Optical Design for Terrestrial Planet Finder[1]

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Abstract— We describe the features of the optical system for Terrestrial Planet Finder, a space-based, cryogenic (35 K) interferometer for direct detection of Earth-type planets around nearby stars. Interferometric nulling suppresses stellar glare by a factor of several thousand or more, and phase chopping distinguishes planet light from the symmetric background. The mid-infrared (7-20 μm) is favorable for detecting planetary emission relative to that from the star, and this spectral region also offers important molecular signatures indicative of key atmospheric gases.

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1. INTRODUCTION

The Terrestrial Planet Finder (TPF) instrument faces a daunting challenge: extraction of light from a planet approximately one million times dimmer than the host star, yet separated from it by as little as 30 milli-arcseconds (0.15 microradians). Such are the characteristics of our solar system viewed from roughly 30 parsecs in the 7-20 μm wavelength range, the spectral region chosen to maximize the planet signal. This signal must be extracted from strong backgrounds, including stellar leakage, exo-zodiacal and local zodiacal light, and the instrument's thermal emission. In addition to this "planet finding" mode, the chosen interferometric design must be capable of acquiring images via rotational synthesis using baselines up to 1 km.

Many possible optical architectures have been considered for planet finding and rotational synthesis. A dual Bracewell interferometer on five separated spacecraft offers the most promising avenue for the TPF goals.

2. BRACEWELL INTERFEROMETER

The Bracewell interferometer [1] is a close relative of the Michelson stellar interferometer, which uses a beamsplitter to combine the light from two "collector" telescopes, one at the end of each interferometer arm. The optical electric fields from each collector add and subtract in the "combiner" depending on their relative phase at the beamsplitter. In the Bracewell configuration, this relative phase is 180° across the entire spectral passband. This gives destructive interference for on-axis light. Light from an off-axis source suffers different optical delays to each aperture, frustrating the precise cancellation that suppresses all wavelengths of on-axis light. This allows transmission at the location of an off-axis planet, while suppressing the light from an on-axis star.

Figure 1 shows how the transmission from a single Bracewell interferometer varies across the sky. The central dark vertical stripe is centered on the star to suppress its signal, while a light source in any of the bright stripes to either side will be transmitted with high efficiency. The angular spacing of the stripes is λ/B, where λ is the observation wavelength and B is the projected separation of the collector telescopes (baseline). For λ=10 μm and B=30 m, the figure shows the first transmission peak at 0.03 arcsec, less than the Earth-Sun angular separation as seen from 10 parsecs. (These dimensions are for reference, not

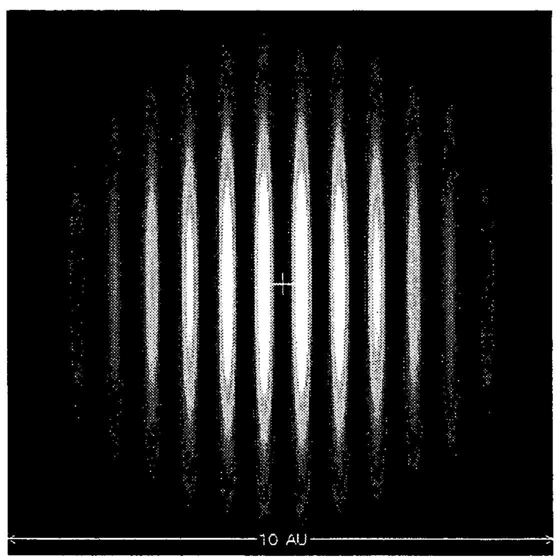


Figure 1: Single Bracewell Fringe Pattern for 10 μm light. On this transmission pattern from a single 30 m Bracewell interferometer, the position of the star is indicated by the cross, and is centered on the achromatic dark fringe (null). The field is 1 arcsec, corresponding to 10 AU at 10 parsecs. The 3.5 m collector mirror diameters give the indicated radial decrease in sensitivity due to diffraction.

necessarily for a robust mission).

Unlike a conventional telescope, an interferometer does not create a 2-D image on a detector array. Instead, a detector measures the sum of all of the light at a given wavelength from the collective sources in the field of view, with each source weighted by the striped transmission pattern. An image of the planetary system is constructed from the rise and fall of the detected signal as the instrument constellation rotates around the line of sight to the star and the transmission stripes sweep across each planet.

Because the spacing of the stripes is proportional to wavelength, narrow spectral regions are detected separately to prevent blurring of the image. This is done using a simple spectrometer, splitting the 7-20 μm passband into about 20 channels.

There are many challenges in the Bracewell approach. We wish to cancel two optical electromagnetic waves with very high precision—matching them in amplitude and phase, in both polarizations, across a 1.5-octave wavelength range. According to the preliminary leakage budget in Table 1, we must match: 1) the intensities of the beams to about 10^{-5}; 2) the total optical paths from the star to the beamsplitter via each aperture to about 14 nm RMS; and 3) the wavefronts to about 100 nm RMS. Each leakage source will likely require active control.

The present TPF architecture, shown in Figure 2, incorporates two interlaced Bracewell interferometers to modulate, or "chop," the planet light while the large background signal contributions remain constant. This phase chopping produces an asymmetric transmission pattern, making sources such as planets detectable on top of large symmetric background signals from the star, exo-zodiacal emission, and changes in the instrument sensitivity. This design reduces the instrument's sensitivity to slow variations in backgrounds that could otherwise mimic planetary signals.

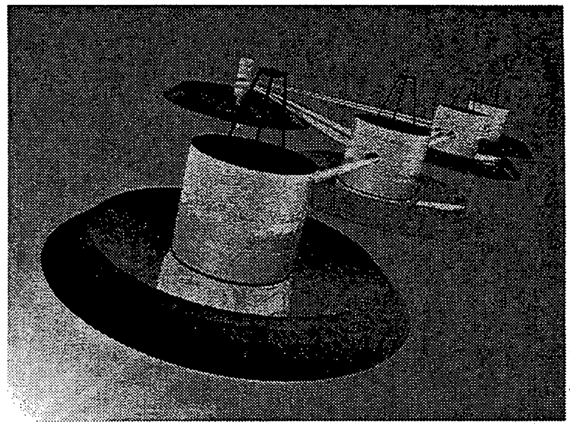


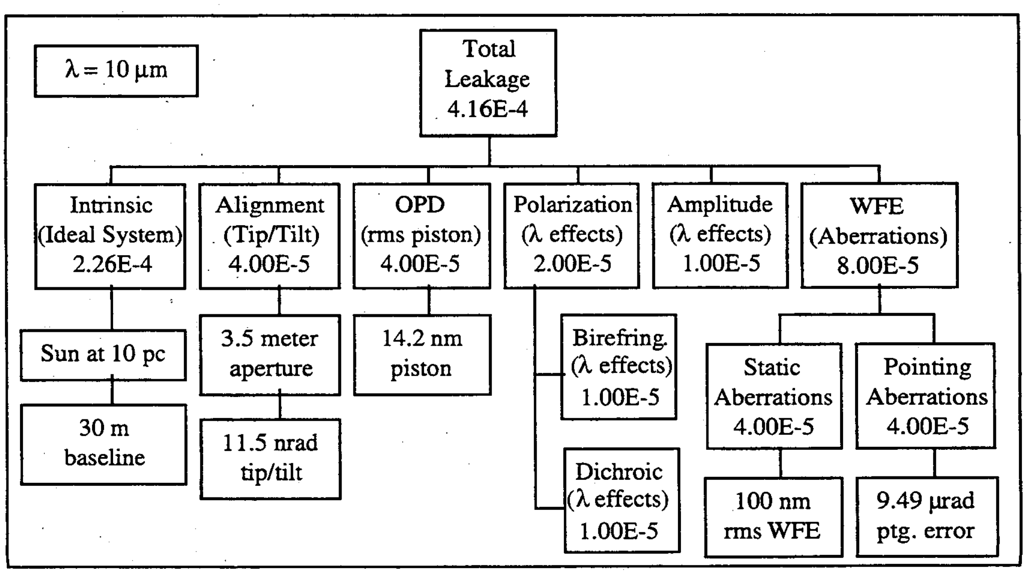
Figure 2: TPF Configuration. This perspective drawing shows the four collinear collector apertures and the combiner system behind them. (from TPF Decadal Review web site, picture by TRW)

To the extent that false modulation signals can be controlled, the planet sensitivity is limited by noise in the backgrounds. This chopped, dual Bracewell architecture allows higher backgrounds and looser optical tolerances than equivalent non-chopped configurations.

3. TPF Instrument Elements

The TPF Instrument comprises all the cold components of the TPF spacecraft. This includes five coplanar instrument elements: one combiner, and four collector telescopes. These are described in subsequent sections. The arrangement shown in Figure 2 provides equal-length

Table 1 Preliminary Starlight Leakage Budget. Leakage is given as a fraction of the original starlight signal.



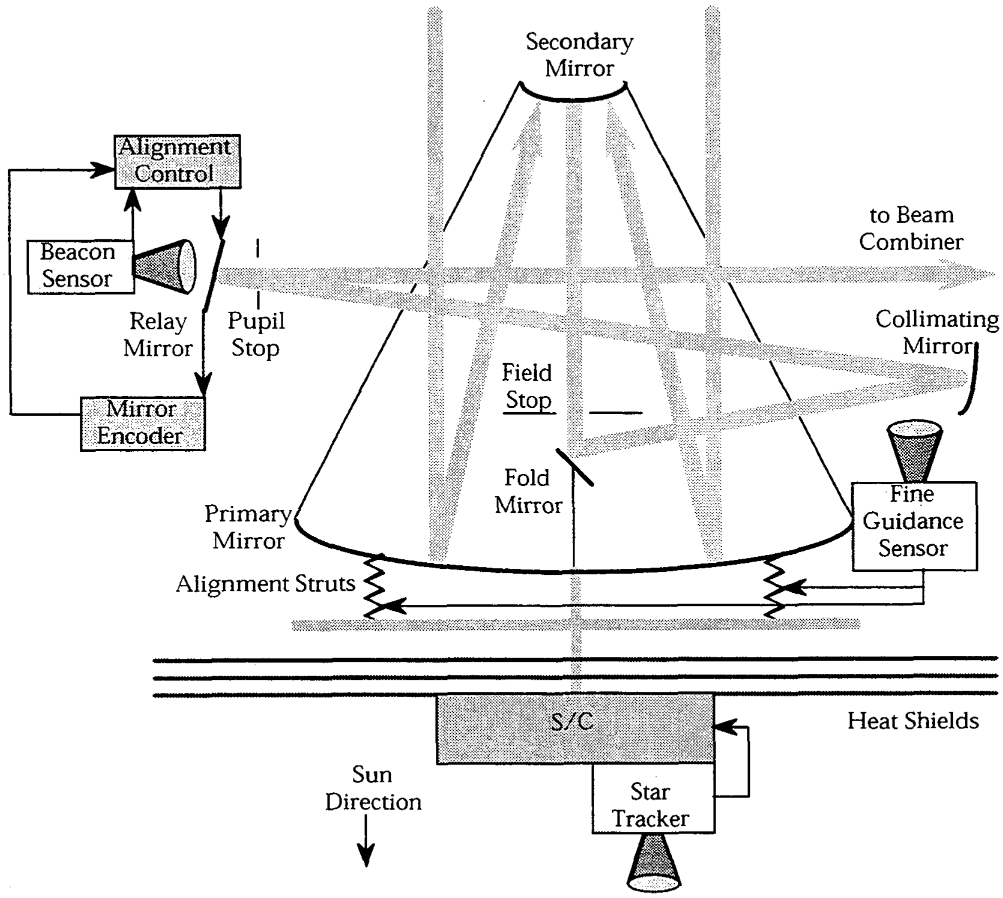


Figure 3: Beam Collector Telescope. Schematic diagram showing alignment systems.

starlight paths, addresses structural stability and alignment considerations, and minimizes polarization effects by employing equal and small incidence angles of reflection throughout.

Each component has an associated beam projection subsystem controlling the input and output beam paths by use of a fast steering mirror. Each of the control loops pointing the projection, relay, and receiving mirrors is driven by centroiding laser beacon inputs on quad cell detectors.

Thermal shields, shown as black saucers under the silver instrument cylinders in Figure 2, passively cool the optics to 35 K while allowing ±45° look angles in the anti-sun direction. The shields also offer some protection from optical surface degradation due to thruster contamination.

4. Beam Collector Telescopes

The main collector requirements for planet finding are very high quality wavefronts, good rejection of stray light, and large enough apertures to produce detectable planet signals.

The collector telescopes (a schematic of one is shown in Figure 3) will use a coudé-folded Ritchey-Chretien optical layout. The collectors will have identical apertures with primary mirrors roughly 3.5 m in diameter. Elliptical shaped primaries of dimension 3 x 4 m may be used for better S/C packaging into the launch vehicle fairing while providing similar collecting area.

A fast-steering mirror projects the collimated output beam from each collector laterally to a relay mirror residing on the adjacent inner collector. That fast-steering relay mirror then directs the beam to the center of the appropriate combiner element receiving mirror. This relay path nearly equalizes all four beam paths from the astronomical source to the combiner spacecraft, as shown in the inset of Figure 4.

The collector telescope must be pointed within a few arcseconds of the target star to keep wavefront errors small. Although an alternate Gregorian design has greater off-axis tolerance, both this and the Ritchey-Chretien design use only a very narrow field of view for TPF. Active pointing of the entire telescope is planned to keep the observed object on axis. With spacecraft attitude control providing ±15 arcsec 3-axis platform pointing, piezoelectric alignment struts can control the fine telescope pointing, commanded by an internal fine guidance sensor.

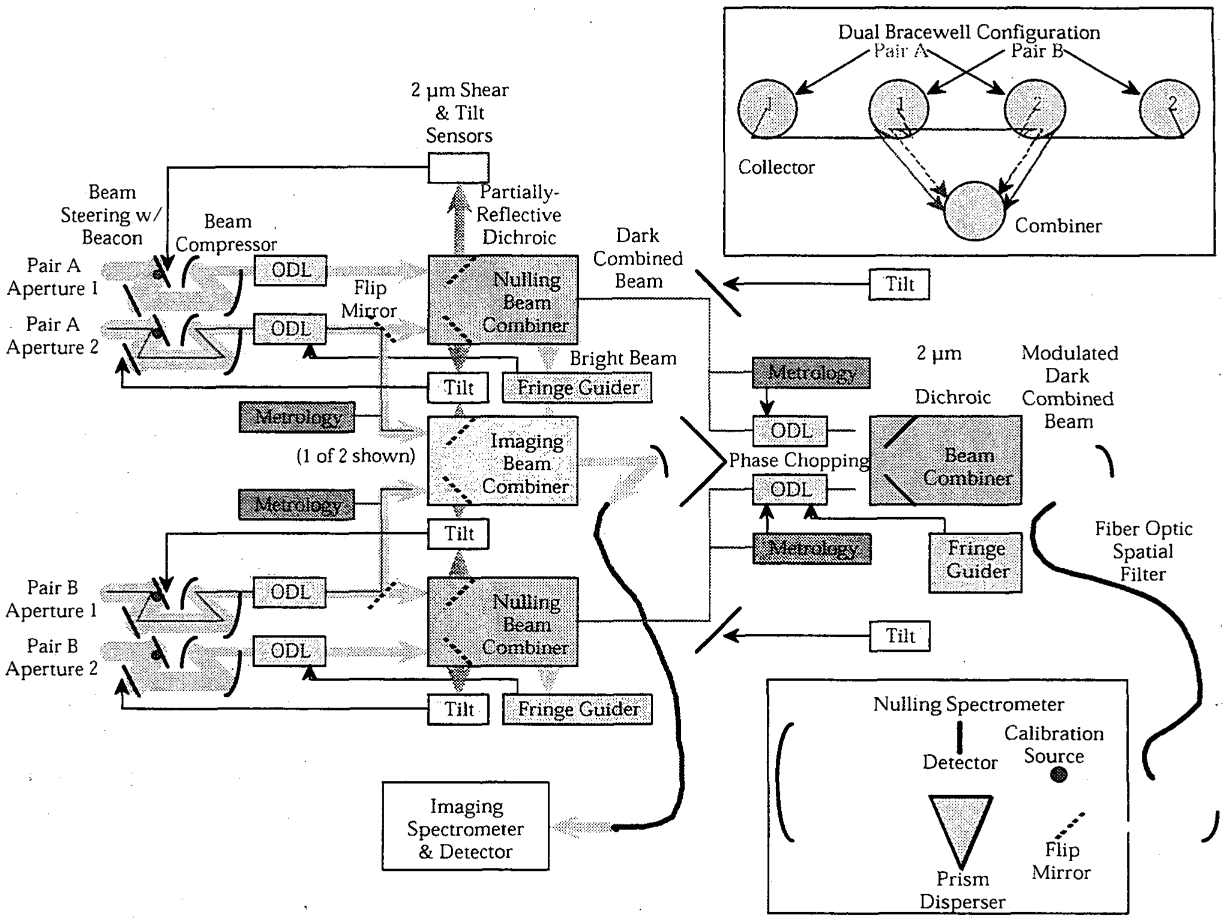


Figure 4: Beam Combiner Schematic. Starlight enters from the left. For planet finding, two nulled, dark beams are combined after relative phase shifts that produce a chopped, asymmetric transmission pattern. A separate beam combiner and optical path are used for rotational synthesis imaging. Not shown are beam conditioning amplitude and wavefront sensors and correctors.

5. Beam Combiner

The beam combiner is the most complex element of the TPF instrument. Its internal optical train is fed by four fast-steering mirrors which receive all the beams from the projection/relay mirrors on the two inner collector spacecraft. In the rotational synthesis imaging mode, the light originating from the innermost and outermost collector pairs is interfered in two separate "imaging" beam combiners. In the planet-finding mode, light from the two interleaved pairs of collectors is interfered in a high-precision "nulling" beam combiner, then the results from these are combined in an imaging-type beam combiner. Figure 4 shows a block diagram of the combiner element optical system.

The combiner components and operation can best be described in terms of its functional subsystems: beam conditioning optics, nulling beam combiner, and imaging beam combiner.

Beam Conditioning

Great care must be taken in transferring the starlight beams from the collector spacecraft to the combiner. The light needs to be delivered without beam vignetting or stray light contamination. Avoidance of beam clipping helps maintain amplitude balance between the interfering beams. Rejection of stray light is needed to keep the planet signal from being obscured.

Careful control of stray light is critical in detection of the extremely faint planetary signal. Stray light will be reduced through the use of cold pupil and field stops in the collector and combiner optical systems. The beams between spacecraft suffer losses from beam expansion and pointing errors. Losses will be minimized by using fairly large (~15 cm diameter) transfer beams to reduce diffraction and by oversizing optics to capture the entire expanded beam at the relay mirrors and the combiner.

The light entering the beam combiner must be corrected for wavefront and amplitude differences between the two arms of a collector pair. The corrective systems will presumably be active. Shorter wavelengths (~2 μm) of the incoming beams are separated from the mid-infrared (7-20 μm) light and used for beam alignment via fast steering mirrors. Each input 15 cm diameter beam is optically compressed to 3 cm to minimize the size of the subsequent optical components in the combiner.

The beam delivery must also match the optical path lengths to within the corrective capabilities of the optical delay lines (ODLs) in the combiner. Fringe detection requires an optical path difference (OPD) less than the coherence length (~100 μm), but precise nulling requires an OPD on the order of 14 nm RMS. The multi-stage ODLs regulate the total OPD between the two arms of a pair to nearly zero using inputs from starlight fringe information and from laser metrology measurements. The necessary dynamic range and precision are achieved with several levels of control, as demonstrated at the Palomar Testbed Interferometer [2] and the Keck Interferometer [3]: a stepper-motor-driven lever mechanism offers a stroke of 2 m and control to 1 mm; a voice coil offers travel of 2 mm and control to 1 μm; and piezoelectric actuators can move up to 2 μm with an accuracy of 1 nm. Use of these actuators decreases the OPD to make possible the detection of the fringes.

The wavefront- and amplitude-corrected light of equal optical path lengths is then launched into either the planet-finding (nulling) or the rotational synthesis imaging beam combiner path by flip-in mirrors.

Planet-Finding

For the planet-finding mode, each Bracewell collector pair nulls the starlight to the best of its ability, producing a "dark beam" containing the planet light and background signals, but with destructively interfered starlight. Nulling beam combiners introduce an achromatic 180° phase shift between the arms of each collector pair to nearly eliminate the starlight. This nulling beam combiner is described in a subsequent section.

The two dark, or "nulled," beams are then combined by an imaging-type beam combiner after traveling through additional ODLs. These ODLs nearly equalize the path lengths between the nulling beam combiners and the imaging-type combiner. One also varies the relative phases of the beams between +90° and -90° at about 0.1 Hz. This "phase chopping" process modulates the net fringe pattern seen by the interferometer on the sky between two mirror-image fringe patterns. The difference of the two chopped patterns is anti-symmetric about the star, and reduces the signals from symmetric sources, such as the star, exo-zodiacal emission, and changes in the instrument sensitivity. Signals from asymmetric sources, such as planets, are maintained. This chopping substantially eases nulling performance requirements by reducing the instrument's sensitivity to slow variations (<<0.1 Hz) in thermal emission and detector sensitivities within the optical system. Without chopping, such effects could mimic planetary signals over the few hours required for a constellation rotation.

The resultant signal after the imaging-type beam combiner is focused onto a spatial filter, which reduces stray light and sensitivity to aberrations in light amplitude or wavefront. The spatial filter isolates light from a small region (approximately one Airy diameter across) around the focus. Leakage in the incoming beam resulting from high-order wavefront aberrations will be strongly suppressed, leaving only the effects of the lowest-order aberrations, such as tilt, focus, coma, astigmatism, and spherical aberration. This filter thus relaxes high-order wavefront requirements on the optical system to approximately 100 nm RMS, as given in Table 1, rather than the 14 nm RMS limit for low-order distortions. This approach has been successfully demonstrated [4].

The spatial filter is nominally a single-mode fiber optic or other waveguide placed at a focus of the starlight beam. A single-mode fiber optic transmits only the light with a specific transverse profile of electric field, and rejects any incident light with a different transverse profile, such as the light falling outside the first Airy ring. Since an upstream field stop selects only the target star, there will be no other star images present at this point.

A spectrometer spectrally disperses and focuses the light onto a detector. The system thus measures the contribution of light from all parts of the configuration's fringe pattern as a function of wavelength. This signal is used to determine the existence, location, and brightness of terrestrial-like planets around nearby stars. Given adequate S/N, key atmospheric gases could be detected from their spectral signatures. A thermal calibration source maintains relative spectral calibration.

Imaging

For rotational synthesis imaging, light from the innermost and the outermost collector pairs interferes in an imaging beam combiner only with the other aperture in that pair. This light travels through a spatial filter and to a spectral detection system, similar to those in the nulling system. Only the beam combiner for the innermost pair is shown in Figure 4, although there is a similar system for light from the outermost pair. Differences between the imaging and the nulling systems include not only the beam combiners, but also the detector systems, as there is a large intensity difference expected in the two systems.

6. NULLING BEAM COMBINER

One of the core requirements of nulling interferometry, as needed for the Bracewell configuration, is to provide precise subtraction of the optical fields from each aperture across the entire spectral passband used. This requires an achromatic 180° phase shift between the two starlight beams so that the beams will subtract rather than add.

The value of this achromatic phase shift is critical for meeting nulling requirements; our goal is 180°±0.08° throughout the passband. For monochromatic light, a 180° delay can be achieved by simply moving a mirror. This

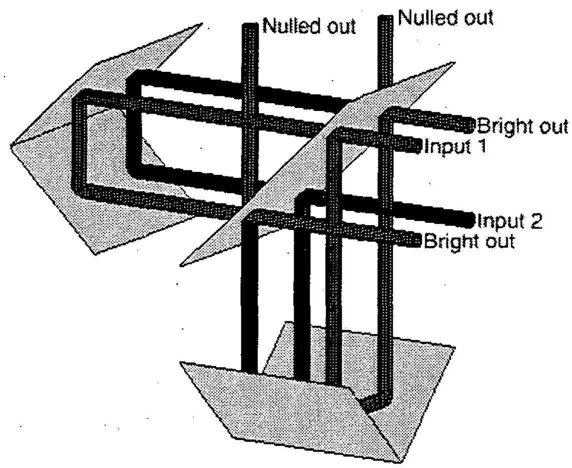


Figure 5: Achromatic Nulling Beam Combiner. Each input starlight beam ("red" and "blue" from different arms of the interferometer) is split at the beamsplitter. The beams undergo polarization flips such that when they recombine, they produce two nulled and two bright output beams (purple).

won't work for TPF's 7–20 μm light: a λ/2 delay at λ=11 μm produces phase shifts varying from 106° to 304° across the passband.

The NASA/Jet Propulsion Laboratory achromatic nulling beam combiner design, shown in Figure 5, overcomes several problems. This excellent candidate design uses reflection from two dihedral mirrors to provide an achromatic null [5]. Each dihedral inverts one component of the incident light's polarization before the beams are combined at the beamsplitter. This provides a net sign inversion of one beam with respect to the other. It also causes a 180° relative pupil rotation, which ordinarily is a serious problem in optical interferometry; but since this is effectively a zero-field-of-view instrument, we only need to ensure that the beams are aligned well in tip and tilt.

Additionally, each input starlight beam encounters the beamsplitter exactly once in transmission and once in reflection, so the amplitude balance of each contribution to the nulled output is unaffected by variations of beamsplitter reflectivity and transmissivity across the 7-20 μm wavelength range. This is an enormous advantage, and eliminates having to compensate those variations explicitly in each beam.

7. Conclusions

This design concept for the optical configuration of the Terrestrial Planet Finder has been developed to help illuminate major design tradeoffs and technology challenges. There will be a lengthy design refinement process required, based partly on technology demonstration programs, before an eventual system design is established in detail. With over a decade remaining before the TPF mission will be launched, the authors and JPL welcome contributions to improving this design concept and assisting in bringing TPF toward its operational success.

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Biography

***Charley Noecker** (Ph.D., 1988, Univ. of Michigan) is a systems engineer at Ball Aerospace & Technologies Corp. (BATC). Since joining the company in September 1995, he has led numerous interferometry activities at Ball, including JPL-funded studies of the Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF). Prior to 1995, he worked at the Smithsonian Astrophysical Observatory (SAO) in Cambridge, MA; there, he participated in studies of the Precision Optical INTerferometer in Space (POINTS), including development of a laser distance measurement system with sensitivity and stability of 2 picometers ($2x10^{-12}$ meters). His career has always followed the path of measuring small things, beginning with doctoral studies of parity nonconservation in atomic cesium.*

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Brian McComas *(M.S., Physics, Univ. of Connecticut, M.S., Electrical Engineering, Univ. of Colorado) is an electro-optics engineer at BATC, where he works in the Integrated Modeling and Simulation Lab. Since joining the company in 1997, he has developed mathematical models and simulations for several interferometry and remote sensing instruments. Prior to joining Ball, he was a Member of Technical Staff at Santa Barbara Research Center, where he was the Responsible Engineering Authority for the Solar Diffuser Stability Monitor (SDSM) on the Moderate Resolution Imaging Spectroradiometer (MODIS). He is currently pursuing a Ph.D. in Electrical Engineering at the Univ. of Colorado.*

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