

# Nulling Interferometric beam combiner utilizing dielectric plates: experimental results in the visible broadband

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## ABSTRACT

The heart of TPF is the nulling beam combiner: a set of optics that combines the light from various collecting telescopes to produce a central destructive fringe rather than the natural constructive fringe.<sup>1</sup> The difficult aspect of the beam combiner is to control the relative phase shifts over a broad spectral range. One method of controlling the phase shifts to create an achromatic null utilizes dielectric plates analogous to using several glasses to make an achromatic lens.<sup>2,3</sup> The optical thickness of two dielectric plates and air path spacing are balanced to generate a phase shift that is independent of wavelength, to a certain requirement. While it is possible to make achromatic phase shifts of 180 degrees using rotation shear, the method of dielectric plates can produce any desired achromatic phase shift, enabling numerous aperture designs for nulling telescope arrays. The phase shift can easily be changed using active control of the plates and delay line, which allows for *in situ* reconfiguration of the interferometric array. Matching dielectric plates and their solutions have been found for TPF which offer a null of better than  $10^{-6}$  from 7-17  $\mu\text{m}$ , and for SIM a null of better than  $10^{-4}$  over a 35% bandwidth in the visible region.

This paper describes a laboratory experiment of achromatic nulling in the visible to SIM requirements. The experiment employs phase shifting interferometry techniques on a spectrally dispersed fringe to measure the phase as a function of wavelength. This phase is then used by a control system that adjusts the tilt of the plates and the air path difference until a satisfactory level of null is achieved. A fast servo adjusts the air path difference to stabilize the phase to the nanometer level. The paper includes a discussion of the design issues, the experimental measure of phase versus wavelength, a description of the control system, and a preliminary measure of the null.

**Keywords:** nulling, beam combining, dispersion, achromatic phase shift, dielectric plates, SIM, TPF

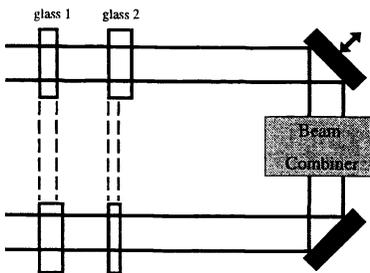
## 1. INTRODUCTION

Several configurations have been proposed for the TPF and Darwin missions,<sup>4</sup> and further configurations are under consideration. An early configuration for Darwin proposed by Mennesson and Marriotti<sup>5</sup> uses five telescopes, with a phase difference between each telescope of a fifth of a wave. The fifth of a wave phase difference can be attained by this nulling technique. This technique is not restricted to a 180 degree phase shift, any fraction of wave can be produced; one can dial-a-phase.

The phase shift is actively controlled by tilting the dielectric plates to vary optical path. Such control would allow for a change of the phase shift *in situ*. The array could be reconfigured in the unfortunate loss of a telescope. Or, for the six element degenerate Angel cross proposed by Mariotti,<sup>6</sup> the array could be split into two arrays in the happy event of the discovery of more than anticipated objects requiring the long integration times for spectroscopy.

## 2. PHASE DELAY WITH DIELECTRIC PLATES

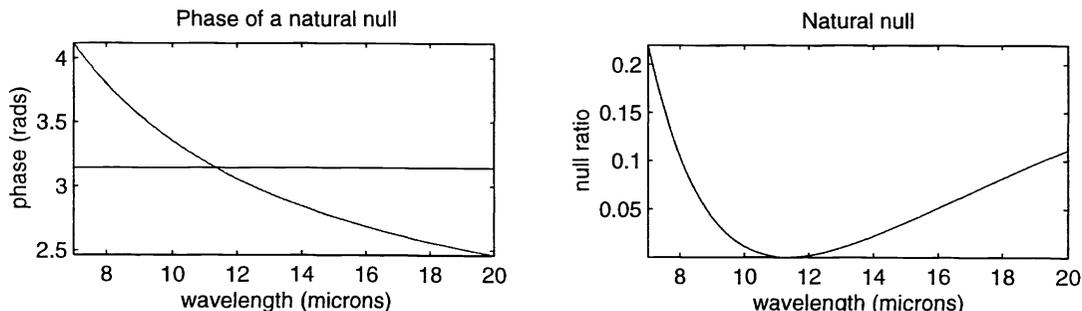
A null can be created by adding optical path delay to the interferometric beam combiner as depicted in Figure 1. The simplest way to add path delay is to move a delay line the appropriate half wave. Monochromatically, this is quite successful. But we desire to operate at a broad bandwidth. At a full octave of bandwidth, half a wave at one wavelength corresponds to a full wave at another wavelength. The phase varies as one over the wavelength as shown in Figure 2. If we could somehow add optical path to the other arm to balance the term that is linear with wave



**Figure 1.** Optical path delay is introduced through mirror spacing and the optical thickness of dielectric materials. The mirror spacing and the material thicknesses are precisely balanced to produce the desired phase shift in a highly achromatic fashion, analogous to an achromatic lens.

number, we could reduce the chromaticity of the null. The null ratio is defined as the ratio of the minimum fringe irradiance to the maximum fringe irradiance.

We can't simply move the delay line of the other arm of the interferometer, but we can add optical path delay through a dielectric medium, such as a glass plate. The resulting phase difference, seen in Figure 3, is balanced in the linear component. The residual chromaticity is a second order curvature due to the dispersion of the dielectric material. This null is still not deep enough for detecting earth like planets.



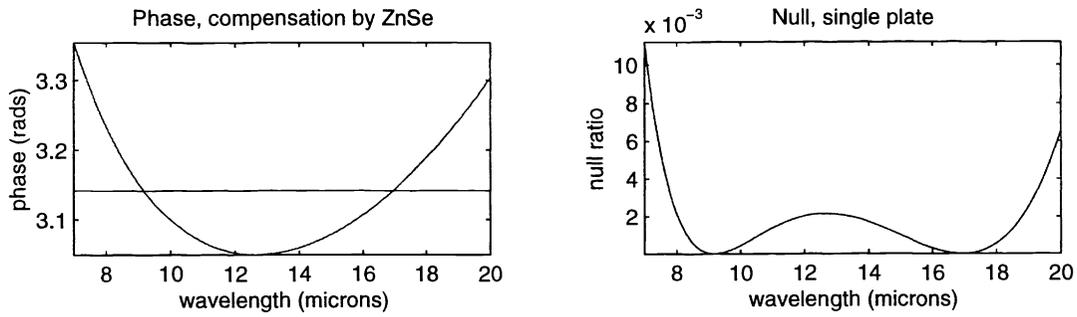
**Figure 2.** The phase and null variation with wavelength for a 30% bandwidth in the 7-20 um region for the case of  $\pi$  phase shift. A phase shift via delay line alone produces a phase variation that is inversely proportional to wavelength.

Fraunhofer was the first to use two different types of glass to balance the dispersion of each glass, thus creating an achromatic lens. We apply the same idea by inserting a plate of a second dispersive material, strategically chosen to balance the dispersion of the first dielectric as illustrated by Figure 4. In the final solution, the air path and the thicknesses of the two plates balance to generate a half wave phase difference which is achromatic. The residual phase error has a third order curvature. The phase error could be further reduced by adding additional plates, but two dielectric plates have been sufficient to yield solutions for both SIM and TPF which are shown in Figures 5 and 6.

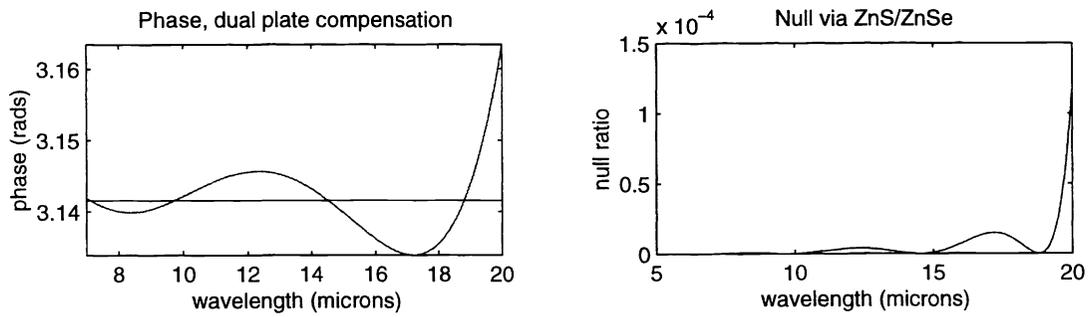
The thickness of dielectric required in the final solution is very thin, on the order of tens of microns. A single plate so thin is not used. Instead, two identical plates are used, one in each arm, where one of the plates has been thinned the appropriate amount. The optical path difference through the dielectric is finely tuned by tilting one of the plates.

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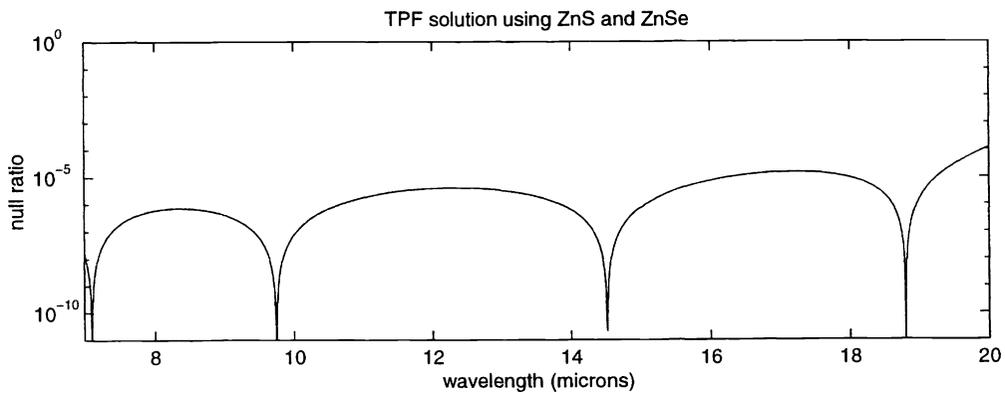
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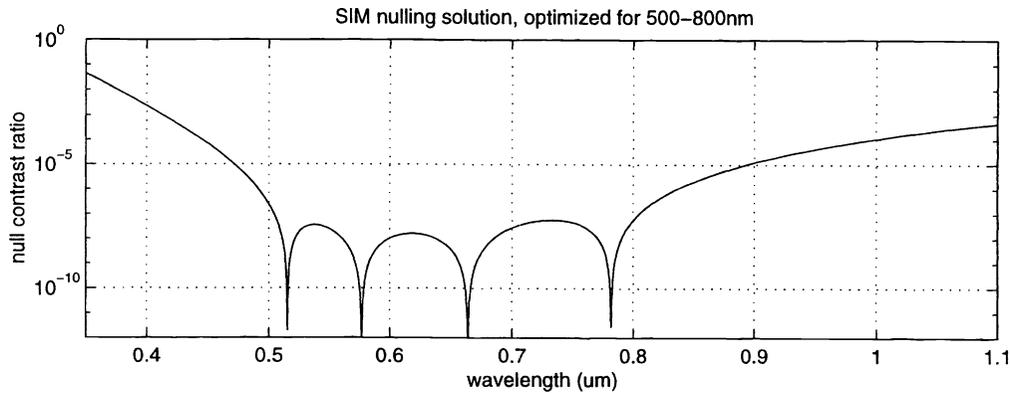
**Figure 3.** The delay line and a single plate of ZnSe and create a less chromatic phase shift. The residual phase error is due to the nonlinear dispersion of ZnSe.



**Figure 4.** The left plot shows the phase compensation using both ZnSe and ZnS plates. Only a third order term is residual.



**Figure 5.** Phase compensation using both ZnSe and ZnS meets the TPF requirements for a null of  $10^{-6}$  from 7 to 17  $\mu\text{m}$ . The null deepens at 7.1  $\mu\text{m}$ , 9.7  $\mu\text{m}$ , 14.5  $\mu$ , and 18.7  $\mu$  which correspond well to the absorption lines for  $\text{CH}_4$ ,  $\text{O}_3$ ,  $\text{CO}_2$ , and water.



**Figure 6.** The technique provides a solution for SIM for a 30% bandwidth in the visible with nulls deeper than the planned path length control allows.

For selecting materials in the infrared, the choices are limited as few materials transmit to 18 microns or beyond. The materials CsI, CsBr, CdTe, CdSe, Ge, ZnS, ZnSe, KBr, KCl, AgCl, and KRS-5 were paired with each other. The best solution was the ZnS/ZnSe combination. This combination has even lower nulls at particular wavelengths that correspond to certain spectral features of interest: ozone at 9.7  $\mu\text{m}$ , CO<sub>2</sub> at 15  $\mu\text{m}$ , and water past 18  $\mu\text{m}$ . However, little data is available on the absorption and index of refraction of infrared materials at cryo temperatures.

For selecting materials in the visible, several rules of thumb have been developed. A single plate of glass may create a sufficient null in the region near the minima in its dispersion. BK7 has the lowest wavelength minima, and also one of the lowest dispersion of the common optical glasses. To pair with BK7, fused silica has a nearly identical curvature to its dispersion in the visible region. This well matched dispersions will allow for lower residual chromaticity. In general, the two glasses should have different indices of refraction but similar dispersion curves.

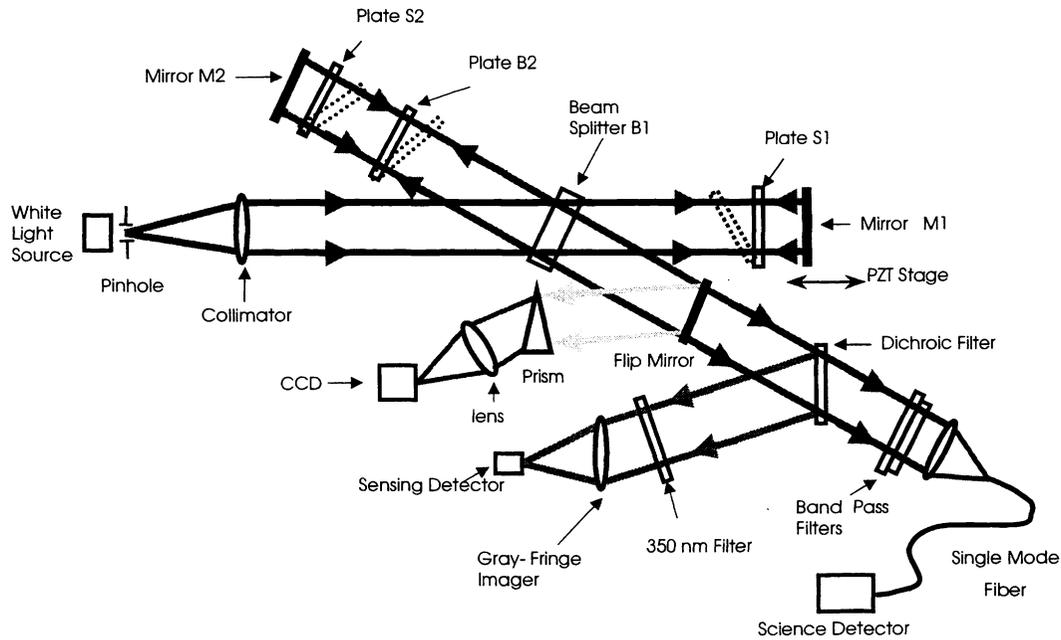
### 3. EXPERIMENT

A laboratory testbed was constructed to demonstrate nulling using dielectric plates at the SIM nulling specifications. The testbed consists of a standard Michelson interferometer with added dielectric phase plates which are actively controlled. The testbed allows for development of the control system and does not address amplitude control issues.

The goal for TPF is a null of  $10^{-6}$ . At a wavelength of 10 microns, this requires that the path lengths are matched within 1 nm and the amplitudes equal to 0.1%. At a visible wavelength, the pathlength of 1 nm will produce a null of  $10^{-4}$  and require amplitude matching to only  $\pm 2\%$ . For these reasons, the laboratory demonstration of phase delay using dielectric plates is implemented in the visible with a Michelson style interferometer as in figure 7. Because a Michelson is a double pass interferometer, the two arms have equal amplitudes, and the phase control issue can be address without simultaneously having to control amplitude inequalities. In a single pass configuration, the beam splitter will contribute a 90 phase shift to the transmitted beam, so that only an additional 90 degrees must be contributed by the dielectric plates. In a double pass configuration, the phase plates must provide the full 180 degrees phase shift so that all the optical thickness are twice what they would be in a single pass implementation.

#### 3.1. Optical Hardware

The interferometer uses phase plates made of BK7 and silica. The matched plates are 8 mm thick, 12.5 mm in diameter from identical lots. A plate of each material was reduced in thickness by 200 microns, with the remaining thickness difference of about 25 microns achieved through tilting the plate by less than five degrees. A beam splitter coating was applied to one BK7 plate, the remaining surfaces received broadband antireflection coatings. We have made an effort to minimize polarization amplitude splitting in the interferometer. To keep the splitting ratio to less than  $10^{-4}$ , the incident angles must be less than eight degrees on the glass plates. Stress birefringence must also be considered. Fused silica has a stress birefringence of 4 nm/cm, which is sufficient for a 8 mm thick plate. The BK7 required the highest grade PSSK, with extra care in annealing to reach an acceptable stress birefringence of



**Figure 7.** Experimental layout of the white light nulling interferometer.

6 nm/cm. The identical end mirrors have an enhanced silver coating with a reflectivity of  $> 99\%$  over the visible band, meeting the requirement for amplitude equalities of  $\pm 2\%$ .

The source is a krypton bulb with high surface brightness. A 25 micron diameter pinhole and an infinite conjugate microscope objective collimate the beam to a diameter of 4 mm.

Each compensator plate sits on a rotary stage adjusted by a Picomotor<sup>TM</sup>. One mirror sits on a Picomotor<sup>TM</sup> driven translation stage for coarse control, and a PZT driven flexure translations stage for fine control. The low-voltage PZT is rated for 5 nm resolution, but by using a higher resolution D/A converter and no need for an amplifier, we hope to achieve a 1 nm resolution of path length control.

The output of the interferometer is fed to three different detectors. The science detector is a single photon counting detector at the end of a single mode fiber that measures the null. The single mode fiber is essential as a spatial filter, to eliminate the background due to scatter and aberrations. Bandpass filters before the fiber select the desired spectral region of 600-800 nm. A dichroic beamsplitter directs shorter wavelengths to a photodiode which acts as the gray fringe sensor, as described in section 3.3, for the fast servo control loop. The final detector measures the chromaticity of the null, the phase versus wavelength. This measurement is made first, to find the correct tilt of the glass plates and mirror spacing to produce an adequately achromatic null, as discussed in section 3.2. After an adequate null solution is found by the control system, the fold mirror is removed so that the interferometer output goes only to the science detector and gray fringe detector.

### 3.2. Measuring Phase Chromaticity

To know how to adjust the phase plates, we must know the behavior of the phase with wavelength. We use a prism to disperse the fringe spectrally, then image the dispersed fringe on a CCD camera. The fringe is then modulated

by the PZT, and sequential frames read from the CCD, so that phase shifting is performed on the dispersed fringe. The reduced data yields a phase at each pixel, where each pixel corresponds to wavelength. Thus a relative measure of the phase versus wavelength is produced.

### 3.3. Control on a gray fringe

A fast servo loop is required to stabilize the null in the presence of air turbulence and mechanical vibration. The null provides a poor signal for a servo, because there are, hopefully, no or few photons in the signal, and the null is the bottom of a cosine fringe, the place in a cosine function least sensitive to changes in OPD. The most sensitive portion of the cosine function occurs at a gray fringe, a quarter of a fringe away from the null. We can maintain common path and sense at the gray fringe by sensing at a different wavelength, a wavelength at which the phase plate configuration produces a gray fringe. The ideal phase plate configuration for this experiment produces a gray fringe at 350 nm. The light levels and fringe phase remain adequate within the tolerances of the phase plate configuration. The 350 nm gray fringe is detected using a highly sensitive silicon photodiode and a narrow band filter. The light level is read and maintained by the servo loop, within allowable tolerances, by the servo loop quickly adjusting the PZT.

## 4. CONTROL SYSTEM

The control system is automated to locate and maintain a null by utilized three tiered control loops. The three input variables of the control system are the optical thickness of the two glasses, and the spacing of the mirror. The output variable is the null, or rather the null at each wavelength in the band of interest. Equivalently, we could considered the phase at each wavelength. The best measure the chromaticity of the null is a measure of the phase at each wavelength, and its linear, second and third order terms.

The three input variables are not orthogonal; they are very close to being collinear. An adjustment of the plates or the mirror spacing mostly adds offset to the phase, a large component linear with wavenumber. Consequently, these three variables must be balanced by large offsets to high precision. A system matrix is used to calculate the offsets. A theoretical matrix is calculated from the Taylor series expansion of the phase term using the Sellmeier Formula to describe the refractive index of the dielectrics. The matrix can also be measured empirically and automatically by the control system.

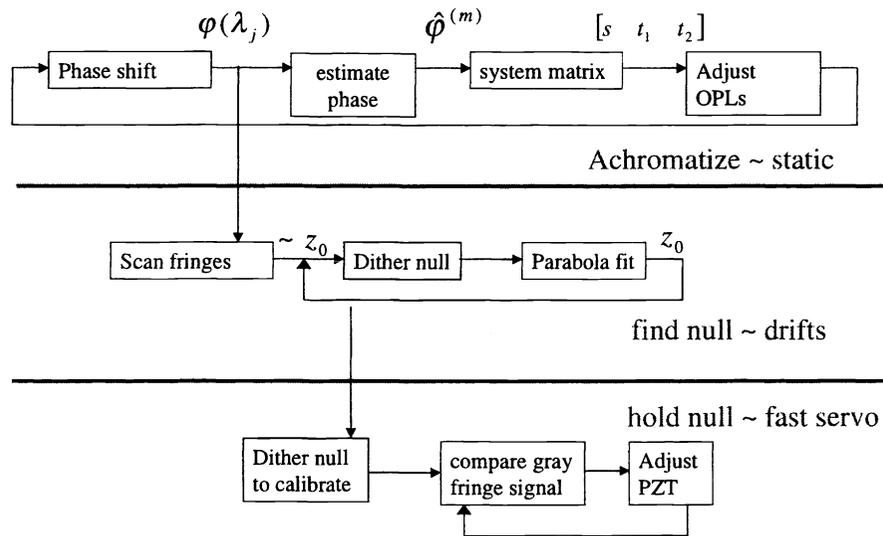
$$\begin{bmatrix} M \end{bmatrix} \begin{bmatrix} s \\ t_1 \\ t_2 \end{bmatrix} = \begin{bmatrix} \phi \\ \phi' \\ \phi'' \\ \vdots \\ \phi^{(k)} \end{bmatrix} \quad (1)$$

The entire control system consists of three nested tiers. The first tier balances chromatic effects by adjusting the tilts of the plates and the mirror spacing. The chromaticity is measured by phase shifting the dispersed fringe. The resultant phase is fitted to a Taylor series. The Taylor series coefficients become a vector that is multiplied by the system matrix to calculate the values of the three input variables: glass thicknesses and mirror spacing. The spacing and thicknesses are adjusted, and the chromaticity remeasured. Once the correct null solution is found, the plates are not adjusted again. The measurements and adjustments occur on a slow time scale, making this a nearly static control loop.

The second tier finds the absolute position of the null. Reading data through the science detector, the central fringe packet is scanned by moving the end mirror with the PZT. The PZT is adjusted to sit at the center of the null. This control loop is intended to be used every ten minutes or so, to adjust for slow drifts in the system.

The final tier is the fast servo loop which actually stabilizes the null in the presence of mild air turbulence and mechanical vibrations. With the PZT positioned at the center of the null, the gray fringe detector signal is calibrated to provide a lock signal. Then the gray fringe signal is the input to a comparative lock loop that adjusts the PZT on a timescale of milliseconds.

All of the computer control and hardware interface is being implemented in linux on a PC. The phase shifting and the fast servo will be implement in the real time linux kernel.



**Figure 8.** The control system consists of three nested tiers. The first tier is static and finds correct phase plate orientation. The second tier locates the null absolutely and accounts for drift. The final tier is a fast servo which stabilizes the null.

## 5. RESULTS

### 5.1. Phase shifting a dispersed fringe

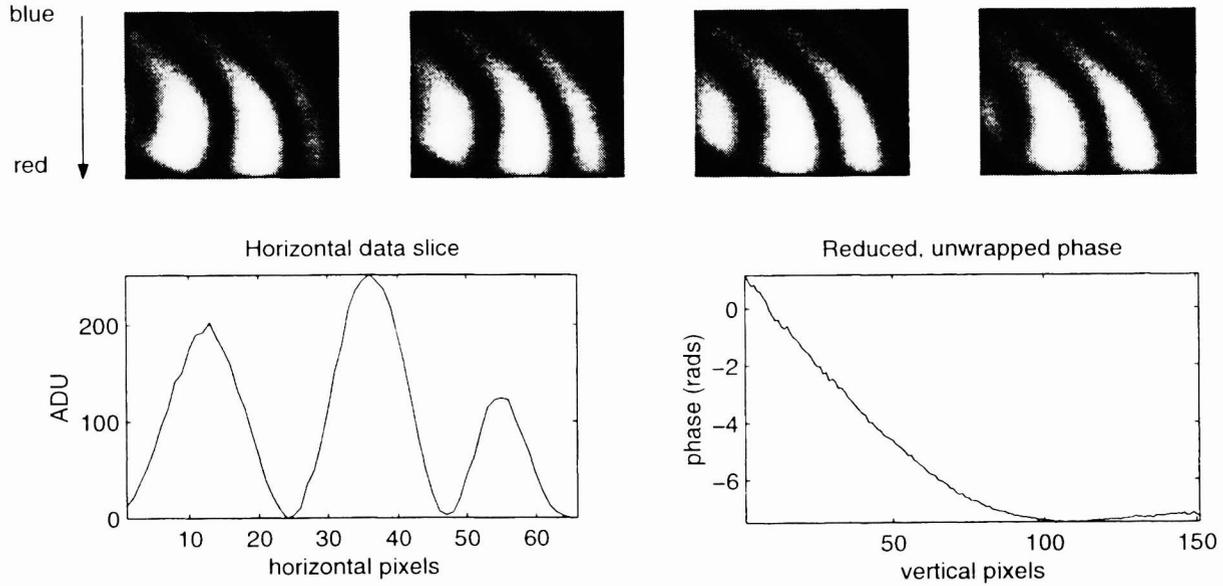
For preliminary testing, only a single polarization and only BK7 was used in the interferometer. The dispersed fringe was phase shifted by one wave using the PZT and sampled at 4 equally spaced delays. The sequence is shown in figure 9. Each pixel corresponds to a spectral sample roughly 3 nm wide. The fringe visibility in each spectral bin was very high, peaking at  $V=.98$ . The data was reduced using the Carre algorithm.<sup>7</sup>

### 5.2. Scanning nulls

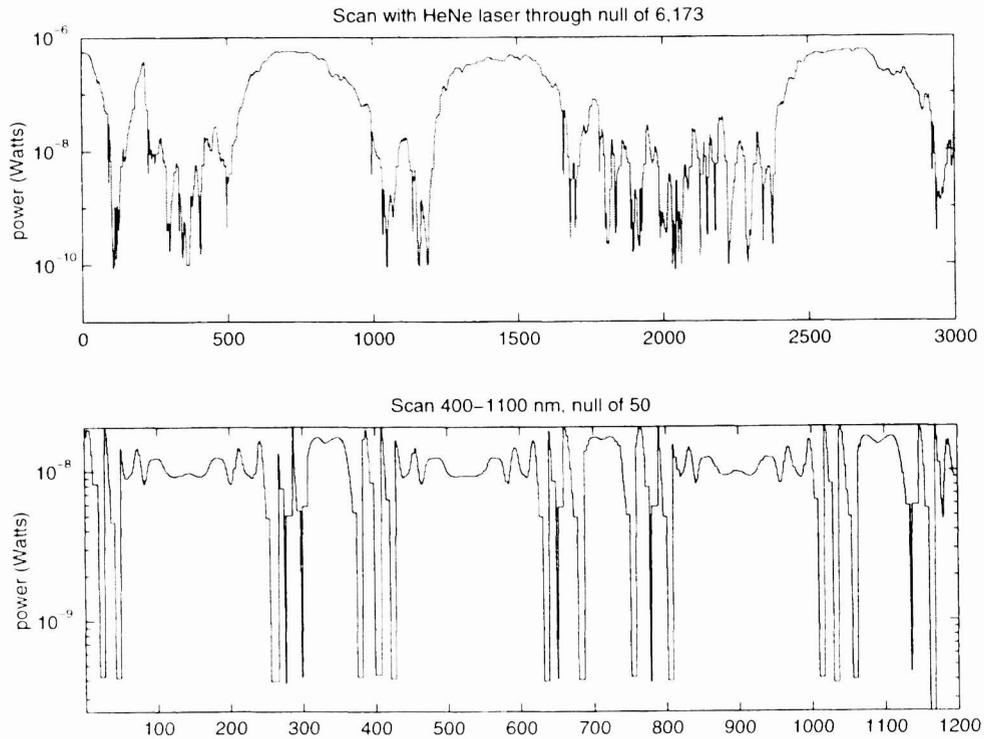
The total null was also measured using a photodiode on the end of a single mode fiber. Figure 10 shows a scan by hand with a Helium Neon laser that achieved a null ratio of 6,173. With the white light source over the full response band of the photodiode (400-1100nm), a PZT scanned through the null and back to produce a null ratio of 50. The theoretically best possible null over that bandwidth with a single plate of glass is 200, only a factor 4 better. The measured null was not optimized because the tilt of the compensator plate was adjusted by hand, as the phase shifting measurement had not yet been implemented.

## 6. FUTURE WORK

The goal of this project is to stabilize for one second a null of  $10^{-4}$  over a 30% bandwidth. We will continue to implement the computer control so that both glass plates may be used, and the full null can be achieved. The second phase of this project will use the computer controlled test bed with a single pass beam splitter to address the beamsplitter design and amplitude control issues. A dual source simulator is under development for second phase.



**Figure 9.** Top is a four frame sequence of phase stepping a dispersed fringe. Bottom left shows a high fringe contrast. Bottom right is the relative phase, reduced via the Carre algorithm.



**Figure 10.** The PZT was adjusted by hand to scan through the fringes with a HeNe laser to achieve a null of 6,173. In white light, a saw tooth wave scanned the PZT to acquire of null ratio of 50.

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