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Final Report
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Mark-III Interferometer

I. Introduction

This work is a continuation of that begun under Naval Research Laboratory Contracts N00014-84-C-2082 and N00014-86-C-2114. All three of these contracts involved participation in the development and testing of the Mark-III stellar interferometer at the Mount Wilson Observatory in California. The effort is a joint project of the Massachusetts Institute of Technology, the Naval Research Laboratory, the U.S. Naval Observatory, and the Smithsonian Astrophysical Observatory. The instrument employs a two-color technique to reduce position errors due to atmospheric turbulence, and can operate with four possible baseline configurations ranging from 9 to 20 meters. Despite its function as a technology development platform, it is also capable of stellar separation and stellar diameter measurements with nearly unprecedented accuracy and sensitivity.

The major contributions of this work are the development of a dispersed-fringe group delay measurement system which can boost the system sensitivity by several stellar magnitudes, and the initial stages of development of an infrared capability, which should increase the future scientific interest of the facility.

Keywords: Astronomy, (AW) *Astronomy*

II. Development Of Dispersed Fringe Group Delay Astrometry Capabilities For The Mark-III Optical Interferometer

A major limitation shared by current ground-based astronomical optical interferometers is their inability to actively measure fringe phase for objects fainter than about 9th magnitude when limited by atmospheric turbulence to coherent apertures, r_0 , of (typically) 10 cm and coherence times, τ_0 , of a few milliseconds. The resulting collection of observable objects not only restricts the general usefulness, but keeps specific applications, such as the goal of linking the optical and radio astronomical reference frames, effectively out of reach. This latter application is one to which high angular resolution optical interferometry is ideally suited.

By borrowing a technique from radio astronomy, the above magnitude limit can be extended. An intentional path length difference (the delay offset) causes the intensity of the light combined from the two siderostats to vary periodically with optical frequency. The power spectrum of the variations contains a peak at a location proportional to the group delay. The group delay is equal to the delay offset and is independent of the phase of the variations. It can thus be integrated over many r_0 - τ_0 frames to increase the signal-to-noise ratio (SNR). Combined with information about the

instrument baseline, the delay can be used to solve for the position of the observed star. The theory, system design, and Mark-III experiments are described at length in the thesis of Edward Jinhyong Kim¹.

Experiments were conducted using the Mark-III stellar interferometer at the Mt. Wilson observatory to demonstrate measurements of the dispersed fringe group delay. A low-resolution spectrometer was added to the Mark-III optics, replacing one of the channels normally used for visibility measurements of the undispersed fringe. A real-time hardware engine was designed and built to compute and accumulate the autocorrelation of the detected spectrum for each coherent integration interval, or "frame." The accumulated autocorrelation data was then transferred to a small computer for computation of the power spectrum.

Two types of tests employing the Mark-III's internal white light source were conducted. The first tests showed that the useable range of delay offsets was limited by the spectrometer resolution and detector artifacts to a range between 14 and 26 microns. The second tests showed the detectability limit (SNR~1) to be between 2 and 4 detected photons per 4-msec frame across the entire dispersed fringe spectrum using only 4000 frames (16 seconds total integration time). A simple processing technique that substantially reduces the effects of periodic artifacts was also developed.

The Mark-III's existing closed-loop fringe tracker can not track at fluxes below 40 photons per 4-msec interval ($m_V \sim 5-6$), indicating that the present Mark-III magnitude limit can be extended by a factor of 10-20 (2.5-3.2 mag) to at least $m_V \sim 8$ using group delay measurements and a 16-second integration time. Using 1-meter apertures with separate processing within each r_0 subaperture and a total integration time of ~30 minutes, the detectability limit should be extended to $m_V \sim 13$, roughly enough to sense the cores of the brightest QSOs. The extrapolated magnitude limit for a SNR of 30 agreed well with predicted limits. The same spectrometer and detector can also be used to make simultaneous dispersed fringe (multi-channel) amplitude measurements with a similar extension in the magnitude limit.

Results were obtained from preliminary observations of four stars. These are believed to be the first stellar observations of dispersed-fringe group delays made with a visible-light stellar interferometer.

The major remaining obstacles to better performance and fainter operation are the presence of spatially periodic detector artifacts, a poor detector quantum efficiency, and the Mark-III's $1-r_0$ aperture limit.

¹ "Dispersed Fringe Group Delay Astrometry Using the Mk III Stellar Interferometer", Edward Jinhyong Kim, S.M. thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, February, 1989.

III. Development Of Infrared Observing Capabilities For The Mark-III Optical Interferometer

Development of an infrared capability for the Mark-III Stellar Interferometer began in September, 1988 with initiation of a design effort. The project involved modifying the interferometer to operate in the near infrared at wavelengths of ~ 2.2 microns. The interferometer would be used at this wavelength primarily for making stellar diameter measurements. The project was originally planned to include design, construction, and implementation of the system at Mount Wilson, the final goal being to successfully fringe track a 2nd magnitude IR source. Due to budgeting constraints and incomplete funding, however, construction and implementation was never completed. The project slowed during the spring of 1989 and ended in May.

The project design was divided into two major areas: optics and electronics. The optical design concentrated on modifying the optics of the current instrument so that they would be effective at the new wavelength of operation. The optical components to be used in the final implementation were selected but were never purchased. The electrical design centered mainly upon the low noise amplifier for processing the signals produced by the photodetector. A prototype of this circuit was built and tested, yielding results close to the theoretically predicted noise levels.

Figure 1 summarizes the necessary optical modifications to the Mark III system. These modifications are necessary because many of the current optical components do not operate effectively in the 2.2-micron wavelength region. The windows that cover the delay lines have been removed, as these windows are not transparent in the 2.2-micron region. A consequence of this is that the delay lines are no longer in vacuum, and this leads to the need for a dispersion corrector to compensate for atmospheric effects. The dispersion corrector consists of a single piece of glass mounted on a rotation stage driven by a stepper motor. The piece is rotated to vary the amount of glass that the light passes through, thus correcting for any differences in the air path lengths of the two arms. The compensator in the other arm of the interferometer is made slightly thicker than normal so that the adjustable dispersion corrector can compensate for path length differences in either direction. While compensating path length in air with path length in glass is not an entirely accurate technique over a broad spectral band, the dispersion effects that are being corrected are sufficiently small that this technique is adequate. Using empirically derived formulas for the dispersion of air, the tilt of the dispersion corrector can be calculated for any given value of path length difference. The corrector is then adjusted in an open loop fashion for each star being observed.

The optical design is made more complex by the need for the optics to work in both the visible and the infrared regions. This is necessary because the photon camera in the angle tracker will operate only in the visible. The

compensator, beamsplitter, and dispersion correcter must all be made of a material such as infrasil, which is highly transparent even into the 2.2 micron region. Actually, the need for a dispersion correcter can be entirely eliminated by replacing the delay line windows with windows made of infrasil, thus preserving the vacuum in the delay lines. However, this was determined to be prohibitively expensive, as these windows must be very thick. Finally, the criteria for good performance in both the visible and the IR creates a problem in the choice of a beamsplitter. There are no normal dielectric materials which operate sufficiently well in both regions. However, there is a resistive material known as inconol which can be used as a coating to create a beamsplitter which operates very well through the visible and out to 2.2 microns. Its only drawback is that it absorbs 33 percent of all incident power.

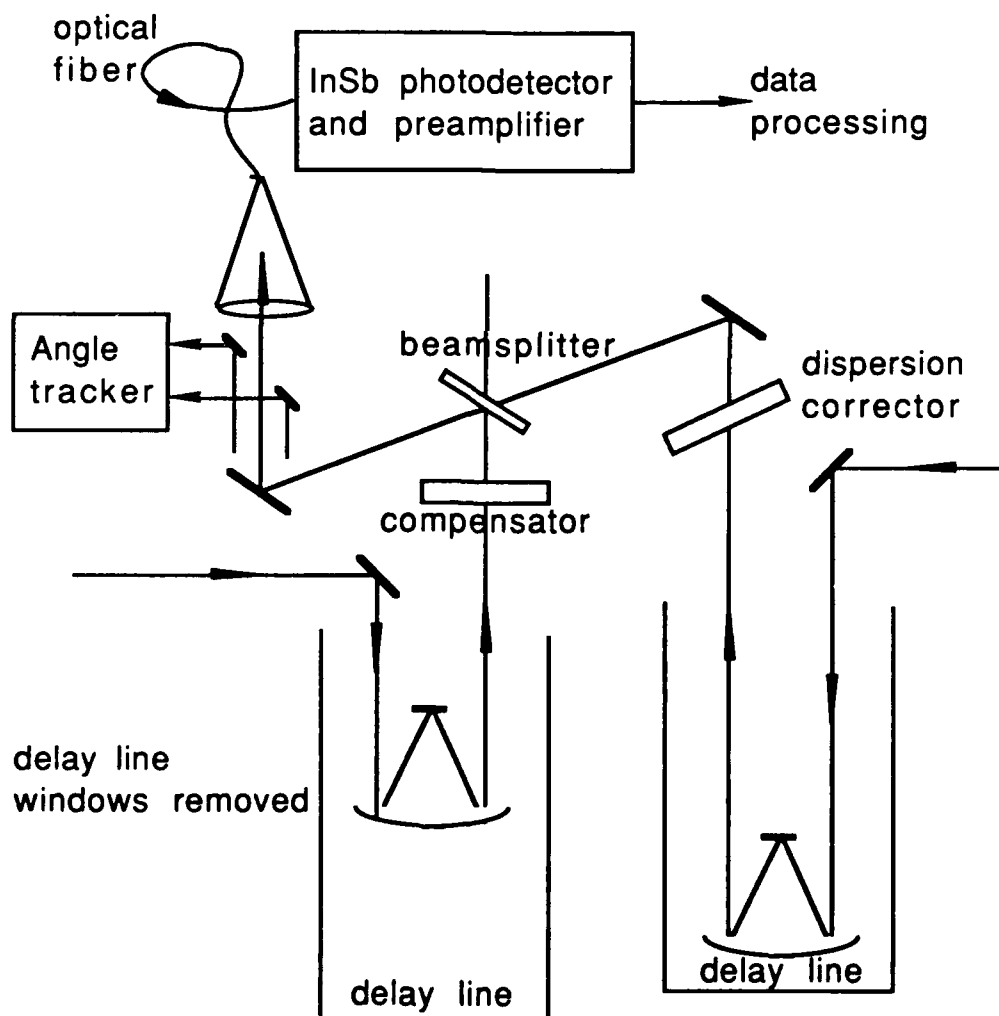


Figure 1. System modifications providing infrared capability

Once the light has passed beyond the angle tracker, it is no longer necessary to have good performance in the visible region. The lens and fiber materials used to feed the light to the photodetector are then less restricted and can be optimized for the infrared. Fluoride glass fibers, which are manufactured by several fiber companies, operate very well in the near infrared and are ideal for our application. The fiber-optic feed is used to carry the starlight from the optical table to the indium antimonide (InSb) photodetector. This detector replaces the photomultiplier tubes (PMTs) in the current instrument, since the PMTs do not operate at 2.2 microns. The detector must be housed in a dewar and cooled with liquid nitrogen in order to reduce its thermal noise. Additionally, it is necessary to build the first stage of electronics directly on the work surface of the dewar in order to achieve optimal noise performance. Infrared Laboratories in Arizona manufactures a dewar and detector system which is ideal for this application and which also has a desirably long hold time in excess of 24 hours.

The most critical element in our electronic design is the preamplifier used to process the signals generated by the InSb photodetector. In general, these signals will be very small and it is crucial that the preamplifier have very good noise performance. For this reason, an integrating charge amplifier was used instead of the traditional transimpedance amplifier. The charge amplifier offers better performance because it avoids the use of a feedback resistor which tends to contribute a lot of thermal noise. The amplifier contains two low-noise front-end JFETS mounted directly on the dewar work surface to reduce stray capacitance. Theoretically, this circuit should produce a noise level of 130 electrons for a 250 microsecond integration time. If the fringe tracking algorithm is repeated 8 times, (with 4 separate integrations per cycle), the total integration time is 8 milliseconds and the predicted signal-to-noise ratio for a second magnitude star is approximately three. A prototype of this circuit was built and tested at room temperature, using a resistor and capacitor to simulate the detector noise behavior, and it showed performance comparable to theoretically predicted levels.

The remaining electronics required for the system are involved with interfacing the InSb photodetector to the data processing equipment on the instrument. In view of severe program funding limitations the project was suspended, by mutual agreement with NRL, before design or construction of this aspect of the system began.

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