MEASURING STARS WITH HIGH ANGULAR RESOLUTION: CURRENT STATUS AND FUTURE PROSPECTS

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ABSTRACT. The current state of knowledge of angular diameters of stars is reviewed and, based on this review and the requirements for the determination of surface fluxes, effective temperatures, radii and masses, targets of sensitivity, angular resolution and accuracy for future programs of stellar angular diameter measurements are established. Long baseline interferometry is the only technique with the potential to meet all the targets. The necessary improvements in sensitivity, angular resolution and accuracy are promised by the approach adopted in the modern Michelson stellar interferometer under development at the University of Sydney and the prototype instrument, which is currently nearing completion, is briefly described to illustrate how the atmospheric and mechanical problems which have inhibited the development of amplitude interferometry may be overcome using modern technology. This program together with the developments taking place at CERGA lead to the conclusion that the prospects for contributions by high angular resolution measurements to the determination of fundamental stellar quantities during the next decade are excellent.

1. INTRODUCTION

Since the completion of the program of stellar angular diameter measurements with the Narrabri intensity interferometer, which has been described in the preceding paper (Hanbury Brown 1985), the Chatterton Astronomy Department at the University of Sydney has been engaged in a program to develop a stellar interferometer with increased sensitivity, resolution and accuracy. The primary objective is to develop an instrument capable of contributing to the determination of fundamental stellar quantities, namely emergeant fluxes and effective temperatures, radii and hence luminosities, and masses. Additional studies would include limb-darkening, stellar rotation, extended atmospheres, emission-line stars and Cepheids.

This paper reviews the current status of angular diameter measurements, discusses the targets for future angular diameter determination

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programs and assesses the potential of available techniques. The
modern Michelson stellar interferometer under development at the
University of Sydney is described briefly to illustrate how the targets
might be met. Since high angular resolution studies of binary stars
are discussed by McAlister (1985) in this symposium the discussion is
restricted to single stars. However, it is emphasized that the
University of Sydney program is just as concerned with the observation
of binary stars (Davis 1983) since for at least the primary components
of double-lined spectroscopic binaries it is possible to determine all
the gross properties (i.e. mass, radius and luminosity) as demonstrated
with the intensity interferometer for α Vir (Herbison-Evans et al. 1971).

2.   CURRENT KNOWLEDGE OF THE ANGULAR DIAMETERS OF STARS

    Discussion in this section is restricted to direct measurements of
angular diameters by interferometry or occultations. A survey of the
literature reveals that angular diameters have been measured for some
150 stars with more than half (~ 90) being determined from lunar
occultations. However, many of the published angular diameters are of
little interest because of the poor accuracy of their determination.
Figure 1 shows the distribution by spectral class of stars whose
angular diameters have been determined with published uncertainties
better than   (a) ±20% (111 stars),   (b) ±10% (82 stars) and   (c) ±5%
(32 stars).   In preparing these histograms a weighted mean angular
diameter was derived for each star for each observational technique
(i.e. for lunar occultations, for speckle interferometry etc.).   Where
a star had been observed by more than one technique, measurements from
the different techniques were not combined and only the most accurate
weighted mean angular diameter was taken for the purposes of Figure 1.
Combination of measurements from different techniques would only affect
the positions of 2 late type stars in Figure 1.
    Figure 1 has two distinct ranges. For spectral types earlier than
G0 the data is dominated by results from the intensity interferometer
whereas for spectral types later than G0 the majority of the data is
from lunar occultations with contributions from the two telescope
interferometer at CERGA (I2T), from the amplitude interferometer and
from speckle interferometry. All the data for classes G, K and M are
for evolved stars.
    The data in Figure 1 have been sorted according to the published
uncertainties in the angular diameters. Independent checks on the
reliability of the data are clearly desirable and ideally the results
for individual stars determined by different techniques should be
compared. Unfortunately, because of the limitations of the different
techniques, there are only a few cases where such comparisons can be
made and the relevant data are listed in Table I. Mira type stars have
been excluded. α Ori has also been omitted because of the apparent
variation of angular diameter with wavelength and time (White (1980).
    Except for ρ Per and α Her where the speckle and amplitude inter-
ferometry results are inconsistent the agreement is generally as good
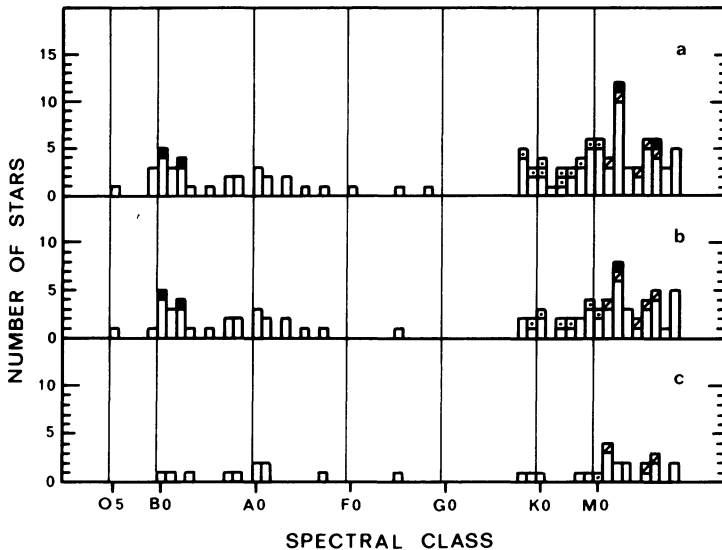as would be expected. Detailed intercomparison of the results from the

Fig. 1. The number of stars with measured angular diameter as a function of spectral class. The distributions are for angular diameters determined to better than ±20% (a), ±10% (b) and ±5% (c).

For spectral classes O, B, A and F: □ represents measurements by intensity interferometry and ■ by Jovian occultations. For spectral classes G, K and M: □ represents measurements by lunar occultations, ▣ by CERGA I2T, ◨ by speckle interferometry and ■ by amplitude interferometry.

different techniques is not warranted because of the small amount of data but Table I serves to emphasize the desirability of obtaining more data, especially for spectral classes earlier than K.

An alternative check on the reliability of data can be obtained by intercomparison of results by the same technique but by different observers with different equipment. This approach is possible for lunar occultations and speckle interferometry although it is limited to late spectral types as shown by the spectral class coverage of the techniques shown in Figure 1. In the case of lunar occultations Ridgway et al. (1980) have compared the error estimates for 66 measurements of 24 stars with the dispersion of measurements for each star. Expressing the deviations from the mean for each star in units of the expected standard deviation, and excluding Mira-type stars, they found excellent agreement between the observed distribution and an appropriately normalized normal distribution for 53 out of 57 observations. The 4 discrepant measurements were for 2 stars and it was concluded that while these results may be the result of real variations it is possible that occasionally (~ 2 out of 57) the occultation technique may be subject to errors which do not reveal themselves in the analysis.

The speckle interferometer results for 3 stars measured by different observers are listed in Table II. α Ori has been omitted for the

Table I. Angular diameters for stars measured by more than one technique.

BS	Star	MK	Intensity Inter-ferometer	Lunar Occultation	Speckle Inter-ferometer	CERGA I2T	Amplitude Inter-ferometer
				Angular Diameter of Equivalent Uniform Disk (milliseconds of arc)			
921	ρ Per	M4 II-III			29 ± 2^{1}		17 ± 2^{2}
1457	α Tau	K5 III		$20.0\ \pm0.1^{3}$*	24 ± 3^{1}		19 ± 2^{2}
2286	μ Gem	M3 III		$12.1\ \pm0.1^{4-8}$*		14.2 ± 0.7^{9}	15 ± 2^{2}
3982	α Leo	B7 V	1.32 ± 0.06^{10}	1.38 ± 0.06^{11}*			
5340	α Boo	K2 IIIp			$20\pm2^{12-14}$*	21.0 ± 1.2^{9}	24 ± 2^{2}
6134	α Sco	M1-2 Iab		$41\ \ \pm1^{15}$	42 ± 2^{12}		42 ± 5^{2}
6406	α Her A	M5 II			$29\pm1^{1,12,16}$*		42 ± 3^{2}
6705	γ Dra	K5 III				$8.3\pm0.6^{9,17}$*	13 ± 5^{2}
8775	β Peg	M2 II-III			16 ± 2^{12}		19 ± 1^{2}

* Weighted mean of published values.

References:
- 1. Welter & Worden 1980
- 2. Currie et al. 1976
- 3. Ridgway et al. 1982
- 4. White 1974
- 5. Ridgway et al. 1974
- 6. Dunham et al. 1975
- 7. Nelson 1975
- 8. Beavers et al. 1981
- 9. Di Benedetto & Conti 1983
- 10. Hanbury Brown et al. 1974
- 11. Radick 1981
- 12. Gezari et al. 1972
- 13. Worden 1976
- 14. Blazit et al. 1977
- 15. Evans 1957
- 16. Worden 1975
- 17. Faucherre et al. 1983

TABLE II. Intercomparison of angular diameters determined by speckle
           interferometry.

BS	Star	MK	Angular Diameters (milliseconds of arc)		
911	α Cet	M2 III	14±5(400) [1*] 25±2(550) [2]		
5340	α Boo	K2 IIIp	18±4(450) [1] 22±3(500) [3]	19±6(420) [4]	
			18±5(500) [1]		
6406	α Her A	M5 II	29±1(510) [2] 31±3(500) [3]	30±1(510) [5]	
			26±3(520) [2]	28±3(520) [5]	
			25±3(550) [2]		

*The mean wavelength of observation in nm is given in parenthesis after
each result.
References: 1. Blazit et al. 1977
             2. Welter & Worden 1980
             3. Gezari et al. 1972
             4. Worden 1976
             5. Worden 1975

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same reason it was omitted from Table I.

    Welter and Worden (1980) have commented on the descrepancy between
the values for α Cet and noted that the star is close to the limit of
their technique. The results for α Boo and α Her A are in reasonable
agreement but again there is insufficient data to warrant detailed
discussion.
    The intercomparison of results between techniques and within
techniques, although restricted by the limited amount of data, can be
summarized as follows. Although a small number of discordant results
exist, the agreement between independent observations of a star is
generally in accord with the published error estimates.
    Where intercomparison of results is not possible, reliance has to
be placed on the internal consistency of data from repeated observations,
preferably obtained with modified equipment configurations, and on the
efforts taken to eliminate systematic errors from the data. This is
particularly true for the results from the intensity interferometer and
this is discussed in detail by Hanbury Brown (1985) in the preceding
paper.

3. FUTURE ANGULAR DIAMETER MEASUREMENTS

    Fig. 1 shows that existing measurements of angular diameters with
an accuracy better than ±5% are spread very thinly across the spectral
classes. There is a real paucity of data for spectral classes from late
A to late G even if the accuracy is relaxed to ±20%. The situation is

even worse if only the main sequence is considered since there are no
main-sequence stars later than F5 in Figure 1. However, it should be
noted that the Sun (G2 V) and the eclipsing binaries YY Gem (MO.5V) and
CM Dra (M4V) have not been included. Angular diameters derived for
these eclipsing binaries from trigonometric parallaxes have uncertain-
ties in the ±5-10% range.

Let us examine the sensitivity, angular resolution and accuracy
required to add substantially to our knowledge of stellar surface fluxes
and effective temperatures for all spectral types via angular diameter
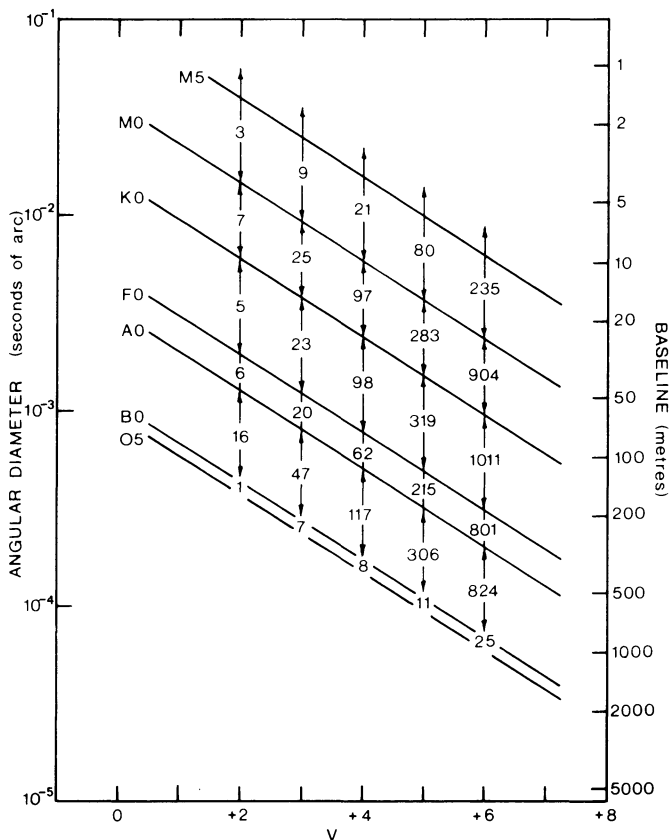determinations.

Fig. 2. Distribution of stars with respect to apparent brightness
and angular size. The diagonal lines represent mean relationships
for the spectral types shown and the figures give the total number of
stars in the Catalogue of Bright Stars (Hoffleit 1964) brighter than
a given V magnitude with declination < +30° for each spectral group
(e.g. there are 215 A-type stars with V < +5). The right-hand ordinate
gives the interferometer baseline required for resolution ($|\gamma|^2 = 0.5$)
at a wavelength of 550 nm.

Figure 2 shows the distribution with respect to brightness and angular diameter of stars brighter than V = +6 and with declination < +30°. The figure suggests that angular diameters for a large sample of stars could be determined with an instrument capable of measuring stars to V = +4. This is true for the middle range of spectral classes but a closer examination of the statistics reveals that for early O and for M main-sequence stars greater sensitivity is required. To measure hot O stars it is necessary to reach at least V = +6 and, in order to obtain a reasonable sample, V(limit) should exceed +7. For main-sequence stars of spectral class MO and later it is also necessary to have V(limit) > +7. In fact, the V(limit) required to measure main-sequence stars increases towards later spectral classes and exceeds +9.5 at M5.

It can be seen from Figure 2 that an angular resolution of ~ 2 x 10^{-4} arcseconds would be sufficient for measuring all except the hottest stars but for these an angular resolution of ~ 4 x 10^{-5} arcseconds is required.

If a measured angular diameter is to be used to determine the emergent flux at the stellar surface (F) and effective temperature (T_e) then the aim should be to measure the angular diameter (θ) with an accuracy such that its contribution to the uncertainty in F is no greater than that from the integrated absolute flux received from the star (f). F, f, θ and T_e are related by

$$F = 4f/\theta^2 = \sigma T_e^4 \tag{1}$$

where σ is the Stefan-Boltzmann constant. From equation (1) it can be seen that the target is to make $2\sigma(\theta) \lesssim \sigma(f)$ where $\sigma(\theta)$ and $\sigma(f)$ are the fractional uncertainties in θ and f.

Figure 3 is a plot of $2\sigma(\theta)$ and $\sigma(f)$ against $(B-V)_0$ for the 32 stars measured with the intensity interferometer. The data is taken from Code et al. (1976). For $(B-V)_0 \lesssim -0.15$ the uncertainties are generally well matched largely because of the increasing uncertainty in the integrated fluxes for the hotter stars. However, for $(B-V)_0 \gtrsim -0.15$, the uncertainty in the integrated flux is of the order of ±4% whereas $2\sigma(\theta)$ ranges from ~ ±4% up to ~ ±28%. On the basis of the evidence shown in Figure 3 future angular diameter measurements should aim at reducing $\sigma(\theta)$ to < ±2%.

Blackwell et al. (1979) have also set a target accuracy of about 2% in θ and 1% in T_e for their infrared flux method which would be commensurate with that of the oscillator strengths being measured at Oxford.

The targets to be aimed at in future angular diameter determinations thus include V(limit) > +7 for spectral classes earlier than MO increasing to V(limit) > +9.5 for M5 main-sequence stars, an angular resolution of 2 x 10^{-4} arcseconds decreasing to 4 x 10^{-5} arcseconds for a sample of hot O stars, and generally an accuracy of $\lesssim$ ±2%.

The difficulties involved in reaching these targets are formidable and have led Barnes and Evans (Barnes & Evans 1976; Barnes et al. 1976; Barnes et al. 1978) to develop an empirical relationship between visual surface brightness and color index based on existing angular diameter
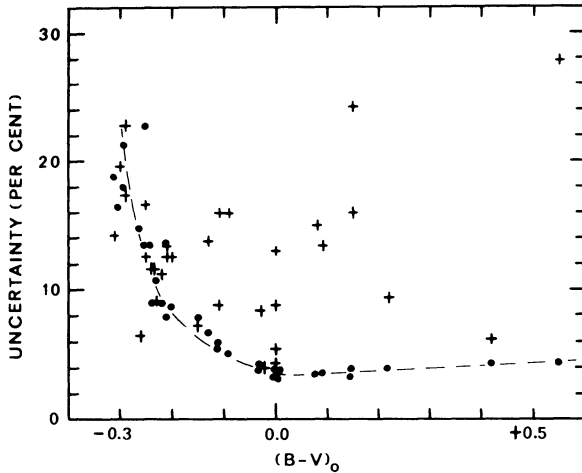
Fig. 3. The uncertainty in integrated flux received from a star (●) and twice the uncertainty in angular diameter (+) as a function of $(B-V)_o$ for the 32 stars measured with the intensity interferometer. The broken line indicates the trend of the uncertainties in the fluxes.

measurements. While it is not fundamental in the sense that it is calibrated with empirical data it has nevertheless found numerous applications (Barnes et al. 1978) in the absence of direct angular diameter measurements. An important feature of the relationship is the fact that it can be applied to stars which are below the current sensitivity of techniques for direct angular diameter determinations. Its usefulness would be extended by improvements in calibration which would be brought about by angular diameter determinations of improved accuracy. This is particularly true in the range of spectral classes A to G where the visual surface brightness relationship is least well defined.

The infrared flux method has been devised by Blackwell & Shallis (Blackwell & Shallis 1977; Blackwell et al. 1978; Blackwell et al. 1979) with the stated intention of providing a fundamental technique that will give angular diameters and effective temperatures for selected stars of virtually any spectral type to a magnitude limit of at least +7 or +8 with an accuracy at least equal to that attainable by other methods and which is completely independent of results from other methods. They have shown (Blackwell et al. 1979) that their results are insensitive to the model atmosphere used, at least for $T_e \leqslant 8000$ K, and that the interstellar extinction is not a significant problem. So far the method has given angular diameters that are larger by 3.8% on average than those measured with the intensity interferometer. This discrepancy may be the result of errors arising from the absolute infrared flux calibration which is crucial to the success of the infra-red flux method. The cause of the discrepancy needs to be resolved and Blackwell and his colleagues are endeavoring to improve the infrared

flux calibration.   It is also important in this context to improve
the spectral coverage and accuracy of direct angular diameter measure-
ments to provide further crosschecks on the results.
     The targets for future angular diameter measurements have been
discussed in the context of surface fluxes and effective temperatures.
Stellar radii, and hence luminosities, can also be determined from
angular diameter measurements for stars of known parallax.   The useful-
ness of this application is currently limited by the accuracy of
existing trigonometric parallaxes.   The radii of stars of known trigon-
ometric parallax can only be obtained with an accuracy better than
±20% for spectral classes AO and later (Davis 1979a).   From one site
there are some 100 stars brighter than V = +10 with trigonometric
parallaxes known to better than ±20% but only ~ 12 better than ±5%.
Thus the targets set above are more than adequate to match existing
parallaxes and, in fact, will be adequate in almost all cases for radii
determined from parallaxes determined with the astrometric satellite
HIPPARCOS (mean error 0.002 arcseconds (Høg 1978)).   This conclusion
is also true for the determination of masses of single stars by the
method proposed by Blackwell et al. (1978) since it too involves
parallaxes.
     High angular resolution observations of suitable double-lined
spectroscopic binaries will also enable stellar masses and radii to be
determined.   The case of binary stars is discussed by McAlister (1985),
but the targets discussed here are appropriate for this application
(Davis 1983).

4.   THE DIRECT MEASUREMENT OF ANGULAR DIAMETERS

     Of the techniques available for the direct measurement of stellar
angular diameters only long baseline interferometry has the potential
to meet all the targets set in the previous section although baselines
in excess of 1 km will be required to achieve an angular resolution
of 4×10^{-5} arcseconds at optical wavelengths as can be seen from
Figure 2.
     The limitation in angular resolution of the lunar occultation
technique restricts it to the measurement of luminous cool stars and
it is here that it has made a major contribution as shown by Figure 1.
Although the technique is capable of measuring angular diameters down
to the 1-2 milliseconds of arc range (Ridgway 1979) the accuracy
deteriorates below ~ 3 milliseconds of arc and, with only a few notable
exceptions, accurate angular diameter measurements will remain restrict-
ed to luminous stars of late G, K and M spectral classes.
     The angular resolution of amplitude and speckle interferometry
using a single telescope is restricted to ~ 15 milliseconds of arc by
the diameters of existing telescope apertures.   Although the angular
diameters of 9 stars have been determined by each technique with an
accuracy better than ±20%, in the cases of 4 of the speckle results and
7 of the amplitude results the angular diameters have been determined
with greater accuracy by other methods.   This is shown by the surviving
results appearing in Figure 1.   Even with the next generation telescopes

under consideration these techniques will not make a significant
contribution to stellar angular diameter determinations.

There are several possible approaches to long baseline interfero-
metry but since intensity interferometry has been by far the most
successful it would seem to be the obvious approach to pursue. A
possible design for a very large intensity interferometer with increased
sensitivity, resolution and accuracy has been discussed by Hanbury Brown
(1974) and Davis (1975). It appears that the resolution and accuracy
targets given in Section 3 could be reached with an intensity inter-
ferometer but that an increase in sensitivity of ~ 80 times over the
Narrabri instrument, which had a limiting blue magnitude B(limit)
~ +2.5 (Hanbury Brown et al. 1974), is all that can be achieved without
great difficulty and prohibitive cost. There is no doubt that a very
large intensity interferometer could be built and that it would work
but a modern amplitude interferometer offers the possibility of greater
sensitivity at lower cost. If reasonable parameters are assumed it can
be shown that it would be necessary to use apertures of the order of
30 m in an intensity interferometer in order to achieve the same
sensitivity as an amplitude interferometer with 10 cm diameter apertures.

The development of amplitude interferometers has been inhibited by
two main areas of difficulty in the past. One is associated with the
severe requirements of mechanical stability imposed by the wavelength
of light and the other is the problem of making accurate measurements
in the presence of the disruptive effects of atmospheric turbulence on
the incoming wavefronts. The problems imposed by the atmosphere can
be avoided by an interferometer in space (see for example Labeyrie
1978; Stachnik & Labeyrie 1984) but since the space proposals are still
at an early stage of development and are not likely to contribute
measurements of angular diameters within at least the next decade they
will not be discussed here. The use of lasers, and modern control,
detection and data handling techniques offers the possibility of over-
coming the mechanical and atmospheric problems in a ground-based
amplitude interferometer and this, together with the sensitivity
advantage of an amplitude interferometer, are the reasons why long-
baseline optical interferometers currently under development are all
amplitude instruments.

A large aperture amplitude interferometer is being developed at
CERGA (Labeyrie 1978) and small aperture amplitude interferometers are
being developed at the Universities of Sydney (Davis 1979b) and
Maryland (Liewer 1979). In the CERGA interferometer the Coudé images
from two telescopes, whose apertures are large compared with Fried's
atmospheric coherence diameter r_0 (Fried & Mevers 1974), are relayed
to a central station where fringes appear in the superposed images
providing the optical paths are matched within the tolerances set by
the coherence length of the light. The prototype instrument (I2T)
using 25 cm diameter aperture telescopes has been successfully used out
to baselines of ~ 40 m to determine $|\gamma|$ for bright stars with
V < 3.1 (Faucherre et al. 1983) ($|\gamma|$ is the modulus of the complex
degree of coherence (Born & Wolf 1964) equal to Michelson's fringe
visibility). Work is in progress to develop telescopes with aperture
diameters of 1.52 m (Labeyrie 1978) for use in this type of instrument.

In the small aperture approach the apertures are restricted to $\lesssim r_0$ (which has a value of ~ 10 cm at a good site) and the effects of atmospheric turbulence are then removed in real time from the measurement of $|\gamma|$. How this is done in the instrument being developed at the University of Sydney will be described in the following section.

The relative merits of the large aperture and small aperture approaches have been outlined by Davis (1976). It is not yet clear which will prove most suited to stellar angular diameter determinations although it is to be hoped that both will be successful so that stars may be observed in common to provide crosschecks. The large aperture approach is expected to have greater sensitivity but a small amplitude interferometer, because it incorporates removal of atmospheric effects in real time from the measurement of $|\gamma|$, should be capable of achieving greater accuracy.

5.   A SMALL APERTURE MODERN MICHELSON STELLAR INTERFEROMETER

A small aperture modern Michelson stellar interferometer is under development at the University of Sydney and a prototype instrument is currently nearing completion in the grounds of the Australian National Measurement Laboratory at West Lindfield, near Sydney.

The prototype instrument represents a logical step following the work of Twiss and Tango with the Monteporzio 2 m amplitude interferometer (Tango 1979a). The principles and theory of a small aperture amplitude interferometer have been discussed by Tango and Twiss (Tango 1979b; Tango & Twiss 1980) and they apply directly to the prototype instrument. Since the design considerations for the prototype (Davis 1979b) and, recently, a more detailed description of the design and layout (Davis 1984) have been published only a very brief summary of the key features will be given here.

The prototype interferometer has a fixed 11.4 m north-south baseline and coelostats mounted on plinths at each end of the baseline to steer starlight into a central laboratory. This laboratory houses the optical system of the interferometer which includes a path length compensator to equalise the light paths from the star to the beamsplitter where the beams from the two sides of the instrument are combined.

5.1 The Elimination of Atmospheric Problems

The effect of atmospheric turbulence is to produce time dependent deformations of the wavefronts reaching the coelostats which will reduce the observed visibility $|\gamma|$ below the true value. The atmospheric effects are circumvented by restricting the effective apertures of the coelostats to $\lesssim r_0$ (the maximum primary beam diameter is 10 cm) so that 'flat' sections of wavefront are selected and also by reducing the mean tilts of the wavefronts using optical servo systems. These steps produce a significant reduction in the loss in $|\gamma|$ (Tango & Twiss 1980) and the residual loss can be estimated from auxilliary measurements. For this reason an auxilliary interferometer is being developed to provide real time measurements of r_0 which will be used

to select the effective aperture size and to provide a correction
factor for the residual losses due to wavefront curvature. The loss
arising from uncompensated wavefront tilt fluctuations and shot noise
in the tilt correcting servo signals, which will cause the tilt
correcting mirrors to dither randomly, can be estimated from the noise
power of the servo error signal (Tango & Twiss 1980). This procedure
has been used with very good results in the Monteporzio interferometer
(Tango 1979a).

The tilt corrected wavefronts from the two arms of the interfer-
ometer are arranged to interfere at nominally zero angle in a beam-
splitter so that, in the absence of aberrations, the complementary
output beams are uniformly illuminated. The irradiances of the beams
are proportional to $(1 + |\gamma| \cos\phi)$ and $(1 - |\gamma| \cos\phi)$ where ϕ is a
randomly varying phase angle resulting from atmospheric optical path
length fluctuations and path equalisation errors. The sampling time
τ of the photon counting detectors measuring the irradiance in the
two beams is made short so that changes in ϕ are not significant during
τ which is expected to be in the range 1-10 ms. The photocounts
registered by the two detectors in τ are processed by a correlator
which basically measures the square of the difference between the two
signals. The data are integrated for a total observing time T and
analysed to yield $2|\gamma|^2 <\cos^2\phi>$, where the brackets indicate an average
over T. If the phase is a uniform random variable $2|\gamma|^2 <\cos\phi>$
becomes $|\gamma|^2$, the square of the fringe visibility. Provision has been
made to introduce a path difference of $\lambda/4$ between the two interfering
beams halfway through the sampling period τ so that the correlator
gives $2|\gamma|^2 <\cos^2\phi + \sin^2\phi>$ instead of $2|\gamma|^2 <\cos^2\phi>$ so that it will not
be necessary to assume that the phase is a uniform random variable
to obtain $|\gamma|^2$.

Tango and Twiss (1980) have shown that irradiance fluctuatons due
to scintillation will have a quite negligible effect on the measure-
ment of $|\gamma|^2$ in a small aperture amplitude interferomter.

5.2   The Elimination of Mechanical Problems

In order to provide the required mechanical stability the component
parts of the prototype interferometer are all mounted on massive
reinforced concrete plinths anchored in a monolithic layer of sandstone
approximately 1 m below ground level. Seismometer tests carried out
prior to site selection established that ambient vibration levels were
acceptable.

Particular care has been taken in the design and construction of
the coelostat mounts to minimize vibration and path length changes
with orientation. The only other component mechanically driven during
an observation is a truck carrying a retroreflector in the optical
path length compensator (OPLC) and this is the most critical component
of the interferometer. This is not simply because it has to match the
optical paths from the star to within a tolerance set by the optical
bandwidth but because it also has to meet a particularly severe require-
ment regarding the smoothness of its motion. Not only has the reflector
to move at the correct velocity but any error or irregularity in the

velocity in the sampling time τ will result in a loss of coherence and an error in the measured $|\gamma|^2$. The tolerances for the OPLC to keep losses in $|\gamma|^2 \leq 1\%$ have been established by Tango and Twiss (1980) and the OPLC for the prototype interferometer, which has been designed and built to meet these tolerances, has been described by Davis (1984).

5.3 The Prototype Program

The prototype interferometer is nearing completion and it will be used to establish the accuracy and reliability that can be achieved in measurements of $|\gamma|^2$ through the atmosphere. In developing the design of the interferometer considerable effort has been made to keep individual sources of error in the measurement of $|\gamma|^2$, both atmospheric and mechanical, to < ±1% so that, at least for bright stars, an accuracy of $\lesssim$ ±2% in $|\gamma|^2$ can be achieved. An accuracy of ±0.02 in $|\gamma|^2$ measured at the optimum baseline $d_o \simeq 1.3 \times 10^{-4} \lambda/\theta$, where λ is the wavelength of observation in nm and θ is the angular diameter in arcseconds, corresponds to an accuracy of ~ ±2.5% in the angular diameter. The limiting accuracy is ultimately expected to be set by the tilt-correcting servo and this will deteriorate for fainter stars. The faintest magnitude at which ±2% accuracy can be achieved depends on how well the corrections for residual losses due to atmospheric effects can be established but at this stage it appears that V(limit) will be in the range +7 to +8 (Tango 1979b). The accuracy will deteriorate rapidly below V = +8 to +9.

The prototype program is the foundation for the major high angular resolution interferometer that we plan to build and the component parts of the prototype instrument have been designed to become the heart of the long baseline instrument. The preliminary specification includes baselines extending eventually to a kilometer or more with the same limiting magnitude and accuracy as for the prototype interferometer. This would enable angular sizes down to ~ 5×10^{-5} arcseconds to be measured with an accuracy of the order of ±2% to a V(limit) of +7 to +8.

Apart from the increase in baseline lengths and the corresponding increase in the effective length of the OPLC there are two additional features which will be included in the major instrument. Firstly, for baselines in excess of ~ 50 m it will be necessary to use an automatic fringe tracking system (Davis 1984) and a system such as that developed by Shao and Staelin (1980) will be incorporated. Secondly, the single spectral channel detectors used in the prototype instrument for the determination of $|\gamma|^2$ will be replaced by photon counting linear array detectors covering a range of the spectrum. This will enable simultaneous observations to be made in spectral lines as well as in multiple channels in the continuum.

A search for a suitable site with stable rock near the surface and large enough to accommodate either east-west and/or north-south baselines of at least 1 km in length is under way.

6.   CONCLUSIONS

The targets for future angular diameter determinations suggested in Section 3, namely V(limit) > +7, angular resolution of $\sim 4 \times 10^{-5}$ arc-seconds and an accuracy of $\leq \pm 2\%$, appear to be within the reach of a ground based small aperture amplitude interferometer of the type being developed at the University of Sydney. They may also be within the reach of the large aperture approach being developed by Labeyrie and his colleagues at CERGA.

The importance of observing stars by more than one technique is stressed. In due course it will be desirable to establish a list of reference stars visible from both the Northern and Southern Hemispheres, including stars occulted by the Moon, for comparison and calibration purposes.

The prospects for contributions by high angular resolution measurements to the determination and calibration of fundamental stellar quantities during the next decade are excellent.

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