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FINAL REPORT

Phase-Coherent Astrometric Interferometry

Naval Research Laboratory

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Phase-Coherent Astrometric Interferometry

I. Introduction

This effort constituted the second stage in the development of the Mark III stellar interferometer, which is a fringe-tracking long-baseline Michelson interferometer designed primarily for wide angle astrometry at the milliarc-second level. Stellar diameters were also measured. This effort was a continuation of work begun under Naval Research Laboratory Contract N00014-84-C-2082.

The instrument is installed on Mount Wilson in California; it is a joint project between the Massachusetts Institute of Technology, the Smithsonian Astrophysical Observatory, the Naval Research Laboratory, and the U.S. Naval Observatory. The instrument employs a two-color technique to reduce errors due to atmospheric turbulence, and its various baselines are laser-monitored to achieve high precision. The instrument can operate with four possible baseline configurations from 9 m NE-SW to 20 m N-S. Most observations have been made with the 12-m N-S baseline.

In addition to participation in the continuing instrument development and initial operation, two major technological development efforts were undertaken. These involve the development of a laser siderostat-position monitoring system and a group delay estimation system. The laser siderostat system employs multiple interferometers to relay the position of the siderostat mirrors to their supporting steel-reinforced concrete pedestals. These systems thus help overcome positional errors due to imperfections in the ball bearings and other support structure. The group delay estimation system permits the fringe position to be continuously monitored on a time scale of milliseconds without the need for real-time precision tracking. As a result the sensitivity of the instrument can be increased an estimated 2.5 stellar magnitudes.

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The technical details of these systems are described in previous progress reports and in the referenced theses and publications. Recent new technical work here, not yet documented elsewhere, is presented in Part III of this report.

II. Results Documented in Publications

The results of this effort have been described in a variety of publications. A basic preliminary paper describing the results of the Mark II interferometer experiments was published in May 1987. This paper "Application of Interferometry to Optical Astrometry"[1] demonstrated the ability of optical interferometry to measure the precise positions of stars over large angles. Fringe phases were tracked over many hours while switching schematically among several stars with indicated positional accuracies of 3 arcsec. The short-term precision of the measurements was substantially greater, a few hundredths of an arcsecond. Based on these results, it was projected that astrometric accuracies exceeding one-hundredth of an arcsecond can be achieved. This paper was awarded the Naval Research Laboratory Alan Berman Research Publication Award in March, 1988. The first page appears in Appendix A.

The Mark III interferometer became operational on Mount Wilson in September, 1986, initially with a 12-m N-S baseline. Early experiments were directed toward studying atmospheric phase measurements. These were initially documented in the paper "Atmospheric Phase Measurements with the Mark III Stellar Interferometer."[2] Measurements of the phase differences for this baseline agreed well with the predictions of a Kolmogorov spatial spectrum over the 0.001-100 Hz frequency range. These measurements indicated that a one-color

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[1] M. Shao, M. Colavita, D. H. Staelin, K. L. Johnston, R. S. Simon, J. A. Hughes, and J. L. Hershey, Astron. J., 93, 1280-1286 (May 1987).

[2] M. M. Colavita, M. Shao, and D. H. Staelin, Appl. Opt. 26, 4106-4112 (Oct. 1, 1987).

atmospherically limited absolute error standard deviation of ∿ 0.065 arcsec could be achieved for 100 sec integration under conditions of 0.5-sec of arc seeing. The first two pages of this paper are attached as Appendix B. They contain schematic diagrams showing the initial configuration of the Mark III instrument.

A more complete paper describing the instrument itself "The Mark III Stellar Interferometer"[3] was also prepared. The first two pages of this manuscript appear here in Appendix C.

A paper expanding on the two-color technique "Two-Color Method for Optical Astrometry: Theory and Preliminary Measurements with the Mark III Stellar Interferometer" appeared in Applied Optics in October, 1987.[4] This study demonstrated a factor of ∿ 5 reduction in the amplitude of the atmospheric fluctuations in stellar position measurements, and suggested that factors ranging from 5-10 over the corresponding one-color measurements could be achieved. The first page of this manuscript is attached here as Appendix D.

By late 1986 the instrument was also used for preliminary astrometric measurements, and a total of 22 stars were observed over large angles. For the ten stars observed over at least 90° of hour angle, the right ascensions were consistent at the 5 ms of time (1σ) level, while the uncertainties in declination were at the 22 mas (1σ) level. A paper "Preliminary Measurements of Star Positions with the Mark III Stellar Interferometer" was published in April 1988 and the first page is attached here as Appendix E.

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[3] M. Shao, M. M. Colavita, B. E. Hines, D. H. Staelin, D. J. Hutter, K. J. Johnston, D. Mozurkewich, R. S. Simon, J. L. Hershey, J. A. Hughes, and G. H. Kaplan, submitted to Astron. Astrophys., May 1987.

[4] M. M. Colavita, M. Shao, and D. H. Staelin, Appl. Opt. 26, 4113-4122 (Oct. 1, 1987).

[5] D. Mozurkewich, D. J. Hutter, K. J. Johnston, R. S. Simon, M. Shao, M. M. Colavita, D. H. Staelin, B. Hines, J. L. Hershey, J. A. Hughes, and G. H. Kaplan, Astron. J. 95, 1269-1277 (April 1988).

Two papers were also prepared concerning initial stellar diameter measurements. The first paper "Initial Stellar Diameter Measurements with the Mark III Interferometer"[6] appeared in the Astrophysical Journal on April 15, 1988. The first page appears here as Appendix F.

The second paper "Angular Diameter Measurements of 24 Giant and Supergiant Stars from the Mark III Optical Interferometer"[7] was also submitted to the Astrophysical Journal. For these 24 stars angular diameters ranging from 3 mas to 17 mas were measured with accuracies of order 0.5 mas. The first two pages of this manuscript appear here as Appendix G.

The design and operation of the laser siderostat system was documented in the Master of Science thesis submitted by Braden E. Hines in February 1988.[8] Two problems emerged in this study. First, the laser interferometers sometimes failed to count a fringe when the slewing rate was too high relative to the modulation frequency of the measurement laser. Similar problems occasionally occurred when one of the four redundant laser beams was incident upon a mirror imperfection, causing signal dropout. Although these errors could be detected, their correction required careful signal analysis. Continuing work is directed toward increasing the capability of this system to operate at higher slew rates and in the presence of mirror and other imperfections.

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[6] M. Shao, M. M. Colavita, B. E. Hines, D. H. Staelin, D. J. Hutter, K. J. Johnston, D. Mozurkewich, R. S. Simon, J. L. Hershey, J. A. Hughes, and G. H. Kaplan, Astrophys. J. 317, 905-910 (April 1988).

[7] D. J. Hutter, K. J. Johnston, D. Mozurkewich, R. S. Simon, M. M. Colavita, Pan. S. P., M. Shao, B. E. Hines, D. H. Staelin, J. L. Hershey, J. A. Hughes, and G. H. Kaplan, submitted to Astrophysical Journal.

[8] B. E. Hines, "Laser Metrology System for Stellar Interferometry," S.M. Thesis, M.I.T., Dept. of Elec. Eng. and Comp. Sci., Feb. 1988.

III. Recent Results from the Group Delay Experiment

The group delay experiment involves development and trial use of a new system for measuring the stellar interference fringes; these positions are the primary data produced by the Mark III astrometric interferometer. The group delay system is designed to replace the high-frequency fringe-tracking system used previously. It operates by spreading across a photon camera the wide band optical signal comprising the two interfering stellar beams. This is the same camera also used for stellar tracking. When the two light beams are perfectly in phase the intensity of the spread optical beam is approximately uniform across its length with amplitude ranging between zero and maximum. As the two beams are offset in delay, the intensity becomes modulated sinusoidally in space across the camera face. A real-time autocorrelator is used to determine the power density spectrum of this signal, and thus this delay offset.

The work on this system not documented elsewhere is described below. The details of earlier work are contained in the annual report for this contract covering the period 1 February 1987 to 31 January 1988. Wiring of the correlator hardware was completed in March, 1988. Testing and debugging continued, using the PC to emulate an increasing number of the correlator controller functions. In April, the correlator along with the rest of the equipment for the group delay experiment was moved to Mount Wilson. All further work was performed at the site.

The PC was eventually configured and used to emulate every control signal, permitting full testing of all correlator functions. This capability is retained (and hopefully never needed) for diagnostic use. Initial testing was performed with the aid of a single-step clock included in the correlator hardware for this purpose. Since this was all done under PC control, the clocking rate was rather slow. The internal correlator controller was installed as soon as possible, and the clock was switched to the 10 MHz full speed clock. The correlator was fed contrived data, and the results checked against the known correct output. Numerous test runs were conducted to exhaustively exercise the correlator. By mid-July, the correlator was considered fully functional. In all, approximately 1.5 MB of software was used to achieve this level of operation.

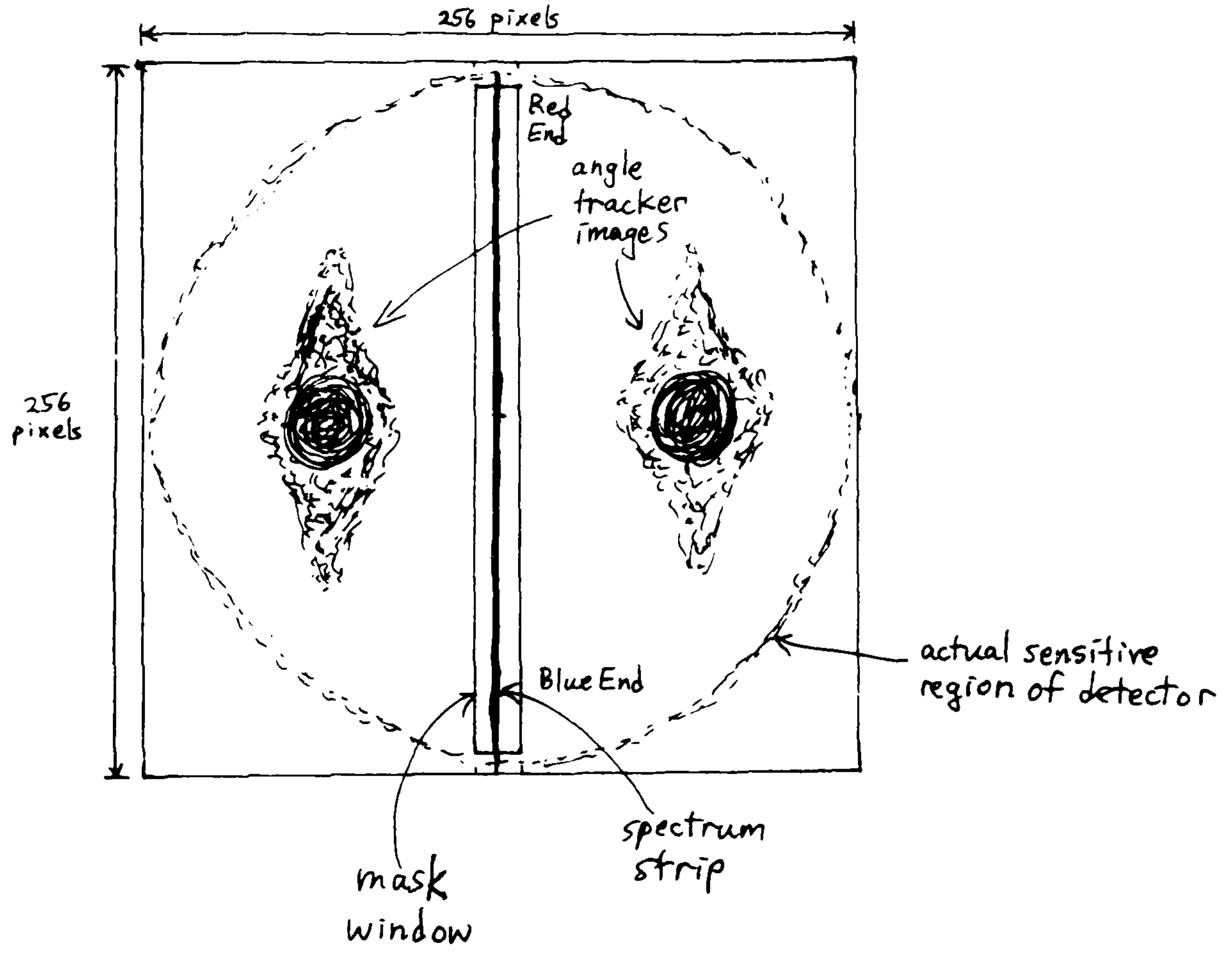
About this time, the other parts of the group delay apparatus began to receive greater attention. The spectrometer optics were assembled and installed on the main optical table right next to the photon camera. The output of the spectrometer, the spectrum strip, was positioned as a vertical line through the center of the camera input aperture [see Figure 1]. The two stellar images used by the interferometer's angle-tracking system were repositioned to either side of the spectrum strip. A user-definable mask ensures that the correlator only accepts as valid input photons which land in certain locations on the camera face. This mask is part of the correlator hardware. For the arrangement of Figure 1, the valid region was defined as a 16 × 240 pixel rectangular window centered on the spectrum strip. Eight pixels were eliminated from each end of the strip primarily because the circular active area of the camera face does not extend all the way to the borders of the 256 × 256 square. Also, the net bandpass of the optical path as configured for these tests did not extend across the full width of the camera face.

A path length difference between the interferometer arms results in intensity variations in the spectrometer output which should be periodic in frequency. The prism dispersion is not linear, however, and the detected spectrum must be rebinned before the autocorrelation is computed. Like the mask, this mapping is user-definable and is part of the correlator hardware. To generate the mapping, the locations of a number of absolute frequency calibration points on the spectrum strip must be determined. This was done using the interferometer's internal white light source and several narrow (10 nm wide) bandpass filters.

With the mapper properly calibrated, tests using the internal white light source could proceed. The active fringe tracker was used to locate the central white light fringe. The tracker was then disabled and offset approximately 10 microns from the central fringe. A peak appeared in the power spectrum at the expected location where none was present before. Two types of tests were then conducted. The first was to vary the offset a: verify that the peak in the power spectrum moved correspondingly. The second was to vary the total photoflux and investigate the behavior of the group delay measurement as the flux was decreased. The ultimate quantity of interest, of course, is the amount of increased sensitivity that can be expected. This will depend on the maximum practical integration time which will in turn be affected by the thermal stability of the interferometer. It will also depend on the available seeing, not a limiting factor during internal tests, but a major limit for stellar observations. A sensitivity increase of at least a factor of 10 (2.5 stellar magnitudes) appears possible. This would allow the Mark III instrument to observe objects at about the 9th magnitude level.

Analysis of the data from these internal tests as well as stellar data taken 21-23 July is now under way. Figure 2 shows sample power spectra of stellar data. On the horizontal axis, one micron of path length offset is approximately equal to one Hertz. Figure 2a shows the power spectrum with the star, photon noise, and camera artifacts. Figure 2b is a power spectrum of the same object, but with the path length offset so large that visibility of the spectrum intensity variations is essentially zero. In both cases, the large spike at low frequencies has been removed in order to improve the vertical resolution of the important features. These "zero-vis" spectra will eventually be used to remove the artifacts, etc., leaving a cleaner image for peak detection.

Figure 1



Relative Positions of Angle-Tracker Images and Spectrum Strip on Photon Camera Face

Figure 2a

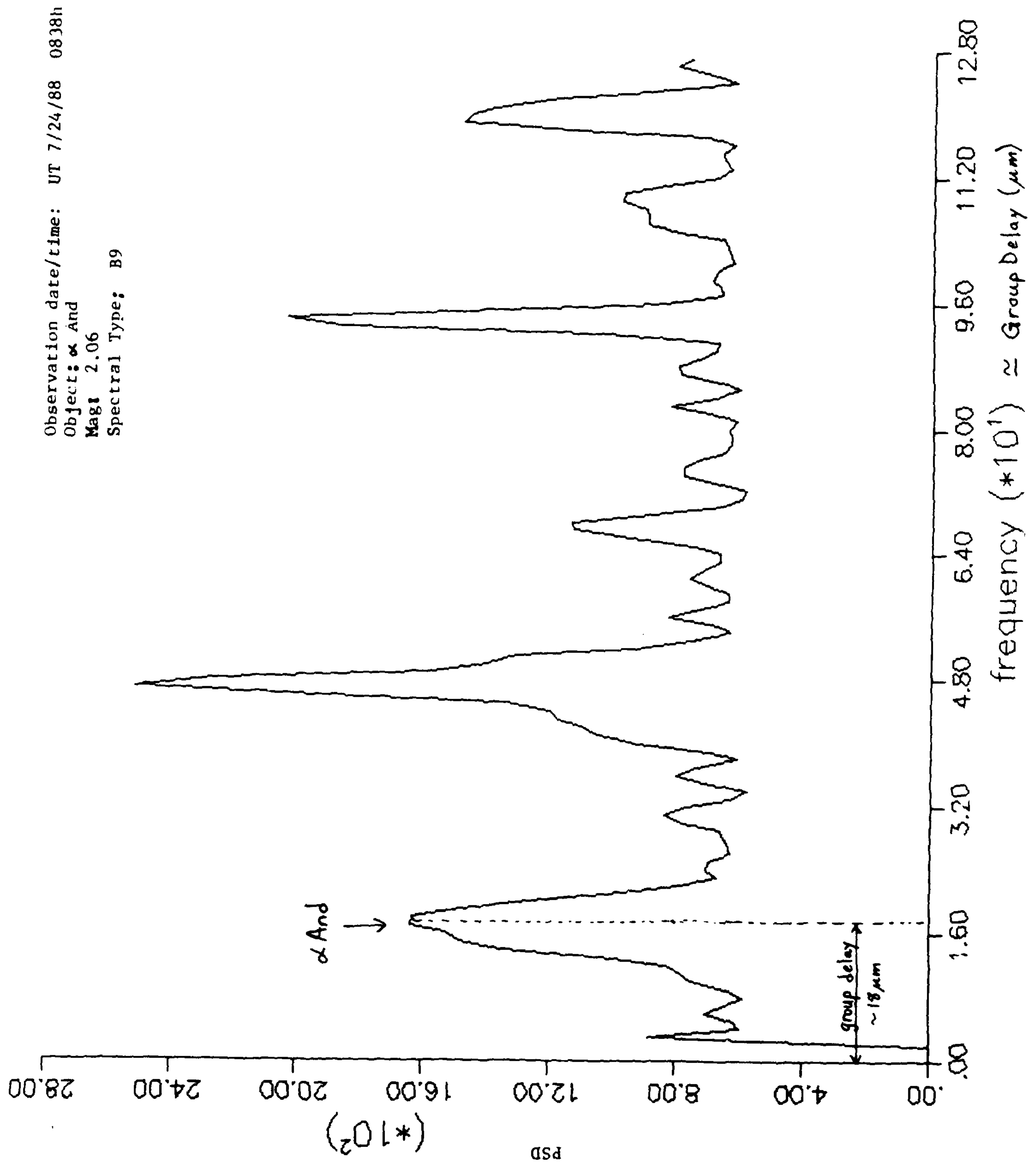
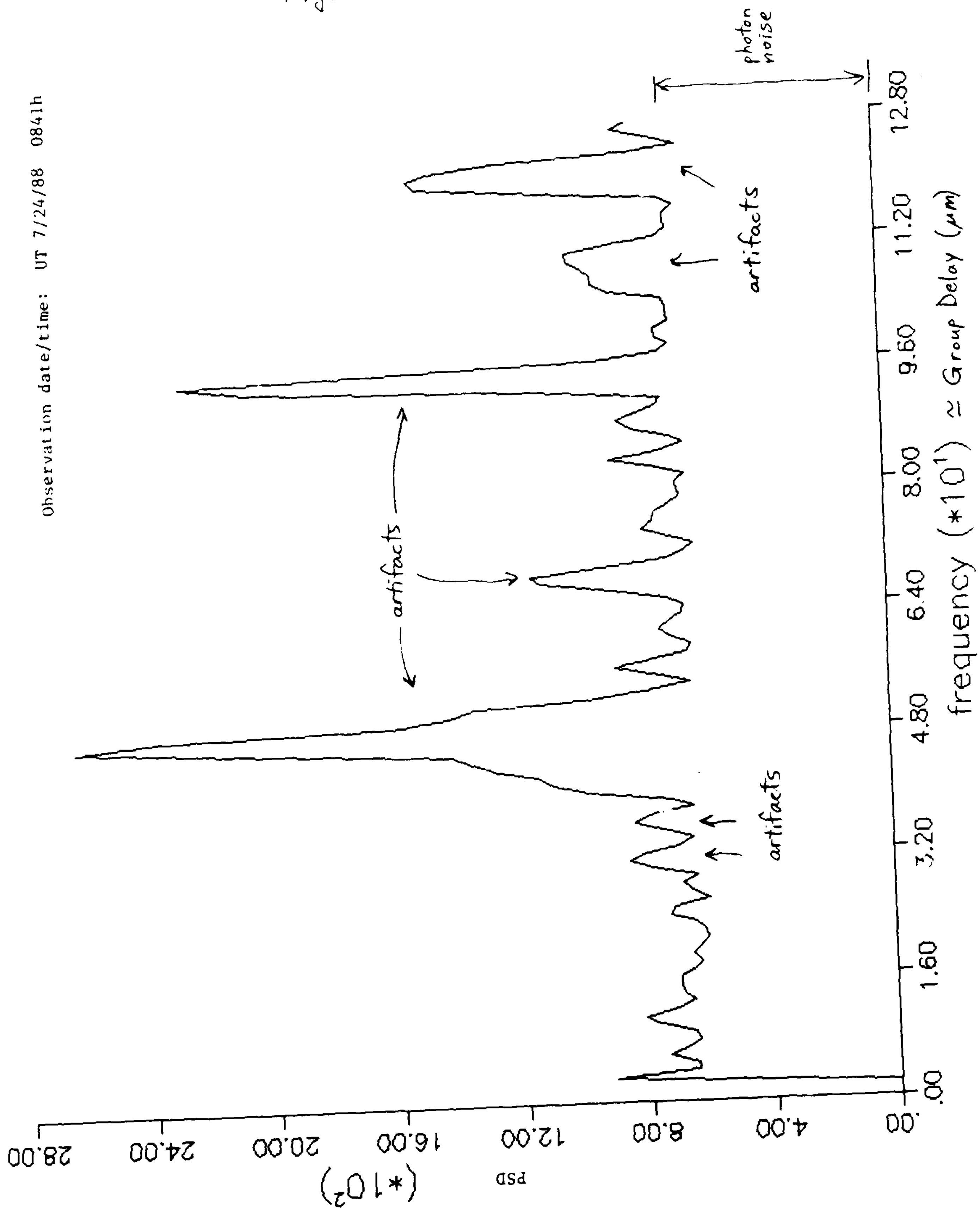

Observation date/time: UT 7/24/88 0838h
Object: α And
Mag: 2.06
Spectral Type: B9
α And
group delay
~18μm
.00
1.60
3.20
4.80
6.40
8.00
9.60
11.20
12.80
frequency (*10^1) ≈ Group Delay (μm)
.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
PSD
(*10^2)

Figure 2b


Observation date/time: UT 7/24/88 0841h
photon noise
artifacts
artifacts
artifacts
.00
1.60
3.20
4.80
6.40
8.00
9.60
11.20
12.80
frequency (*10¹) ≈ Group Delay (μm)
.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
PSD
(*10²)

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APPLICATION OF INTERFEROMETRY TO OPTICAL ASTROMETRY

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ABSTRACT

An optical interferometer capable of tracking phase and measuring fringe visibility has demonstrated the ability to measure the precise positions of stars over large angles. This instrument has tracked phase over periods of many hours while switching sequentially among several stars. The 3.1 m separation of the siderostats has been measured to an accuracy of 50 μ, indicating positional accuracies of 3 arcsec. The formal error of the least-squares solution for the baselines is of the order of a micron. The major limitations to accuracy were thermal instabilities and unmonitored siderostat positions. With improvements, this technique should be capable of astrometric accuracies exceeding one-hundredth of an arcsecond.

I. INTRODUCTION

Since Fizeau first pointed out the possibility of using interferometers in astronomy in 1862 (Muller 1962), astronomers have sought to use interferometry to overcome the limits on optical resolution set by atmospheric turbulence. The first measurement of a star's diameter was accomplished by Michelson and Pease in 1918. Subsequent successful instruments have included the intensity interferometer of Hanbury Brown and Twiss (Hanbury Brown 1974) which measured the angular diameters of 32 bright stars, and the pupil-plane amplitude interferometer of Currie *et al.* (1974). Direct interferometry with independently pointed apertures was first demonstrated by Labeyrie (1975), who observed interference fringes on Vega with a 12 m baseline. Since that time, several stellar interferometers have been built or are under construction (Tango 1978; Davis 1978; and Koechlin 1978). However, all of these instruments are amplitude interferometers in which only visibility measurements of the fringes are made.

The first phase-coherent interferometer was the Mark I stellar interferometer (Shao and Staelin 1977; Shao and Staelin 1980). This instrument demonstrated white-light fringe tracking on Polaris. An improved version, designated the Mark II instrument, has since been developed. This instrument has a longer baseline, larger input apertures, and a sky coverage of approximately 30° from zenith. It first tracked fringes in August 1982. In September 1984, a series of measurements were made to demonstrate the applicability of this instrument to the measurement of the positions of stars over large (> 20°) angles. This paper describes these measurements and their underlying principles. These same principles have been used by radio astronomers since the early 1970s.

II. THE MARK II STELLAR INTERFEROMETER

The Mark II instrument is a phase-coherent Michelson interferometer. A schematic diagram is presented in Fig. 1. Two small mirrors, S1 and S2, intercept light from a star which is combined at beam splitter BS and detected at photodetector P. The variable delay line DL makes interference fringes possible by adjusting for the difference between the two path lengths from the beam splitter to the stellar wave front via each arm of the interferometer. This adjustment, commonly called the delay, must change with time in order to compensate for the rotation of the Earth when tracking celestial sources, as well as to track out atmospheric turbulence. The fringe pattern, i.e., the intensity of the light at the photodetector as a function of delay, is proportional to the Fourier transform of the optical bandpass of the system.

The sensitivity of the interferometer is proportional to the

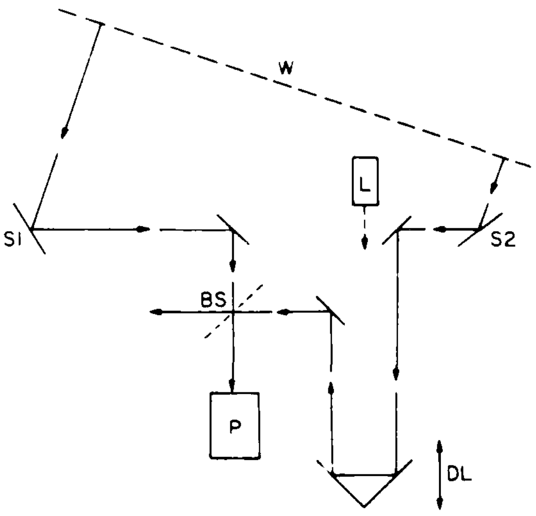

FIG. 1. Schematic diagram of an optical interferometer.

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APPENDIX B

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Atmospheric phase measurements with the Mark III stellar interferometer

M. Mark Colavita, Michael Shao, and David H. Staelin

The Mark III interferometer is a phase-coherent stellar interferometer designed for astrometry. Operating through the turbulent atmosphere, the instrument is also a sensitive detector of atmospheric phase fluctuations. The effect of phase fluctuations on astrometric accuracy is reviewed, and phase measurements obtained with the instrument at Mt. Wilson using a 12-m base line are presented. These measurements agree well with the predictions of a simple Kolmogorov spatial spectrum over the frequency range of 0.001–100 Hz. From these measurements, the outer scale of turbulence for propagation through the entire atmosphere is estimated to be >2 km. The standard deviation for an absolute astrometric measurement estimated from these measurements is $\sim 0.14T^{-1/6}$ sec of arc for long integration times for conditions of 0.5-sec of arc seeing. For star-switched relative measurements, this error should decrease as the square root of the number of switching cycles.

I. Introduction

The Mark III astrometric interferometer is a phase-coherent white-light stellar interferometer designed for astrometry. It became operational on Mt. Wilson in Sept. 1986 using, at present, a 12-m N–S base line. It succeeds the 3.1-m Mark II interferometer[1] which operated on Mt. Wilson from Aug. 1982 until Sept. 1984 and incorporates a number of improvements over that instrument, especially in the area of thermal stability. The instrument measures the phase of the white-light fringe in two wide spectral channels covering ~0.6–0.9 and 0.4–0.6 μm. The fringe phase in the red channel serves as the error signal for a white-light fringe servo which controls the position of a laser-monitored delay line, while the fringe phase in the blue channel is used with the two-color method. Continuous fringe tracks vary from a fraction of a second to tens of seconds, depending on the seeing. Figures 1 and 2 present a photograph of the Mark III interferometer site and a schematic diagram of the instrument. The instrument is discussed in detail in a separate paper.[2]

Atmospheric turbulence is the fundamental factor limiting the performance of all ground-based astrometric instruments, affecting both sensitivity and accuracy. While in practice instrumental limitations can dominate performance, the intent in the design of the Mark III instrument was to keep systematic errors sufficiently small that atmospheric turbulence would be the only significant error mechanism when rapid star switching was employed. Section II describes the effects of turbulence on measurements of stellar position, both for the case of a simple Kolmogorov spatial spectrum, and for the case of a model incorporating a finite outer scale. Section III presents atmospheric phase measurements obtained with the Mark III interferometer at Mt. Wilson in the fall of 1986. Data from the Mark II instrument are also presented. Only one-color observations are considered in this paper. The use of two-color methods to reduce atmospheric errors is an important part of the operation of the Mark III instrument and is discussed in detail in a separate paper.[3]

II. Atmospheric Effects

After propagating through the turbulent atmosphere, an initally coherent wave will exhibit a finite coherence area and a finite coherence time. The coherence diameter r_0 is that aperture diameter over which the rms phase fluctuations of the wavefront are ~1 rad. With a slow angle tracker, this parameter is given by[4]

$$r_0 = 1.68[k^2 \int_0^\infty dh C_n^2(h)]^{-3/5}. \tag{1}$$

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Fig. 1. Site of the Mark III stellar interferometer at Mt. Wilson.

where k is a wavenumber, C_n^2 is the structure parameter, and the integration is over the propagation path. The spatial variance of the phase fluctuations across the interference fringe is approximately twice that of the fluctuations across a single wavefront. The coherence time T_0 is that time interval during which the rms phase fluctuations of the interference fringe are equal to 1 rad. With a slow fringe tracker, and for the case of a long-base line interferometer, this parameter is given by[5]

$$T_0 = 1.36\left[k^2 \int_0^\infty dh\, C_n^2(h) V^{5/3}(h)\right]^{-3/5}$$

$$= 0.81(r_0/V), \quad V(h) = V. \tag{2}$$

where V is the wind speed. Finite values for r_0 and T_0 restrict the maximum usable subaperture size and the maximum usable coherent integration time for a stellar interferometer.

While atmospheric phase fluctuations limit the sensitivity of a ground-based interferometer, the more serious problem for astrometry is that the turbulent atmosphere corrupts the angle of arrival of the stellar wavefront, i.e., the apparent position of the star. The statistics of the angle-of-arrival process $\alpha(t)$ severely limit the accuracy possible from a single-color absolute astrometric measurement. The angle of arrival $\alpha(t)$ is related to fringe position $x(t)$ via $x(t) = \alpha(t)B$, where B is the interferometer base line and to phase difference $\Phi(t)$ via $\Phi(t) = kx(t)$, where $k = 2\pi/\lambda$ and λ is the wavelength of observation.

The most useful description of the angle-of-arrival process is its power spectrum $W_\alpha(f)$. In the geometric-optics approximation, the contribution to the power spectrum attributable to each atmospheric layer can

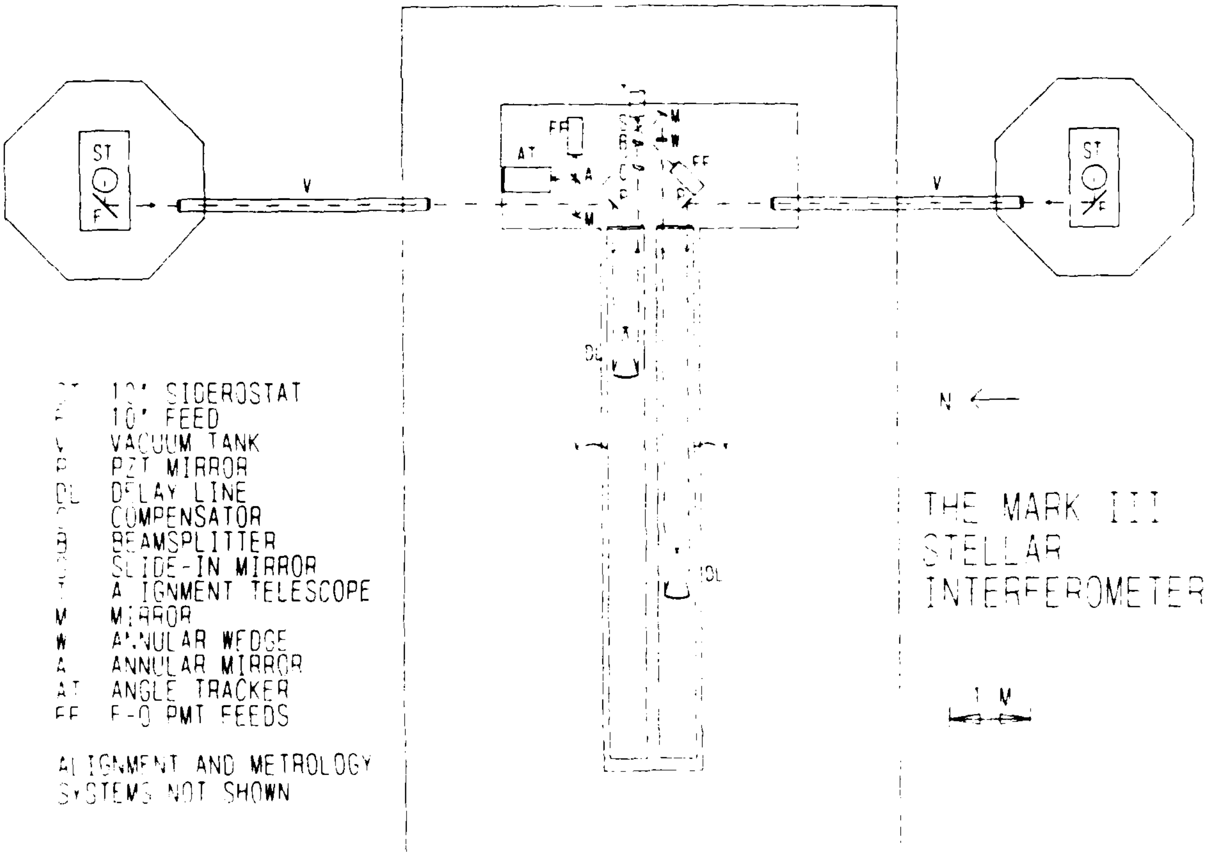

Fig. 2. Approximately to-scale schematic diagram of the Mark III stellar interferometer.

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THE MARK III STELLAR INTERFEROMETER

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Summary. The Mark III interferometer is an operational long baseline stellar interferometer on Mt. Wilson with four possible baseline configurations from 9 meters NE-SW to 20 meters N-S. The interferometer was designed to be a highly automated astronomical instrument to measure stellar positions and diameters to a magnitude limit of seven. Initial fringe observations were made in September 1986 with a 12-meter N-S baseline. In the following months, semi-automated astrometric and stellar diameter measurements were also made. This paper describes the hardware and software components of the instrument and its operational characteristics.

The interferometer has several novel features. One is the use of optimal estimation and control algorithms (e.g. Kalman filters) in the control loops. Another is the ability to operate both as a closed-loop phased interferometer and eventually as an open-loop or absolute coherent interferometer. High thermal stability and mechanical accuracy should permit the instrument to point blind at an astronomical object and maintain optical path equality to within the limits set by the atmosphere. In this absolute interferometric mode of operation, it should be possible to observe faint astronomical objects that are too dim for phase tracking. In theory, measurements of amplitude, group delay, and closure phase will be possible to 14 mag.

Key words: stellar interferometry, astrometry, stellar diameters, optical array, proper motion

APPENDIX D

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Two-color method for optical astrometry: theory and preliminary measurements with the Mark III stellar interferometer

M. Mark Colavita, Michael Shao, and David H. Staelin

The two-color method for interferometric astrometry provides a means of reducing the error in a stellar position measurement attributable to atmospheric turbulence. The primary limitation of the method is shown to be turbulent water vapor fluctuations, which limit the amount of improvement over a one-color measurement obtainable with a two-color estimate. Secondary atmospheric effects caused by diffraction from small refractive-index inhomogeneities and differential refraction for the observation of stars away from zenith are shown to introduce errors that behave as white noise and which should usually not be significant. Other potential error sources due to photon noise, systematic instrumental effects, and imperfect data reduction are also considered. The improvement in accuracy possible with the two-color method is estimated as a factor of 5–10 over the corresponding one-color measurement. Some preliminary two-color measurements with the Mark III stellar interferometer at Mt. Wilson are presented which demonstrate a factor of ~5 reduction in the amplitude of the atmospheric fluctuations in a stellar position measurement.

I. Introduction

The accuracy of conventional ground-based astrometric measurements suffers from the deleterious effects of atmospheric turbulence. Because of the nature of the low-frequency differential atmospheric phase fluctuations, which behave almost as $1/f$ noise,[1] very long integration times are usually required to obtain highly accurate measurements of stellar positions.[2,3] However, the accuracy of such long-duration measurements is typically limited by systematic instrumental errors. For the case of relative astrometry,[3] the situation is somewhat improved. However, the ultimate limitation to high accuracies remains the turbulent atmosphere. The application of the two-color method to interferometric astrometry[4,5] provides a means for reducing the atmospheric contribution to the error in a stellar position measurement.

Two-color techniques for the precise measurement of long paths through the open atmosphere have been used successfully for geodetic ranging[6,7] and have application to satellite ranging[8,9] and altimetry.[10] In this case, the problem which the two-color techniques address is the determination of the path-averaged refractive index needed to convert an apparent measurement to the proper vacuum distance. In astrometric applications of two-color techniques, the interest is in the measurement of angles. Large atmospheric scales are thus rejected, and the nonunity atmospheric refractive index does not introduce errors. In this case, the two-color method is employed to correct the errors caused by turbulent fluctuations in refractive index, which usually contribute only a small amount to the error in the range-finder case.

The use of two-color techniques is similar in both the range-finder and astrometric cases. For astrometry, let α_1 and α_2 be the stellar positions, i.e., the angles of arrival, observed at wavelengths λ_1 and λ_2. The two-color estimate of the stellar position α_{2C} can be written

$$\alpha_{2C} = \alpha_1 - D(\alpha_2 - \alpha_1), \tag{1}$$

where D is the atmospheric dispersion,

$$D = [n(\lambda_1) - 1]/[n(\lambda_2) - n(\lambda_1)], \tag{2}$$

and $n(\lambda_1)$ and $n(\lambda_2)$ are the atmospheric refractive indices at wavelengths λ_1 and λ_2. For $\lambda_1 = 0.7$ µm and $\lambda_2 = 0.5$ µm, the dispersion is ~87.1. In Eq. (1), the quantity α_1 is a measure of the true stellar position plus the instantaneous atmospheric error, while, in principle, $D(\alpha_2 - \alpha_1)$ is a measure of the atmospheric error

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APPENDIX E

PRELIMINARY MEASUREMENTS OF STAR POSITIONS WITH THE MARK III STELLAR INTERFEROMETER

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ABSTRACT

Preliminary astrometric measurements with the Mark III optical stellar interferometer using a 12.005 m north–south baseline were made during seven nights in November 1986. A total of 22 stars were observed over large angles in a 3000-Å wide band centered at 7000 Å. As expected, the estimated precision of the relative positions increases with hour-angle coverage. For the ten stars observed over at least 90° of hour angle, the right ascensions are consistent at the 5 ms of time (1σ) level, while the uncertainties in declination are at the 22 mas (1σ) level. With this small data set, the question of systematic errors cannot be fully examined. A discussion of observational techniques, errors, limitations of this system, and future plans is presented.

I. INTRODUCTION

Determining accurate positions of stars over wide angles allows important measurements not otherwise possible. For example, fundamental constants, such as those of precession, nutation, and galactic rotation require wide-angle astrometry. Measurements at optical wavelengths are being supplanted by those made in the radio bands. Positions of extragalactic radio sources accurate to a few milliarcseconds are now available over the northern hemisphere from radio observations. A similar precision is needed in the visible, if we hope to independently align radio maps with optical images made with such systems as the *Hubble Space Telescope*, which will have a resolution of 80 mas.

Classical astrometry uses the meridian transit circle to determine the position of stars over large angles to accuracies of order 0.1 arcsec. The new FK5 optical reference frame is believed to be internally consistent at the 0.05 arcsec level at epoch 1987. The alignment of this reference frame with respect to the radio reference frame has yet to be determined. We believe that the radio reference frame is probably internally consistent at the level of a few milliarcseconds (Johnston and DeVegt 1986; Ma *et al.* 1986).

Modern techniques are evolving that promise improved accuracy in determining star positions. Space techniques such as the *HIPPARCOS* satellite promise a reference frame of stars down to magnitude 10 with accuracies of a few milliarcseconds. As space techniques are very costly and deployment in orbit is uncertain at this time, the development of ground-based techniques is very important. Initial measurements with an interferometer at Mount Wilson Observatory gave stellar positions accurate to 3 arcsec (Shao *et al.* 1987). A new-generation instrument, the Mark III stellar interferometer, is in the process of fabrication. Here we report preliminary measurements with that instrument using the initial 12 m north–south baseline.

Further, interferometry appears to be a technology that *offers improved accuracy for both ground and space observations*. Before space-based observations are planned in detail using this technique, experience must be gained through the development of ground-based systems.

II. THE INSTRUMENT

The Mark III interferometer is the third in a series of optical interferometers built on Mount Wilson, California. Stellar fringes were first tracked with this instrument in September 1986. By November, the system was operating well enough to allow stellar observations to continue all night. This instrument was specifically built to do fundamental astrometry. Several features were incorporated into its design to allow it to accomplish this goal. The fringes were tracked in a closed-loop mode, to allow accurate measurement of the delay. Star tracking and fringe tracking were completely automated, allowing rapid switching between stars. One hundred sixty observations were accomplished during one night. The light from the siderostats was mixed in a central, temperature-controlled building, and the siderostats were mounted on massive concrete piers. As a result, the baseline is fairly stable at the micron level. Other features designed and built, but not yet operational, are expected to further improve the performance of the system. We will limit our description of the instrument to the points relevant to the astrometric performance. A full description of the instrument is given in Shao *et al.* (1988).

The interferometer consists of two 25-cm-diameter siderostats, mounted on massive, insulated concrete piers and currently operating with a north–south baseline of 12.005 m. Four additional piers have been constructed, allowing future observations with a 20 m north–south baseline, as well as with two oblique baselines. From the siderostats, the light

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APPENDIX F

INITIAL STELLAR DIAMETER MEASUREMENTS WITH THE MARK III INTERFEROMETER

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ABSTRACT

We report initial stellar diameter measurements made with the Mark III stellar interferometer. The visibility measurements showed fluctuations of 1%–3% for a 10 s integration consistent with photon statistics as the predominant source of noise. Measurements of the unresolved star β Tau were used to calibrate the instrumental and atmospheric biases which reduce the measured visibility. We report angular diameters, at 706 nm, of 6.15 ± 0.25 mas, 8.70 ± 0.15 mas, 5.0 ± 0.5 mas, and 7.2 ± 0.4 mas rms for the stars α CMi, β Gem, α Per, and α UMa, respectively. These angular diameters were calculated, assuming a uniform disk, from the visibility measurements, the wavelength of observation, and the projected interferometer baseline. The angular diameters corrected for limb darkening are also presented. In the next observing season, the instrument should be able to make very precise diameter measurements on a large number of stars brighter than 7 mag.

Subject headings: instruments — interferometry — stars: diameters

I. INTRODUCTION

The Mark III interferometer is a joint project among the Smithsonian Astrophysical Observatory, the Massachusetts Institute of Technology, the Naval Research Laboratory, and the U.S. Naval Observatory. The instrument is located on Mount Wilson, California. First fringes were observed in 1986 September with a 12 m baseline.

Long-baseline optical stellar interferometers have traditionally been used to measure the diameter of stars. The Mark III interferometer (Shao *et al.* 1988), unlike other operational stellar interferometers (Labeyrie 1975; Davis and Tango 1986), was designed principally for fundamental astrometry (Mozurkewich *et al.* 1987). Consequently, the instrument was designed with such characteristics as extreme thermal stability and submicron mechanical accuracy and makes extensive use of laser metrology. These features are not usually necessary for stellar diameter measurements. In addition, the instrument was optimized for high astrometric sensitivity through the use of very wide optical bandpasses, at the expense of some accuracy in the measurement of visibilities. It was subsequently modified to enable accurate visibility measurements to be made simultaneously with astrometric measurements, and a set of preliminary stellar diameter measurements were made in 1986 November. The next section describes the hardware used for making these initial visibility measurements, and the third section describes the observation and analysis procedure. The last section summarizes these initial measurements of α CMi, β Gem, α Per, and α UMa.

II. THE MARK III INTERFEROMETER

The instrument is an active-fringe-tracking long-baseline optical interferometer. Figure 1 shows a schematic of the instrument. A star tracker, or autoguider, keeps the interfering wavefronts parallel to a fraction of an arcsec. The vacuum delay lines are monitored with laser interferometers with 5 nm resolution and can be set with 10 nm accuracy. An active fringe-phase-tracking servo-system keeps the optical paths in the two arms equal to a fraction of a wavelength of light in the presence of mechanical error, thermal drift, and atmospheric turbulence. Presently, light from one side of the beamsplitter is used for fringe tracking and light from the other side is used for visibility measurements through a narrow bandpass filter. In 1986, the magnitude limit of the instrument was set by an interim star tracker rather than by the fringe tracker. In 1987, an improved star-tracking system (Shao *et al.* 1988) will enable visibility measurements of $V = 7$ objects.

The fringe-detection scheme is based on a path-length modulation technique that was also used on two previous long-baseline stellar interferometers on Mount Wilson. A mirror on a piezoelectric stack (PZT) is moved in a 500 Hz triangle-wave pattern with a one-wavelength *p-p* motion. During each 1 ms sweep of the PZT, the number of detected photons in four equally spaced time bins is recorded, as shown in Figure 2. Successive 1 ms scans are co-added to yield the desired coherent integration time. These quantities—*A*, *B*, *C*, and *D*—are used to estimate the visibility. The amplitude of the path-length modulation is monitored by a laser interferometer and is controlled by a low-bandwidth servo with a precision of ~0.1% to reduce the systematic errors that arise when the modulation amplitude is different from the wavelength of observation. In order to minimize the systematic errors in the visibility measurements attributable to atmospheric turbulence, the amplitude measurements were made with an effective aperture of 2.5 cm, an optical bandwidth of 10 nm, and a

Angular Diameter Measurements of 24 Giant and Supergiant Stars From the Mark III Optical Interferometer

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ABSTRACT

We report preliminary stellar diameter measurements of 24 stars made with the Mark III optical interferometer. The stellar diameters reported here were obtained using 12.0-meter and 8.3-meter baselines with a center wavelength of 674 nm and a bandwidth of 10 nm. The observed visibilities were normalized using observations of 9 stars of small angular diameter. We present the calibrated visibilities and best-fit uniform-disk models for 24 giant and supergiant stars of angular diameters 3 mas to 17 mas, with accuracies of order 0.5 mas.

I. INTRODUCTION

The direct measurement of stellar angular diameters has been the principal goal of most attempts at astronomical interferometry since the pioneering work of Michelson and Pease (1921). In addition to Michelson interferometry, these methods include: lunar occultations (Evans 1955), intensity interferometry (Hanbury Brown 1968), speckle interferometry (Labeyrie 1970), amplitude interferometry (Curie, Knapp, and Liewer 1974), and infrared heterodyne interferometry (Sutton et al. 1977). The angular diameter of a star, when combined with the measured integrated flux from the entire photosphere yields the emergent flux at the stellar

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