PRESENT STATUS AND FUTURE PLANS FOR THE TWO COLOR ASTROMETRIC INTERFEROMETER PROJECT

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A 3-meter two telescope stellar interferometer has been used to observe fringes for the past year in order to study the feasibility of using long baseline interferometers for astrometry. We have demonstrated that two color fringe measurements are capable of significantly reducing the astrometric error due to atmospheric turbulence. Currently, we are investigating the thermal and mechanical sources of error in the instrument. The results of our study will be incorporated into the design of the 20 meter astrometric interferometer which will be built in the next 1-2 years. The key to the 20-meter interferometer is the laser system which we expect to monitor all the mechanical and thermal imperfections relevant to astrometry at the 10^{-3} to 10^{-4} arc sec level. A slight modification of this system could be used in a space based interferometer for 1 to 10 microarcsecond astrometry of faint objects.

INTRODUCTION

A stellar interferometer is an instrument that combines the light from two spatially separate telescopes as shown in fig. 1. The goal of interferometry is to achieve very high angular resolution with relatively small optics. While interferometry has long been used in radio astronomy, the technology for optical interferometry has only become available recently.

The type of stellar interferometer that is potentially the most sensitive and the most accurate for astrometry is the phase-coherent wide band interferometer. However, the required mechanical tolerances

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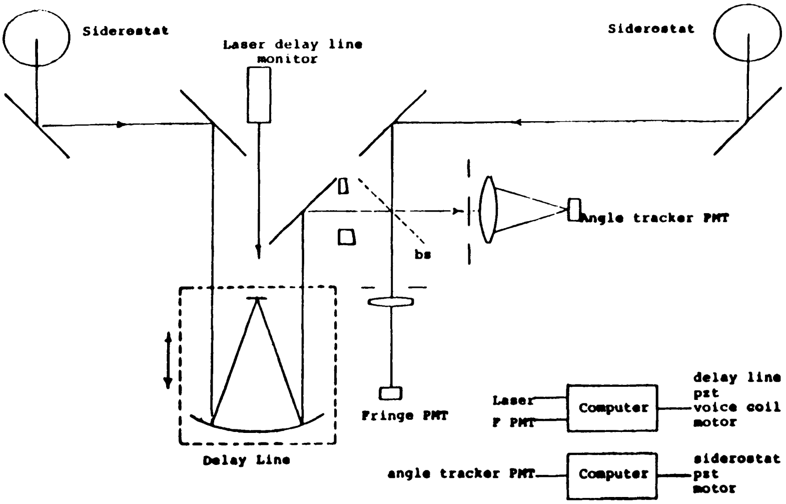

Fig. 1. Closed Loop Two Telescope Stellar Interferometer.

for such an interferometer are moderately severe. The pointing of the optical telescopes must be accurate to ~0.5 arc sec. More importantly, the optical path length from the star to the detector via the two arms must be equal to within a half wavelength of light. This equality of optical path lengths must be maintained in the presence of thermal expansion and atmospheric turbulence. Once the technical problems are solved however, an astrometric interferometer is potentially capable of making extremely accurate measurements of angles between stars.

Experiments to develop the technology for stellar interferometry began with a prototype interferometer designed to look only at Polaris. This instrument was installed at Mt. Wilson in 1978 and observed fringes in 1979. The purpose was to demonstrate the ability to point two separate alt-az mounted mirrors with 0.5 arc sec precision and control the optical path lengths with the fractional wavelength accuracy. The main source of time-varying path length error in this instrument is the atmosphere. A one arc sec tilt of the wavefront due to atmospheric seeing across the 1.6 meter baseline would cause a 13 wavelength error in the path length adjustment of the interferometer. A servo-controlled optical delay line was used to compensate for fringe motion due to the atmosphere with a precision of ~0.1 micron.

MARK II INTERFEROMETER

Construction of the Mark II interferometer was begun at MIT in 1980. This instrument, while basically the same as the Mark I had a slightly longer baseline of 3.2 meters but instead of just looking at Polaris, was designed to track fringes from stars within 15 degrees of the zenith. Fig. 2 is a schematic of the instrument in simplified form.

While a detailed description of the instrument will not be attempted, a brief explanation of several key components will be given. The Mark II has a laser monitored optical delay line. The delay line is used to equalize the path lengths in the two arms of the interferometer and has to move to cancel the effects of the atmosphere as well as the path change due to the fact that the interferometer baseline is fixed to a rotating earth. The laser monitors the position of the delay line with a precision of 50 Å. The delay line is enclosed in a vacuum chamber, in order to eliminate the first order effect of atmospheric refraction on the fringe position. Two independently steered siderostats are run closed loop to achieve the 0.5 arc sec pointing accuracy. Two star tracker error sensors are used to determine the pointing error. Both tracker error sensors use the same telescope so that thermally induced errors will be the same for both. The star light fringe tracker is identical to the previous one except that instead of using the fringe phase directly as the error signal to the servo, the fringe phase is added to a calculated diurnal fringe rate.

Fringes from a number of stars were observed in the summer of 1982. However, these observations pointed out the existence of a large number of problems, which resulted in several hardware modifications.

The purpose of the Mark II interferometer is twofold. One was to demonstrate the two color technique for reducing the astrometric error due to the atmosphere in a quantitative way. The second purpose was

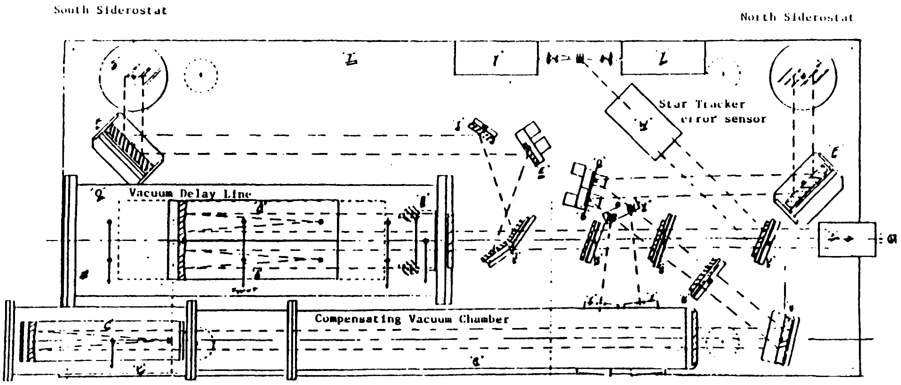

Fig. 2. MIT-NRL Stellar Interferometer. Layout of optical components on Mt. Wilson, Calif.

to make preliminary astrometric measurements to determine the major sources of instrumental error. The design of the Mark III would then be based on these results.

Data that demonstrates the two color technique was taken in late summer of 1983. Fig. 3a shows the motion of a star caused by several effects, primarily atmospheric turbulence. The apparent position of that star was measured at two different wavelengths; the difference in the red and blue position is shown in fig. 3b. We note that because in this case the atmosphere is not very dispersive, B-R is only a few milliarcseconds peak to peak. The internal error of the B-R

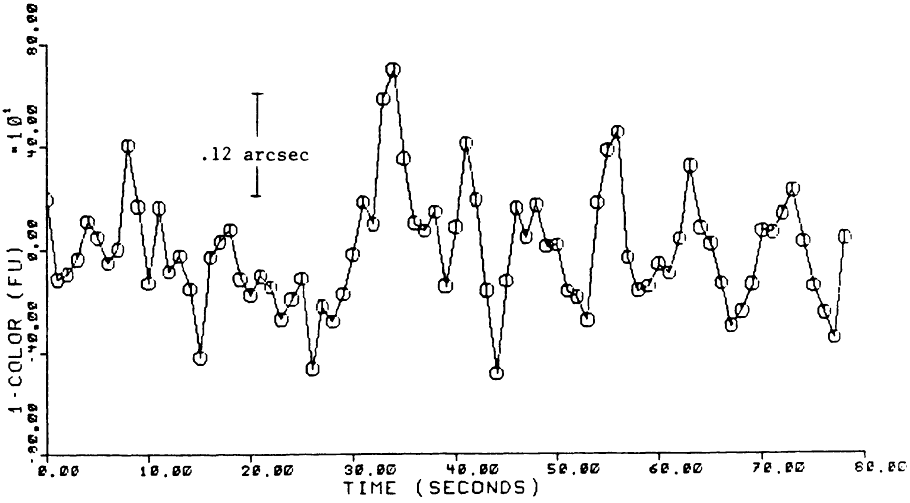

Fig. 3a. Red Fringe Position vs. Time.

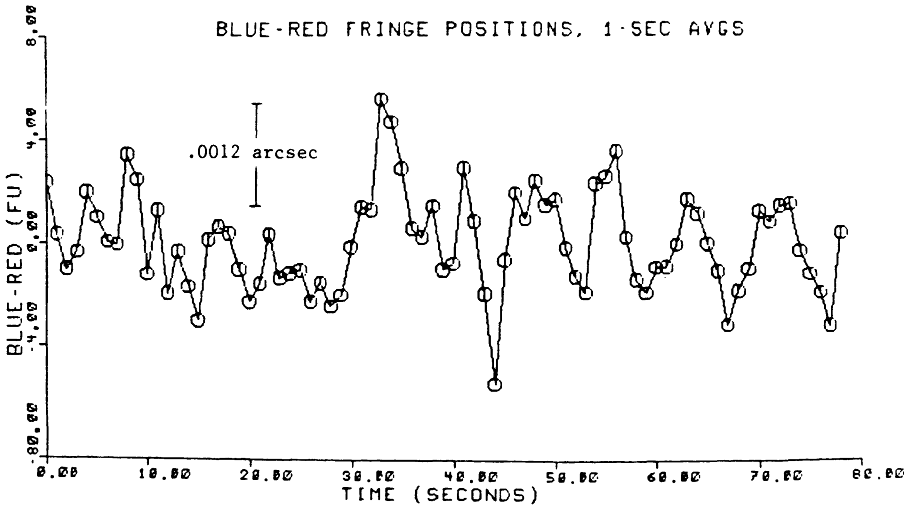

Fig. 3b. Dispersion (Blue-Red Position) vs. Time.

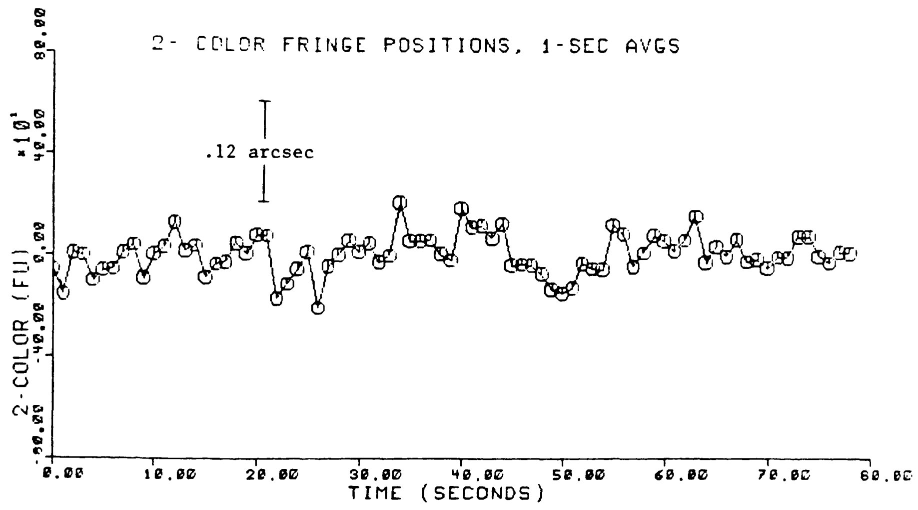

Fig. 3c. Two-Color Position vs. Time.

measurement for a one second integration is several hundred microarcseconds when the two color technique is applied. This internal error is multiplied by a factor of 100 to give an rms error of 0.02 arc second for a one second integration. This is shown is fig. 3c.

In order for the two color technique to work the internal errors of the blue-red position must be extremely small, about 1/10 of a milliarcsecond when the resolution of the interferometer is 20 milliarcseconds. The systematic and random error of measuring fringe position must be on the order of 1/400 wavelength. The random errors are due to photon statistics and integration of few tenths of a second is sufficient to reduce this error to acceptable levels. There are significant systematic errors in measuring the fringe phase of a non monochromatic source at this level of precision. The first problem is to identify the effective wavelength of the light so that the phase measurement can be converted to a path length measurement.

One problem of long baseline interferometers operating at visible and infrared wavelengths is that the atmosphere is not phase stable. For baselines that are much longer than the phase coherence length r_0, the atmosphere is phase stable only for a short length of time τ_0. Both r_0 and τ_0 are proportional to $\lambda^{6/5}$, with $r_0 \sim 10$ cm and $\tau \sim 10$ msec for $\lambda = 0.5$ microns. Because the atmosphere, in theory, can change the fringe phase by many wavelengths, astrometric interferometers that measure phase must have some method for identifying the fringe whose phase is being measured. The central fringe in a broad band interferometer can be identified because it has several unique characteristics. One characteristic is that the fringe visibility is greatest for the central fringe. The second is that at the center of the central fringe, the phase is zero at all wavelengths. In the Mark II two color interferometer phase data is discarded if the optical path error is greater than λ/4. In addition, the fringe visibility in both red and blue channels must be greater than a predefined threshold, and the phase in the red and blue channels must match. Fig. 4 is a scatter plot of red and blue phase. The points that correspond to the central fringe are well separated from the points that correspond to a noncentral fringe. Fig. 5 is a similar plot for red and blue visibility. Again difference between central and noncentral is visible though not as clearly as with phase. With both phase and visibility criteria for locating the central fringe, incorrect identification is very unlikely.

In order to convert phase to optical path length, the effective wavelength of the light must be known. The effective wavelength depends on a number of parameters such as the spectral response of the detector, the spectral response of the optics including filters, the temperature of the star, atmospheric absorption, etc. Instead of measuring all the spectral characteristics, and then calculating the effective wavelength, we have decided to use the interferometric data to derive the wavelength. The instrument measures fringe phase by scanning the delay line by .63 microns at 500 Hz. The fringe pattern is then sampled at four points. Since the fringe pattern is related to the spectrum by a fourier transform, in principle it is possible to derive the effective wavelength from the sampled fringe pattern. The four samples can be used to estimate fringe phasing, fringe visibility, star light intensity and effective wavelength. The

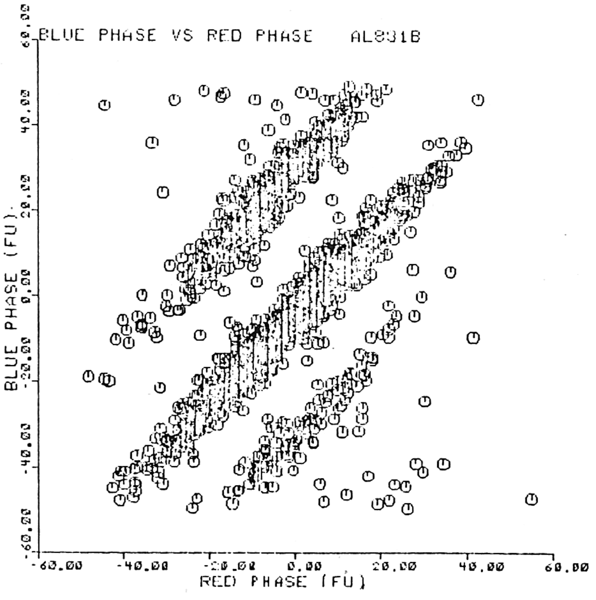

Fig. 4. Density Plot of Red Phase vs. Blue Phase.

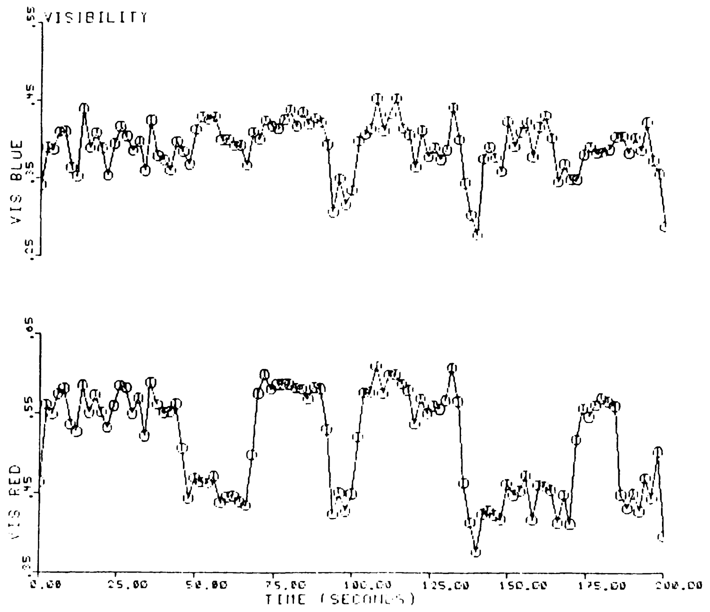

Fig. 5. Red and Blue Visibility During Fringe Hopping.

estimate of wavelength is very sensitive to noise so usually the wavelength is determined by a least squares fit of 5 to 10 thousand scans of the fringe.

Fig. 3 shows the residuals of the fringe position, after the motion due to earth rotation was removed for 80 seconds of data. Fig. 6 shows the fringe position as a function of time for couple of hours, again with earth rotation removed. The first and most obvious difference between figs. 3 and 6 is that the residuals are much larger for the 2 hour length of data. In our opinion, the larger fringe position errors are due to thermal and mechanical instability of the instrument.

A number of effects were incorporated into the model used to correct for earth rotation, including nutation, seasonal and diurnal aberration, and solid earth tide. The position of the star was precessed to the time of observation. In this test only one star was observed and its known position was used to derive the baseline of the interferometer. Fig. 6 shows the residuals of the fit as a function of time. The same star was observed on several nights. The derived baseline vectors were different from one night to the next by an amount approximately five more than the internal consistency of a 3 hour observation. Clearly the long term drift of the instrument is a serious problem.

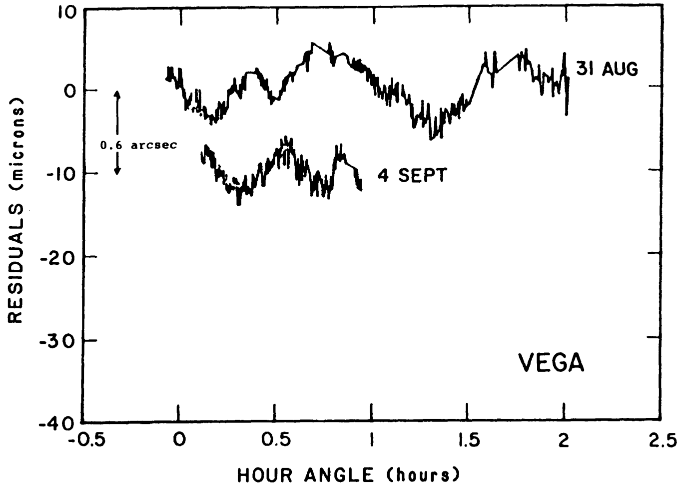

Fig. 6. Fringe Position for Vega for 1 hr 46 min.

FUTURE PLANS, MARK III INTERFEROMETER

The principal obstacles to building an operational astrometric interferometer are the mechanically and thermally induced instrumental errors. The purpose of the Mark III interferometer is to test a number of schemes to use laser metrology to create, in effect, an astrometric instrument that is mechanically and thermally perfect. All known errors for wide angle (>15 degree) astrometry at the milliarcsecond level will be monitored or corrected.

The instrument will have three possible baseline orientations: 20-meter N-S, 15 meter NE to SW and 15 meter NW to SE. With the 20-meter baseline, the resolution is 2.5 milliarcseconds. A system of 5 lasers will monitor the position of each siderostat mirror, eliminating the errors caused by imperfect bearings and thermal expansion of the mirror mounts. The position of the mirrors will be monitored relative to a set of corner cubes attached to an invar plate bolted to a concrete pier that is thermally insulated. In addition, the central beam combiner will be housed in a temperature controlled building. All mirror mounts will be made of materials that have matched temperature coefficients. All optical elements that move, such as the delay line and siderostat, will have their motion monitored by laser interferometers. However, it is not practical to monitor all the stationary optical components. In order to reduce the astrometric error due to the slow thermal drift of these optical components, the instrument will switch between stars that are widely separated. In this way, large angle relative measurements can be made at a level that is limited only by the thermal drift of the unmonitored optical components on a star switching time scale.

In order to accomplish rapid star switching, the siderostats and delay line are designed to slew at moderately high rates. The siderostats will be designed to slew at 2.5 degrees per second with 0.1 arc sec resolution. The delay line will slew at 0.6 meter per second and be stable to 100 Å. Software for automatic star acquisition will also be developed. Initially we expect to switch between stars on a time scale of 5 to 10 minutes. In a benign thermally controlled environment, the instrument should be stable to approximately 0.1 microns or 0.001 arc sec on this time scale. While we have tried to anticipate all the sources of instrumental error, only observational experience will enable us to find and correct design flaws. Initial operation of the Mark III is expected in late 85 to early 86.

Fig. 7 shows the layout of the Mark III interferometer. In addition to astrometry, this instrument may be used at a later date with longer baselines and larger apertures to measure both amplitude and phase for image reconstruction at visible and near IR wavelengths.

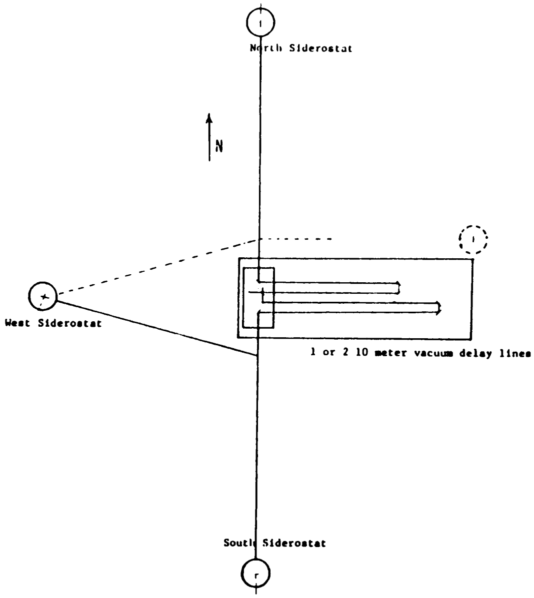

Fig. 7. Future, 20-Meter Astrometric Interferometer.

Discussion:

JOHNSTON: If the instrument were used today, what would the accuracy be? And what three years from now?

SHAO: Right now, only about 0″.2 for larger ranges. After switching to laser, we should go to a few hundredths of arcseconds. In three years, we are hoping for a milliarcsecond.

JOHNSTON: In small angles?

SHAO: We are hoping for 0″.001 for large angles.

HØG: I asked a question about determining refraction.

SHAO: 20 mas for one second of integration was the best number we have gotten so far. This is now running against the thermal stability of the instrument.