Measurement of Atmospheric Turbulence over a Horizontal Path using the Black Fringe Wavefront Sensor

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ABSTRACT

The black fringe wavefront sensor (bfwfs) uses the peak of a visibility function, or the location of the maximum contrast fringe center as obtained in a self reference interferometer, to identify the zero optical path difference (opd) and resultant phase of a wavefront. The bfwfs is described in two previous papers [1,2] and only a brief description will be described in this report. In the current work the first use of the the bfwfs for the measurement of atmospheric turbulence will be described. The drive voltage of a scanner mirror is synchronized to a max peak detector circuit to provide a real time voltage output which is equivalent to the phase (opd) at an array of subapertures. The surface height of a test object, or equivalently the opd due to atmospheric turbulence, is thus obtained. An argon laser acts as a point source beacon for the sensor. Using a self-reference interferometer, the heterodyne beat from the dominant 514.5nm and 488nm lines produces a visibility function with minimum to minimum separations of 9470nm. Results of measurements of phase over an array of detectors will be shown .In addition an adaptive optics system will be described using the black fringe wavefront sensor and a Mems mirror to correct atmospheric turbulence.

1. Introduction

A technique for measuring direct phase, without a wavefront reconstructor, without a phase stepping algorithm, and without requiring a Zernike or other polynomial fit to the measured phase would have advantages in measuring aberrations produced by atmospheric propagations over long ranges[3]. The bfwfs was developed to measure phase, in an absolute sense, by relating the voltage of a fringe scanning mirror to the maximum contrast fringe peak produced by a multiline or incoherent laser source. No fringe reduction software is required, and a minimum digitization of fringe peaks are required to obtain the location of the maximum. Previous published work has demonstrated measurement of externally generated aberrations at a 200hz frame rate and 1/20 pv accuracy using a radial shear interferometer (RSI) with shear ratio of 1/2 [1,2].This was accomplished with static aberrations in a lab environment.

The primary purpose of the current work is to demonstrate the viability of using the bfwfs, combined with a RSI self reference wavefront sensor, as a means to measure, and later correct, phase aberrations induced in a laser subjected to highly turbulent conditions. The calculation of a phase structure function and power spectral density (psd) plot is used as an initial test of the technique.

The remainder of this paper will describe the optical set up, receiver and transmitter details, and the focal plane geometry used to obtain the phase structure function and psd. This is followed by a discussion of the method used to obtain the structure function, the results obtained, conclusions from the atmospheric measurements, and a final discussion of an adaptive optics system based on this arrangement.

2. METHOD

Horizontal propagation of lasers in the atmosphere produces severe degradation of the far field beam profile, beam wander, jitter, and intensity fluctuations. In addition, speckle effects due to target interactions with the laser can produce intensity drop-outs. The following scheme was used to measure atmospheric phase over a horizontal range: A multiline Argon laser was driven at high currents to produce a broadband multiline source which reduces speckle. A radial shear interferometer was used as a self reference interferometer . This increases throughput, compared to a point diffraction interferometer, while being insensitive to tip/tilt effects of turbulence. A final insertion of the bfwfs allows simultaneous independent phase measurements at every pixel of a focal plane due to the simple peak detection circuitry. Drop outs due to intensity fluctuations at a particular subaperture do not effect neighboring subapertures. Phase is quickly recovered from an individual saturated or low level pixel intensity using a simple sample and hold circuit, and subsequent phase measurements continued. The details of this system are explained in the next sections.

2.1 Use of the Black Fringe WFS with a Multiline Argon Laser

Ordinarily the longitudinal modes of a single line argon laser are spread over a frequency bandwidth of approximately 5GHz. The resulting coherence length of 60mm ($C/\Delta\upsilon$), would not produce a distinguishable black fringe peak. However, using a multiline output produces an envelope function as a result of the addition of the individual laser lines in the interferometer. Since the separate lines are in phase and operate simultaneously, the output intensities are summed rather than multiplied[5]. The resultant interferogram fringe intensities are modulated by a characteristic beat frequency . In the case of argon there are typically six lines obtained with wavelengths of 457nm , 476nm ,488nm ,496nm ,501nm , and 514.5nm .In most cases the 488nm and 514nm lines are dominant which produces a synthetic wavelength , and characteristic coherence length of ,

$$L_c = \lambda^2 / \Delta\lambda = 9.47 \text{ um.} \qquad (1)$$

This produces regions of fringe minimum separated by 9.5 um. However the presence of the other lines produces other beats so that the combination has a mixed pattern, depending on the amplitude, or intensity, of the contributing line. For our purposes, the zero opd location is easily determined by the maximum fringe peak where all lines are in phase. This visibility behavior is seen in the oscilloscope photo of the intensity profile shown in fig. 1. Also shown is a portion of the sinusoidal PZT scan , and the horizontal line representing the voltage output phase from the max detector circuit. Note that the intersection of the scan voltage and phase coincides with the fringe peak.

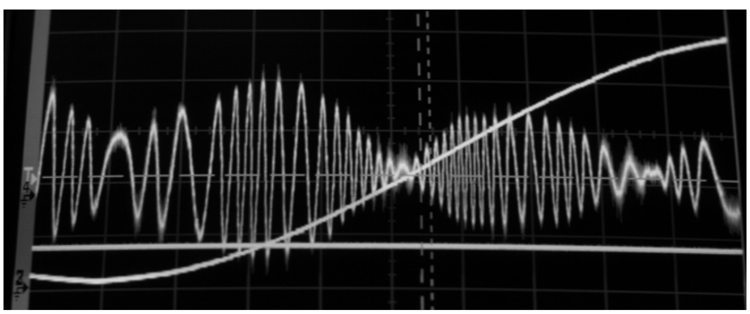

Fig. 1 Fringe scan of radial shear argon interferogram, showing 9.6 um beat and detection of zero OPD from max detector (horizontal line of constant voltage)

By using a multiline source, such as an Argon laser, we obtain good far field propagation of the TEM_{00} beam, while maintaining measurement of the zero OPD phase location using the peak of the beat spectrum. A superluminescent laser diode , or high power multimode fiber laser are other options. White light sources, or high power LED's could be used, but at limited ranges.

2.2 Use of a Radial Shear Interferometer as a self Reference interferometer

Because of previous experience using a heterodyne interferometer to measure atmospheric phase, a point diffraction interferometer (PDI) was initially considered as a self reference device [5,6]. First introduced by Smartt[7], the PDI generates a reference wavefront from a spatially filtered portion of the aberrated wave. The use of this device for adaptive optics was reported in 1993[6], and has been used in commercial devices to test laser diodes and fibers. Although quite useful in laboratory setups in which a lot of light and no turbulence is present, the need for a spatial filter of ~ ½ the airy disc[8]to obtain a reference wavefront, makes the instrument susceptible to beam jitter and results in a final transmittance of less than 1% .

We have been investigating another self reference interferometer which has many attributes of the PDI but with better transmission and jitter performance. The radial shear interferometer (RSI) is discussed in Malacara's optical testing text of 1987 [9]. Although requiring a radial shear, it has a unique attribute not commonly known. The RSI may be simply explained as an interference of two different sized images of the test wavefront. . When the center of curvature of the wavefronts are at the same location, they produce a shear in the radial direction. For sufficiently large shears, but small values of s, where s = R1/R2, R being the radius of the inner or outer beam , the interferometric fringe pattern is almost identical to a Michelson amplitude splitting interferometer. As a result, the usual conversion of measured wavefront slope to wavefront phase , as required in other shear interferometers, is avoided. The resultant wavefront reconstruction is eliminated, and the radial shear interferogram can be treated as a direct phase measurement approximation. Although the RSI has been used to measure aberrations of a laser wavefront[10], and other authors have noted the Michelson interferometer comparison for large shears, we believe this report is the first discussion and implementation of the device for measurement of phase aberrations in the atmosphere. The radial shear interferometer is hampered by at least two artifacts of its implementation: the measured wavefront is only an approximation to the true input wavefront (based on the shear ratio) , and it cannot be used reliably with a centrally obscured telescope because of the radial shear. Nevertheless, we felt that these deficiencies are outweighed by its potential ease of use in this field application compared to the problems of light loss and jitter control needed for the PDI. It can be shown that the wavefront measured by an RSI differs from the wavefront measured by a PDI or Michelson interferometer by a factor of $(1-S^n)$, where n is the order of the radial wavefront error polynomial and S is the radial shear [2]. Each coefficient of the Michelson, or PDI, wavefront is related to the RSI wavefront by,

$$W(r,\theta)_{RSI} = W(r,\theta)_{PDI} / (1 - S^n) \qquad (2)$$

Previously we showed that a shear of only ½ was sufficient to allow rms phase measurements of a phase plate(D/ro~3) which differed by only 1/100 wave from a PDI operating at 633nm [2]. Adopting this design for this experiment, the optical layout is shown in fig. 2. The radial shear is produced by using a 200mm focal length input lens, followed by a 200mm fl lens in the test leg and 400mm fl lens in the reference leg. The resulting telescope combinations produces radially sheared ,superimposed beams with diameter ratios of ½ at the output of the final nonpolarizing cube beamsplitter.

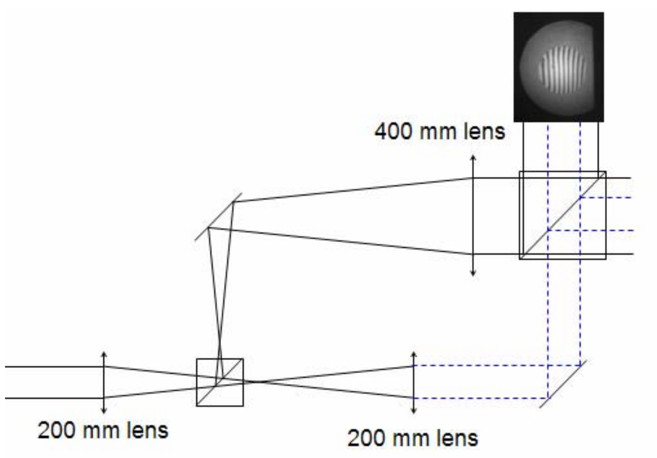

Fig 2 Radial Shear Interferometer (Shear = ½) used for atmospheric measurements

2.3 Transmitter,Receiver, and Range Layout

The transmitter consisted of an Argon laser, used as a beacon point source, and positioned on a breadboard attached to a tripod. A 20x beam expander, followed by two tip/tilt flats was used to project a 25mm collimated beam to the receiver which was located at a range of 1200m. The receiver consisted of a 120mm diameter, 540mm fl (f/4.5) refracting telescope, followed by a 50mm fl collimating lens. The resulting 10.8x magnification sent a 11mm diameter beam to the RSI , producing superimposed 22mm and 11mm radial sheared beams which were imaged on to a 2x8 Si array. This array had pixel sizes of 1mm x 1 mm, with a separation of 200um. The complete experimental layout is diagramed in fig. 3.

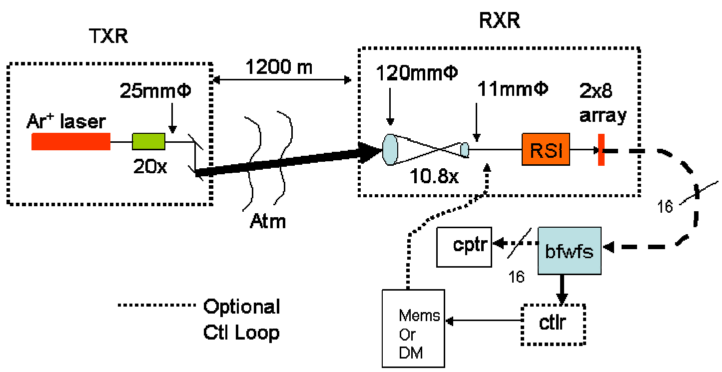

Fig 3 Transmitter and receiver layout for atmospheric phase measurements showing RSI radial shear interferometer,bfwfs black fringe wavefront sensor, and optional control loop for AO

2.4 Phase Structure Function measurement

Atmospheric phase fluctuations caused by turbulence is a nonlinear process whose understanding has never been completely understood. Tatarski and Kolmogorov used statistical methods to arrive at equations governing random processes to arrive at a general understanding of the phenomena. However, even this treatment relies on several simplifications to give a tractable result. Following this statistical treatment of turbulence, the magnitude of phase error across a wavefront can be described in terms of a phase structure function which is a measure of the mean squared phase difference between two points in an aperture,

$$D_\Phi(r_1\text{-}r_2) = < [\Phi(r_1) - \Phi(r_2)]^2 > \qquad \text{wave}^2 \qquad (3)$$

which can also be considered an ensamble average of these points. For the case of horizontal propagation of a laser beam in the atmosphere, $\Phi(r_j)$ in (1) is the phase accumulated by a ray which has traversed the atmosphere along a given path and arrived at the receiving aperture, or focal plane, at position r_j . Using a focal plane with pixel locations of $r_j(x,y)$, the structure function was computed from phase measurements at each pixel as referenced to a single pixel.

Restricting turbulence scale sizes to larger then the so called inner scale (a few mm's) and much less then the outer scale (meters), the structure function in (1) may be approximated by ,

$$D_\Phi(r_1\text{-}r_2) = 6.88 \, [(r_1\text{-}r_2)/r_O]^{5/3} \qquad (4)$$

A similar treatment can be used to arrive at a general relation for a psd of the measured phases as,

$$PSD \sim Cf^{-11/3} \qquad (5)$$

where C is a constant proportional to Cn^2 and other atmospheric conditions. The bfwfs measurements were recorded with a 2 x 8 array , and the phase structure function and psd calculated for two tests at 72m and 1200m at different times of day. Graphs were constructed of $D_\Phi(r_1\text{-}r_2)$ vs the pixel separation $r = r_1\text{-}r_2$ for the given geometry of the arrays. The bfwfs could be used to compare an actual measurement of the structure function and psd with that predicted by equation (4) and (5) from the Kolmogorov assumptions of turbulence.

A second, subsidiary goal of this calculation was to verify that the bfwfs was giving reasonable results of atmospheric phase measurements. We have no absolute reference to indicate whether accurate phase measurements were made, as would be the case for any technique. However, based on prior work by other researchers using several interferometer techniques[11], it is expected that a phase structure function should at least approximate the r^5/3 dependence indicated in equation (4) and the psd the $f^{-11/3}$ behavior of equation (5).

3. RESULTS

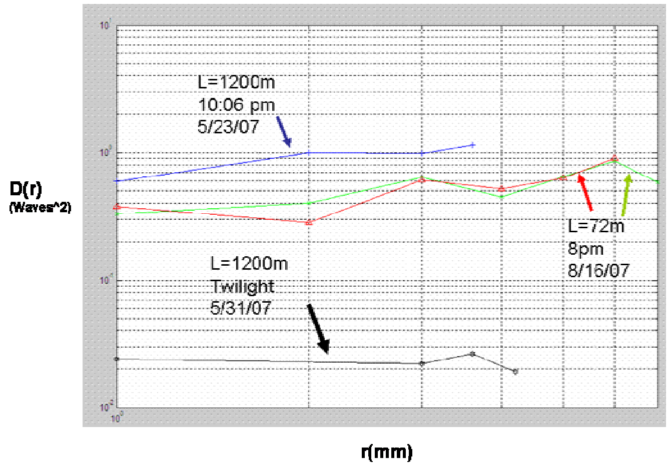

Fig. 4 Experimentally Derived Phase Structure Function obtained using 4x4 and 2 x 8 arrays at distances and times shown

Fig. 4 shows the results of a calculated phase structure function for one experiment at a range of 72 meters and two other tests at a range of 1200 meters. All calculations used a 10 sec average. All ranges in this report imply distance from the transmitter to the receiver. The 72 meter test was done by a double pass of the beam using a retro flat at 36m, while the 1200m test was using the Argon laser at one end of the range. Considerable variability is obtained in the tests which corresponds with the atmospheric conditions and topography of the range. The 72 m tests on 16Aug2007 were carried out in the late evening over a concrete pad and on a day when temperatures were approximately 90 deg F. The first 1200m test was done at 10:06 pm under conditions of light wind wind and r_o values near 20mm. The second 1200m test was done at twilight under pristine conditions with r_o values approaching 120mm, the aperture of the telescope.

Fig.5 repeats the 72 m plot but includes the Kolmogorov expression (4) for reference. For the structure function plots for the 72 m data values of r where obtained with pixel separations of 1mm to 7mm using the two rows of the 2x8 array. The 1200m data used only a 4 x 4 array which allowed a maximum separation of 4.2 mm along the diagonal. All separations refer to the focal plane but should be scaled by the magnification of 10.8x when comparing the results to the Kolmogorov theory. Definite trends toward the $r^{5/3}$ behavior is evident in the 72m data. For the plot shown a value of ro=20mm was assumed based on scintillometer data of fig.7. PSD"s for the 72m and 1200m tests is shown in Fig.8 which clearly indicates an $f^{-11/3}$ behavior for the 1200m twilight case, but not for the 72m test.This psd is typical behavior for horizontally projected laser beams, as is our results of coefficients in the range from 1.2 to 1.7 in Fig. 5 [12]. Expressions 4 and 5 are based on Kolmogorov's assumptions which are restricted to a strict range for the inner and outer scale values of lo and Lo. Not enough tests were made to attempt any quantitative comparison with the Kolmogorov theory, but our secondary goal of demonstrating phase measurement using the RSI/bfwfs and multiline Argon was considered achieved based on these preliminary tests over ranges of 72m and 1200m.

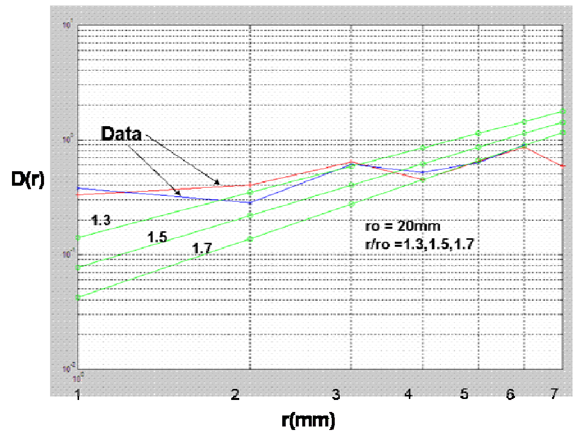

Fig 6 Phase Structure Function data(8/16/0) D(r) vs r , compared to $6.88(r/ro)^{(k)}$ with ro=200mm,k=1.3,1.5,1.7

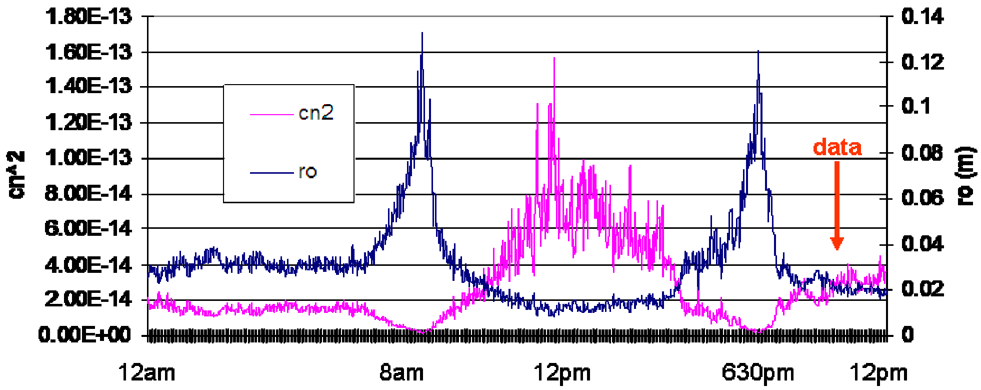

Fig 7 Scintillometer data or r_o and C_n^2 for 72m data of 8/16/07

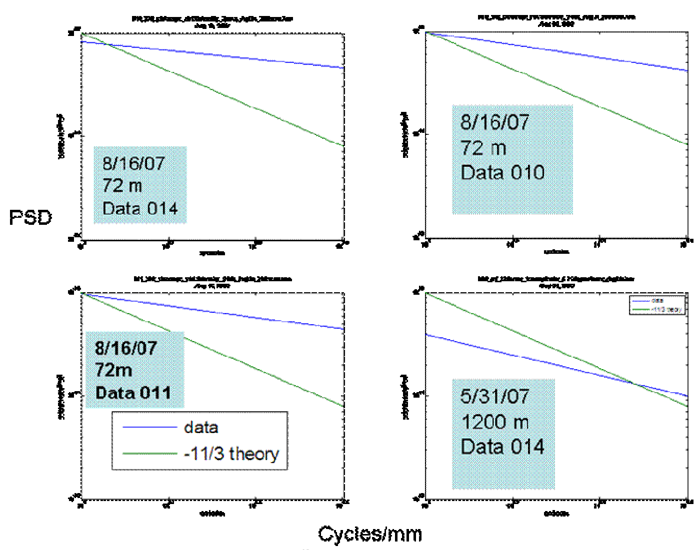

Fig 8. PSD showing $f^{-11/3}$ behavior for only the 1200m case

4. Summary/Conclusions of RSI/bfwfs atmospheric phase measurements

These first tests of the measurement of atmospheric phase perturbations using a multi-line Argon laser as a beacon point source, RSI as self reference interferometer, and the black fringe wavefront sensor were primarily completed to demonstrate the viability and potential use of the technique. A measured phase structure function was shown to quantitatively follow an expected r^5/3 dependence as expected from a Kolmogorov treatment of turbulence. Trends in the data also show qualitative agreement with scintillometer measurements of r_o and Cn^2 and an expected $f^{-11/3}$ psd relation for the 1200m data.

5. Use of the RSI/bfwfs for AO correction

A straightforward method to confirm whether we are measuring the phase of the atmosphere correctly is to use the Argon/RSI/bfwfs system in conjunction with a corrector mirror to improve long range imaging or beam propagation of a beacon laser. This is our ultimate goal with this device and would give immediate indication of how closely the phase measurements measured the actual atmospheric behavior. The nature of both the bfwfs and RSI combination has several advantages for such a correction system. There is a difference, however, to the nature of the RSI transform in equation (2) and its relation to the use of the RSI as a self reference interferometer in an adaptive optics control system. Clearly, for optical testing in which a few low order aberrations are dominant, large values of radial shear of ¼ to 1/10 may be necessary to reduce the ($1\text{-}S^n$) term to allow phase accuracies of 1/40 peak to valley (pv), which can be obtained by Michelson or Fizeau type optical testing interferometers. Such large shears would produce intensity losses equivalent to the square of the shear, since this is a diameter ratio. Such large magnifications could also induce internal aberrations due to fabrication errors of the lenses needed.

However for the applications considered in this experiment, correction of atmospheric turbulence, scintillation, and other higher order spatial effects, the RSI could have a definite role without the need for such high values of shear. Horizontal propagation produces random wavefronts which can contain Zernike coefficients with magnitudes of 0.1 to 0.2 λ for 25 or more terms. The RSI should sense most of these aberrations and be able to make a significant correction using a suitable corrector mirror or device. The lowest order tilt terms can be corrected by a quad cell and fast stirring mirror, and the other higher order terms will receive progressively better correction as the control loop proceeds. The nature of the RSI process produces a reference wave from the center of the aberrated wave. For highly aberrated wavefronts the first few frames of data will have a maximum error due to the ($1\text{-}s^2$) term caused by focus and x and y astigmatism. As the correction device applies conjugate phase to the received wavefront, these low order aberrations will be reduced, and the resultant reference wavefront improved on each iteration. As this process continues and as any severe aberration is introduced, due to a local hot spot in a beam or anomaly in the path, a servo operating at typical closed loop frame rate of 100 Hz will correct the large low order terms in the first few frames.

6.0 References

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