N93-13582

THE MOUNT WILSON OPTICAL INTERFEROMETER:

THE FIRST AUTOMATED INSTRUMENT AND THE PROSPECTS FOR LUNAR INTERFEROMETRY

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Introduction

Before contemplating an optical interferometer on the Moon one must first review the accomplishments achieved by this technology in scientific applications for astronomy. This will be done by presenting the technical status of optical interferometry as achieved by the Mount Wilson Optical Interferometer. The further developments needed for a future lunar-based interferometer will be discussed.

Background

Long Baseline Optical Interferometry (LBOI) is the use of discrete elements to obtain the detailed spatial structure of celestial objects. The light received from two independent apertures is brought together with the light paths being made equal through the use of a delay line or correcting plate as shown in figure 1. The first known successful application of LBOI to measure the diameters of stars was accomplished by A. Michelson in 1920 with the successful measurement of the diameter of Betelgeuse. This was done using mirrors mounted on a 20-ft beam placed on the 100-in. Mount Wilson telescope. The diameters of six stars, all giants and supergiants of late spectral class, were measured. This interferometer was abandoned because it was too difficult to stabilize the light paths. In 1960, R. Hanbury Brown developed the technique of intensity interferometry with which the diameters of 32 bright blue stars were measured. In the 1970s, Labeyrie directly combined the light beams from two telescopes. He obtained fringes on Vega with a 12-m baseline using the I2T interferometer. These instruments all used the visibility of the crosscorrelated signal to determine the diameters of stars. The crosscorrelated signal is a complex number containing not only the visibility or amplitude but also phase. The phase gives detailed positional information on the source of the signal.

In 1968, R. Hanbury Brown stated that Michelson's interferometer, or one in which the signals are mixed before detection, is applicable to many astronomical problems but technical problems remained. To produce significant results, the separation must be considerably larger than the 20-ft baseline originally used by Michelson, the instrument must be free from errors due to atmospheric seeing, and the results must be recorded in some objective way which is independent of the skill of the individual observers.

The sensitivity of an interferometer is proportional to the optical bandpass, the area of the collecting aperture, and the length of the coherence integration time. The diameter of the collecting aperture is limited to approximately 10 cm for one arcsec seeing by the spatial coherence of the Earth's atmosphere at optical wavelengths (5500 Å). That is to say that the randomness of the turbulence in the atmosphere leads to randomization of the phase on a single aperture or mirror over a spatial distance greater than 10 cm. Similarly the coherent integration time is also limited to approximately 10. To maximize the sensitivity, wide bandpasses are needed. This in turn results in an interference pattern which is very narrow. This pattern is only a few fringes wide and requires active fringe tracking to maintain coherence in the presence of atmospheric turbulence. This in turn limits the sensitivity of Earth-based interferometers to approximately 10 magnitude (Visual) when only a single atmospheric coherence cell is used.

The Mount Wilson Interferometer

As noted, before 1978 all LBOI used only the amplitude of the crosscorrelated signal. The first phase coherent optical interferometer that recorded the amplitude and phase of the crosscorrelated signal using a phototube, computer, and precise delay line to track the differential atmosphere phase path was developed by Shao and Staelin, who tracked the "white light" fringe of Polaris in 1979. This instrument has been improved by the use of the larger apertures, longer baselines, and wider sky coverage into the Mark II and Mark III interferometers.

Figure 2 shows a schematic diagram of an optical interferometer as embodied in the Mark I-III interferometers. The light from a celestial object in the two arms of the interferometer is brought together at the photomultiplier where, when fringes are observed, there is a maximum in intensity. The major innovation is the dither delay line, which vibrates at a frequency of a kHz with an amplitude of about a wavelength of the light being observed. Once fringes are detected, the dither delay line allows them to be tracked at the ms time scale. This is accomplished also by the precision delay line that can be set to 100 Å accurately and read out to 50 Å accuracy. By varying the delay line, the peak amplitude of the fringe pattern can be scanned, thus compensating for variable path length delays. A computer controls the position of the delay line, finds the maximum in the fringe amplitude, and records the delay, amplitude, and phase of the crosscorrelated signal. Thus the path lengths in the two arms of the interferometer can be made equal and tracked on timescales of ms. Since the timescale for turbulence in the Earth's atmosphere is of order 10 m, the interferometer can compensate for phase fluctuations due to atmospheric turbulence.

In addition to measuring the sizes of stars, interferometry can also precisely measure their positions. The USNO has an active program in astrometry and was seeking new technology to improve the accuracy of the positions of stars. Therefore the development of optical/IR interferometry for astrometry was sponsored by the Office of Naval Research. In 1982, a joint program in optical interferometry aimed at astrometry was undertaken by the Naval Research Laboratory (NRL), the United States Naval Observatory, the Smithsonian Astrophysical Observatory (SAO), and the Massachusetts Institute of Technology (MIT). The result was the Mark III interferometer.

Since the major impetus of the NRL/USNO/SAO/MIT program was primarily astrometry or the precise measurement of the positions of stars, the apertures collecting the light from the stars had to be made to rapidly and automatically switch from star to star in a preprogrammed sequence. This required, aside from pointing the mirrors precisely at the stars, that the finding and tracking of the central fringe also be totally automated.

The Mark III stellar interferometer was built to demonstrate fundamental astrometric measurements. A secondary goal was to initiate a program of accurate stellar diameter measurements leading to an instrument for imaging stars. Since astrometric measurements of high precision require repeated measurements, among the goals of this instrument were that it be easily operable, reliable and capable of extremely accurate measurements. A number of active subsystems were incorporated into the instrument to achieve these goals. The interferometer can be divided into five major subsystems: (1) a star tracker, (2) the optical delay line, (3) the stellar fringe acquisition and tracking system, (4) a laser metrology system, and (5) the siderostat pointing and control system.

Figure 3 shows the Mark III stellar interferometer, which is locaterd on Mt. Wilson, approximately 80 m east of the 100 in. telescope where Michelson and Pease made the first measurements of stellar diameters. Six and ten meters north, south and east of the central building are located the siderostat piers. In the figure, the siderostats are mounted on the innermost piers. The siderostats are located in huts that provide weather protection for the siderostats. The hinged roofs of the huts swing open for observing. Local seeing effects are reduced by routing the starlight through vacuum pipes from the siderostats into the main building. The main building contains the optics that combine the beams, the delay line, etc. The light is directed into the main building by the flats and is directed by piezoelectrically controlled mirrors toward the vacuum delay line. After reflection by the delay line's retroreflectors, the beams are combined at the beamsplitter. Part of the light is directed into the optical fibers that feed the phototubes and part of it is directed toward the star trackers. The trailer to the left of the main building houses the computers and observers. There are four possible baseline configurations form 8.3 m NE-SW to 20 m N-S as shown in figure 4. Also shown is a 4-30 m variable baseline along a N-S line that is capable of amplitude measurements that can be used to measure stellar diameters and evaluate atmospheric turbulence.

Astrometric measurements have been carried out with this instrument. As already stated, these observations involve observing as large a number of stars as possible to measure the baseline length and solve for the star positions. The number of stars observed is limited by how quickly the siderostats can move from star to star and the integration time of the individual measurements. At the present time it takes about 1 min to move between stars and 1 min to obtain an ample amount of data on the individual star. Figure 4 shows the observed delays as a function of time for the observations made on November 11, 1986, with a 12 m N-S baseline. The delay changes as the orientation of the baseline to the stars varies with the Earth's rotation. Rapid measurements must be made among several stars to determine the baseline length and its orientation as the baseline length drifts by approximately a micron an hour.

Measurements made in the fall of 1986 demonstrated that one-color observations could determine star positions in one coordinate to 20 mas. Measurements made in 1988 in two colors made during six nights of observation using the 12 N-S and 8.3 S-E m baselines of 12 stars displayed a formal accuracy of 6 to 10 mas in both celestial coordinates. It is very difficult to compare the accuracies of these star positions to anything available at the present time. The formal accuracy of the best star positions, i.e., the FK5 catalog, which is a compilation of the best available optical data, is at the 50 mas level at epoch 1988. The positions of these stars were in agreement with the FK5 positions at the 50 mas level for over half the stars. Repeated measurements with the Mt. Wilson instrument will have to be made to ascertain the systematic errors on the optical interferometric measurements.

Stellar diameters have also been measured with this instrument. A 12 m baseline at optical wavelengths has a minimum fringe spacing of 8 mas on the sky. If we consider stars to be spherical, which is a rough first approximation which is probably correct at the few percent level, then a one-dimensional variable baseline can be used to measure stellar diameters. the variable 4–30 m baseline has measured the sizes of about 20 stars as of November 1988. Figure 6 shows the observations for the star alpha Arietes. The least squares fit to the stellar diameter is 6.29 mas with an RMS error 0.12 mas. The dotted lines in figure 6 show the visibility curves for a uniform cylinder having a diameter 0.25 mas larger and smaller than the least squares value.

Observation with the Mt. Wilson interferometer will continue in 1989 to evaluate the effects of the atmosphere over long baselines, extend the measurements of stellar diameters and to repeat the astrometric measurements. Further, this instrument will be used to demonstrate prototype systems for future Earth- and space-based optical interferometers.

Developments Necessary for Imaging

The Mt. Wilson interferometer is a two-element interferometer. It has shown that interferometric fringes can be obtained over baselines of length 5 to 30 m and that the operation of an interferometer can be automated from pointing the telescopes to setting the delay line and phasing the instrument.

For true interferometric imaging of objects at optical wavelengths, three key technologies must be developed: simultaneous combination of beams from multiple elements, longer optical delay lines, and a metrology system to precisely monitor the geometry of the instrument. Longer delay lines are needed to compensate for the variable arrival of the signals at the apertures if baselines longer than 20 m are to be used. These necessary developments should first be undertaken and proven with a ground-based instrument.

Thus, the next logical step in the development of optical interferometry is to build a ground-based instrument for high angular resolution imaging of stars, stellar systems, and other celestial objects. This instrument will be the highest resolution imaging instrument ever used at optical wavelengths, and will achieve resolutions exceeding even those available from Very Long Baseline Interferometry techniques in the radio in all but the shortest radio wavelengths. This instrument will represent a tremendous advance over any currently existing optical interferometer, offering improvements of a factor of 10 or more in sensitivity, resolution, and imaging speed.

The instrument will be located on a suitable mountaintop where atmospheric conditions will facilitate optimum performance. The overall size will be about 250 in diameter, with at least six independent telescopes or siderostats forming a reconfigurable array. Light from these telescopes will be combined interferometrically in a central optics laboratory to produce the basic visibility amplitude and phase data used to form images.

The research carried out with such an interferometer will have a profound effect on the technology of imaging objects at great distances and will greatly aid in our understanding of the physical attributes such as size, shape, distance, and mass of celestial objects such as stars. The capability of imaging objects will be at least two orders of magnitude better than the Hubble Space Telescope. This improvement in resolution will allow many important astronomical discoveries to be made.

This interferometer is to be the first to image objects directly at optical wavelengths using both the amplitude and phase of the crosscorrelated signal. Early in the program the technology of simultaneously combining three beams and making phase closure measurements should be accomplished. Later the multiple-element instrument will demonstrate from the ground the capabilities of imaging celestial objects. After this an evaluation of the capabilities of using this technology in a space-based system can be made. The first space-based interferometer will be in Earth orbit but later instruments could be located on the Moon.

Interferometry in Space

The advantage of space-based optical interferometry is freedom from viewing objects through the Earth's atmosphere. For an Earth-based optical interferometer, the sensitivity of the instruments is proportional to seeing to the third power. This allows the phase across the observing aperture to be constant whereas on the Earth, for seeing of order one arcsec, apertures larger than 10 cm cannot be used for a single coherent aperture at 5500 Å. Apertures of size 10 cm must be summed. Further, integration times greater than 10 mas cannot be used (again assuming one arcsec seeing).

Imaging objects on the Earth with a conventional phase-stable interferometer using a single atmospheric coherence cell will be limited to objects brighter than 10th magnitude. If by summing different cells in the Earth's atmosphere increases the collecting area of the interferometer, or if a natural or artificial reference source can be found or generated to increase the integration time, fainter magnitudes can be reached. An interferometer in space will not have this limitation because very large optics can be used. The limitation on the imaging magnitude will be the stability of the space-based platform and the figure and stability of the large apertures. Therefore, for a space-based system, the intrinsic stability of the interferometer or the metrology system, i.e., the system measuring the spatial stability of the interferometer, will set the limiting magnitude constraint.

For free-flying interferometers, the stability of structures in space must be studied and metrology systems must be developed to overcome the shortcomings of the structures. The sizes of stars vary from 60 to 0.1 mas while the size scales of extragalactic objects are of order a few mas or less. This leads to useful baselines at optical wavelengths of order 10 m (10 mas) to 1000 m (0.1 mas) for imaging objects. It is very doubtful that structures as large as 100 m would be built for a free-flying interferometer, thus, for the longer baseline, either multiple free-flying satellites will be used, or the interferometer will be placed on the Moon.

Other reasons for placing an interferometer in space are to improve the instrumental stability and astrometric measurements. A free-flying space astrometric instrument would probably use a very short baseline, but there would be no limit on baseline length for a lunar instrument except that the object not be resolved. For an interferometer based on the lunar surface, the problems of instrumental stability should be simpler because massive structures can be used for stability. Note that the Mt. Wilson interferometer has massive piers which move at about a micron per hour. Thermal effects should have a much slower timeconstant for a lunar instrument since thermal effects will vary with the lunar rotation period whereas a satellite in earth orbit will have a much shorter thermal period unless it is sun synchronous.

Conclusion

The Mt. Wilson interferometer has demonstrated the necessary technologies of telescope coalignment and optical delay lines. Three further developments in ground-based interferometry are needed before the development of space-based interferometry. These are the simultaneous combination of beams from multiple elements, longer optical delay lines, and a metrology systems to precisely monitor the geometry of the instrument. After these developments take place, the study of space-based structures should be undertaken to evaluate the applicability of Earth-orbiting interferometers. In the long term, optical interferometry will need baseline lengths of order 100 m or greater for imaging and multiple free-flying individual apertures, or a lunar based interferometer must be considered. The technology for a lunar interferometer appears to be close in hand as it is just an extension of the Mt. Wilson interferometer and should require a minimum of technology development. Thus the prospect of a lunar interferometer should be carefully considered when the development of the Moon for scientific purposes is undertaken.

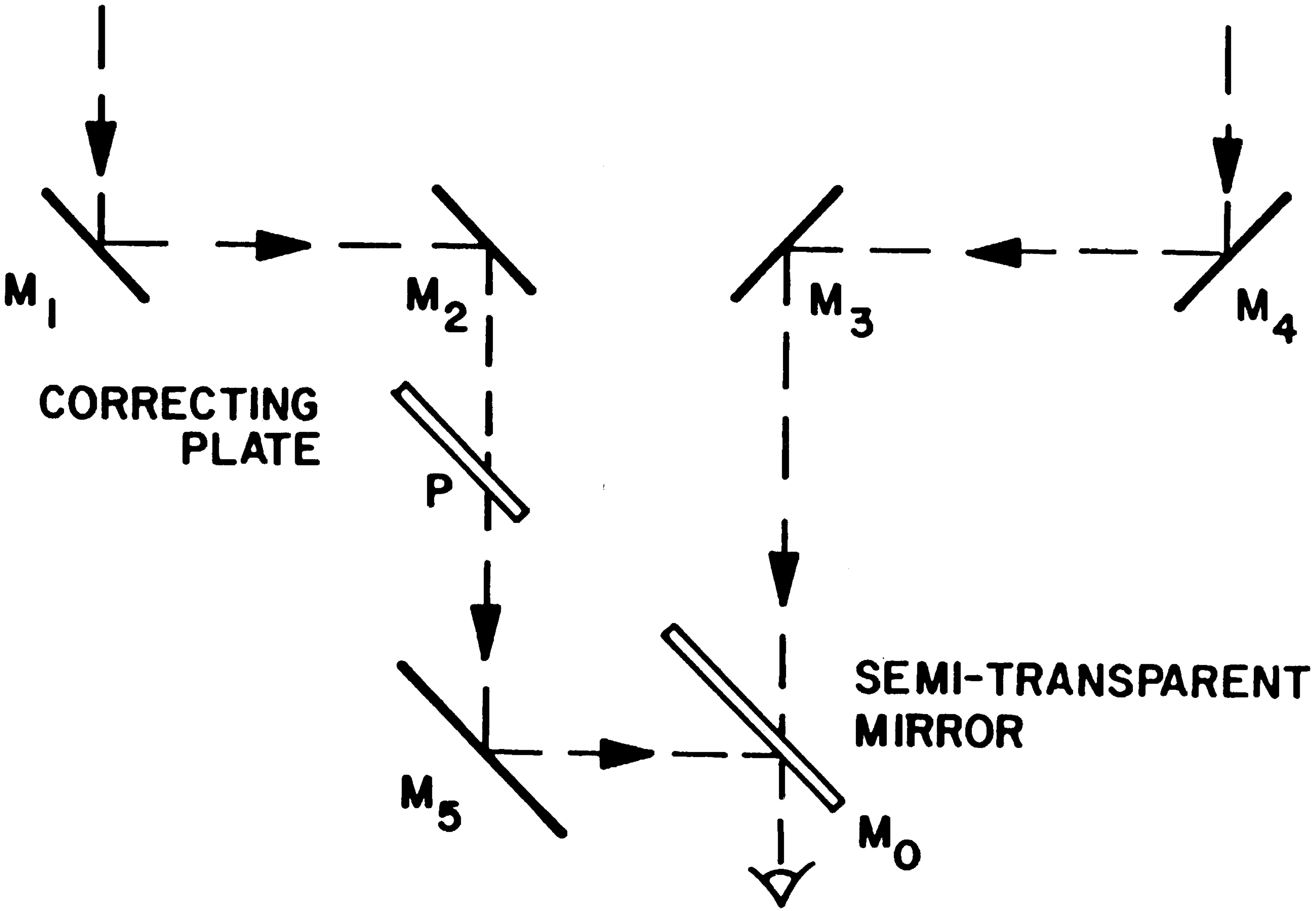

Figure 1: A schematic representation of a Michelson interferometer.

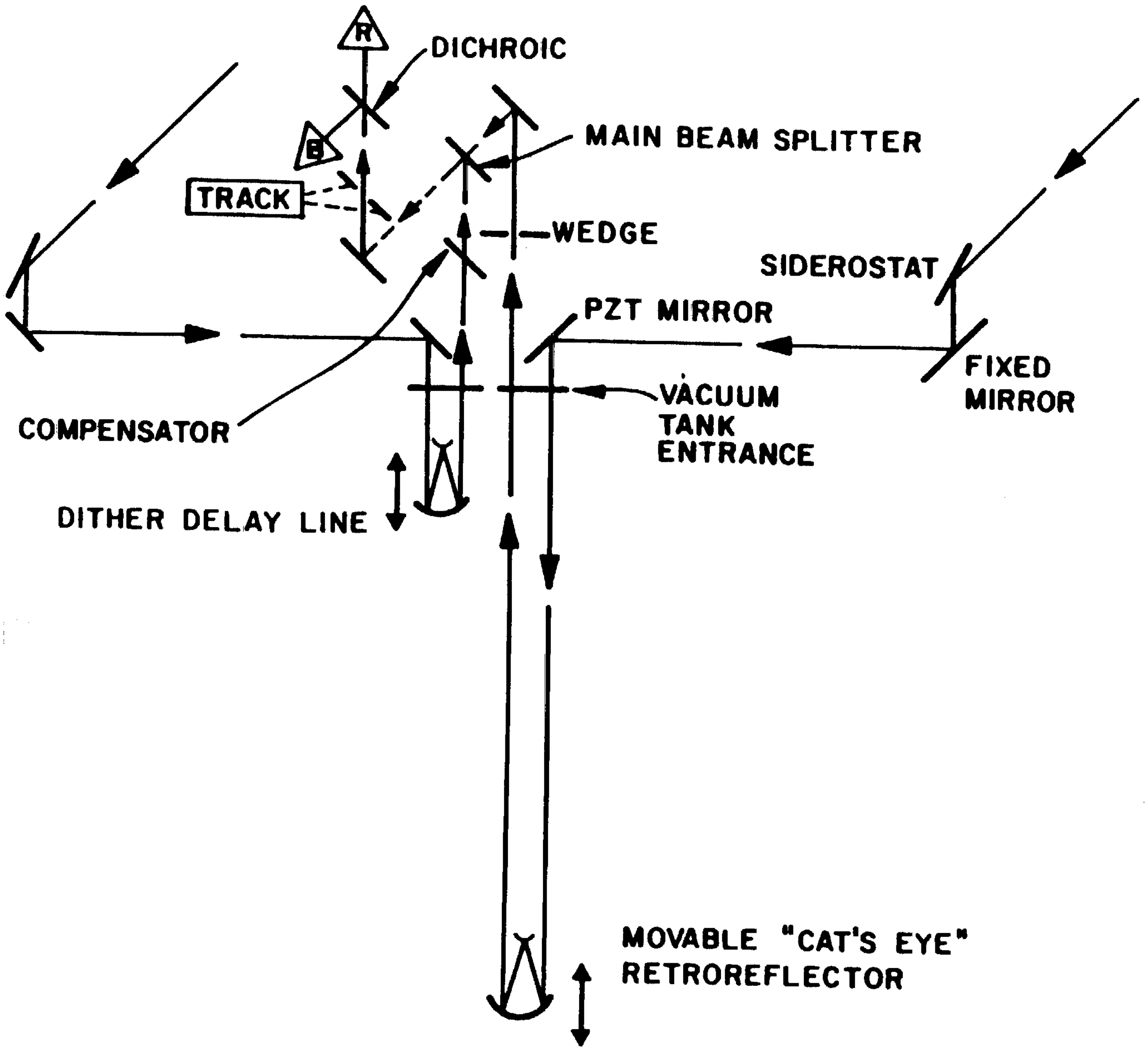

Figure 2: Diagram of a Michelson interferometer as embodied in the Mark I-III stellar interferometer. Note the dither delay line and the precise delay line to phase the interferometer.

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Figure 3: The Mark III of Mt. Wilson stellar interferometer. Note the 100-in. telescope dome in the background.

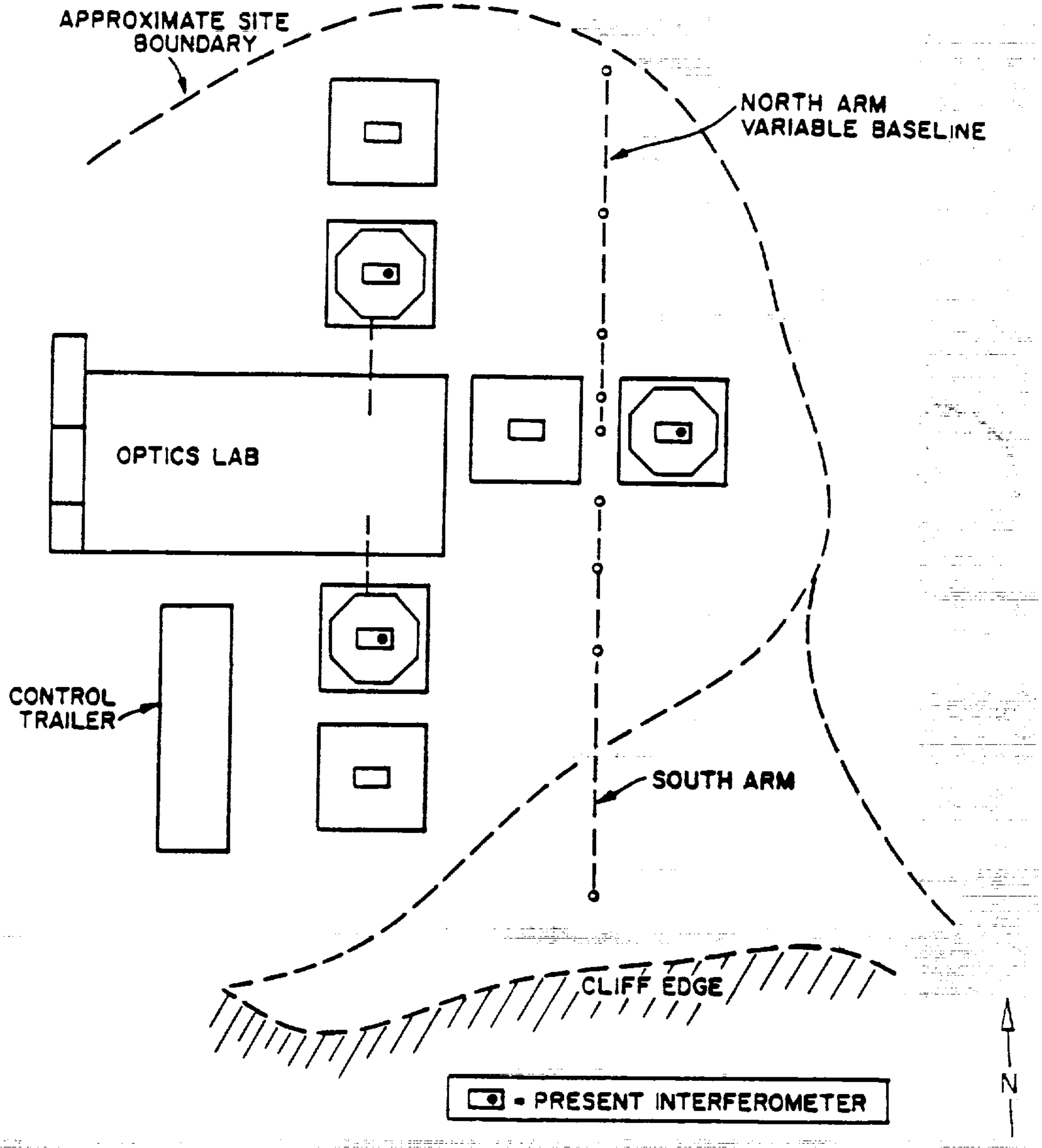

Figure 4: Diagram of the layout of the Mt. Wilson stellar interferometer. Note the 4-30 m North-South variable baseline.

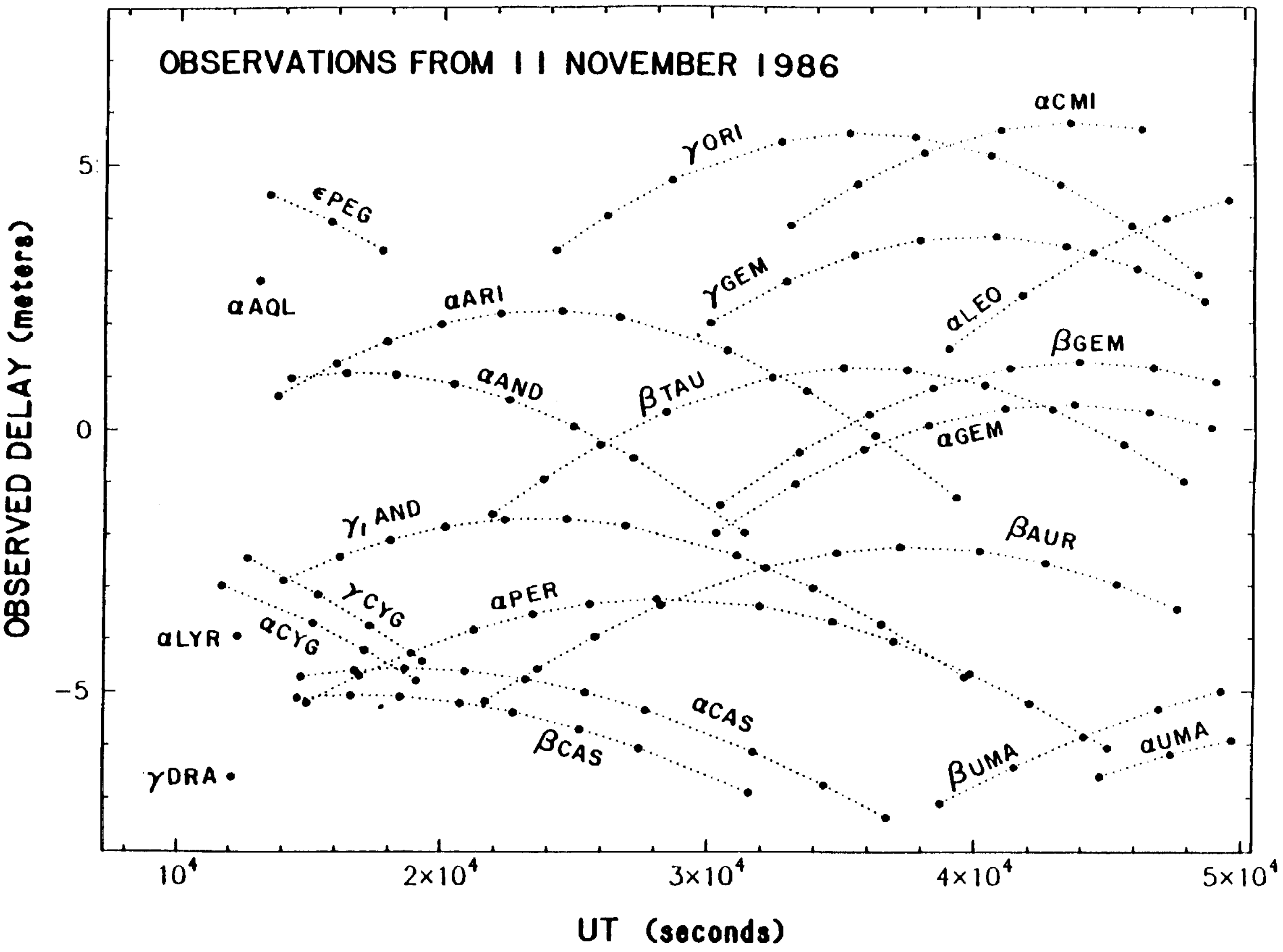

Figure 5: The observed delay as a function of time for November 11, 1986. Note that the arc contains the observation of a single star. On this night, more than 180 observations were made of 20 stars.

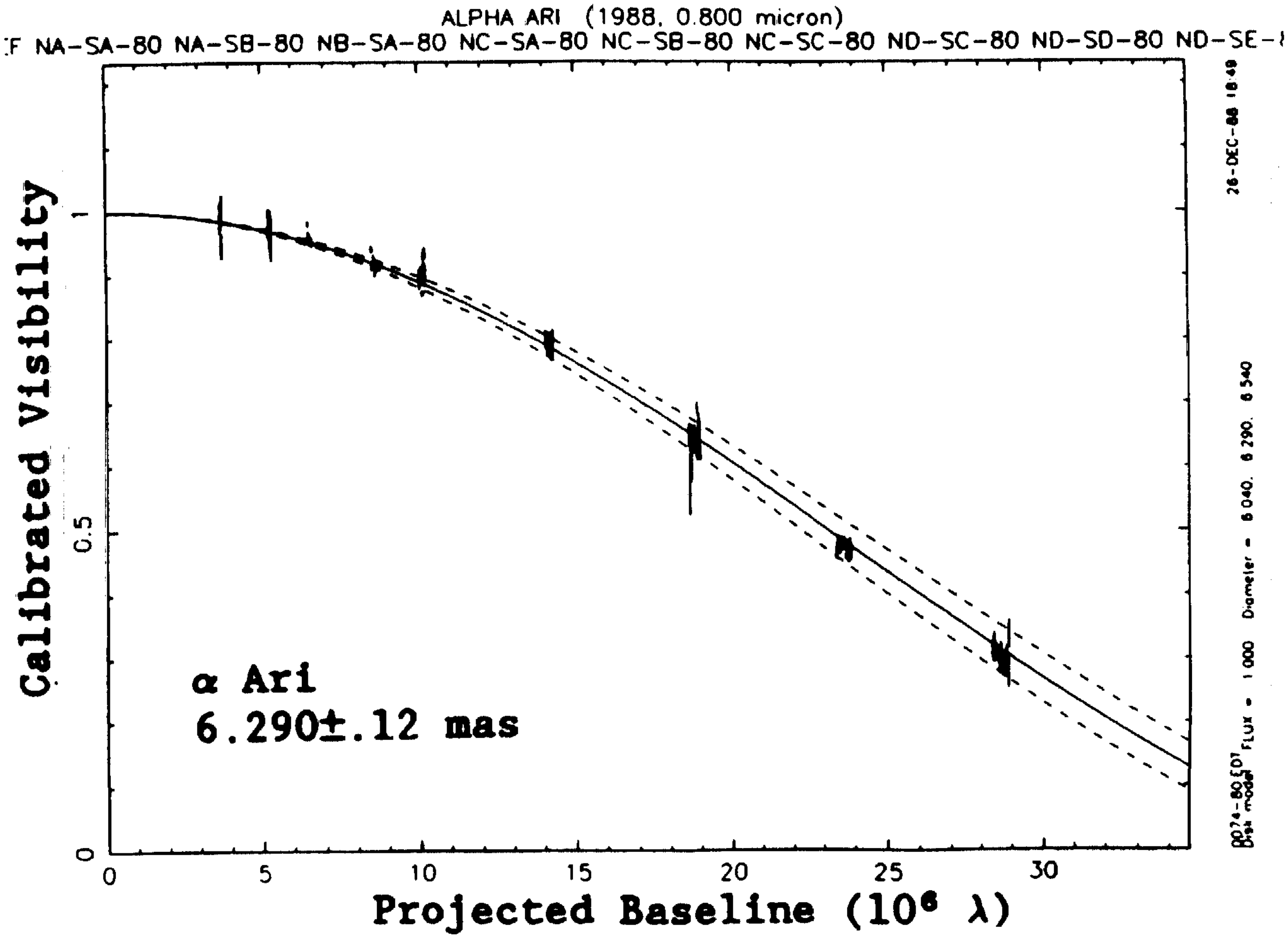

Figure 6: Visibility curve for the star alpha Arietes obtained with the 4-30 m variable baseline. The solid curve is the least squares fitted visibility curve to the data which has a diameter of 6.29 mas. The dotted lines are the expected visibility curves for a cylinder 0.25 mas higher and lower than the least squares value.