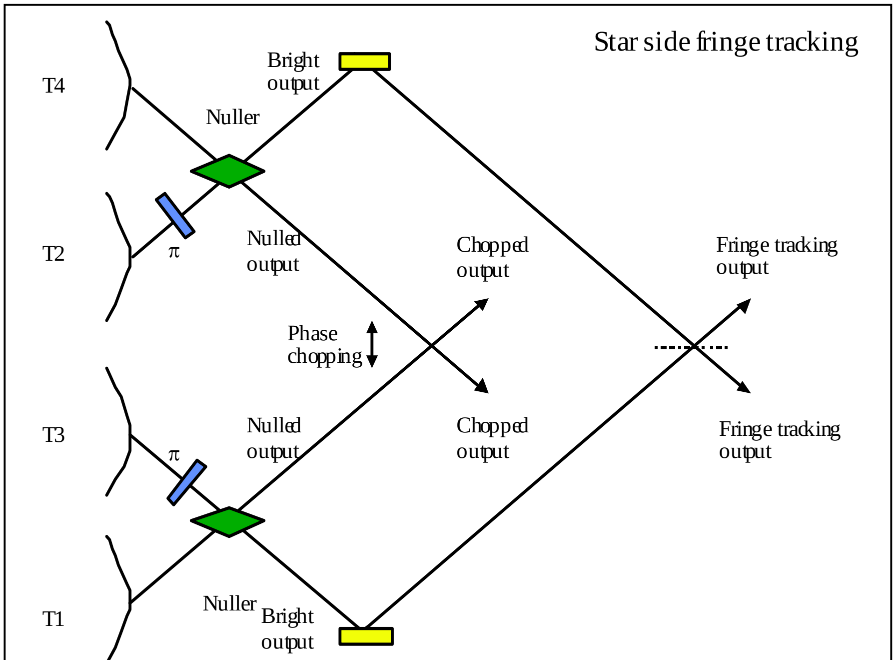

Figure 6: Fringe tracking using light from the star side of the beamsplitter.

The testbed control system has different working states; an initialization state in which the testbed is brought up from a cold start and alignments are made, a calibration state in which the fringe trackers and alignment sensors are set up for optimum nulling, and the run state during which the science data is acquired. During the run state the software acquires data from the science detector, maintains the testbed alignment and the internal OPD determined from the fringe tracker and the metrology system, and changes the phase of the planet so that it appears to rotate around the star. Also during the run state the software logs the data to a hard drive. Since data logging can occur for 5000 seconds and occurs at 10 kHz on many channels, large data files can be collected. These files are subsequently reduced using a software program before the final analysis.

4. FRINGE TRACKING

The fringe tracker can be implemented in a number of ways. Some schemes, such as that implemented on the nulling interferometer [10] recently installed on the Keck telescopes, require a separate beamsplitter and a metrology system to link the fringe tracking beamsplitter to the nulling beamsplitter. For the flight system and therefore for the testbed also we chose a system that allows fringe tracking and nulling to be performed on the same beamsplitter. This scheme can in principle be extended to the cross combiner beamsplitter, so that phase chopping and fringe tracking across the formation can be accomplished on one beamsplitter. A practical difficulty with this scheme is that in the baseline TPF layout the cross combiner beamsplitter is physically moving as a part of the phase chopping process. Since for accurate fringe tracking we need certain phases between the incoming beams on the beamsplitter this design restricts us to the use of certain wavelengths that have the correct phases for each position of the chopping beamsplitter.

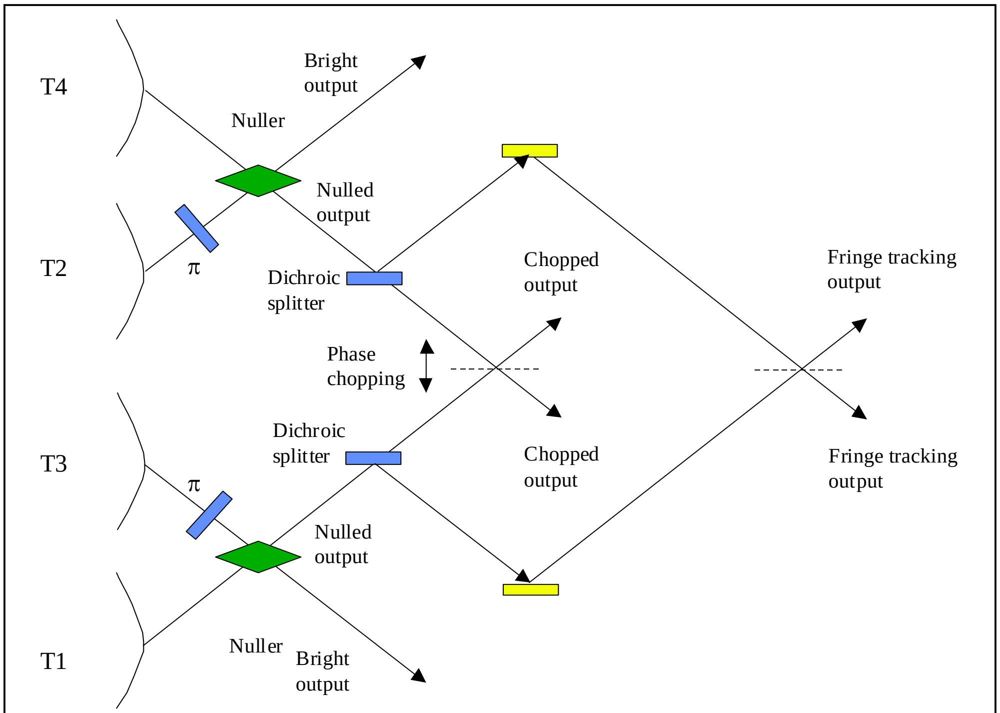

Figure 7: Fringe tracking using light from the planet side of the beamsplitter.

For the purpose of discussion we show three main fringe tracking layouts; figure 3 illustrates nomenclature to be used below. At the nulling beamsplitter the unwanted star light leaves on one side and the planet light leaves on the other. We term the side of the beamsplitter on which the starlight exits the ‘star

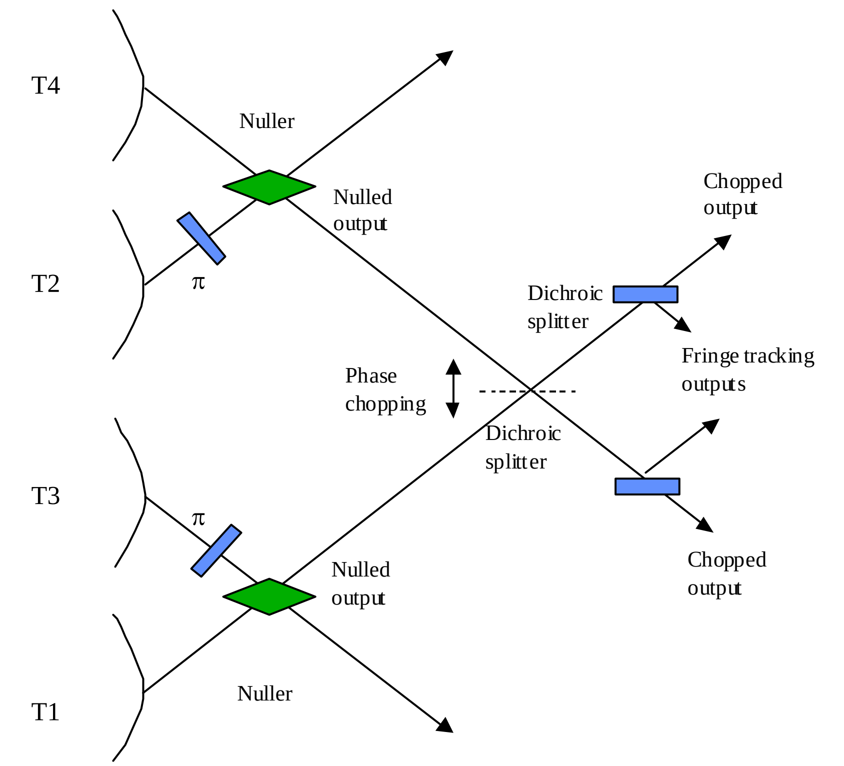

Figure 8: Fringe tracking on the cross-combiner using the phase chopping beamsplitter.

side', and the other side the 'planet side'. We can now build a cross-combiner fringe tracker which operates on light leaving either the star side or the planet side of the nulling beamsplitter. The two geometries are shown in figures 6 and 7. In figure 6 the fringe tracking light exits on the star side, is reflected from a mirror and interferes with light from the other side of the telescope formation on a separate fringe tracking beamsplitter. The laser metrology system is then used to transfer the optical path differences from the fringe tracking beamsplitter to the chopping beamsplitter. Conversely in figure 7, the fringe tracking light that exits on the planet side is reflected from a dichroic mirror which separates it from the science light, before being interfered on the fringe tracking beamsplitter. Again the metrology is used to set the correct OPD at the chopping

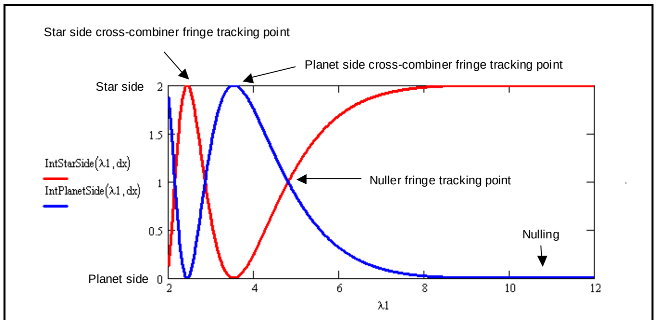

Figure 9: Showing the wavelengths that can be used for fringe tracking on the star side and on the planet side of the nulling beamsplitter.

beamsplitter. Finally figure 8 shows the set up for fringe tracking on the chopping beamsplitter. In this case the fringe tracking light again exits on the planet side of the beamsplitter and it interferes across the formation on the chopping beamsplitter. Since the chopping beamsplitter moves a distance of approximately 2.5 micron, the cross-combiner fringe must undergo a phase change that is a multiple of π during this phase chopping process. Therefore only certain fringe tracking wavelengths would be possible under this scheme.

Fringe tracking at the nulling beamsplitter

The choice of wavelengths for fringe tracking at the nulling beamsplitter is mainly determined by the properties of the phase plates used to create the broadband acrobatic null. Depending on the thickness of the phase plates and their variation of refractive index with wavelengths, certain wavelengths become useful for fringe tracking. A number of different schemes have been studied for use on the testbed. Since the testbed uses monochromatic laser light for nulling it does not in principle require any phase plates. However, a design criterion was that the testbed should be capable of being modified to use thermal light to demonstrate a limited broadband nulling capability. During the testbed program the testbed will be demonstrated in a configuration using no phase plates as well as in configurations with phaseplates. Under the no-phaseplate scheme, the null for the laser light is achieved by adding 5.3 micron of optical path into one beam. This results in a phase shift which is an odd multiple of π/2 at 3.53 micron.

Table 2 shows some phase plate configurations that were considered. Figure 9 illustrates the possible fringe tracking wavelengths that could be used with a pair of the zinc selenide and zinc sulfide phase plates used in a configuration optimized to yield a broadband null over the range 10 to 11 micron.

Fringe tracking at the cross combiner beamsplitter

When fringe tracking across the telescope formation on a separate beamsplitter, we would like to optimize throughput by choosing a wavelength which is constructively interfered at the nulling beamsplitters and therefore at a maximum intensity when it reaches the cross combiner beamsplitter. The wavelengths at which this occurs is again dictated by the phase plates. For fringe tracking on the chopping beamsplitter we would be even more restricted and might

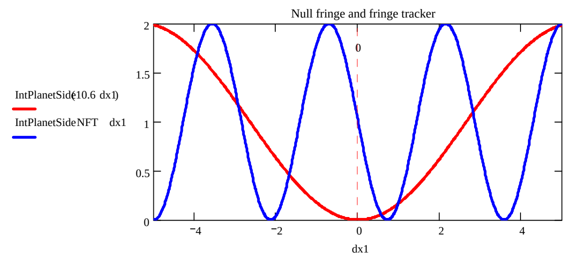

Figure 10: Relative intensity of the null and fringe tracker fringes against optical path difference. The fringe tracker is at the half-way point and the null fringe is at minimum at zero OPD. Here the fringe tracking wavelength is 2.85 μm.

expect to have design the phase plates including the criterion that the desired wavelengths are constructively interfered at the nulling beamsplitter. Figure 10 shows a model of the fringes at the nulling beamsplitter for the nulled light at 10.6 μm and the fringe tracker at 2.85 μm. When fringe tracking on the chopping cross-combiner beamsplitter we would use a wavelength that is both constructively interfered at the nulling beamsplitter and that is also at the half-way point for both chop states on the chopping beamsplitter.

5. TEST PLAN AND OBSERVATION SEQUENCES

The TPF interferometer will typically observe stars for many hours. The telescope formation during that time will perform a full 360° rotation around the line of sight to the star. To reproduce this observation scenario on the testbed we plan to modulate the phase of the planet in such a way that it appears to rotate by 360° around the star. To do this, after the four planet beams are formed a small amount of delay can be added or subtracted to each beam by small positional adjustments of mirrors. After the delay modulation the planet beams are combined with the star beams and passed into the beam combiner. The delay modulation adds a linear ramp of phase to the planet light across the spacecraft formation simulating light coming from a source that is slightly off axis with respect to the star. This OPD ramp can be monitored periodically using the external metrology system.

While a typical observation for TPF might last 10 hours, testbed observations will last a little less than 2 hours. On the testbed we are limited mainly by the time that the infrared detectors will remain cold without requiring a liquid nitrogen fill.

One goal of the testbed is to reproduce some of the acquisition sequences that will have to be performed by the TPF interferometer. These sequences include pointing and shear alignment, finding the fringe, setting up the phase plates and optimizing the null.

CONCLUSION

The testbed is designed to simulate key performance parameters of a TPF interferometer. The sensitivity of the nulling architecture to small fluctuations in amplitude and phase brings a requirement for a high degree of control over the interferometer. This requirement is somewhat mitigated by the use of single mode spatial filters at the output of the beam combiner. However these filters are not yet available and the testbed has been constructed using a very small pinhole as a substitute. Under future plans this pinhole should eventually be replaced by newly developed single mode fibers operating in the near infrared.

To demonstrate the effect of the small amplitude and phase disturbances the testbed has been constructed with numerous systems to perturb both the phase and the alignment of the incoming star and planet beams. Having been perturbed, the beams enter the part of the testbed that simulates the TPF beam combiner. Here the delay lines and other actuators correct the disturbances imposed on the beams. Alignment sensors, metrology gauges and the fringe trackers built into the testbed coupled with an extensive control system allow the stable nulling performance that is required.

With such a complex system there are many possible architectures. Some of the possible fringe tracking architectures have been described. The relationship of these architectures to phase plate systems used for inverting the electric field of one of each pair of incoming beams has been discussed.

The testbed architecture, while not identical to that expected to be used in flight, is nonetheless clearly related to the flight system. Results from the testbed calibration, operating methods and control systems should be scaleable and transferable to a flight system. Thus the testbed should demonstrate the feasibility of a complex nulling beam combiner. In the future, significant work will have to be done to convert the design into an effective space system. Such designs are already being studied at JPL and a compact flight beam combiner layout exists today.

The testbed has only recently been completed, but nulling results are expected soon and the program calls for detection of planets with a contrast ratio of one million to one against the star in the next year. Combined with numerous other testbeds both at JPL and elsewhere, the Planet Detection Testbed results should help lead to the development of a robust nulling space interferometer design.

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