A System Level Testbed for a Mid-infrared Beam Combiner for Terrestrial Planet Finder

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Abstract— Direct optical detection of earth-like planets orbiting nearby stars is the goal of the Terrestrial Planet Finder project. One instrument which may have the capability to detect such small, faint objects in proximity to the parent star is the infra-red nulling interferometer. A four input beam combiner is being built to test aspects of the beam combination and planet detection problem. This paper describes the design developed for a ground testbed. The testbed is capable of simulating the detection process for a faint planet orbiting a nearby star. The testbed includes a star and planet source with a contrast ratio of 10^{-6}. In the beam combiner, two infrared nulling interferometers are linked to null the starlight and phase chop the light from the planet, allowing its detection in the presence of the thermal radiation background.

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1. INTRODUCTION

Direct optical detection of earth-like planets orbiting nearby stars is the goal of the Terrestrial Planet Finder project. Such planets are located at small (~0.1 arc sec) angles to star and might be detectable by either thermal emitted radiation or by the directly reflected light from the star. The relative intensity of the planet radiation compared to the star ranges from $\sim 10^{-9}$ (at visible wavelengths) to $\sim 10^{-6}$ (at thermal infrared wavelengths). These two factors create a challenging detection problem; an important goal of the TPF project is the development of instruments capable of meeting this challenge.

One possible planet-finding instrument is based on a nulling infrared interferometer. The nulling interferometer enables rejection of the bright light from the star and detection of the much fainter planet light. Using a pair of telescopes working as a stellar interferometer, the rejection of the starlight is achieved by placing a null fringe, that is an achromatically destructive fringe, over the star. At the small angle that the planet makes to the star, the fringe is constructive, allowing light to reach the detector. Nulling interferometers are being developed at the Jet Propulsion Laboratory (JPL) and elsewhere. To achieve the necessary performance, these interferometers will be flown in space; the accompanying spacecraft array designs include various possible configurations[1] of telescopes, either free-flying in formation or attached to a boom. Designs using four telescopes in a linear array, and designs using six telescopes in a two-dimensional array are being studied. The light from the telescopes is interfered in a beam combiner, the complexity of which varies considerably between telescope array designs.

For detection of weak signals in the mid-infrared, some form of chopping is usually necessary to enable modulation of the signal against the thermal background. TPF beamcombiner designs generally include phase-chopping, enabling modulation of the planet against the local zodiacal and exo-zodiacal light and the self-emission of the telescopes. Phase chopping is accomplished between (at a minimum) two pairs of nulling telescopes, so the simplest beam combiner must combine beams from four separate telescopes. A beam combiner testbed for the Terrestrial Planet Finder (TPF) is being built at JPL with the aim of testing many aspects of beam combination and particularly the detection of the planet signal by phase chopping. Called the TPF Planet Detection Testbed (PDT), it incorporates features of a real TPF-like observation. It includes a star and planet source with variable planet to star contrast ratio (the expected contrast ratio for an earthlike planet is about $3\ 10^{-7}$). This four-beam source can be correctly phased to simulate a planet orbiting at variable radii from a parent star. The source feeds a four-beam combiner via a set of eight optical delay lines which can simulate variable positions of the telescopes in space both across and along the line of sight to the star. By controlling the phasing of the planet light in the four beams, simulated rotation of the telescope formation can be accomplished, replicating a complete TPF observation sequence. The beams are nulled in pairs in modified Mach Zehnder beam combiners, attenuating the

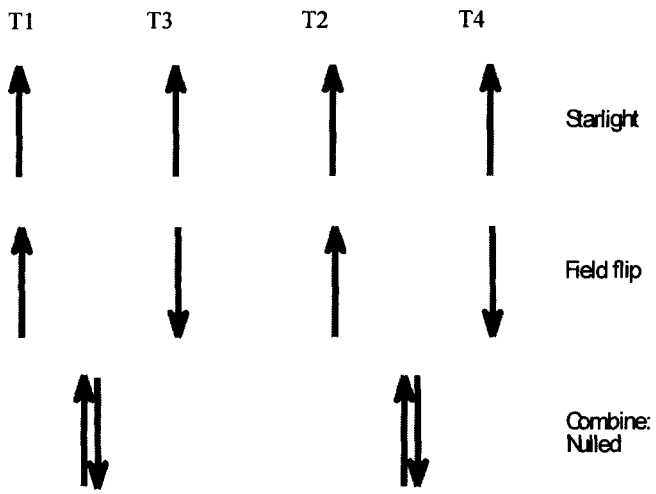

Figure 1: Phasors for starlight entering the beam combiner.

light from the star by $\sim 10^{-5}$, and then phase chopped to reveal the planet signal after a period of observation which could be many hours in duration.

Two separate metrology systems have different functions. One metrology system monitors the star and planet source to maintain correct phasing and is independent of the main metrology system. The second, the main system, represents the internal metrology required for the TPF beam combiner and works in combination with the fringe trackers. The interferometer system must fringe track the star on three baselines. Two baselines allow phasing of the nullers and the third baseline allows phasing across the formation. Internal metrology is injected near each telescope and measures the path differences to six separate beamsplitters. One set of metrology paths effectively measures the fringe tracker position, and the second set is used to transfer that measurement to the nullers and cross-combiner. This system allows the nullers to null continuously and the phase chopping to modulate the planet, while the fringe trackers independently sweep the fringe. This paper discusses the detailed layout of the testbed and compares its design and performance to a possible TPF beam combiner designed for planet detection in space.

2. Beamcombiner Design

Nulling Beamcombiner

A dual Bracewell interferometer consists of two pairs of telescopes arrayed along a line. For TPF, these telescopes might be free-floating spacecraft accompanied by a fifth spacecraft carrying the beamcombiner, or it might be a single large structure carrying all the telescopes and ancillary equipment. In either case, the beam combiner will null pairs of beams and then cross-combine them in a phase chopping stage. Numbering the telescopes from 1 to 4 along the array, then one way to combine the beams is to null in pairs from telescopes 1&3 and from telescopes 2&4. The operation of the nulling and phase chopping beamcombiner is illustrated in Figure 1 which shows the relationships of the incoming radiation as phasors. At the telescopes, the light from the star arrives in phase, while the light from the planet has a phase gradient across the telescope array. Before entry to each nuller, an achromatic phase shift of π is applied to one input beam; for the starlight this causes destructive interference at the first beamcombiner stage. For the planet light, the phase gradient will ideally create an initial phase shift of π between the input beams, so that the extra phase shift causes constructive interference at the beamcombiner.

Phase chopping

Referring to Figure 2, the constructively combined output beams from the two nullers are cross-combined in the phase chopping stage. Because of the phase gradient across the array the planet light from the two nullers has a $\pi/2$ phase difference. By adding or subtracting a further $\pi/2$ phase shift, the planet light can then be constructively interfered or

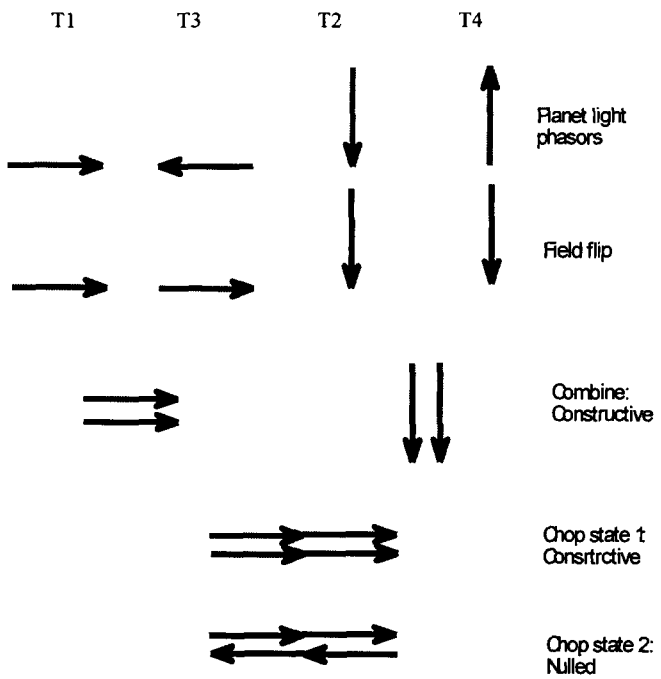

Figure 2: Phasors for planet light entering the beam combiner and phase chopper.

destructively interfered, thus causing a modulation of the planet signal. Other thermal background radiation from the sky or the instrument itself can also pass through the beam combiner, but if it is isotropic, it will produce the same signal for either phase shift of $\pm\pi/2$, so that it can be subtracted from the signal.

Fringe tracking

A G0 star resembles a blackbody radiator with a temperature around 6000K. At a wavelength of 10 μm, the thermal signal from a planet at a temperature of 300K is near its peak,

while the radiation from the star increases at shorter wavelengths, peaking near the visible. So, while rejected stellar photons at 10 μm could be used for fringe tracking, shorter wavelength photons are more numerous and offer improved phase resolution. For the Keck telescope nullers[2], an atmospheric absorption window at 2.4 μm creates a favorable wavelength at which to fringe track. In space, other wavelengths could be chosen. At 2.2 μm with a 200 nm bandwidth, 5% throughput and 3.5m telescope apertures, a fringe tracking accuracy of about 0.3 nm is possible (neglecting detector and other noise sources) with a bandwidth of about 100 Hz. Using the usual rule of thumb, the control bandwidth will be of order 10 Hz. Each nuller requires a fringe tracker, and a further fringe tracker is needed across the formation to phase the cross-combiner.

Mechanical vibrations of the spacecraft or of the ground test system will produce rapid disturbances of the OPD and beam tilt and these must be tracked using high speed laser metrology. On the MAM testbed at JPL, OPD measurements show fluctuations of up to 100 nm at about 100 Hz. To control these vibrations would require a control loop running a high speed actuated mirror to correct the OPD at

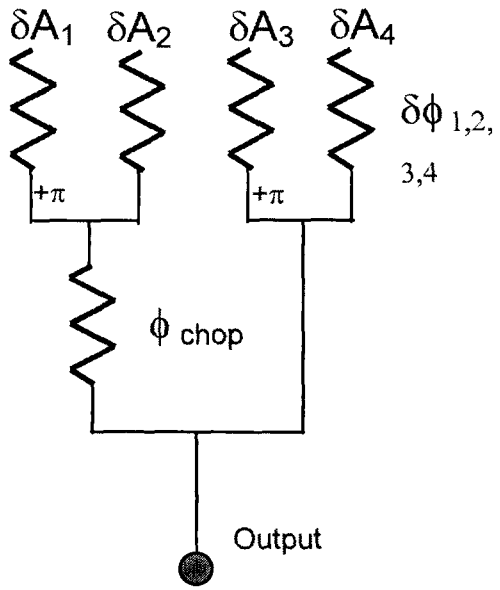

Figure 3: Schematic of a numerical model for phase and amplitude errors in the beam combiner.

about 1 kHz, and an OPD error signal at about 10 kHz. Other means such as improved vibration isolation and damping might be employed to reduce these requirements, and of course in space the vibration environment may be quite different.

Figure 4: Layout of the cross-combiner.

Beamcombiner performance model

To study the effect of small amplitude and phase disturbances on the null and on the planet detectability, a numerical model of the beamcombiner was created using Mathcad. Figure 3 shows a system schematic. Four input beams have variable electric field amplitudes and phases. One of each pair of beams is field-inverted (π phase shift applied), then the beams are nulled and cross-combined with a $\pi/2$ phase chop. The model was implemented for a single wavelength. Star and planet electric fields were modeled with the desired initial phases and amplitude ratios and applied to the inputs. By varying the planet phases sinusoidally, rotation of the spacecraft formation around the line of sight to the star can be simulated. Small, random amplitude and phase disturbances were applied to the electric fields, and these disturbances had power spectra equivalent to 1/f noise.

Mathematical models have also been developed[3] and the results could be compared with this numerical model. The results of both models show that while first order errors in amplitude (δA_i) or phase ($\delta\phi_i$) are suppressed by the phase chopping, second order terms which appear across the cross-combiner such as $\delta A_1 \delta\phi_2$ (amplitude and phase second-order term from telescope 1 and telescope 2), are not suppressed. The implication of this is that the stability of the null has to be very high, and roughly equivalent to the relative intensity of the planet being detected. To achieve this stability would require control of amplitude to ~0.1% and of phase to ~ 1 nm on each input beam.

3. Testbed Design

Modified Mach Zehnder Nuller

The Modified Mach Zehnder (MMZ) Nuller has been described elsewhere[4]. It consists of an arrangement of two beamsplitters and three mirrors which creates four output beams from two input beams. A field-inversion device[5] (periscope or phase plate) preceding the nuller inverts the electric field of one input beam. Referring to Figure 4, each input beam is split into two at the first beamsplitter and combined with the other input beam at the second beamsplitter. One side of this second beamsplitter produces the two nulled output beams, the other side produces the constructively interfered beams. The rejected stellar photons exit the nuller along that path. The most important feature of the Mach Zehnder nuller is that each input beam is treated identically in terms of reflections and transmissions on the optical surfaces on its way to the nulled output. This yields the potential for deep, broadband, polarization insensitive nulling.

Phase chopping cross-combiner

Figure 5 shows the layout of the cross-combiner. Two MMZ nullers produce two output beams each. These are combined on a pair of beamsplitters (which may be independent). These beamsplitters may be actuated so as to achieve phase

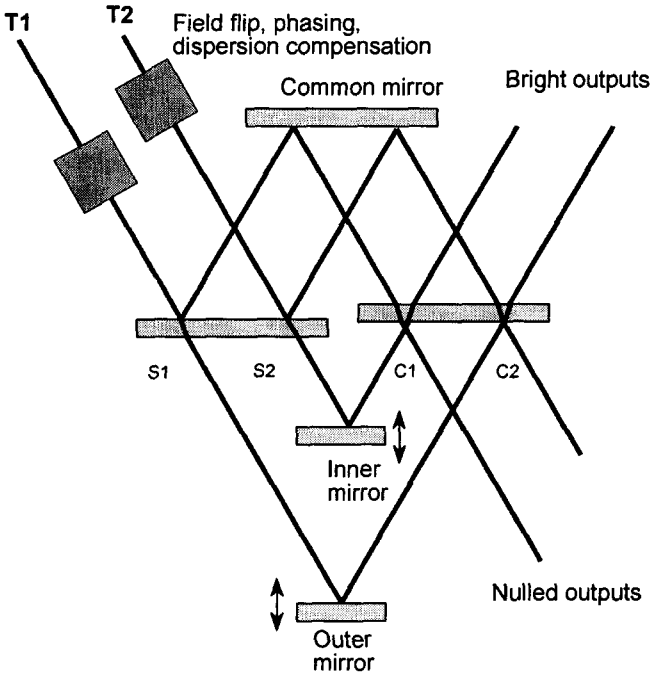

Figure 4: Layout of the modified Mach-Zehnder nuller.

chopping. The beamsplitters are preceded by a compensator plate in one beam pair. Each side of the last pair of beamsplitters produces an output signal, so two sets of signals, in-phase and anti-phase are available for detection.

Star and Planet Source

To achieve deep nulls from a broadband artificial star source requires that two identical beams are provided to the nuller. This can be achieved using an MMZ arrangement as a source. Elsewhere[6], a retro-reflecting MMZ source is described, while here a sequential source is described.

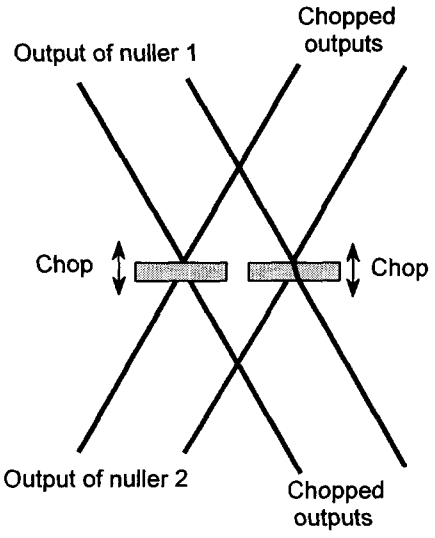

Figure 5: Operation of the phase chopping cross-combiner.

Figure 6 shows the layout. A single beam is fed into one input of the MMZ and four output beams are produced. Two

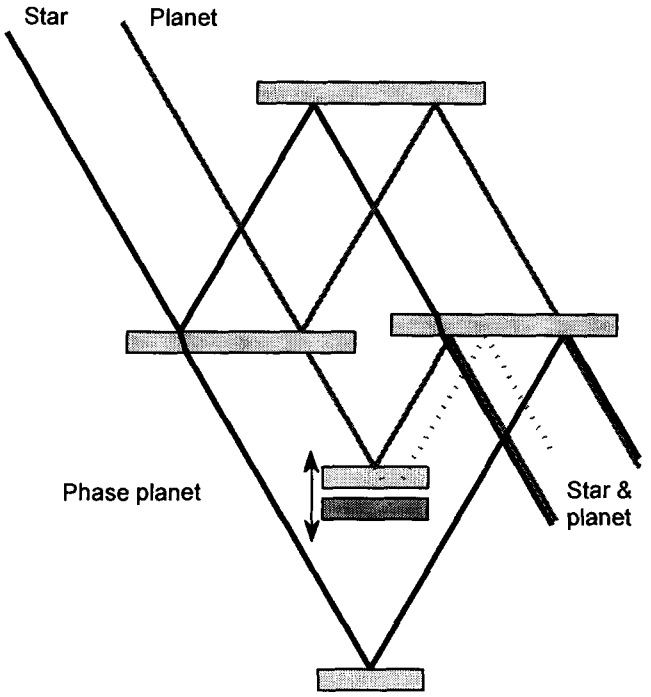

Figure 6: Forming a two-output star and planet source.

of these beams are symmetrical, and two are asymmetric in terms of optical paths. The lower right output paths are symmetric and can be used for the star source. To add a planet, a second, weaker beam is fed into the second MMZ input. It combines with the first beam at the outputs, and also is symmetric. Both the star and the planet beams can be phased by moving one of the two smaller mirrors to produce the correct phase profile at the output. In the case of the planet beam a phase difference at the output of π can be easily introduced, with a negligibly small beam shear. For the planet beam this phase difference is chromatic, which mimics the effect across the telescope array. The overall throughput of this source is 0.5, half the useful source light exiting the system at the second beamsplitter.

To make a four-beam star and planet source, a pair of star beams and a pair of planet beams are produced, and then combined in two more MMZ arrangements. The full layout is shown in Figure 7. The overall throughput is 0.25, with each output beam having one sixteenth of the input beam power.

Testbed Throughput

For planet light, measured on a single side of the cross-combiner beamsplitter, the testbed has a maximum possible throughput of one sixteenth the initial input beam power.

Wavelengths

The testbed was designed to work with both broadband and narrowband sources. The systems baselined for narrowband operation are:

A CO_2 laser operating at 10.6 μm for nulling.

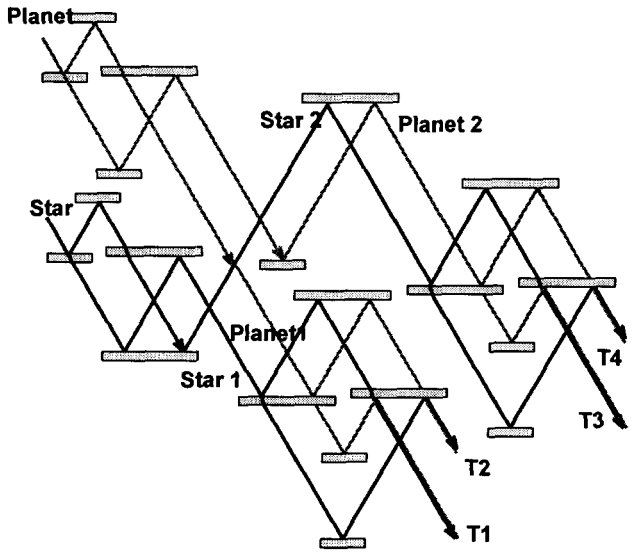

Figure 7: Forming a four-output star and planet source.

A HeNe laser operating at 3.4 μm for fringe tracking.
For broadband operation, a thermal source operating at about 1200K was included. In this case, fringe tracking wavelengths could be chosen to suit the available detectors and beamsplitter properties.

Electric field inversion

The testbed is designed to use either periscopes or phase plates to invert the electric field.

4. Fringe Tracking Scheme

Fringe tracker

One of the most difficult design challenges is the fringe tracking scheme. Both nullers and the cross-combiner need fringe tracking, and a key desire is to hold the null stable so as not to lose any planet photons (estimated to arrive at the rate of about 1/s). These photons can be picked up as long as the output of both sides of the cross-combiner beamsplitter are sent to a detector. For this kind of beam combiner, the choices are either to use the same beamsplitter to fringe track the shorter wavelength or to use a separate beamsplitter. The first method will be briefly discussed, while the latter method is discussed in detail in the following sections..

Method 1: In the first case, since the fringe tracking light would be constructively or destructively interfered in the same way as the 10 μm light, some phase dispersion must be introduced between the 10 μm light and the fringe tracking light. This can be achieved by introducing a small thickness of glass in one input beam. If phase plates are being used for field inversion, this can be readily achieved. For example, sets of ZnSe and ZnS or of AgCl and NaCl phaseplates can optimized to produce a broad electric field inversion over the range 7 to 12 μm (see Figure 8). At shorter wavelengths, the fringe phase at the beamsplitter varies from π and at ~2.2 μm, the phase is about $\pi/2$ allowing detection of a signal on either side of the beamsplitter. The use of this kind of fringe tracking has been suggested[7]. A variation of this scheme is discussed below under "Alternative beam combination methods".

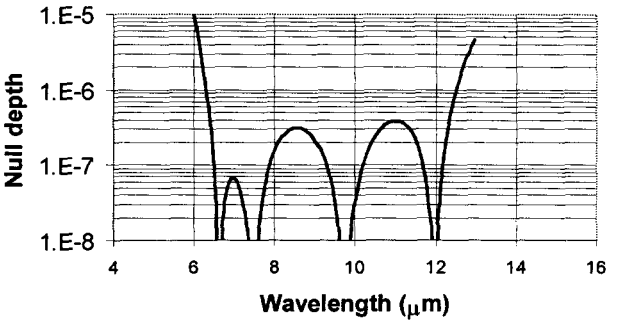

Figure 8: Model of null depth across a broad band using ZnSe/ZnS phaseplate pairs.

The phasing of the cross-combiner is not straightforward with this scheme, mainly because of the phase chopping. The cross-combiner beamsplitter is moving (either in reality or effectively by motion of delay lines placed ahead of the nullers) and the motion is of order 5 μm, about two waves of the fringe tracking wavelength. Assuming the fringe created here is symmetrically located at the center of the nulled fringe it might be possible to infer the cross-combiner OPD from the fringe detector measurements at the two chop states. The fringe tracking wavelength used at this second location could be another wavelength, 1.8 μm for example. Alternatively, a second fringe tracking beamsplitter would have to be used in a technique similar to that discussed in Case 2.

Method 2: In the second case, that of fringe tracking on a second beamsplitter, laser metrology can be used to transfer the OPD measurements from the 2.4 μm beamsplitters to the 10 μm beamsplitters (an example is the fringe tracking system used on Keck[8]). For the Planet Detection Testbed, conservation of all the planet photons is not required, so only one output would be used from each nuller. The other output beamsplitter could be used for fringe tracking. Figure 9 shows the scheme in more detail. The outer mirror is used to phase the 3.4 μm light on the beamsplitter. A detector located on the bright output side observes the fringe. The fringe is swept using a voltage ramp on a piezoelectric stage attached to the mirror, and the detector samples the fringe using the four bin algorithm to determine the fringe phase.

To phase the cross-combiner, the outer mirror is used to phase the 3.4 μm light so that it is transmitted to the null side of the beamsplitter, passing through the cross-combiner beamsplitter and interfering with the fringe tracking light from the other nuller. The fringe sweep is now made by

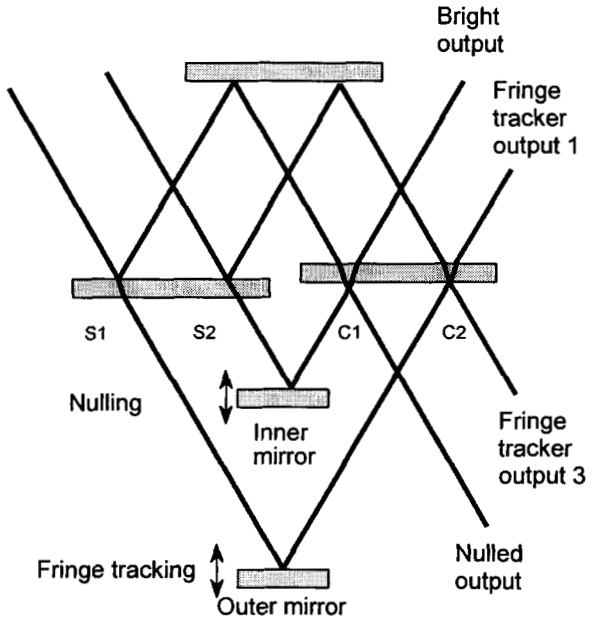

Figure 9: Method of fringe tracking on a separate beamsplitter.

moving the cross-combiner beamsplitter. To summarize, the sequence of events is to sweep the nuller fringe tracking mirrors, determining the fringe phase, then set the mirrors to send all the light to the cross-combiner, and sweep the cross-combiner beamsplitter to determine the phase across the formation. The metrology system (detailed next) then transfers the knowledge of the OPD to the nulling beamsplitters. This fringe tracking method will work for both field-inversion methods.

OPD Metrology

In a TPF-like geometry four telescopes would collect starlight and transmit it to the beamcombiner. Metrology is necessary to monitor the paths to the nulling and cross-combining beamsplitters.

Phasing the nullers—Method 1: The fringe tracker determines the position of the fringe at low bandwidth and the metrology system has the function of maintaining the fringe location in the presence of vibrations. A metrology beam from each telescope is retroreflected back to the launcher from a corner cube located after the nulling beamsplitter. The desired mean distance to the beamsplitter is derived from the fringe tracker, while the metrology system responds to higher frequency perturbations of the OPD.

Phasing the nullers—Method 2: The fringe tracker determines the position of the fringe at low bandwidth and the metrology system has the two functions of transferring the fringe location from the fringe tracking beamsplitter to the nulling beamsplitter (low bandwidth) and of maintaining it in the presence of vibrations (high bandwidth). Figure 10

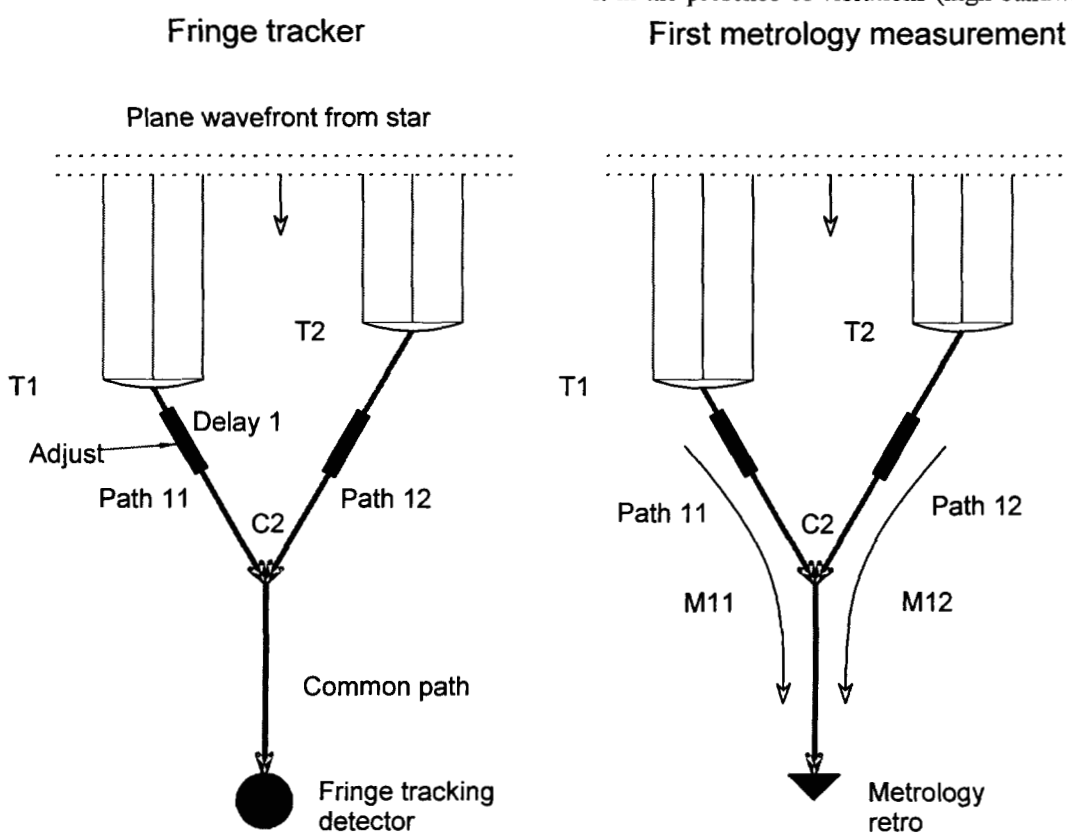

Figure 10: Operation of the fringe tracker and making a metrology measurement of OPD.

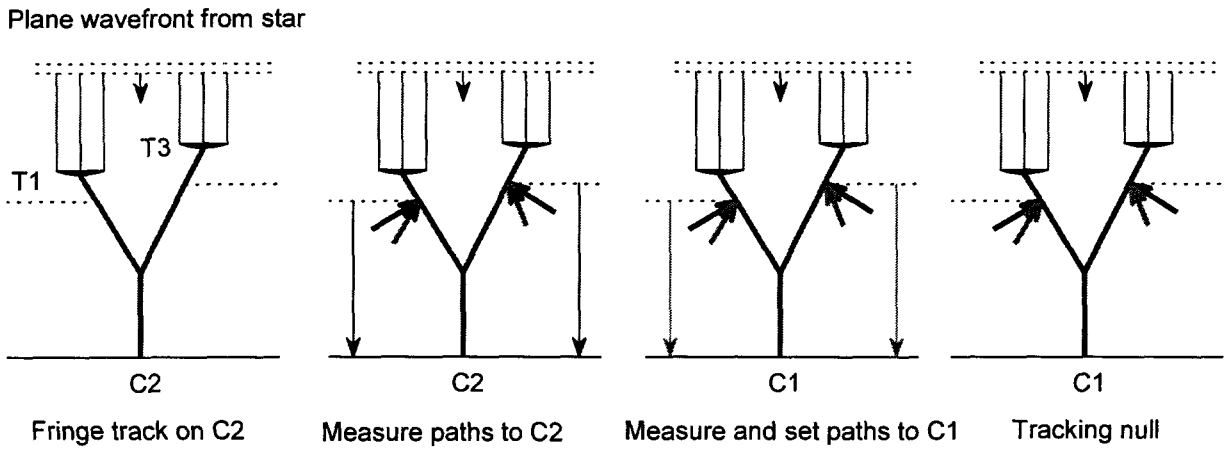

Figure 11: Summary of the fringe tracking scheme enabling transfer of OPD measured using metrology from the fringe tracking beamsplitters to the nulling beamsplitters.

shows the basis of the scheme. At the left of the figure, the telescopes sit at arbitrary positions in space, collecting light from the star. The fringe tracking beamsplitter is used to locate the center of the fringe using a delay line. Two metrology beams are injected near the telescopes to measure the distances from telescopes 1 and 2 to the fringe tracking beamsplitter. If properly aligned, the metrology beams combine at the beamsplitter and then follow a common path so that they can be reflected back to the launchers from a common retroreflector. The two beams have the same wavelength (1550 nm), but different frequency shifts so that they can be distinguished at their respective detectors. They measure metrology paths M11 and M12 to position C2 on the beamsplitter (as shown in Figure 9).

To set up the OPD to the nullers a second set of metrology beams is injected by the same metrology launcher. This set has a wavelength of 1570 nm and will be reflected from another retroreflector on the nulling beam path. (The two retroreflectors have interference filters placed in front of them to separate the return signals.) These metrology gauges measure paths M21 and M22 (not shown) to position C1 on the beamsplitter. To achieve a null on the nulling beamsplitter it is necessary to make the path difference M11-M12 equal to the path difference M21-M22. Moving the inner mirror on the nulling path varies the nuller OPD to set the correct distance. (There will in general be some static offsets which will also need to be accounted for, depending on the presence of phase plates, and any beamsplitter thickness differences. These offsets can be determined by calibrations.)

Figure 11 shows a summary of the fringe tracking scheme. One, the fringe tracking beamsplitter is used to locate the center of the fringe. Two, metrology beams (1550 nm wavelength, with two different frequency shifts) measure the distances from telescopes 1 and 2 to the fringe tracking beamsplitter. Three, a second set of metrology beams (1570 nm wavelength, with the same different frequency shifts) measure the distances from telescopes 1 and 2 to the nulling beamsplitter. Four, the phase of the nuller is adjusted so that the two sets of metrology gauges have the same differential OPD. Having also applied any fixed offsets, the nulling beamsplitter is exactly at null.

In reality, the fringe tracking OPD is always changing; it executes a full sweep of the fringe every second, so some calculations have to be made to determine the correct readings on the second set of gauges.

Phasing the cross-combiners—Method 2: A similar scheme phases the fringe on the cross-combiner. To make this measurement, the fringe tracking mirror is moved to a fixed position to constructively interfere the fringe tracking light at the nulled output side of the beamsplitter. With the outer mirror transferring all the fringe tracking light to the cross-combiner beamsplitter, and the other fringe tracker for the other nuller set up the same way, the center of the fringe across the array can be located. The same metrology beams used previously for fringe tracking the nullers measure the distances from telescopes on the two sides of the formation to the cross-combiner beamsplitter. Again, the second set of metrology beams (1570 nm wavelength) measures the distances across the array to the phase chopping beamsplitter. Then the phase of the chopper is adjusted so that its mean location is where the two sets of metrology gauges have the same differential OPD. This fringe tracking scheme is accomplished using just two metrology lasers, and four frequency shifts (one for each telescope). Fringe tracking across the formation is interleaved with fringe tracking each nuller pair. The metrology beams in the fringe tracking paths are required to measure the OPDs at fairly low bandwidth to account for drift rates of the formation and thermal expansions. The metrology beams in the nulling and chopping paths are required to measure the OPDs over a

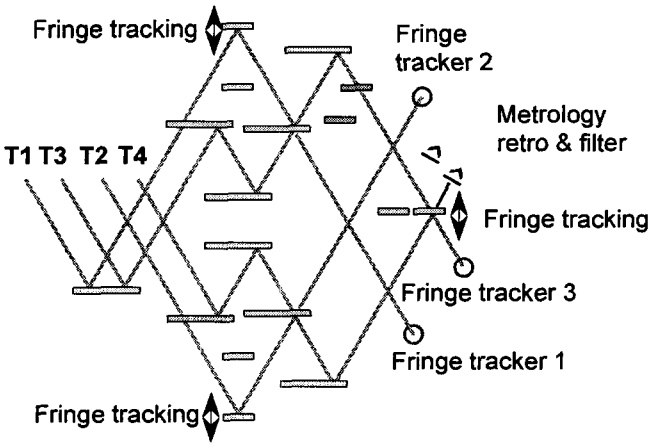

Figure 12: Optical paths for fringe tracking. The metrology beams follow similar paths to the retroreflector.

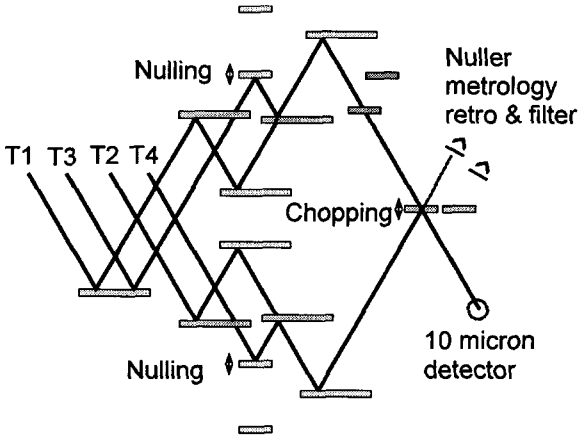

Figure 13: Optical paths for nulling and phase chopping. The metrology beams follow similar paths to the retroreflector.

broad frequency range to account for the same drifts, but also for mechanical vibrations.

The optical paths for fringe tracking and nulling/cross-combining are respectively shown in Figures 12 and 13. The metrology beams from each telescope are retroreflected back to the launchers from corner cubes located after the cross-combiner beamsplitters. The nulling and fringe tracking retroreflectors are discriminated by interference filters which allow only one of the metrology laser beams to pass through.

Metrology on the star and planet source

The star source requires a similar metrology setup (schematically shown in Figure 14). An additional laser operating at 1590 nm is used to inject light back through the star and planet source to a retroreflector placed behind a dichroic on the star path at a point before the star beam starts to divide. This allows continuous high speed metrology of the star source, important for stable nulling. Another retro in the planet beam performs the same function, but only intermittently, since continuous fine control of the planet signal is not required. The planet can still be detected even if its phase drifts many degrees.

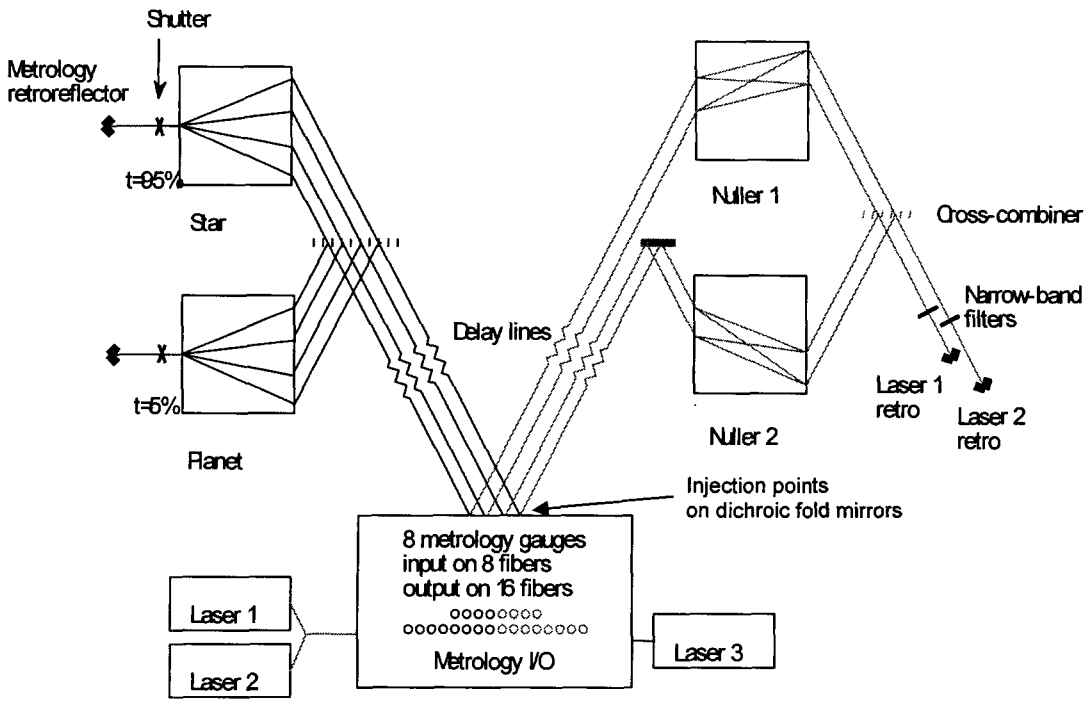

Figure 14: Schematic of metrology system showing the 12 metrology beams injected on dichroic fold mirrors. The system allows high speed path control across the testbed.

To summarize, the following phases need to be controlled or measured using OPD metrology:

1/ Phasing of the star beams, near continuously, at high bandwidth.
2/ Phasing of the planet beams, intermittently, at low bandwidth.
3/ Phasing of the nullers continuously, at high bandwidth.
4/ Phasing of the cross-combiner continuously, at high bandwidth.

ALTERNATIVE FRINGE TRACKER

A variation on method 1 which fringe tracks on the same beamsplitter as the null is to take the output beam on the "bright" side of the nulling beamsplitter. Between 2 and 3 microns there are several waves of phase change introduced by the phase plates. The output beam can be dispersed on a camera and the position of the fringes will give the OPD of the beam. Figure 15 shows the fringes formed on one side of the beamsplitter by ZnSe and ZnS pairs of phaseplates. On that side of the beamsplitter bright fringes form at wavelengths 2, 2.2, and 2.6 μm. On the other side of the beamsplitter bright fringes form at 2.1, 2.4 and 3 μm. This light could in principle be used in the cross-combiner to phase the chopping system, thus achieving high efficiency in the fringe tracking system.

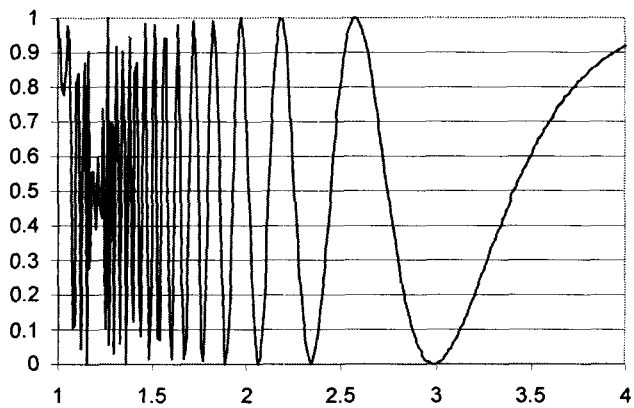

Figure 15: Light intensity as a function of wavelength at the "bright" output side of the beamsplitter.

5. DISCUSSION

While the four-telescope formation is the simplest phase-chopping set, when used with the MMZ nullers, the beam combiner complexity is high. An additional level of complexity would be added when it is realized that to extend to the full TPF wavelength range requirement of 7 to 17 micron, another set of nullers would need to be added because of fabrication limitations of beamsplitter and anti-reflective coatings. Additional fringe tracking should not be needed though, since metrology systems can be used to achieve the null on the second combiner.

To achieve the highest efficiency with the planet photons, both outputs of the MMZ need to be used for nulling. To achieve this, a second beamsplitter needs to be added forming a separate fringe-tracking path. One of many possible layouts is shown in Figure 16. This system uses dichroics instead of mirrors to form the MMZ nuller inner, outer and common mirrors. It also requires one additional metrology path.

Another difficulty with the MMZ nuller concepts described above is the large number of beamsplitters encountered by the metrology beam. Since it is used in double pass, the beam is split 6 times. Taking into account sources of stray light in the metrology beam launcher which interfere with the measurement, the low return efficiency may limit the accuracy of the laser metrology to a few nm. This limit might be avoided by amplifying the metrology laser signal using a single mode fiber amplifier after the cross-combiner before returning it.

Moving away from the MMZ, possible single beamsplitter nullers may be possible. One type of single beamsplitter is a mirror with the substrate is patterned with a reflector, leaving gaps between. This beamsplitter does have the disadvantage that it produces two nulled output beams, so two cross-combiner beamsplitters and metrology systems would still be needed. Another possibility is to try to develop a much more symmetric conventional sandwich-type beamsplitter. Such a beamsplitter most probably would be used with some additional phase and amplitude correction devices.

6. SUMMARY

Possible implementations of the beam combiner for a dual Bracewell nulling stellar interferometer based on the modified Mach Zehnder nuller have been studied. A few methods for fringe tracking the nullers and the cross-combiner are possible, and a system based on four bin type fringe trackers has been described in some detail. These beamcombiner systems will need to utilize high speed laser metrology to control rapid fluctuations in OPD caused by environmental sources. More development is needed to reduce or mitigate the high system level complexity of these designs.

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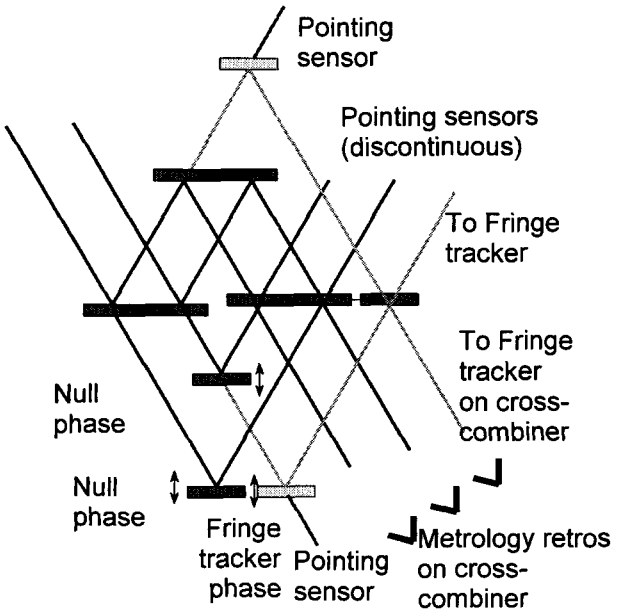

Figure 16: Part of the fringe tracking scheme for two-output nulling on the MMZ nuller

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