BINARY STAR OBSERVATIONS WITH THE MULTI-APERTURE AMPLITUDE INTERFEROMETER

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I. INTRODUCTION

A. HISTORY AND OBJECTIVES

The basic goal of the Amplitude Interferometer Program at the University of Maryland has been to achieve very high angular resolution, far beyond the angular resolution which is normally permitted by the Earth's atmosphere.[1,2]. This program is primarily directed to the observation of objects of astrophysical and astrometrical interest.

The initial general science objective has been the measurement of the angular diameters of various single stars at various wavelengths. As shall be discussed later, this has been achieved on the current equipment.[3,4,5,6,7,8].

The second objective of the Amplitude Interferometer Program is the study of binary and multiple star systems. Some initial tests have been conducted to validate the approach and the expected accuracy using the existing Amplitude Interferometer (AI). However, detailed tests and/or a regular observing program require the multiplexing capablity of the next generation Amplitude Interferometer (the Multi-Aperture Amplitude Interferometer) in order to have a reasonable observing efficiency for the use of the telescopes which would be involved

Other programs of the Multi-Aperture Amplitude Interferometer (MAAI) in this discussion consist of observing the surface features of super giants of late spectral type and of stellar shells. Preliminary data on Alpha Orionis and other stars has already been obtained. In addition, other fainter objects are much more effectively suited to an observing program using the MAAI. This list includes objects for which actual imaging [9,10] of the object will be of significant interest, that is, the surface structure of stars, Seyfert galaxy cores, quasi-stellar objects, and various other objects. The MAAI program will not be discussed further in this paper.

B. SINGLE APERTURE AMPLITUDE INTERFEROMETER

The Amplitude Interferometer has already been used for an extended series of observation. This instrument has been designated as the Single Aperture Amplitude Interferometer (SAAI). We will review the principles of operation of the Amplitude Interferometer by reference to the SAAI (which actually refers to a single pair of apertures). The general configuration of the optical components are shown in Figure 1. The starlight, after it has been focussed by telescope shown on the left, enters the guide eyepiece, which is a portion of the Amplitude Interferometer. The latter attaches to the telescope somewhat like a Cassegrain spectrograph. It is then brought to a focus. The light is then re-collimated by a small "inverted" Cassegrain telescope and passes into a Koester prism. After thus combining the light from the two apertures interferometrically, the two beams leave the Koester prism and pass through interference filters to define the spectral bandpass (200 Ångstrom or less) which has been selected for this particular observation. The light falls upon the detector, which is a photon-counting photomultiplier system (using Bendix channeltrons).

The quality of the data depends upon the accuracy of the telescope guiding. Since 1974 a set of internal "image stabilizers", operating with a time constant of the order of one second or less, has been included. This has been driven by a photon-counting quadrant detector system (the Automatic Guider System).[11.]

In order to properly project the results of the SAAI to the expectations of the new generation Amplitude Interferometer (the MAAI) we shall consider some of the methods and some of the results of the SAAI Program on single stars.

The Amplitude Interferometer operates with light essentially obtained in the "aperture plane" of the telescope. Since the primary atmospheric effects on the wavefront at this point are phase-delay and tilts of the wavefront, a properly designed Interferometer may detect "fringes" with quite high visibility, approaching unity for an unresolved object. A primary limitation will concern the small aperture size (about four centimeters) which is a "trade-off" between the amount of light accepted and some systematic errors introduced by the atmosphere.

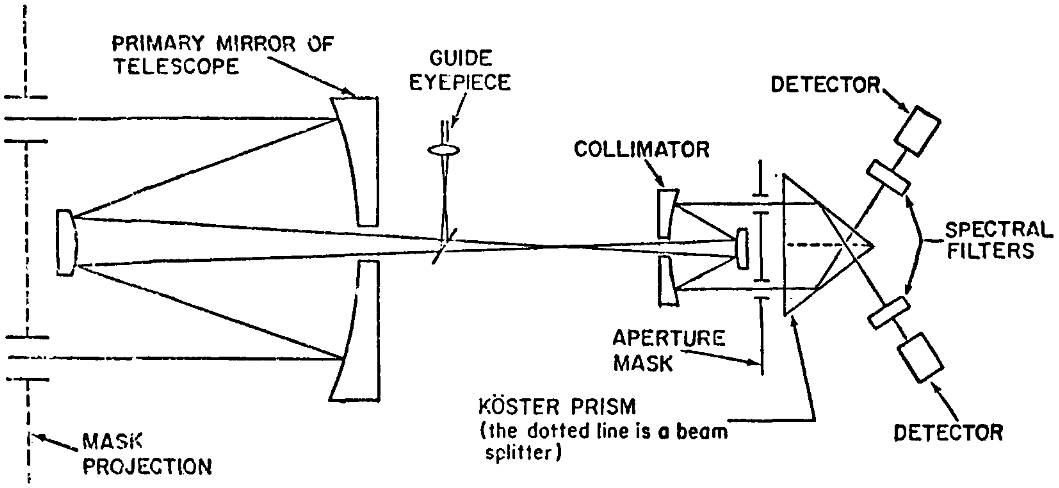


Figure 1 **Schematic Diagram of the Basic Optical Configuration of the Amplitude Interferometer**

Let us now consider some Amplitude Interferometer data from Alpha Orionis that was obtained in 1973 on the 100-inch telescope. The triangles illustrate the visibility of the fronges for an unresolved reference star (typically a star of early spectral type with a similar brightness). There is a slight decrease in fringe visibility with the increasing separation, probably due to irregularities in telescope guiding. The data points indicated by the solid dots show the visibility measured for Alpha Orionis. The data for the separation of 60 centimeters was taken at both the beginning and the end of the run on Alpha Orionis (this the normal observing procedure). The error bars are internal errors computed from the varience of subsequences of data which are computed for each point separately. Each point required approximately five minutes of observation. This data is discussed in more detail in other publications.[5,6,7].

The data (as in Figure 2) is fitted by a "least squares" procedure to a nominal stellar profile, and a "diameter", as well as several other parameters, are thereby derived. This procedure is repeated on two more nights of the same run on the same telescope. This data is then combined to obtain a diameter which may be published. The random error (in the sense of a presumed standard error) is e estimated by the internal agreement of the data from the three nights and the internal varience from each night. An estimate of various systematic effects which would not change from night to night is combined with the random error to yield the total estimated error.[9,10].

The stability of the data which has been obtained with the Single Aperture Amplitude Interferometer has been studied on various "non-variable" stars. As a single example, the measures of Alpha Orionis in successive years are indicated in Figure 3. Weather problems in 1975/76 resulted in rather poor data, as indicated by the internally generated error bars as well as the offset of the datum. This data illustrates that our methos od obtaining the total error bars may, if anything, be somewhat conservative.[12].

Over 200 diameter measurements of a variety of different stars at different wavelengths have been made. As discussed below, the data taken in the latter few years of this program agrees, for stable stars, within one or twol milli-arcseconds from one year to the next. This is also in agreement with the formal estimates derived for each individual measurement. Most of these observations have been conducted on the 100-inch telescope on Mt. Wilson and the 200-inch telescope on Palomar Mountain.

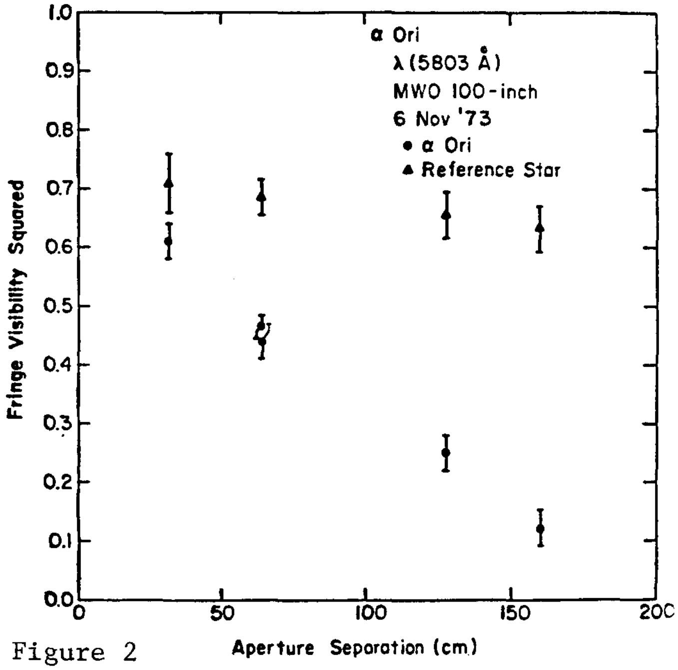


Figure 2

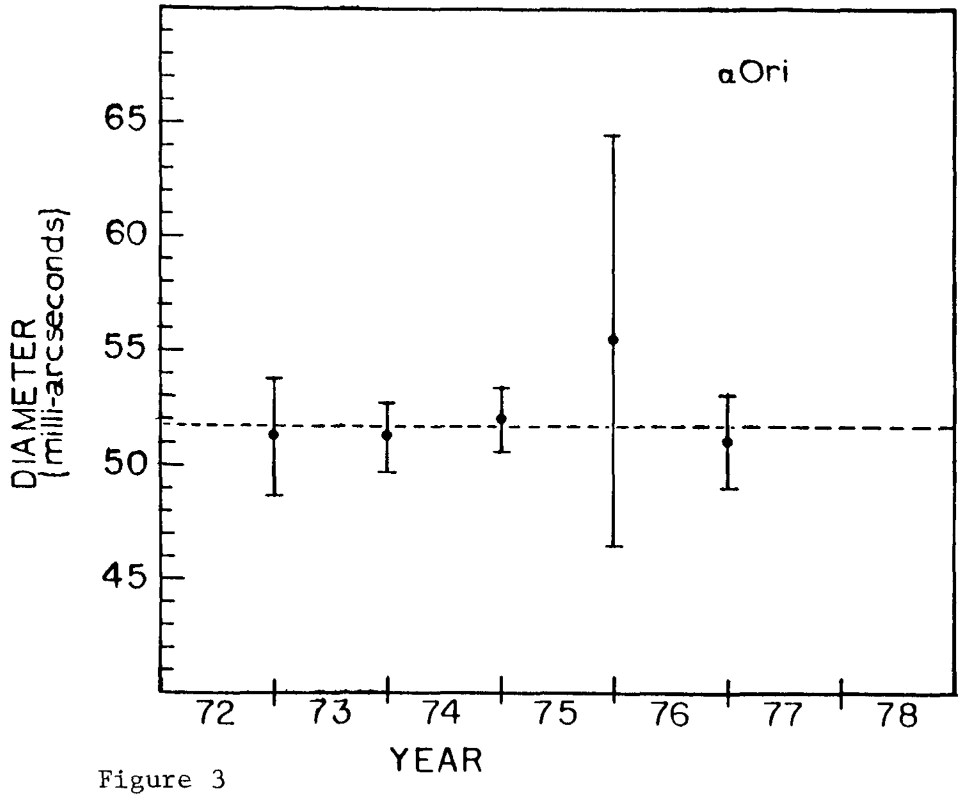


Figure 3

A short series of test observations have been conducted on binary systems.[8]. These were performed on the 60-inch telescope on Palomar Mountain, primarily to evaluate the technique and to evaluate the requirements for data analysis. Such observations are not particularly effective with this instrument (SAAI) since it requires many separate aperture separations and orientations. However, the observations did not reveal any unexpected difficulties. In order to obtain the various different spatial frequencies with the SAAI, one must change the aperture separations by using various aperture pairs in an internal mask within the SAAI. One obtains the various position angles by rotating the line between the apertures. This is performed, in turn, by rotating the entire instrument.

C. OTHER UM INSTRUMENTS FOR BINARY STAR OBSERVATIONS

The primary observations discussed here were conducted on the Single Aperture Amplitude Interferometer.

A new instrument, the Multi-Aperture Amplitude Interferometer, was fabricated several years ago. It requires the use of a 100 by 100, rapid scanning, photon-counting array detector. The development of the latter has been slower than projected. Binary and multiple star systems will be a major objective in the MAAI Observing Program. An Amplitude Interferometer which has far higher resolution (the vary long baseline Amplitude Interferometer) is also under development, with a proto-type in the field.[7,8,9.] However, this type of instrument will be discussed in more detail in this symposium by Dr. John Davis of Sydney University. Another instrument developed at the University of Maryland which bears on the binary star question is the Two-Color Refractometer. This Two-Color Refractometer [17.] (TCR) may be used to detect and measure binary star systems for which the components are of different spectral type. This instrument performs the measurement by evaluating the relative angular separation between the red and blue images to an accuracy of a few milli-arcseconds. This instrument is discussed separately at this symposium by Christy, Wellnitz, and Currie.

Finally, some observations have been conducted with a Charge Coupled Device. This array detector is particularly useful for stallar systems with wider separations. However, this data will not be reported at this meeting.

D. MULTI-APERTURE AMPLITUDE INTERFEROMETER

In this section, we provide a very brief description of the theory and the operation of the Multi-Aperture Amplitude Interferometer. Space is not available for a full discussion, and more complete descriptions are available elsewhere.[12,13,14.]

1. General Approach

As expressed in the previous section, the SAAI samples a single Fourier component at a single wavelength, at any one time. Expressed in another language, the SAAI measures one monochromatic element in the "u-v plane" at one time, i.e., one "spacial channel." The amount of light which may be accepted at this particular position angle (or orientation) and at this particular separation is limited by various atmospheric parameters (seeing disk diameter, relative delay, etc.[1,2.]) Each "spacial channel" typically uses a four centimeter operation. For the SAAI, to increase the number of samples in separation, one uses an internal mask to select a set of predetermined relative separations (note where the samples occur in Figure 2). One can also rotate the instrument to sample additional position angle angles. We require one pair of photo-multipliers for the one spacial channel.

The objective of the MAAI is to sample all the several thousand "spacial channels" at one time. Thus, we need several thousand SAAI's operating in parallel. We are able to "multiplex" all of the optics. However, in the MAAI, we need to use the equivalent of many independent photoelectric detectors to sample the many "SAAI's" in parallel.

Thus, in the language of radioastrometry, the MAAI consists of a filled non-redundant array. We may discuss this in terms of the MTF (Modulation Transfer Function) which has some similarity to the Fringe Visibility for an unresolved source. The MTF or OTF (Optical Transform Function) for a diffraction-limited lens [18.] is shown in Figure 4A. In Figure 4B, we have the OTF for the SAAI, while Figure 4C illustrates the OTF for the MAAI.

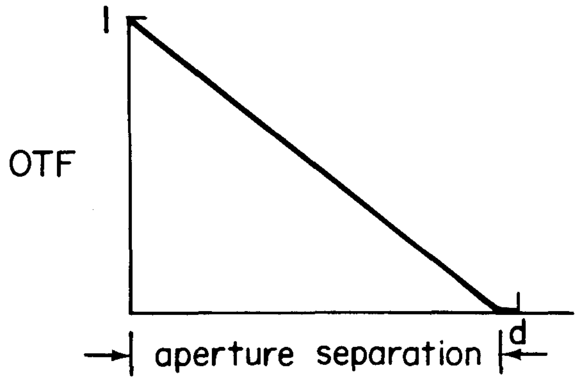


Figure 4A OTF for Diffraction Limited Lens

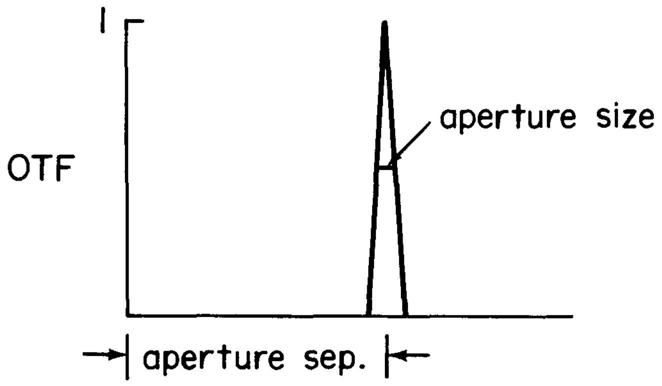


Figure 4B OTF of SAAI

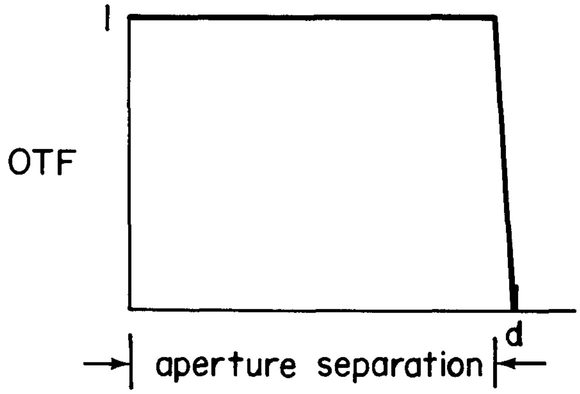


Figure 4C OTF for MAAI

This illustrates the reason that the MAAI has a higher resolution than a diffraction limited lens.

2. Implementation

The design of the MAAI "Multiplexes" the optics and essentially all other components. Several new subsystems are added (i.e., differential phase adjustment, remote control of spectral filter and blocking, and an inversion prism). However, the major change is the array detectors. They must be capable of a complete scan in a few milliseconds or less, must have multi-level, photon-counting capability and must have a size of the order of 100 by 100 elements.

For this we are using an intensified CCD.[19-23] . The electronics and computer interfaces will be capable of operation with either the internally intensified CCD (I-CCD) and the externally intensified CCD.

3. Status

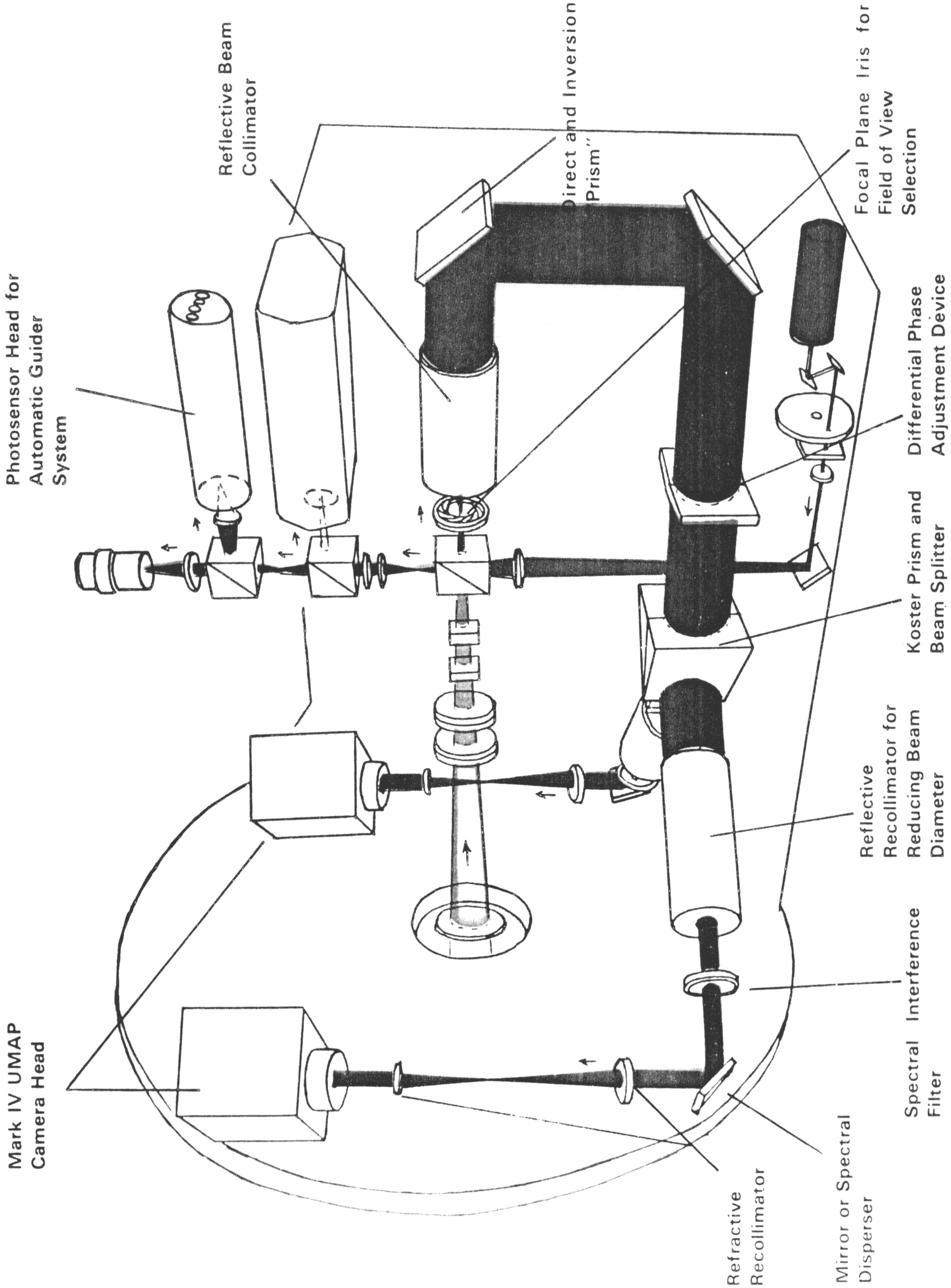
The MAAI has been completed for three years, and has been tested on the 36-inch telescope at the Goddard Optical Research Facility. The main difficulty has been in obtaining the array detectors. An ICCD has been operated at the focal plane of the telescope and has demonstrated a dynamic range of 10^5. However, we have not obtained the required two devices which are suitable for use in the MAAI. We are now proceeding to fabricate the I-CCD , using GEN-I image intensifiers. The objective is to start operation on the telescope within six months.

E. LIMITS IN MAGNITUDE AND RESOLUTION

There are two approaches for the discussion of the limiting performances of the MAAI. These are necessarily theoretical approaches since it is not yet in regular operation in an observing program. One appraoch is to discuss the theoretical limits of its performance, derived from the optimal performance of the instrument and a detailed projection of our current expectations of the relevant atmospheric conditions that will be encountered. This "theoretical" limiting performance has been achieved in the operation of the Single Aperture Amplitude Interferometer. However, in this process, we have found limits in certain modes of operation arising from the evaluation of the atmospheric phenomena which were more limiting than the original theory. In this paper, we will address a "conservative" limiting performance. The guiding principle of this "conservative" evaluation shall be that we will not project the known atmospheric parameters into domains which have not yet been fully explored. We will also not project the effects of instrumental performance and procedures beyond the basic performance of the SAAI and the effects of the improvements which are clearly defined for the MAAI. Thus, the guiding principle is that we shall not project atmospheric parameters, nor instrumental component performance beyond our current experience. We shall also continue to use the "10%" criteria which has been used for the design and operation of the Single Aperture Amplitude Interferometer. The "10% criteria" requires operation such that a major change in the atmosphere at any time can induce no more than a 10 per cent error in the value of the square of the fringe visibility.

1. Resolution

For the SAAI, we have found it quite practical to observe objects that are sufficiently small such that the value of the square of the fringe visibility has dropped to half its projected value for zero separation. This has given reliable


Mark IV UMAP Camera Head
Photosensor Head for Automatic Guider System
Reflective Beam Collimator
Direct and Inversion Prism''
Focal Plane Iris for Field of View Selection
Differential Phase Adjustment Device
Koster Prism and Beam Splitter
Reflective Recollimator for Reducing Beam Diameter
Interference Spectral Filter
Mirror or Spectral Disperser
Refractive Recollimator

and reproduceable data on the diameters of a variety of objects. In principle, observations could be conducted on even smaller objects (yielding higher resolution) but there is a significant propagation of systematic errors which has led us to be wary of this region. We may now project this measurement accuracy and precision to the question of parameter estimation for the case of the general binary system. Thus, under this criteria, the system will have a resolution of 25 milli-arcseconds for a telescope with a one meter aperture. The precision for determining the value of this separation depends upon a significantly larger family of parameters. In general, the separation my be expressed for different telescopes in the form of the following table:

TELESCOPE APERTURE	RESOLUTION	PRECISION
48-inch	20 milli-arcseconds	0.2 milli-arcseconds
60-inch	16 milli-arcseconds	0.1 milli-arcseconds
100-inch	10 milli-arcseconds	0.1 milli-arcseconds
200-inch	5 milli-arcseconds	0.1 milli-arcseconds

The limit in the precision of the determination of the separation will primarily be determined by the calibration procedures. Thus, this does not depend upon telescope aperture in a trivial manner. The calibration procedures will be discussed later in this paper.

II. CALIBRATION

The calibration of the MAAI System will be of particular importance for its use in an observing program of binary and multiple star systems. These calibration procedures must, due to the nature of the MAAI, be significantly different than those procedures which are conventionally used for observing programs on binary stars. In this section, we shall discuss some of the procedures which are planned for calibrating the MAAI. Some of these procedures have already been tested and some of them are now in the planning or testing stage.

The primary difficulty concerning the calibration procedure is that, unlike the case of a program using the eye, a photographic plate or an array sensor in the focal plane, a trailed star gives essentially no useful calibration information. Thus, in a program using the MAAI, we are essentially isolated from the conventional calibration techniques and the associated wisdom. For these reasons, it seems useful at this time to publicly review the problem and solutions and then solicit comments concerning this calibration problem.

A. PROCEDURES FOR CALIBRATION OF ANGULAR SEPARATION

We will now discuss various possible methods which might be used for the calibration of the separation scale of the MAAI. Although this discussion will be directed toward the best single method of calibration, in fact, we will use all of these methods during the initial part of the program in order to provide a complete understanding of any anomolies. The "calibration" will, in general, be correct for a given epoch, for a given pointing direction in the sky. In addition, it will depend critically upon the temperature and temperature gradients within the telescope.

1. Direct Focal Length

The most obvious and direct method to determine the scale of the angular separation is to use the focal length of the telescope as well as the focal length of the internal optics in the MAAI. The most direct method to obtain the former is by the observation of wide binary systems with an eyepiece. The latter may be obtained by laboratory measurements, using special optical calibrators. This method has been the primary technique used in the current program for stellar diameter measurements using the SAAI. However, the variation of the focal length of the reflecting telescopes with changing temperatures renders this method less than ideal. This has been, in fact, one of the major sources of systematic errors within the stellar diameter measurements program.

2. Reference Binaries

The classical method for the calibration of the MAAI would be the use of well-determined binary systems. However, those binary systems which are close enough to be observed well by the Amplitude Interferometer are not known with suffucuent accuracy to be competitive with either the accuracy or the precision which is projected for the MAAI system. Thus, while a long-term program of observing multiple star systems with separations in the range of 0.15 to 0.50 arcseconds will serve as a cross calibration, this type of observation is too time-consuming of telescope time to be used to keep track of the changes hour by hour in focal length which depend upon the temperature and the temperature gradients. Thus, it would be too large a program to observe these as the regular set of reference systems. However, such a program of observation will be used to provide a long-term cross-reference with respect to the "diffraction bars" in order to establish or verify the latter method.

3. Diffraction Bars on Telescope Aperture

This technique for the calibration of the angular separation scale consists of placing an optical obstruction, in the form of several parallel bars, over the telescope aperture. These "diffraction bars" would be mounted near the secondary mirror and would extend across the entire telescope aperture. They would have a known width and a known separation. By appropriate use of materials like invar, to support the "calibration bars", the bar structure may be fabricated in a manner such that the separation of the bars will not change significantly. Any residual change will have a form which can be calibrated quite accurately. The set of bars would be mounted for an MAAI run, but is entirely separate from the basic structure of the telescope. To an effective approximation, the primary mirror is reimaged on the detector array. (This is due, in part, to the necessary re-collimation and, in part, due to reimaging certain aspects of atmospheric turbulence. As a result, the bars will appear on the MAAI array detector as dark areas in reasonably sharp focus. Thus, this technique will permit a calibration which is totally independent of the variations in the various focal lengths which affects the instrument. During a critical measurement series, this will serve as a continual monitor of the calibration of the separation. This procedure yields an absolute calibration and does not, in principle, need to be cross-referenced.

Although the optical systems and the details are quite different, this use of the "diffraction bars" has some similarity to the procedure involving a Ronchi grating to form a "ghost" image of a star. Thus, in photographic observations of binary stars, the Ronchi grating forms a "star" with a known brightness ratio and a known angular separation from each of the stars which is being observed.

B. CALIBRATION OF ORIENTATION OR POSITION ANGLE

When the MAAI is used to observe a binary system, the basic data on the position angle of a binary system consists of the orientation of the "visibility pattern" computed from the data obtained from the two array detectors. The orientation is with respect to some computed from the data obtained from the two array detectors. The orientation is with respect to some "joint" set of coordinate axies in the two CCD arrays within the instrument. Thus, we can measure, with great accuracy, the orientation of the "visibility pattern" and therefore the orientation or the position angle with respect to axis of the array detector in the MAAI. We may also relate this to the Koester prism. For the present discussion we may assume that the statistical errors in the determination of this orientation are small. They will generally be that 0.1 milliarcseconds. Thus our primary problem is the accuracy and the precision to which we may relate this internal angle to the position angle in the sky.

1. Direct Calibration

Direct calibration by reference to the motion of the star or star groups when the telescope drive rate is changed provides little data.

2. Reference Binaries

The use of reference binaries for a calibration of the position angle has the same difficulties as was discussed in the previous section on the use of reference binaries for the calibration of the angular separations.

3. Reference to Diffraction Pattern of Secondary Spider

For the accurate calibration of the position angle, we plan a different method. Thus for the position angle, we will use an intermediate calibration procedure, which uses a different detector system. This is because the Amplitude Interferometer is not capable of "observing" the orientation of a trailed star with anywhere near the required accuracy. This "diffraction spike" procedure will make use of the direct image at the focal plane. This will be imaged into an integrating detector (probably a CCD) in which one trails the star image and then integrates for a long time to bring out the defraction pattern due to the secondary support structure (the spider). The latter portions of the image will establish the orientation of the spider i.e., the position angle of the spider. The orientation of the spider will then be used an an intermediate standard. If the light now passes into the Multi-Aperture Amplitude Interferometer when the starlight falls on the CCD, the re-imaged spider will appear as a dark region. Since we have determined the orientation of the spider with respect to the sky from the direct image, we may now pass this information on to the MAAI array. Thus we will have a direct read-out (defined by shadows on the array) of the orientation of the binary star system with respect to the spider.

C. SPECIAL ADVANTAGE OF THE MAAI

Since the MAAI operates on with the wavefronts before they are combined by a lens (or, more accurately, combined by a non-linear detection process in the focal plane) the resultant high visibility or high Modulation Transfer Function for all separations has the possibility of reducing the systematic effects due to the atmosphere. In addition, the MAAI will permit accurate measurements to be performed on quite faint objects. Its numberical accuracy (as projected from the data obtained with the SAAI) is particularly useful for multiple star systems and for differential photometry. Thus, it should provide an accurate relative color index for the individual stars. It may also be used to detect reflection or emission halos about the individual stars in the system and/or any has exchange (it if is sufficiently luminous).

The MAAI will also yield an accurate measure of objects which are about a factor of two smaller than the diffraction-limited system. This has already been illustrated with data from the SAAI (which has resolved and measured stars which were "unresolved" with speckle interferometry). Practically, this means the observation of a given object may be conducted on a telescope which has a smaller aperture by almost a factor of two. In addition, the MAAI gives a real time display of the Fourier Transform of the image, so when one may estimate when sufficient data has been collected.

D. SPECIAL OBJECTS OF INTEREST

In this section, we discuss specific clases of multiple star systems which we intend to observe.

1. FK4 Catalog

One of the families of objects which will be observed using the MAAI will be the stars within the FK4 Catalog. The objective of this program will be to identify those stars which are binary systems and thus not suitable for certain navigational purposes.

2. Search for Extra-Solar Planetary Systems

In this case, we will observe known binary star systems with the objective of finding perturbations in the motion of one of the stars due to a fainter third companion rotating about one of them. Thus, we will use the very high angular precision of the MAAI to detect the small amplitude oscillations of one of the stars. The latter would be seen as variations of the angular separation of the two stars[24].

3. Spectroscopic Binaries

The set of spectroscopic binaries , especially the double-lined binary systems, will permit a rapid expansion of our data base for stellar masses and absolute luminositie. The ability to do broad- band photometry will permit a clarification of the spectro -type of the star. However, it is not clear what level of photometric accuracy is required and it is not clear how seriously mass exchange in these closer systems will affect the sample.

4. Cosmic Distance Scale

This program would consist of a detailed study of the binary systems in the Hyades cluster. The same method would be used to extend the observations to binary systems in more distant clusters.

5. Mu Cass

This astrometric binary system is of particular interest due to its impact on the question of the primordial helium abundance. Instrumentally, it is quite difficult due to the faintness of the companion ($\Delta M = 4-5$). Thus, this will be a test of the MAAI system capabilities. A successful observation will permit a confirmation of the recent reinterpretation of earlier results by Wickes .

E. ACKNOWLEDGEMENTS

The current status of the Multi-Aperture Amplitude Interferometer within the Amplitude Interferometry Program is the result of the considerable efforst of many individuals. Among those who have been intimately involved are S.L. Knapp, K.M. Liewer, R.H. Braunstein, J.L. Johnson, W.L. Wickes, J. Giganti of the Electronics Development Group, F. Meraldi, and F. Derosier of the Mechanical Shop.

DISCUSSION

CURRIE: Any large phase errors in this instrumental system need to be removed in real time within the optics; they cannot be removed in a post-run analysis. As the MAAI is described here, this is not an active servo loop which stabilizes, as it is in the case of a "rubber mirror" type of system. This would be a considerable modification to the existing hardware and is not planned. The kinds of plans we have for the future consist of the combination of the very long baseline amplitude interferometer and the multi-aperture amplitude interferometer. The very long baseline will initially be limited to 6th and 8th magnitude. By combining many parallel paths (as in the MAAI), one could hope to process, in the interferometric method, the many channels of data.

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