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# Exoplanet Interferometry Technology

## Milestone #4 Whitepaper

### Planet Detection Demonstration

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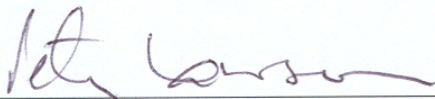
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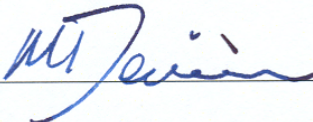
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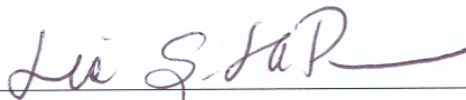
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# Exoplanet Interferometry Technology Milestone #4 Whitepaper

## Planet Detection Demonstration

### 1. Objective

In support of technology development for the Exoplanet Exploration Program, this white paper explains the purpose of Interferometry Technology Milestone #4, specifies the methodology for computing the milestone metric, and establishes the success criteria against which the metric will be evaluated.

### 2. Introduction

The intent of this technology milestone was established in the TPF-I Technology Plan (JPL Pub. 05-5, June 2005). The completion of this milestone is to be documented by the Program, reviewed by the EIRB, and approved by NASA HQ. Prior milestones are listed and described in Appendix 13. The milestone described here addresses planet detection.

#### Milestone #4: Planet Detection

Using the Planet Detection Testbed, demonstrate detection of a simulated planet signal at a star/planet contrast ratio of  $\geq 10^6$ . This demonstrates that several opto-mechanical control loops can be integrated and operated in a testbed configuration that includes the principal functional blocks of the flight instrument. These functional blocks include fringe tracking, pathlength metrology, beam shear and pointing control, 4-beam combination and phase chopping. Success shows that an instrument can be operated with a stability representative of flight requirements and within a factor of 20 of the contrast that permits the suppression of the background noise from local and exo-zodiacal dust clouds. *Milestone TRL 4.*

For a space-based telescope array operating in the mid-infrared, suppression of the starlight by a factor of  $10^5$  is sufficient to reduce the stellar photon rate to below the background level set by local zodiacal emission. At a  $10\ \mu\text{m}$  wavelength the exo-earth flux is  $10^{-7}$  of the stellar flux,  $\sim 100$  times fainter still, so that further suppression is necessary to achieve a planet detection. This additional suppression is realized through a combination of phase chopping modulation of the planet signal, the rotation of the telescope array and the use of a spectral fitting technique that isolates the planet signal.

### 3. Milestone 4 Objectives

The Planet Detection Testbed (PDT) is a breadboard system intended to demonstrate techniques that will be required for detection of exoplanets using a mid-infrared telescope array. As a breadboard system operating in a normal room environment it differs from a flight demonstration system in two principal ways. One, the layout of the system is not the same as that envisioned for a flight system; it is designed to be flexible, facilitating additions and changes so that different approaches can be tried. It does however embody the controls and sensors necessary for operation in space. Two, flux levels in the testbed are much higher than for flight because the warm environment provides a much larger background than would be observed in space. Therefore sources and sensors of thermal radiation are of different types than would be used in space. These differences are discussed in more detail in the next section.

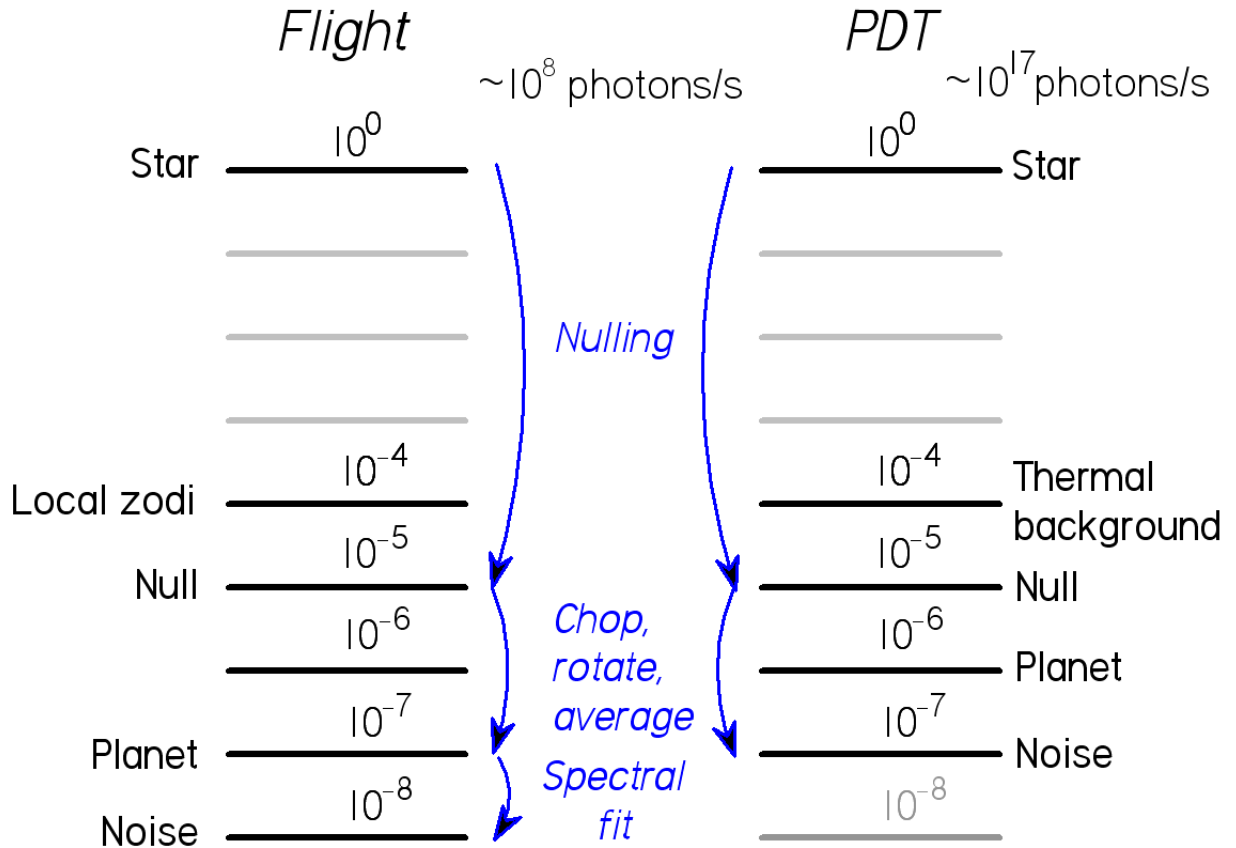


Figure 1: Photon rates for the planet detection process for flight and PDT.

Key exoplanet detection techniques can be tested and demonstrated in the PDT. ('The PDT' is often referred to in this document simply as 'PDT'). To reach the flight goal of detection of a planet  $10^7$  times fainter than the parent star, a series of steps (illustrated on the left of Figure1) must be taken:

1. The star's apparent intensity is reduced relative to the planet by a factor of 100,000. This is done by interferometric nulling.
2. The interferometer array is rotated around the line of sight to the star to search the whole region around the star for a characteristic planet signature. In PDT this is done by controlling the optical path relationships between the planet source beams, simulating the phase changes caused by rotation of the telescope array around the line of sight to the star. During this rotation, stable nulls need to be maintained; PDT has systems and control loops analogous to those needed for flight in order to control the instability noise and maintain deep nulls.
3. The planet signal is modulated against the bright radiation background. This is done using phase chopping. The combination of rotation, phase chopping and averaging over time reduces the noise level by a factor of 100 to  $10^{-7}$  of the stellar intensity.
4. The technique of spectral fitting uses correlations between null fluctuations across the spectral band to reduce the instability noise. This yields a further factor of 10 in reduction of the noise level.

Thus, the combination of these four techniques yields the necessary performance. In the current milestone the objective is to demonstrate the first three parts of this process; the stable nulling, the array (or planet) rotation and the phase chopping. The fourth part, spectral fitting, requires a broadband source and spectrometer and will be left to a future milestone; the necessary systems are being prepared this year. In this milestone, illustrated on the right of Figure 1, nulls of approximately  $10^{-5}$  will be maintained on each nuller for periods of 10000 s. The artificial planet,  $10^6$  times fainter than the star, will be optically phased to simulate 360 degree rotations of the array in timescales of  $\geq 2000$ s. Phase chopping, fitting and averaging will be utilized to gain further starlight suppression by a factor of 100. The suppression effect achieved using these techniques in which the nulled starlight at  $10^{-5}$  is reduced to  $10^{-7}$  will be representative of flight performance.

Two models have been used to estimate the suppression available through chopping, fitting and averaging. One is an analytical model, the other is a numerical model. Estimates for the suppression vary according to the disturbance models for phase and intensity of the beams. As the nominal worst case, random temporal disturbances in electric field amplitude and phase having a  $1/f$  power spectral dependence were added to each input beam. As the nominal best case, random disturbances having a flat power spectral dependence (“white noise”) were added. For  $1/f$  spectra, suppression ratios are weakly dependent on experiment duration and typical values are 25 to 50. For white noise spectra, suppression ratios improve with the square root of the duration and are typically between a few hundred and a few thousand for likely experiment durations. The target suppression ratio of 100 will be achieved by a reduction of the natural  $1/f$  disturbance spectrum by the testbed control systems.

#### 4. Planet Detection Testbed

The Planet Detection Testbed, pictured in Figure 2, was developed to demonstrate the feasibility of four-beam nulling, achievement of the required null stability and the consequent detection of faint planets using approaches similar to the ones contemplated for a flight-mission. The most promising architectures for a flight mission employing synthesis imaging techniques (the X-Array and the Linear Dual-Chopped Bracewell) are four-beam nulling interferometers that use interferometric chopping to detect planets in the presence of a strong mid-infrared background.

The flight mission will use a phase chopping technique to modulate a sensitivity/fringe pattern around the star. This modulation technique is in many ways similar to the use of a chopper wheel that allows the detection of infrared sources against a thermal background and/or drifting detector offsets. In this case the thermal background on the sky includes the local and exozodiacal light. To achieve this modulation the interferometer uses two nullers each phased to null out the starlight, and a second beam combiner, known as the cross-combiner, which takes the output from the nullers and phases it to form the moving sensitivity pattern. A dark null fringe is fixed over the star and the constructive bright fringes move alternately to each side of the star, thus moving on and off the planet. If there are other planets in the field of view, their signals will also contribute depending on their locations and by rotating the fringe system around the star the whole planetary system can be observed. Signal processing is then used to determine the location of the planets orbiting the star.

The primary objective of the Planet Detection Testbed is to simulate this observing scenario and demonstrate the instrument stability needed to make this process work. Stability is an important requirement of the detection process. The detected signal is the difference in the measured photon flux between the two chop states and this signal has both stochastic and systematic noise components. Integration over time reduces the stochastic components and good instrument stability is needed to minimize systematic components which may appear as low frequency fluctuations with timescales similar to a planet signal. Some of these systematic components can be removed by signal processing using expected correlations across the broadband light spectrum. The PDT has the following main components: a star and planet source to generate a planet to be observed, a pair of nullers to null out the starlight, and a cross-combiner to allow modulation of the detected planet signal. To provide the ne-

cessary stability, the testbed has pointing and shear control systems, laser metrology systems and fringe trackers to maintain the phase on the star.

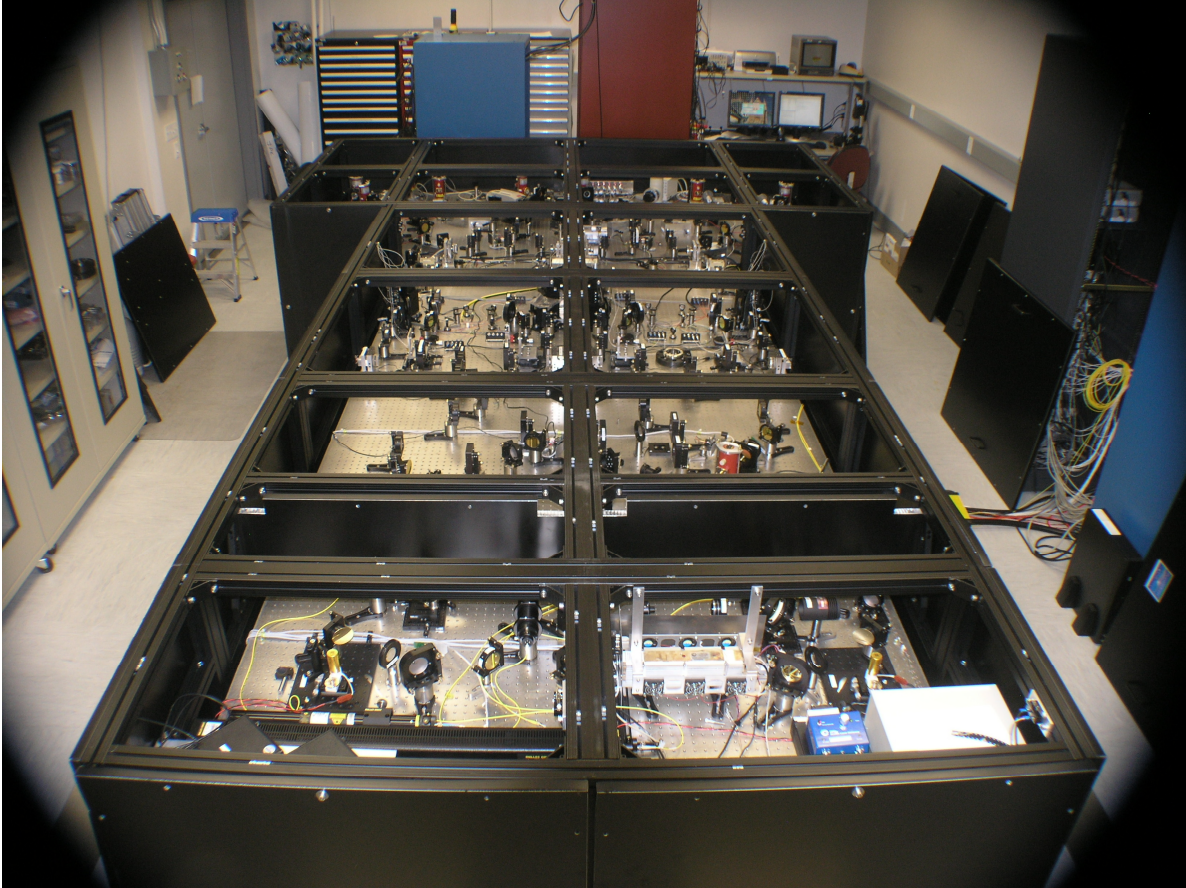


Figure 2: View of Planet Detection Testbed from the source end. In normal operation, the testbed is completely covered

The PDT will demonstrate active control of two nulling beam combiners (four input beams in total), operated at null depths of approximately 1 part in 100,000 and with sufficient stability to detect a planet signal that is 1,000,000 times fainter than the simulated starlight with a signal to noise ratio of 10. This constitutes a simulation of three of the four main parts of the starlight suppression technique, deep interferometric nulling, phase chopping and formation rotation to modulate the planet.

## 5. Testbed Description

The Planet Detection Testbed, illustrated schematically in Figure 3, produces four mid-infrared beams of light from the star and another four from the planet, combines star and planet beams in pairs to produce four star planet beams as if detected by the four telescopes. These beams are then nulled and cross-combined. This latter process reproduces the operation of the flight beamcombiner. In the figure, beamsplitters and phaseplates are shown in blue, mirrors in yellow. A  $\pi$  phase shift is introduced into one of each beam pair by a combination of optical path differences in glass and air. The star and planet beams are chopped in a standard method for detecting faint infrared signals in the presence of a background. These choppers are synchronized so that the star and



planet are chopped simultaneously. The precise detection process is discussed in detail below. An important element of the testbed plan is to demonstrate control of the nullers and the cross-combiner at levels close to those needed for flight, and to show realistic faint planet detection within a period of about two hours in the presence of ambient laboratory noise and optical disturbances.

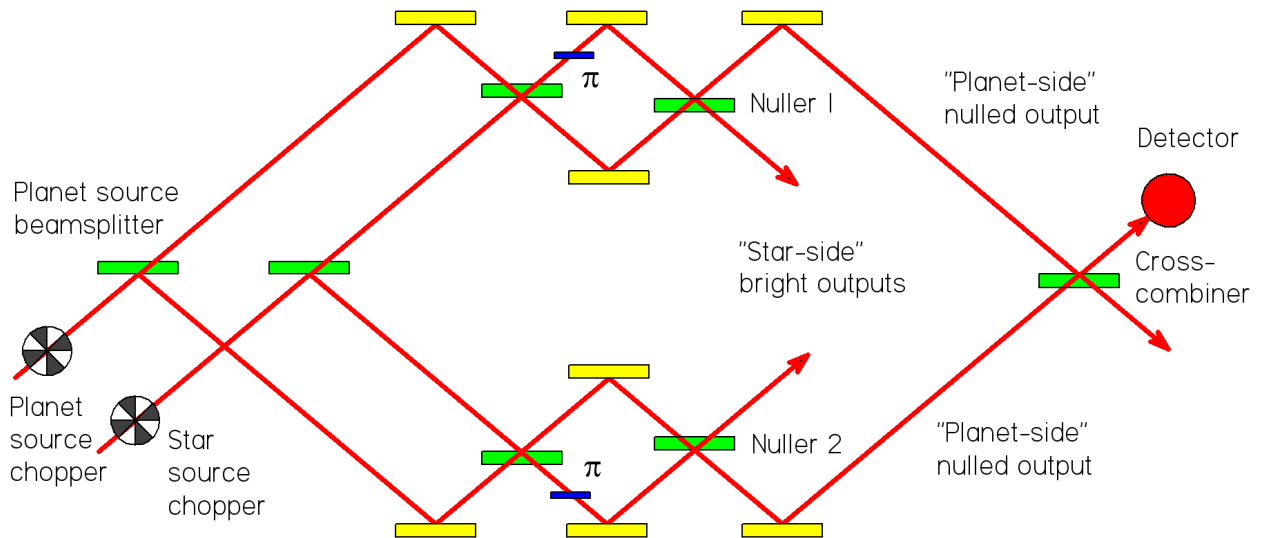


Figure 3: Schematic layout of the testbed.

Figure 4 shows part of a mechanical layout drawing of the testbed. An artificial star is formed from the outputs of a carbon dioxide laser and a thermal source. The carbon dioxide laser light provides 10.6 micron wavelength radiation which is to be nulled and the thermal source provides broad band radiation, portions of which are used for fringe tracking on the star. For example, the nulling fringe trackers currently use radiation between 2.2 and 2.53  $\mu\text{m}$ . The starlight is passed through a chopper and pinhole and then split into two beams. These beams are split again forming four beams (the functional parts of one beam are labeled in the figure and are reproduced in each beam) and, after this second splitting stage, combined with four beams from a second thermal source. This second source, limited to a band of radiation 1  $\mu\text{m}$  wide and centered between 8 and 12  $\mu\text{m}$ , forms the artificial planet.

The four starlight beams are controlled by near-identical systems. Each beam has a fast and a slow delay line enabling both rapid, fine control of optical path length, and slower, coarse control. The slow control can, for example, compensate for slow drifting of the overall optical path caused by thermal changes in the laboratory. The fast delay lines can compensate for higher frequency changes in optical path length caused, for example, by vibrations. The control signals for the delay lines are derived from the outputs of two sets of sensors. One, the laser metrology system, provides three measurements of optical path along sections of each beam train, so there is a total of 12 metrology signals. This measurement system provides a fast response to vibrations, and has a small drift at longer (tens of seconds) timescales. The second path length sensor is the fringe tracker which has a slow response ( $\sim$ one second) but can provide one nanometer accuracy or better. The fringe tracking signal is available when two starlight beams combine on a nulling beamsplitter. There are three fringe trackers, one for each nuller and one for the cross-combiner.

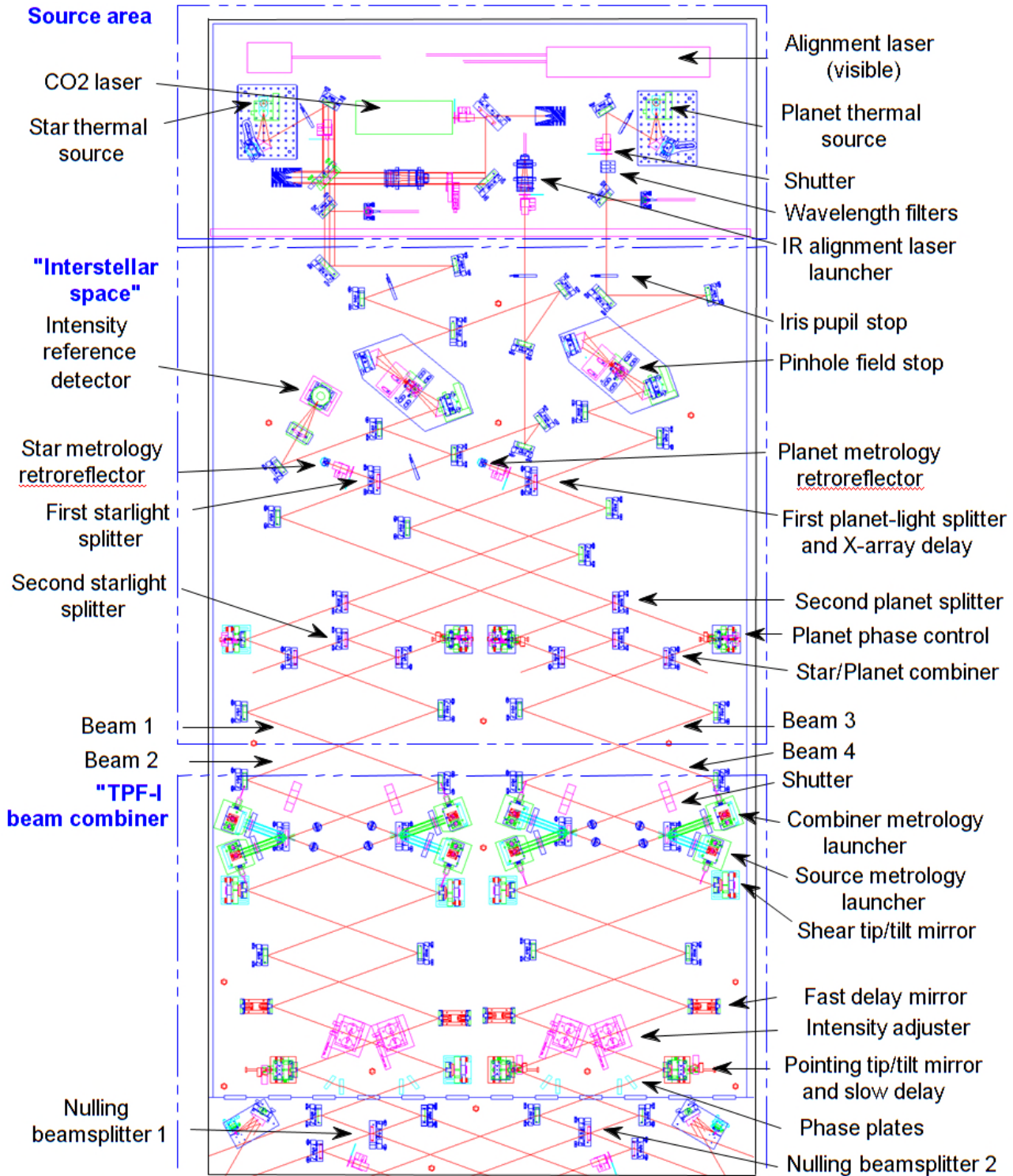


Figure 4: Testbed layout from sources through “interstellar space” to nulling beamsplitter.

Each beam has two piezoelectrically controlled tip/tilt mirrors. The first mirror (in combination with the second) allows for adjustment of the shear of the starlight within each beam train and the second mirror is used to adjust the pointing. The control voltages exerted on these two mirrors enable the intensity of the light striking the detector to be held constant to the 0.2% level, an important requirement for deep nulling. The control signals for these mirrors come from a pair of quad cell sensors mounted near the nulling beamsplitters. The sensors derive their signals from a diode laser beam injected into the beam train before the first beamsplitter. This laser beam follows the path of the star's radiation and thus provides a reference to the starlight pointing and shear within the testbed. One sensor measures shear to  $\sim 10 \mu\text{m}$  sensitivity and the other measures pointing to  $\sim 1 \mu\text{r}$  sensitivity.

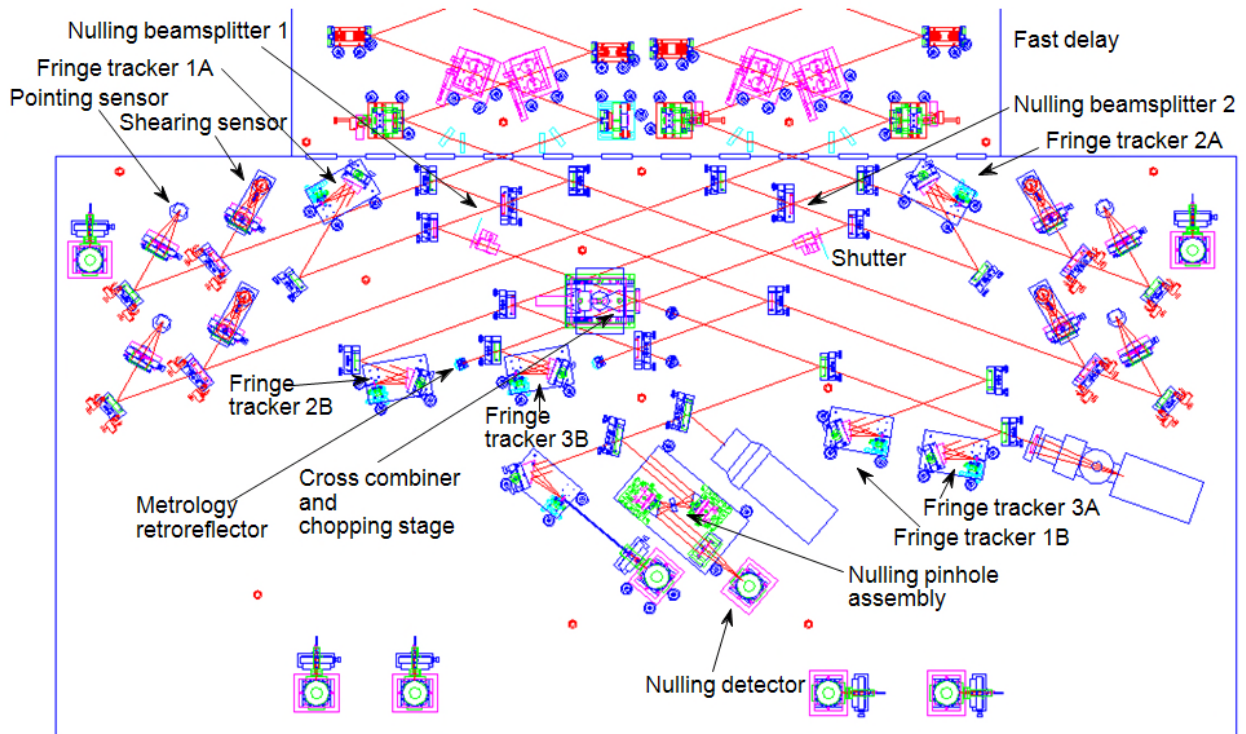


Figure 5: Layout of beamcombiner.

Each beam has a phase plate which enables correction of the small ( $<4 \mu\text{m}$ ) thickness differences between the beamsplitters. By adjusting the phase plates to certain thickness differences, phase differences between the  $10 \mu\text{m}$  radiation and the fringe tracking radiation at  $2.5 \mu\text{m}$  can be adjusted so that the fringe trackers have maximum sensitivity when the  $10 \mu\text{m}$  starlight is being nulled.

Figure 5 shows the physical layout of the beamcombiner. At the two nulling beamsplitters, two starlight beams are combined and then at the cross-combiner all four beams are combined. At this location a delay line called the chopping stage enables a phase difference to be produced between the outputs of the two nullers. This phase difference which is introduced at an approximately 2 s period causes the planet signal to be modulated. The chopping stage has been designed to move  $\sim 6$  microns with extremely low induced beam tilt (again, for stable performance).

The overall optical throughput of the testbed varies with wavelength but near  $10 \mu\text{m}$ , the source area throughput is  $\sim 56\%$ . Most loss is at the pinhole. The beamcombiner area throughput is  $\sim 6\%$ . Most of the loss is at a pair of beamsplitters used to separate the fringe tracking light. Unlike the other optics in the testbed, no special reflec-

tive coating was applied to these bare germanium surfaces. For any future broadband experiments, it would be worthwhile investing in more efficient surfaces to gain a factor of  $\sim 7$  in throughput. At the detector, an  $8\ \mu\text{m}$  diameter pinhole is used to provide spatial filtering. The loss at this component is approximately 50%. In flight, more efficient single mode fiber spatial filters will be used.

Using a somewhat different setup from the present one, the testbed has demonstrated four-beam nulling with null depths of 250,000:1 and the detection of a simulated planet at a contrast level of two million times fainter than its star. The current testbed setup more closely emulates a detection as it would be performed in space and incorporates a set of four planet beams that enter the main beam train after the second set of beamsplitters. Since the relative phases of these planet beams can be individually controlled, the apparent wavefront from the planet can be tilted so that the planet light makes a slight angle to the star light. By varying the tilt in a controlled sinusoidal fashion the testbed simulates the telescope array rotation around the line of sight to the star.

System alignment, control, and calibration techniques and software have been developed and tested as necessary parts of the testbed. The testbed control system is based on a dual processor PC with the addition of an FPGA-based metrology data acquisition system. Analog signal input and output is accomplished using a set of boards giving 36 output channels and 64 input channels. Twelve metrology gauges provide 24 digitized metrology signals to the FPGA card which processes each channel at 100 kHz, averages it and places it directly into the PC memory. All the I/O channels operate simultaneously at 5 kHz, so that data is always synchronized with a single master clock. Simultaneously, all input and output data and much other information is logged to a hard disk. In post-processing, relevant data streams can be selected for analysis. In addition, real-time data can be observed in a 3 second long ring buffer so that detector inputs can be used for processes such as fringe-finding without having to log to disk.

All real-time processes run on one of the two CPUs which loops continuously to execute its I/O activities and data processing. The user's control processes run under Windows-XP on the second processor, and access to the real-time process is achieved through Active-X calls. Control routines for the testbed are scripted in Matlab. This enables us to access data and control the real-time process directly without interfering with the timing. Testbed control can be achieved either by command line scripts or via graphical user interfaces (GUIs). The result is a flexible system which when coupled with the data logging facility allows access to the data and control signals at both high and low levels as needed.

### State of the Art

As shown in Figure 6, the PDT has demonstrated detection of a planet at a contrast ratio of 2 million to 1 in a four-beam combiner. The setup was a little different to the current one; in that experiment, control was exerted using lock-in techniques for tilting and phase control and the planet was detected by phase-chopping at the source rather than at the beamcombiner. However, the test showed the feasibility of faint planet detection using interferometric nulling. In the current test, the phase chopping will be done at the beamcombiner and the controls will be more representative of a flight control system. Following these successful tests, the PDT has been rebuilt to include tilt and shear sensors that in February 2007 demonstrated intensity stability in each arm of the interferometer to better than 0.2%. The tip/tilt control systems also afford for the first time effective phase control using the fringe trackers. In the dither-stabilized system, the fringe tracker outputs were too variable to maintain nulls deeper than a few thousand to one. Consequently, in those tests the nuller optical paths were stabilized directly on the nulled output, achieving  $10^{-5}$  null depths.

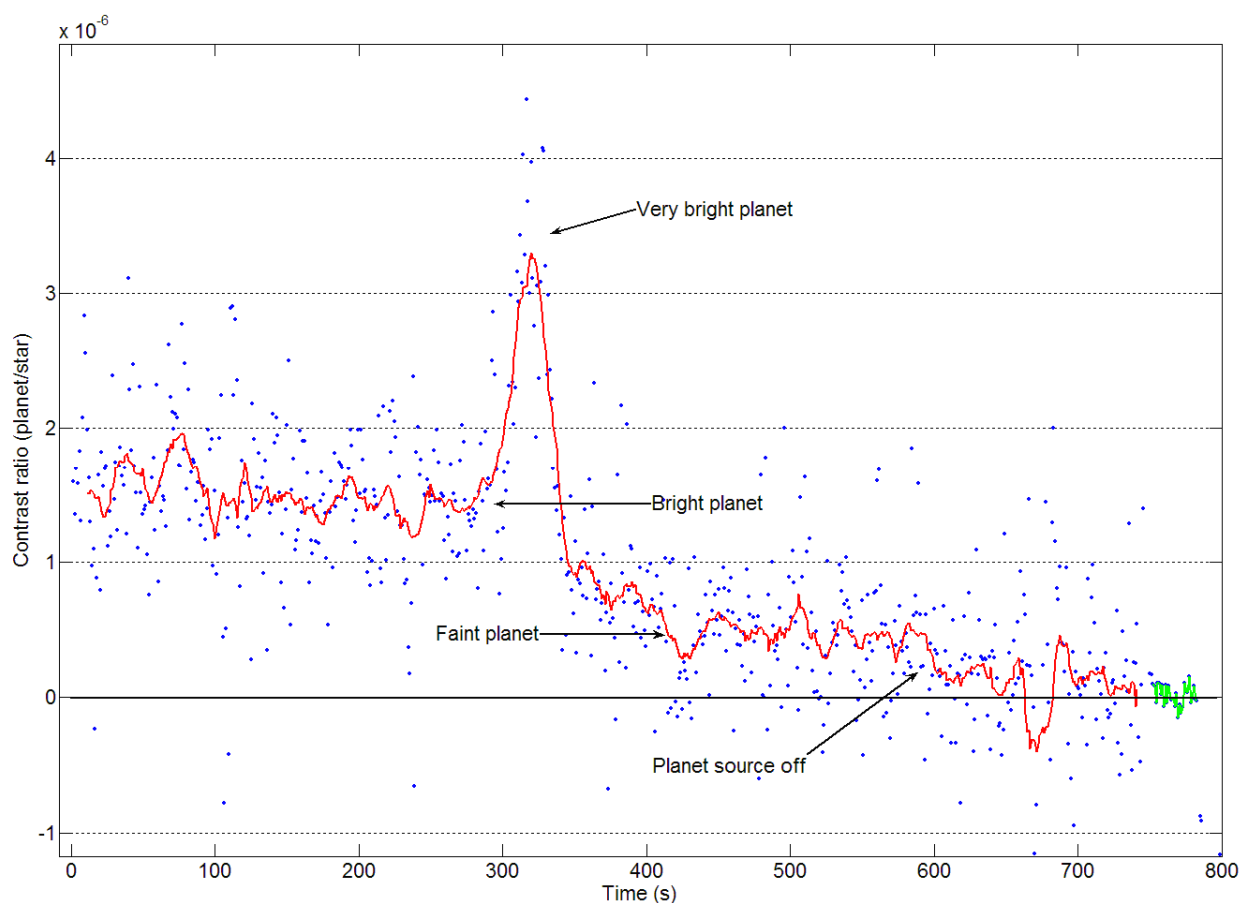


Figure 6: Detection of a faint planet at a contrast ratio of  $2 \times 10^6:1$  using phase chopping at the planet source. The blue dots are the raw data from the testbed and constitute single data outputs from a 1 second chop cycle. The red line is a 20 second rolling average through the blue dots. The green dots at the right are the chopped background noise with the star and planet turned off. The variability in the raw data is primarily due to instability noise. The planet intensity was varied during the experiment by changing the planet source heater current. At the beginning the planet contrast was  $\sim 7 \times 10^5:1$ , then it was decreased briefly to  $\sim 2 \times 10^5:1$ , then increased to  $\sim 2 \times 10^6:1$ . Near 600 seconds, the planet source was turned off and the signal decays towards zero.

## 6. Differences between Flight and Lab Demonstration

There are several important differences between the lab demonstration and the baselined flight implementation: flux levels, representative control loops and calibration, timescales, polarization, ambient environmental conditions versus cryo-vacuum and detector types. Each is addressed briefly below.

**Flux levels:** Figure 1 shows the key relative flux levels at a  $10 \mu\text{m}$  wavelength for (a) flight and (b) this milestone. Levels are normalized to the flux of the unsuppressed star. The exact ratios will depend on wavelength and the specific design of the flight system. The star is suppressed using nulling by a factor of  $10^5$ , bringing down the detected flux well below the level of the Local Zodi background. Chopping and averaging over the observation time reduces the level by a further factor of  $10^2$ , down to the level of the planet at  $10^{-7}$  (this can also be

viewed in the map domain – the planet signal appears in a single pixel, but the noise is scattered into many pixels. For a coronagraph this is the distinction between starlight suppression and contrast). The technique of spectral fitting (Lay 2006) is then used to achieve a further factor of 10 suppression of the noise relative to the planet, resulting in an SNR of 10. Spectral fitting exploits the different spectral signatures of the interferometric planet signal and the residual stellar leakage, and requires broadband starlight. This milestone demonstrates the factor of  $10^2$  suppression below the  $10^{-5}$  null obtained from chopping and averaging. Since the star is simulated with laser light, it is not possible at this stage to demonstrate spectral fitting. Therefore the levels shown for PDT in Figure 1 are adopted for this milestone, with the planet intensity at  $10^{-6}$  relative to the star.

The absolute flux levels for PDT also differ by necessity from those in flight. In the flight scenario, the dominant source of background noise is emission from the Local Zodi ( $T \sim 300$  K, optical depth  $\tau \sim 4 \times 10^{-8}$ ). For the PDT the dominant source of background noise is emission from the ambient thermal background ( $T \sim 300$  K, optical depth  $\tau \sim 1$ ), approximately  $2 \times 10^7$  higher than the Local Zodi. All the photon flux levels for PDT are scaled up accordingly. There are two consequences: (1) the control loops and calibrations are operating in a significantly different flux regime. This is addressed below. (2) There will be negligible photon noise contributing to the null residual in the PDT experiment. The flight error budget has two main sources of noise: photon noise (straightforward to estimate given the flux level) and instability noise. The PDT experiment is addressing only the instability noise contribution.

In a subsequent phase of the PDT we plan to demonstrate broadband nulling with spectral fitting as illustrated on the left of Figure 1. A bright, broadband arc source will be employed together with a low noise camera. Since the source will be relatively weak compared to the laser, the noise levels will be higher but the additional contribution of spectral fitting to noise reduction can be demonstrated.

**Representative control loops and calibration:** maintaining a stable null over long periods in the presence of spacecraft motions requires a number of active control loops and calibrations, e.g. tip/tilt control, fast optical path difference control (metrology), slow optical path difference control (fringe tracking), equal intensity calibration, calibration of fringe tracking set-points, and Adaptive Nulling. With the exception of Adaptive Nulling (a broadband correction; Milestone #1), all of these are represented in the PDT with an architecture that is scalable to flight. At this point however, we make no attempt to scale the PDT control loop performance to the flight conditions. There are 3 reasons for this: (1) the flux levels and detector performance differ by many orders of magnitude; (2) the flight disturbance environment is currently unknown but is likely very different from that seen in the lab; and (3) there are many layers of control and calibration with non-linear inter-dependencies that make it difficult to compare the various contributions between flight and testbed systems. While detailed model validation is a vital step in the future technology development for a flight mission, it is beyond the scope of the current milestone. The controls architecture implemented in PDT is representative of flight, but the environmental differences mean that the quantitative performance characteristics are dissimilar.

**Timescales:** the baseline flight scenario calls for one or more rotations of the array per observation, with a typical rotation period of order 50,000 s (14 hours). The current experiment is limited to timescales of  $< 10,000$  s by the “hold time” of the detector dewars. As for the discussion of control loops above, the PDT will simulate the observation period over a period of several hours with a flight-like set of calibration steps, but the period will not be scaled in a quantitative way to flight timescales.

**Polarization:** in the flight system, the adaptive nuller component of the beam train will split the two linear polarization states and correct each independently for phase and amplitude deviations before recombining the light into a single beam. The Adaptive Nuller’s optical system has been designed with dual polarization operation in mind although this function is not currently implemented; the laboratory demonstration operates on unpolarized light without splitting the components. The addition of two polarizing prisms would allow separation and re-

combination of the polarizations. The PDT utilizes only one polarization of the laser light but uses no polarizing optical components; it would be expected to work equally well with either polarization state.

**Cryo-vacuum:** the flight system will operate in vacuum at low temperature ( $\sim 40$  K), compared to the ambient air environment of the laboratory demonstration. The laboratory is a more challenging disturbance environment from a mechanical point of view and the room temperature thermal background is a significant source of noise in the experiment. Future engineering work outside the scope of this testbed will address the needed opto-mechanical components that operate in vacuum at low temperature.

**Detectors:** in flight, CCD array detectors will be used. When exposed to light, these devices accumulate electronic charge in each pixel. Periodically the array is discharged by being ‘read out’, converting the number of stored electrons into a voltage. Associated with these detectors are intrinsic noise sources such as read-out noise and dark current noise. In PDT, the detectors are of the photoconductive type. When exposed to light, photoelectrons are emitted into the semiconductor material, causing a change in the electrical conductivity. A bias current flowing through the material is used to sense the conductivity change. The large bias current and the thermal background noise are then removed by lock-in detection using mechanical chopping. Amongst other noise sources, these sensors produce dark current noise, Johnson noise from the detector shunt resistance and preamplifier noise. Since the two detection mechanisms are significantly different, the consequent detector noise characteristics are not easily matched.

**Testbed metrology:** the testbed uses laser metrology systems to monitor internal paths and also an ‘external’ path to the source. The metrology systems are band limited to frequencies above  $\sim 1$  Hz so that the DC component of the external and internal paths is not measured. Thus the testbed uses the metrology only to correct for testbed vibrations induced by the environment and not to track the null fringe, making it analogous to the flight system.

## 7. Testbed Operations and Procedures

### 7.1. Definitions

The planet detection demonstration requires measurement and control of an interferometric null. In the following paragraphs we define the terms involved in this process, spell out the measurement steps, and specify the data products.

- 7.1.1. Star Laser Source.** The source for the starlight to be nulled is a carbon dioxide laser with a very narrow spectral line width operated at a wavelength near 10.6 micron.
- 7.1.2. Star Thermal Source.** The source for the portion of the starlight to be used for fringe tracking is a 50  $\mu\text{m}$  diameter pinhole illuminated by a ceramic filament source with an equivalent blackbody temperature of 1200 K. Radiation between 2 and 3 micron is used for fringe tracking the star. It is not intended to simulate any particular collector design or expected flux.
- 7.1.3. Planet Thermal Source.** The source for the planet light to be detected is a 50  $\mu\text{m}$  diameter pinhole illuminated by a ceramic filament source with an equivalent blackbody temperature of 1200 K. Radiation between 10 and 11 micron will be detected from the planet using a filter to narrow the bandwidth. The flux can be adjusted using an iris and/or the current supplied to the filament to achieve the desired star/planet intensity ratio at 10 micron.
- 7.1.4. Laser metrology.** The laser metrology system uses three lasers operated at 1530, 1550 and 1575 nm wavelengths to enable optical pathlength monitoring in the various arms of the interferometer. This system can be used to provide inputs to the testbed control loops.

- 7.1.5. Null Fringe.** The null fringe is a destructive fringe for the laser source near the center of the thermal source's broadband interference envelope.
- 7.1.6. Null Depth.** The null depth is the ratio of intensity at the constructive CO<sub>2</sub> laser fringe peak to the intensity at the destructive fringe.
- 7.1.7. Suppression Ratio.** The suppression ratio is the ratio of the mean intensity of the un-nulled light observed after the cross-combiner to the rms intensity in the field of view. See the discussion under 'Signal to noise ratio'.

## *7.2.Measurement of the star intensity*

Since the laser source used as the star at the 10 micron wavelength is very bright, its power must be attenuated using a neutral density (ND) filter before allowing it to fall on the detector. When nulling, the ND filter is removed from the beam, allowing the full stellar intensity to be nulled. A star intensity measurement is obtained as follows:

- 7.2.1.** All four beam shutters are closed. A neutral density filter of known optical density (OD) between 100 and 1000 is placed in the laser output path.
- 7.2.2.** Each beam shutter (n) is opened in turn and a measurement of the detector signal (Vn) is made.
- 7.2.3.** The total stellar signal is calculated by  $OD * 4 * \{V1 + V2 + V3 + V4\}$ . The factor of four accounts for the two beamsplitters which have reflectivities of 50%.

## *7.3.Measurement of the planet intensity*

The thermal source used as the planet at the 10 micron wavelength is very faint. A planet intensity measurement is obtained as follows:

- 7.3.1.** All four beam shutters are closed. The star thermal source and laser source are shuttered.
- 7.3.2.** Each beam shutter (n) is opened in turn and a measurement of the detector signal (Vpn) is made.
- 7.3.3.** The total planet signal is calculated by  $4 * (Vp1 + Vp2 + Vp3 + Vp4)$ .

## *7.4.Measurement of the null depths*

Each null measurement is obtained as follows:

- 7.4.1.** For each nuller (1 and 2) in turn, with the ND filter in place, the piston mirror is moved to the vicinity of the bottom of the fringe.
- 7.4.2.** The ND filter is removed and a control loop is started which drives the piston to the bottom of the null fringe. A measurement of the detector signal (Vn1 or Vn2) is made.
- 7.4.3.** The null depth is calculated by  $Vn1 / (OD * 2 * (V1 + V2))$  for nuller 1 and  $Vn2 / (OD * 2 * (V3 + V4))$  for nuller 2.

## *7.5.Fringe tracking*

Each fringe tracker consists of two detectors positioned to detect the outgoing light on either side of either a nulling beamsplitter or the cross-combiner beamsplitter. The beamsplitters have reflectivity  $R(\lambda)$  and transmis-



sivity  $T(\lambda) \sim (1 - R(\lambda))$ . At the nulling beamsplitter, the two incoming beams which derive from an identical beamsplitter (for example the first starlight beamsplitter shown in Figure 4) therefore have, in general, different intensities. At the nulled output side of the beamsplitter (herein referred to as the planet side), because this is a symmetry output, the outgoing intensity of both beams measured alone will be the same,  $T^*R$  and  $R^*T$ . At the other output, the star side, the beams will generally be unbalanced with intensities  $T^*T$  and  $R^*R$ . The fringe visibility is given by  $(I_1 - I_2)/(I_1 + I_2)$  and so the visibility will be unity on the planet side and generally something less on the star side.

In the case of simple beamsplitters the intensities on each side of the beamsplitter after interference are given by:

$$I_p = 2RT + 2RT \sin(\phi) \text{ and } I_s = TT + RR + 2RT \sin(-\phi)$$

so that the intensities vary in opposite phase  $\phi$  with identical amplitudes but different visibilities.

It can be shown that:

$$\sin(\phi) = \frac{I_p(m + 1/m)/2 - I_s}{I_p + I_s}$$

where  $m$  is the ratio  $R/T$ . Using this formula with measurements of  $R$  and  $T$  the fringe phase can be directly detected using a pair of detectors located on each side of the nulling beamsplitters. In this document, the symmetry, planet side detector is referred to as fringe tracker 1,2 or 3 A, the star-side detector is denoted 1,2 or 3 B. As shown in Figure 5, fringe trackers 1 and 2 track the null fringes and fringe tracker 3 the cross-combiner.

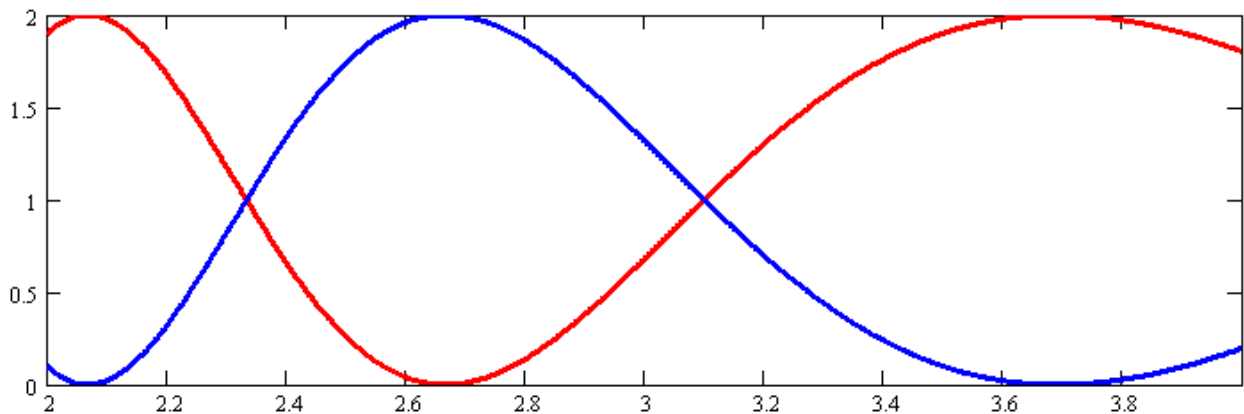


Figure 7: Relative intensity on the star side (red) and the planet side (blue) for a ZnS phaseplate set (actual R/T ratio not taken into account). The X-axis shows wavelength in  $\mu\text{m}$  and the Y-axis shows intensity in arbitrary units.

### 7.6. Controlling the fringe phase

Since the starlight which is to be nulled is produced by a narrow linewidth laser source, the nulled fringe can be found at intervals of the laser wavelength  $\lambda$  with an offset of  $\lambda/2$  from zero optical path difference. However, we wish to introduce some phase so that the fringe trackers are at the point of maximum slope when the laser light is nulled. Using a model to add extra material (ZnSe or ZnS) into one of each beam pair, solutions can be found that have the desired phase shifts. Figure 7 shows, for example, a simplified calculation of the light transmitted

across the nulling beamsplitter for a differential thickness of  $-1.000 \mu\text{m}$  of ZnSe,  $35.739 \mu\text{m}$  of ZnS and  $-83.637 \mu\text{m}$  of air path.

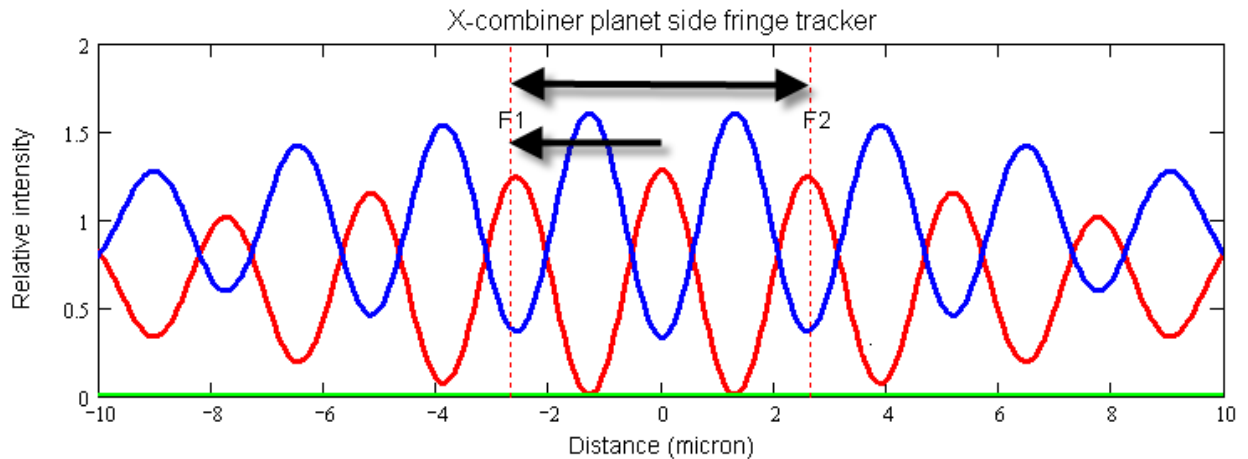


Figure 8: Cross-combiner fringes showing the calculated intensity on the A and B sides of the beamsplitter. At the location 0 micron where there is zero optical path difference across the cross-combiner, the initial phasing of the cross-combiner is performed. Subsequently at the two locations F1 and F2, the two halves of the chop cycle are executed.

Ideally the null fringe will be tracked at the cross-over point near  $2.35 \mu\text{m}$  since at this point roughly equal numbers of photons will reach the fringe tracking detector pair. Near  $2.65 \mu\text{m}$ , almost all the light is transmitted to the cross-combiner, so an ideal phaseplate differential thickness should be found across the nulled pairs to utilize this light for phasing the cross-combiner. PDT uses fringe tracker detectors with bandpass filters transmitting light between  $2.2 \mu\text{m}$  and  $2.53 \mu\text{m}$  for null fringe tracking. The precise setup would vary with the choice of phase-plate thicknesses and types, so for a ZnSe phaseplate set, the detector wavelengths may be different, but still within the  $2$  to  $3.6 \mu\text{m}$  range.

At the cross-combiner, the fringe will be tracked in three locations: 1/ in the initial setup, the cross-combiner will be phased to have a constructive  $10 \mu\text{m}$  fringe across the star. 2/ and 3/, when chopping, the cross-combiner will move from a phase of  $-\pi/2$  to  $+\pi/2$  across the star; locations F1 and F2 on Figure 8. Ideally the fringe tracker can use the same fringe to track at all three points, requiring an optical path difference (OPD) shift of  $\lambda/2$  measured at the laser wavelength. Assuming a laser wavelength of  $10.6 \mu\text{m}$ , the OPD shift will be  $2.65 \mu\text{m}$ , so a fringe tracker operating near this central wavelength can be used. PDT uses a fringe tracker with a band-pass filter transmitting light between  $2.38$  and  $2.89 \mu\text{m}$  for cross-combiner fringe tracking.

When chopping, the cross-combiner stage moves at a steady velocity to ramp between the two chop states. The cross-combiner phase is held steady using the fringe tracker/metrology loop at location F1 for  $800 \text{ ms}$  before ramping up, taking  $200 \text{ ms}$ . The loop then holds at location F2 for  $800 \text{ ms}$  before ramping down, taking an additional  $200 \text{ ms}$ . The chop cycle therefore takes  $2$  seconds. The chop cycle time has been lengthened compared to the cycle time used in the experiment of Figure 6 to allow time for the fringe tracker control loops to settle after the ramp. In the previous experiment the chop cycle did not affect the path control.

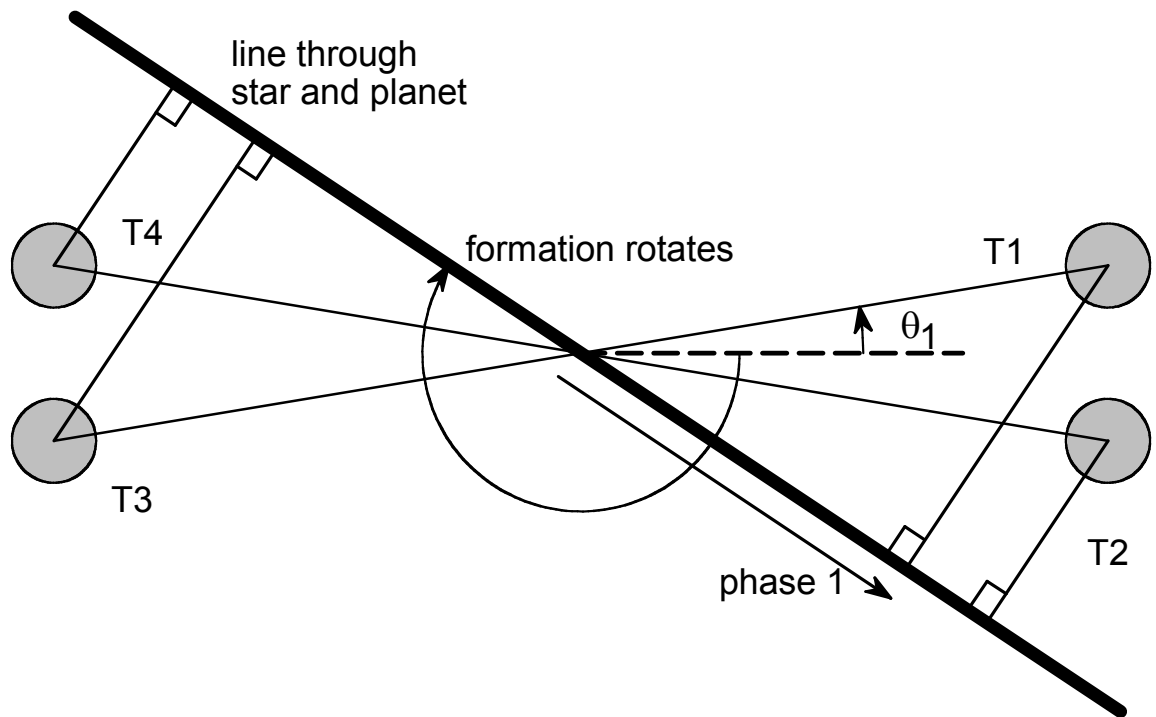


Figure 9: Rotation of the formation. Along a line drawn through the planet and the star, the planet phase varies with a constant slope. As the formation rotates, the portion of that phase observed at each telescope varies with the cosine of the angle made to the line by the vector from the formation center to the center of that telescope. The phase for telescope 1 is shown.

### 7.7. Planet detection

The planet detection method involves simulation of a rotation (or rotations) of the telescope array while nulling the star. The simulated rotation is achieved by varying the phase of the four planet beams in a sinusoidal fashion so that the planet appears to move from one side of the star to the opposite side and back again. The phase  $\psi$  for the  $i$ th telescope is given by:

$$\psi_i = \frac{\pi R \Omega}{\lambda} \cos(2\pi \omega t + \theta_i)$$

where  $R$  is the distance of the telescope from the formation center,  $\lambda$  is the infrared wavelength,  $\Omega$  is the angular offset of the planet from the star,  $2\pi \omega t$  is the rotation angle of the array and  $\theta_i$  is the angle made by the  $i$ th telescope to a line bisecting the array; see Figure 9. For the testbed, we choose values of displacement on the planet phase control stages to give realistic values of  $R\Omega$ . By choosing different values of  $\theta_i$  we can set up X-array formations or linear formations.

Characteristic planet signals will be obtained from the beam combiner depending on the spacecraft formation geometry and the distance of the planet from the star. To detect the planet signal in the output signal, which will contain substantial instability noise, the measured signal for one rotation will be compared with (correlated with) a series of planet signal templates. Two such signal templates are shown in Figure 10. The correlation will

yield a two-dimensional map of the correlation in space as shown in Figure 11. A second, similar processing step will yield absolute planet signal magnitude.

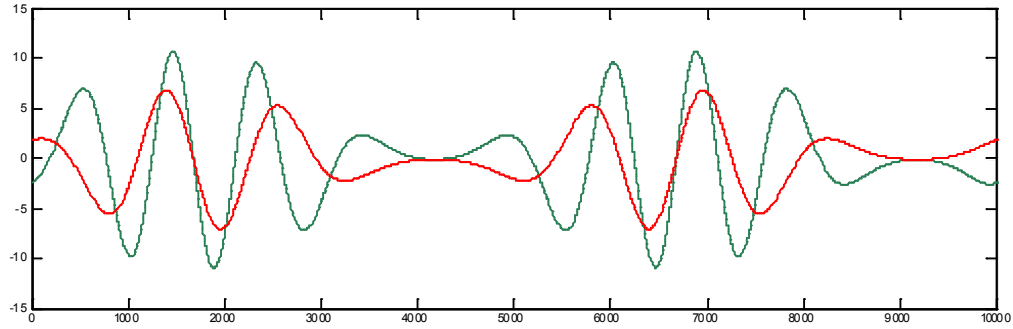


Figure 10: Signal template models for planets at 0.25 (red) and 0.33 (green)  $\mu$ radian from the star. Array dimension  $R$  is 60 m, wavelength is 10.6  $\mu$ m. Vertical axis is intensity in arbitrary units. The horizontal axis is marked in arbitrary angle units and represents a single rotation of the array.

### 7.8. Signal to noise ratio

To test a recorded testbed signal  $S(t)$  for the presence of a planet signal we create a series of planet signal templates  $T(R, \theta, t)$  where  $R$  is the radius from the star,  $\theta$  is the rotation angle and  $t$  the time and calculate:

$$\Phi(R, \theta) = \frac{\sum S(t) * T(R, \theta, t)}{\sqrt{\sum T(R, \theta, t) * T(R, \theta, t)}} \quad (1)$$

for all values of  $\theta$  ( $0$  to  $2\pi$ ) and  $R$  of interest. The summation is over the set of chop samples. If  $S$  contains a planet the result is proportional to the planet intensity. If no planet signal is present but  $S$  contains instability noise, the noise signal at any location  $R, \theta$  can be found. The rms noise level (and therefore the suppression ratio) for any particular planet position is then found by integrating around the star at constant radius. If the signal contains a planet, the noise level will be only an estimate and can be found by subtracting the fitted planet signal from the trace and testing again. Since the fitted planet signal will contain some of the noise, the result will be the noise minus some fit error and will be an underestimate of the background noise.

## 8. Milestone #4 Validation Procedure

### 8.1. Introduction

The milestone validation test consists of three parts.

- 8.1.1. With the planet turned off, the suppression of the starlight by a factor of 100 below the null will be shown. This will be done following the procedures detailed below. In outline, the testbed will be set up as if for planet detection and measurements will be made of the nulling detector output. This output will consist principally of the star laser light leakage. Data processing will establish the four beam null depth and the noise suppression ratio after chopping and averaging.

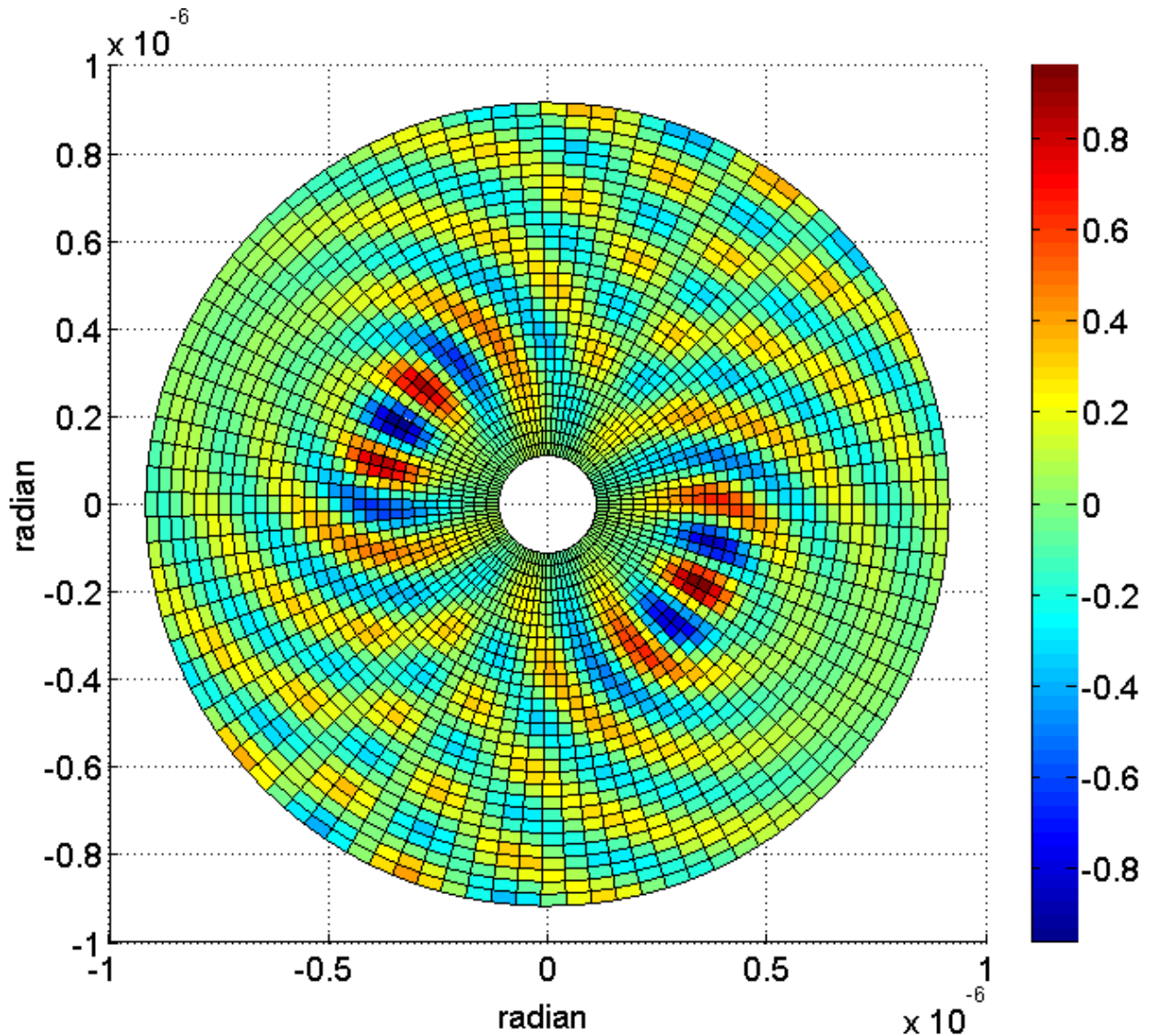


Figure 11: Simulation of the normalized cross-correlation map for a planet located near  $0.3, -0.2$   $\mu$ radian from the star located at the center. The planet has a negative symmetric image on the opposite side of the star which may be removed by further processing.

The detection of a planet 10 times fainter than the null will be shown under similar operating conditions. The planet detection process is split into two parts.

- 8.1.2.** A measurement of the absolute planet signal magnitude will be obtained by running a test with all required systems running except that the star's laser source will be off. This will yield a planet signal free of instability noise but with any other noise still present. The test will 1), verify that the planet path lengths are being correctly controlled and 2), yield a measurement of the planet signal intensity so that the star to planet intensity ratio can be calculated.

- 8.1.3.** A detection of the planet signal will be made by running a test with similar conditions to 8.1.1 and 8.1.2 and with both planet and star sources on. The four beam null depth can be measured from the data. The planet signal can be detected in the data and compared with the planet signal from 8.1.2. The suppression ratio will be assumed to be that found in 8.1.1.

These tests will be run three times on different days to verify the repeatability of performance.

## *8.2.Procedure for test with star and planet*

- 8.2.1.** The testbed light sources are turned on.
- 8.2.2.** Unshuttering one beam at a time, the nulled light is aligned with the receiving pinhole and maximized by adjusting the beam shear and pointing under a control loop. When the alignment is optimized, the pointing/shearing control loop for the beam is turned on.
- 8.2.3.** Beams 3 and 4 are shuttered and beams 1 and 2 are phased by adjusting the slow delay on beam 2 to move to the center of the broadband (2.5  $\mu\text{m}$ ) fringe envelope on fringe tracker 1. At this point the 10  $\mu\text{m}$  interference will be near the null while the fringe tracker will be near the maximum slope of its fringe.
- 8.2.4.** A control loop is engaged which seeks the minimum on the ten micron fringe and then the optical path is locked using another control loop which controls on the combiner laser metrology signals from beams 1 and 2.
- 8.2.5.** Now the starlight is shuttered off and the planet light admitted to the system. With the star nulled, the planet can be identically phased by nulling its light using the picomotors attached to the planet delays. This effectively places the planet on the line of sight to the star.
- 8.2.6.** The starlight shutters are opened.
- 8.2.7.** Beam 2 is shuttered and beam 3 opened. The cross-combiner stage is set at the center of its travel. The cross-combiner is then phased by adjusting the slow delay on beam 3 to move to the center of the broadband (2.5  $\mu\text{m}$ ) fringe envelope on fringe tracker 3. At this point the 10  $\mu\text{m}$  interference will be near the constructive peak and the fringe tracker will be near the maximum slope of its fringe.
- 8.2.8.** A control loop is engaged which seeks the maximum on the ten micron fringe, and then the optical path is locked using another control loop which controls on the combiner laser metrology signals from beam 1 and 3.
- 8.2.9.** Now the starlight is shuttered off and the planet light admitted to the system. The X-array stage is centered. With the star constructively interfered at the cross-combiner, the planet can be identically phased by constructively interfering its light.
- 8.2.10.** The starlight shutters are opened.
- 8.2.11.** Beam 2 is now shuttered and beams 3 and 4 are phased by adjusting the slow delay on beam 4 to move to the center of the broadband (2.5  $\mu\text{m}$ ) fringe envelope on fringe tracker 2. At this point the 10  $\mu\text{m}$  interference will be near the null while the fringe tracker will be near the maximum slope of its fringe.

- 8.2.12.** A control loop is engaged which seeks the minimum on the ten micron fringe, and then the optical path is locked using another control loop which controls on the combiner laser metrology signals from beams 3 and 4.
- 8.2.13.** The starlight is shuttered off and the planet light admitted to the system. With the star nulled, the planet can be identically phased on nuller 2 using the picomotors attached to the planet delays.
- 8.2.14.** The starlight shutters and the individual shutters on beams 1, 2, 3 and 4 are opened. Control loops are started which utilize fringe tracker and metrology signals to control the optical path on each nuller and on the cross-combiner.
- 8.2.15.** Additional control loops are started which coordinate control motions on beams 3 and 4 so that when the cross-combiner loop operates the beam 3 slow and fast stages to maintain the cross-combiner phase, OPD is also maintained between beams 3 and 4. This maintains the deep null on nuller 2.
- 8.2.16.** The nulls are optimized by engaging a pair of loops which correlate nulling detector output with fringe tracker outputs and actively adjust the fringe tracker setpoints. Once optimized, these loops are turned off.
- 8.2.17.** The cross-combiner fringe tracking loop is turned off.
- 8.2.18.** The chopping stage is adjusted to a position approximately  $-\pi/2$  away from the constructive fringe on the cross-combiner as measured by the  $10\ \mu\text{m}$  light. At this point fringe tracker 3 will be near its maximum slope.
- 8.2.19.** The cross-combiner fringe tracking loop is turned on.
- 8.2.20.** The cross-combiner chopping loop is turned on. This loop moves the cross-combiner stage between the plus and minus  $\pi/2$  points on the  $10\ \mu\text{m}$  fringe so that the array appears to look slightly to the left and then slightly to the right of the star. A data stream is produced which contains the difference between the detector outputs in the left and right chop states; a single number for each chop cycle.
- 8.2.21.** Now the planet rotation can be started. The control loop adjusts the phases of the planet beams to move the apparent position of the planet to a particular location space. After this the phases of the beams are adjusted in a controlled fashion to simulate the rotation of the array around the line of sight to the star.
- 8.2.22.** Periodically, the planet rotation is suspended, and the nulls re-optimized on the two nullers. Then the rotation is resumed.
- 8.2.23.** The chop cycle data is analyzed for the presence of a planet signal using the following method. A series of template planet signals is produced for planets ranging at distances from 0.1 to 1.0 microradian from the star. Each signal is cross-correlated with the chop cycle data using equation 1. By varying the phase of the templates, a map of correlation value against radius and sky angle can be produced.

### *8.3.Procedure for test with star only*

- 8.3.1.** The testbed light sources, excluding the planet source are turned on.
- 8.3.2.** The same procedure as for the test with star and planet is followed except that 8.2.5, 8.2.9 and 8.2.13 are omitted.

- 8.3.3. 8.2.22 is revised as follows. Periodically, the test is suspended and the nulls re-optimized on the two nullers. Then the test is resumed.
- 8.3.4. The testing process follows the method of 8.2.23. The result is a map of the rms noise over the field of view. The suppression ratio is the mean signal observed on the detector divided by the rms noise.

#### 8.4. Procedure for test with planet only

- 8.4.1. The testbed light sources are turned on.
- 8.4.2. The same procedure as for the test with the star and planet is followed except that under 8.2.21, the star laser source is shuttered closed.
- 8.4.3. 8.2.22 is revised as follows. Periodically, the planet rotation is suspended, the star laser source shutter is opened and the nulls re-optimized on the two nullers. Then the star laser source shutter is closed and the rotation is resumed.
- 8.4.4. The testing process follows the method of 8.2.23. The result is a map of the rms planet signal over the field of view.

Procedures 8.2, 8.3 and 8.4 will be repeated on two more occasions on different days with at least 48 hours between each demonstration.

## 9. Success Criteria

### 9.1. Required elements

The following is a statement of the elements that must be demonstrated to close Milestone #4. Each element includes a brief rationale.

- 9.1.1. Detect a planet at a contrast of  $\leq 10^{-6}$  relative to the star at a signal to noise ratio of  $\geq 10$ .
- 9.1.2. Show residual starlight suppression from phase chopping, averaging and rotation  $\geq 100$ .

*Rationale: The noise rejection to be demonstrated is the flight requirement and would allow earth-like planet signal extraction when the spectral fitting method is also employed. A typical science observation would require an array rotation period of 50,000 s (~14 hrs), and thus the time-series duration of 10,000 s demonstrates long-term stability of the system, approaching flight-level requirements.*

- 9.1.3. The tests 8.1.1 and 8.1.3 must each run for a total duration of 10,000s and may include one or more planet rotations at timescales  $\geq 2,000$  seconds. Test 8.1.2 may run for a shorter duration.
- 9.1.4. Elements 9.1.1 to 9.1.3 must be satisfied simultaneously on three separate occasions with at least 48 hours between each demonstration.

*Rationale: This provides evidence of the repeatability of the starlight suppression.*

### 9.2. Certification Process

The Program will assemble a milestone certification data package for review by the EIRB. In the event of determination that the success criteria have been met, the project will submit the finding of the review board, together with the certification data package, to NASA HQ for official certification of milestone compliance. In



the event of disagreement between the project and the EIRB, NASA HQ will determine whether to accept the data package and certify compliance or request additional work.

### 9.3. Certification Data Package

The milestone certification data package will contain a narrative report including a discussion of how each element of the milestone was met, an explanation of each plot or group of plots, appropriate tables and summary charts and a summary of the overall milestone achievement.

Among the data to be included in final report will be:

- 9.3.1. Graphs showing the testbed nulling output with star only, planet only and with both star and planet.
- 9.3.2. Graphs showing the estimated planet signal (when appropriate) calculated from testbed metrology.
- 9.3.3. Graphs showing the measured planet position in space.
- 9.3.4. Graphs showing the measured noise distribution in space.
- 9.3.5. Statistical data on the nulling output such as mean and rms null depth and graphs of power spectral density.
- 9.3.6. Statistical data on the noise distribution mean and rms intensity noise. Graphs of power spectral density of intensity and phase noise for each beam.

## 10. References

Stefan R. Martin, Piotr Szwaykowski, Frank M. Loya, Kurt Liewer, "Progress in testing exo-planet signal extraction on the TPF-I Planet Detection Testbed," in *Advances in Stellar Interferometry*, edited by J. D. Monnier, M. Schöller, W. C. Danchi, Proc. SPIE 6268, 626818 (SPIE, Bellingham, WA, 2006).

Stefan Martin, "Progress in four-beam nulling: results from the Terrestrial Planet Finder Planet Detection Testbed," in 2006 IEEE Aerospace Conference, Big Sky, Montana (2006).

Stefan Martin, Piotr Szwaykowski, Frank Loya, "Testing exo-planet signal extraction using the Terrestrial Planet Finder planet detection testbed," in *Techniques and Instrumentation for Detection of Exoplanets II*, edited by D. R. Coulter, Proc. SPIE 5905, 70-79 (SPIE, Bellingham, WA, 2005).

Stefan Martin, "TPF Planet Detection Testbed: a four beam infrared testbed demonstrating deep, stable nulling and planet detection," in 2005 IEEE Aerospace Conference, Big Sky, Montana (2005).

P. R. Lawson and J. A. Dooley, Editors, *Technology Plan for the Terrestrial Planet Finder Interferometer*, JPL Pub 05-5 (Jet Propulsion Laboratory: Pasadena, CA, 2005).

<http://planetquest.jpl.nasa.gov/Navigator/library/tpf414.pdf>

Oliver P. Lay, "Removing instability noise in nulling interferometers", Proc. SPIE **6268**, 62681A (2006)

## 11. Appendix: Control loops

The following section outlines the operation of the principal control loops that are used on the testbed. Because of the large differences in flux levels, while the flight system might use similar control techniques when nulling, testbed alignment and phasing methods are probably not representative of a flight system.

### 11.1. Lock-in dither loop

The most generally used loop is a lock-in control loop. It is used to optimize pointing and shearing of the beams on the nulling detector, and also to find the null and peak of the fringe. Figure 12 shows the general scheme. A small sinusoidal modulation is applied to a linear stage or to a tip/tilt stage. In this latter case, the stage executes a circular angular motion, sweeping the reflected beam around a cone. The signal sensed by the detector is band-passed and mixed with the output signal and then low-passed producing a phase-sensitive output. This output is summed with the initial offset and the driving sinusoid. By changing the sign of the gain, the system can seek the peak or the minimum of the input. For tip/tilt stages the two axes, horizontal and vertical, are driven with orthogonal control signals and the mixing process produces two orthogonal error signals which drive the angular offsets.

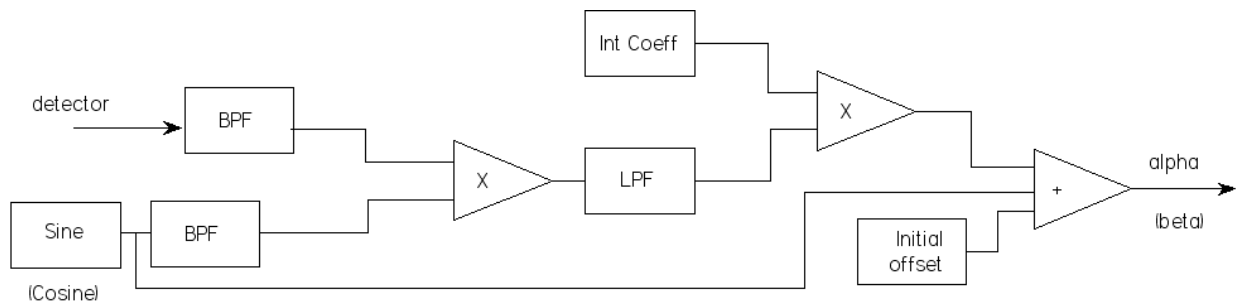


Figure 12: General layout of a lock-in dither loop.

For pointing and shear alignment, a second lock-in is started on the shearing tip/tilt mirror, running at a different excitation frequency. To produce shear, the drive to the shearing mirror is also applied (inverted) to the pointing mirror and summed with the pointing mirror's own drive.

### 11.2. Tip/tilt pointing loop

Once the alignment is optimized, the tip/tilt pointing and shearing loop is started, Figure 13. It uses the outputs of the pointing and shearing sensors to control the beam position and angle within the testbed.

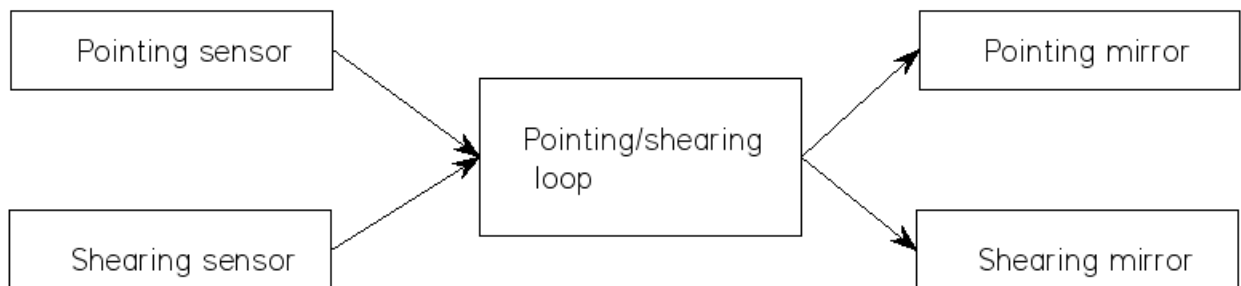


Figure 13: Pointing and shearing alignment loop.

### 11.3. Nuller pistons loop

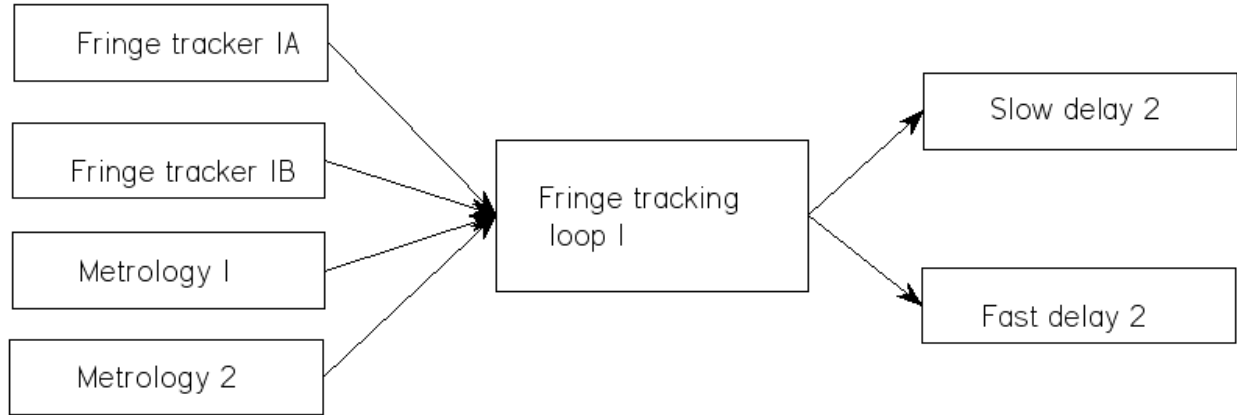


Figure 14: Fringe tracking loop using fringe trackers and metrology.

For fringe tracking when nulling, inputs from both the fringe tracking detectors and the metrology system are used, see Figure 14. These inputs are combined in such a way that the low frequency signal components from the fringe trackers are used to set the overall OPD, and the high frequency inputs from metrology are used to deal with testbed vibrations. The cross-over frequency is approximately 1 Hz. Almost all the control output goes to the fast delay stages, with the slow delay stages being used to desaturate the fast stages with a long time constant.

11.4. Cross-combiner chopping pistons mode

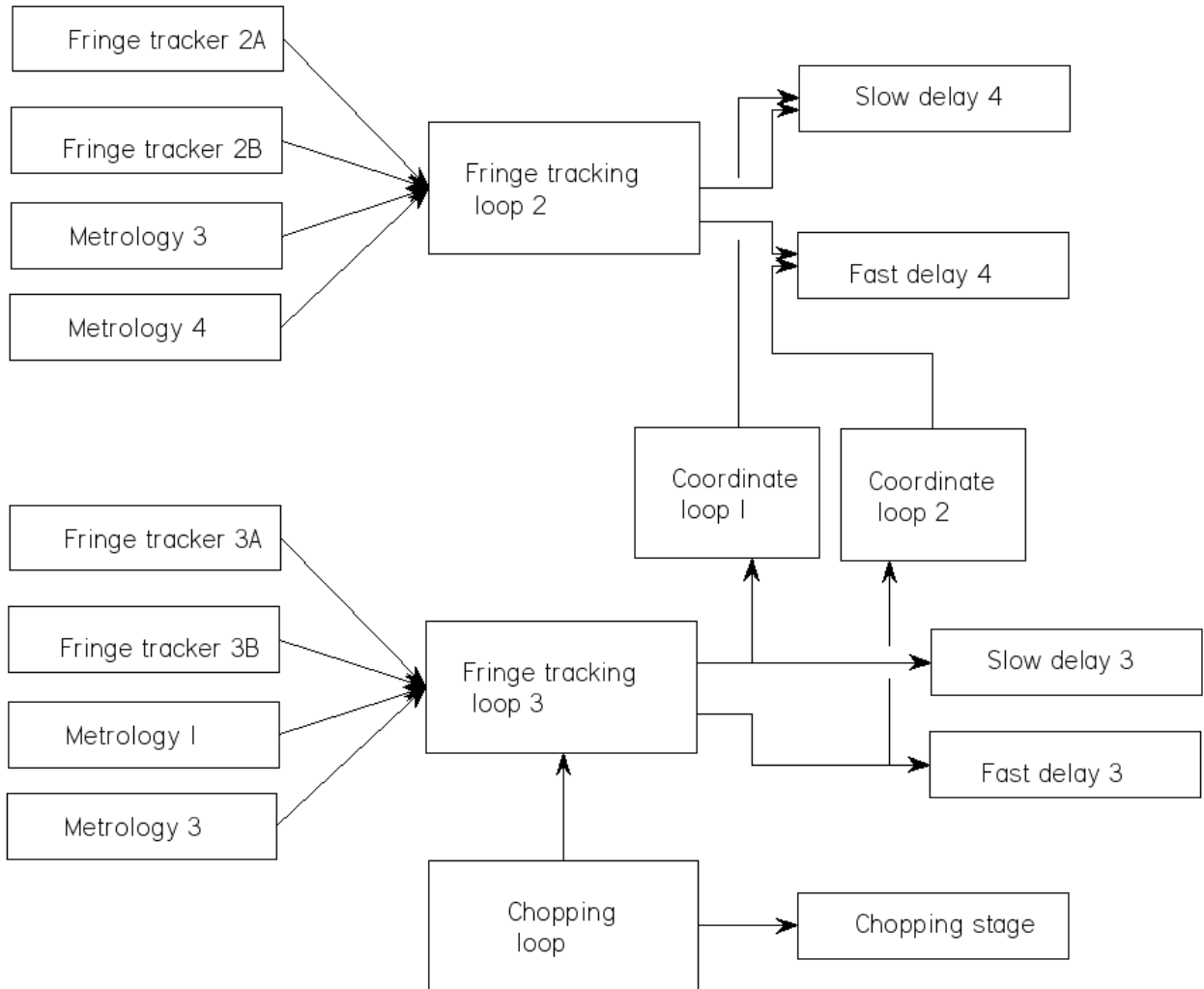


Figure 15: Fringe tracking loop setup when chopping.

Figure 15 shows the loop layout for nuller 2 and the cross-combiner. A more elaborate control system is required when chopping on the cross-combiner. The chopping stage moves between set points and the slow and fast delays 3 take care of cross-combiner phasing drifts. Since a movement on either of these stages would affect the null on nuller 2, the control signals for slow and fast delays 3 are fed forward via coordinate loops 1 and 2 to slow and fast delays 4. This minimizes null disturbances.

### 12. Appendix: Note on signal levels and noise on the detectors

Given basic differences between the current experiment and a flight system, the exact flight conditions are impossible to recreate. However, it may be possible to make a fairly congruent setup. Figure 16 shows a more detailed signal level schematic specific to the PDT which illustrates some of the practical issues when trying to simulate a particular signal-to-noise scenario. In the initial setup, sufficient neutral density filtering is inserted into the laser source to enable alignment and phasing of the nulling beams. At this point, the detector output is  $\sim 1$  Volt and the noise level (primarily amplifier noise) is  $10^{-4}$  V. The target  $10^{-5}$  null is at  $10^{-5}$  V, near a second, digitization noise level imposed by the analog to digital converter at  $\sim 10^{-5}$  V. The planet will be at  $10^{-6}$  V and the target absolute noise floor of the experiment will be at  $10^{-7}$  V. To limit the noise scenario, to choose an example, we would remove (once nulling) all the ND filters from the star source beam, pushing up the star, the null leakage and the post-chop noise by a factor of 1000. Also we would raise the lock-in detector's gain setting. This gain change will push down the digitization noise and simultaneously raise the amplifier noise, which could then be brought above the null leakage. Then the requirement would be to set up the planet signal at the correct relative intensity, given the available flux and transmission characteristics of the testbed. At the time of writing this paper, the exact flux and noise setup for the experiment has not been decided. The plan is to achieve a setup which allows demonstration of the key processes of chopping and averaging to reduce the instability noise, rather than attempting to mimic the flight scenario.

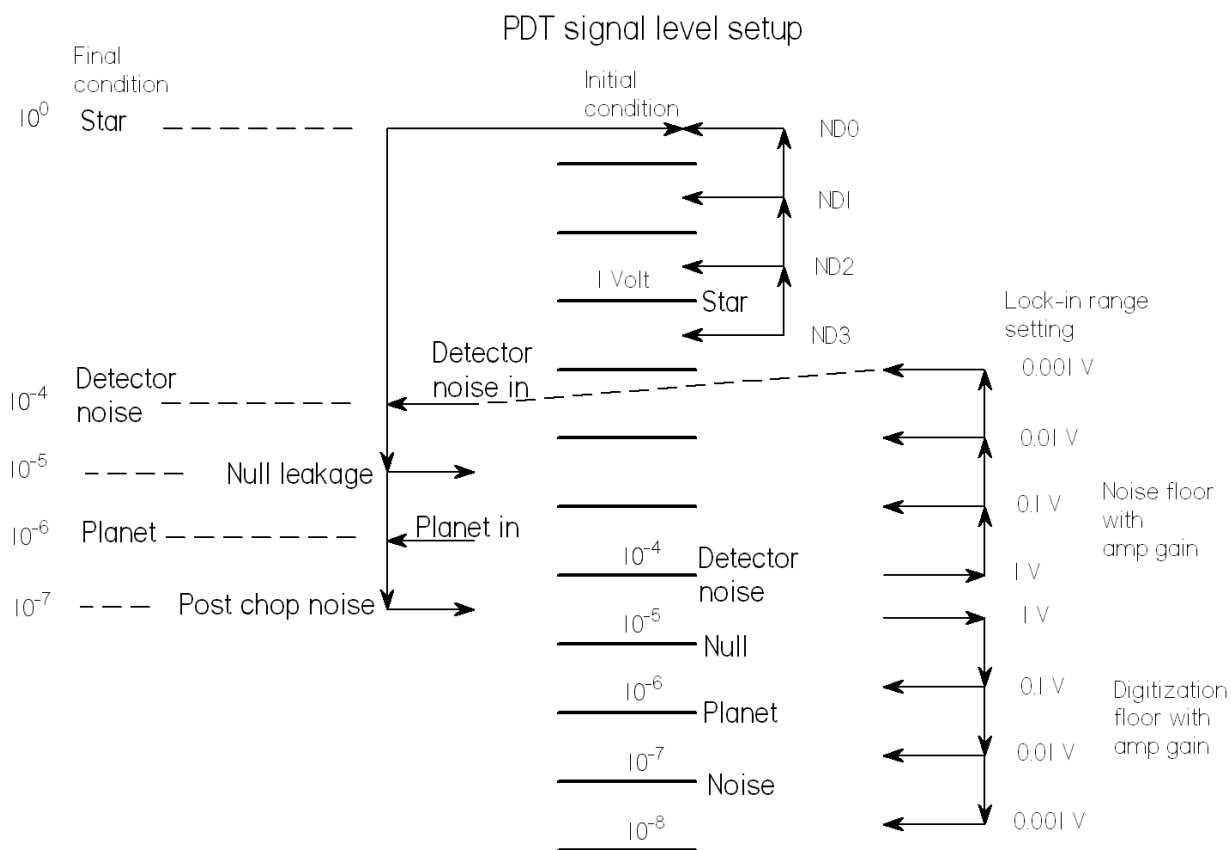


Figure 16: Signal level choices and interactions in the planet detection testbed.

## 13. Appendix: Previous Milestones

This appendix lists the technology milestones that have been established under the TPF-I project for the development of a formation flying array capable of measuring and characterizing the atmospheres of Earth-like exoplanets at mid-infrared wavelengths. Possible future milestones are also outlined.

### *13.1. Milestone #1: Amplitude and Phase Control Demonstration*

Using the Adaptive Nuller, demonstrate that optical beam intensity can be controlled with a precision of  $\leq 0.2\%$  rms and phase with a precision of  $\leq 5$  nm rms over a spectral bandwidth of  $> 3$   $\mu\text{m}$  in the mid IR for two polarizations. This demonstrates the approach for compensating for optical imperfections that create instrument noise that can mask planet signals.

"TPF-I Milestone #1 Whitepaper: Amplitude and Phase Control Demonstration," Edited by R.D. Peters, P.R. Lawson, and O.P. Lay (Jet Propulsion Laboratory, 18 December 2006).

"TPF-I Milestone #1 Report: Amplitude and Phase Control Demonstration," Edited by R.D. Peters, P.R. Lawson, and O.P. Lay, JPL Document D-38839 (Jet Propulsion Laboratory, 24 July 2007).

### *13.2. Milestone #2: Formation Flying Performance Demonstration*

Using the Formation Control Testbed as an end-to-end system-level hardware testbed, demonstrate that a formation of multiple robots can autonomously initialize, maneuver and operate in a collision free manner. A key maneuver, representative of TPF-I science will be demonstrated by rotating through greater than  $90^\circ$  at ten times the flight rotation rate while maintaining a relative position control to 5 cm ( $1\sigma$ ) per axis. This is the first step in a full validation the formation control architecture and algorithms and the testbed models developed by the Formation Algorithms & Simulation Testbed while physically demonstrating a scaled version of the approach to achieving the angular resolution required for the detection of terrestrial planets.

"TPF-I Milestone #2 Whitepaper: Formation Control Performance Demonstration," Edited by D.P. Scharf and P. R. Lawson (Jet Propulsion Laboratory, 25 May 2007).

"TPF-I Milestone #2 Report: Formation Control Performance Demonstration," Edited by D.P. Scharf and P. R. Lawson, JPL Document D-43009 (Jet Propulsion Laboratory, 16 January 2008).

### *13.3. Milestone #3: Broadband Starlight Suppression Demonstration*

Using either the Adaptive Nuller or the Achromatic Nulling Testbed, demonstrate that mid-infrared light in the 7-12  $\mu\text{m}$  range can be suppressed by a factor of  $\geq 10^5$  over a bandwidth of  $\geq 25\%$ . This demonstrates the approach to broadband starlight suppression (dimming of light across a range of wavelengths) needed to characterize terrestrial planets for habitability. Flight-like nulls are to be demonstrated at room (non-flight) temperature.

"TPF-I Milestone #3 Whitepaper: Broadband Starlight Suppression Demonstration," Edited by P.R. Lawson, R.O. Gappinger, R.D. Peters, and O.P. Lay (Jet Propulsion Laboratory, 10 October 2007).

### *13.4. Future Milestones*

At the time of writing, Milestones 1 and 2 have been accomplished and work is under way to complete Milestones 3 and 4. Milestone 4 is described in this document. Future milestones may include the following:

- 13.4.1.** Spectral filtering for planet signal extraction. This demonstration is the final level of noise rejection required to extract a planet, beyond starlight suppression, chopping, rotation, and averaging. It would be accomplished with the Planet Detection Testbed by introducing broadband light with a central wavelength near 10  $\mu\text{m}$ .
- 13.4.2.** Multi-spacecraft collision-avoidance demonstration using multi-spacecraft simulations, followed by demonstrations in a robotic testbed. These demonstrations will show autonomous control of two or more robots, with automated protocols for advanced sensing and avoidance of collisions under several possible scenarios.
- 13.4.3.** Fault-tolerance demonstration of spacecraft control using a multi-spacecraft simulations, followed by demonstrations in a robotic testbed. These demonstrations will show autonomous recovery from several fault scenarios, including failed thrusters, stuck (open) thrusters, and faulty sensors.
- 13.4.4.** Integrated modeling of the observatory concept that includes dynamic disturbances (e.g. from reaction wheels). This model would be validated with experimental results from the testbeds. A simulation would show that the depth and stability of the starlight null could be controlled over the entire waveband to within an order of magnitude of the limits required in flight to detect Earth-like planets, characterize their properties, and assess their habitability.

Further milestones might include cryogenic testing of components, subsystems, and systems, and flight demonstrations of formation flying sensors, thrusters, and autonomous guidance, navigation and control algorithms.