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Measuring the Sizes of Stars*

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Abstract. The Chatterton Astronomy Department aims to apply interferometers with very high resolving power to optical astronomy. The programme of the stellar intensity interferometer at Narrabri Observatory was completed in 1972 and since then the work has been directed towards building a more sensitive instrument with higher resolving power. As a first step a much larger intensity interferometer was designed but was not built because it was large, expensive and not as sensitive as desired. Efforts are now being made to design a more sensitive and cheaper instrument. A version of Michelson's stellar interferometer is being built using modern techniques. It is hoped that it will reach stars of magnitude +8 and will work reliably in the presence of atmospheric scintillation. It is expected to cost considerably less than an intensity interferometer of comparable performance. The pilot model of this new instrument is almost complete and should be ready for test in 1984.

Key words: stars, angular diameter—interferometry—atmospheric scintillation

1. Introduction

The long-term objective of the Chatterton Astronomy Department of the School of Physics (University of Sydney) is to apply interferometers with very high angular resolving power to optical astronomy. This has already been done with great success in radio-astronomy and there is good reason to believe that it would be equally fruitful in optical astronomy. We are apt to forget that the progress of astronomy, indeed of science, depends intimately on developing new tools and methods of observing the world around us.

The first objective of our programme was to measure the apparent angular diameters of the bright visible stars. We were, by-the-way, not the first people to try to do this; Galileo, for example, tackled the problem experimentally. He hung a fine silk cord vertically, and then measured the greatest distance from his eye at which this cord could be made to occult the bright star Vega. In this way he came to the conclusion that the angular diameter of Vega is about 5 arcsec. In doing this experiment Galileo was trying to find an answer to one of the most troublesome objections to the idea, suggested by Copernicus, that the Earth orbits the Sun. It had been pointed out that, if the Earth really does go around the Sun, then the bright stars should appear to move relative to fainter and more distant stars (orbital parallax). By measuring the angular size of Vega

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and by assuming that it is a similar body to the Sun, Galileo was able to show that the bright stars are so far away that their annual movement in the sky would not be detectable. For reasons which we now understand, Galileo's measurement gave an absurdly large value for the angular size of Vega; nevertheless it served his purpose.

Our own interest in measuring angular diameters is different. If, for example we measure the angular diameter θ of a star and we also know its distance d, then by simple trigonometry we can find its actual physical diameter $D = d\theta$. Alternatively we can find the flux of light F_λ emerging from its surface if we combine our measurement of θ with a measurement of the flux of light f_λ received from the star at the Earth, where

$$F_\lambda = 4f_\lambda/\theta^2 \tag{1}$$

The quantity F_λ gives us the actual flux of light radiated by unit area of the star's surface and is fundamental to the study of models of the star's atmosphere.

Another important piece of information about a star which we can find is the effective temperature T_e of its surface. To do this we measure the flux of light f_λ received over the whole of the spectrum and then compute T_e from,

$$\int_\lambda F_\lambda \mathrm{d}\lambda = \sigma T_e^4 \tag{2}$$

where σ is Stefan's constant.

2. The major difficulties in measuring angular size

The first major difficulty is to make an instrument with sufficiently high resolving power to measure the extremely small angles which are involved. For example, if we aim to measure a reasonable sample of main sequence stars we must measure angles of the order of 10^{-4} arcsec which, at optical wavelengths, necessarily involves building instruments with baselines of 100 m and more—and that is not easy.

The second major difficulty is to make precise and reliable measurements in the presence of atmospheric scintillation. Turbulence in the atmosphere inevitably introduces fluctuations into the relative time of arrival of the starlight at separated points on the Earth. For small separations these fluctuations correspond roughly to changes in pathlength of about 10^{-6} D where D is the separation. What happens at greater spacings, such as 100 m, is not yet known and it would be very interesting to know.

Another effect of turbulence is to introduce temporal and spatial fluctuations into the amplitude and phase of the wavefront of the light from a star. The temporal fluctuations are known to have a frequency spectrum which extends up to 20 or 30 Hz or even more, depending on the wind speed. The spatial fluctuations have a characteristic size which depends upon the site, the weather, and the time of day; typically they have a characteristic length of 10 cm.

2.1 *Michelson's Stellar Interferometer*

The first successful attempt to measure the angular diameter of a star was made by Michelson and his colleagues in 1920 using an interferometer mounted on the 100-inch telescope at Mt Wilson. The number of stars which they could measure was severely limited by the maximum possible separation (20 ft) between the two mirrors of their instrument which restricted their measurements to stars with angular diameters greater than 0.02 arcsec. Altogether they measured 6 stars, all of which were giants or supergiants because the resolving power of their interferometer was not sufficiently high to measure any common or main-sequence stars.

Following this work a determined effort was made by Hale and Pease to extend the measurements to fainter stars by building a larger instrument with a baseline of 50 ft. This larger instrument was completed but never worked satisfactorily. The difficulties appear to have been two-fold; firstly there were the mechanical difficulties of making the instrument sufficiently rigid and of guiding it precisely; secondly it was difficult to see the interference fringes by eye, let alone to measure them accurately, as they danced about under the influence of atmospheric scintillation. The whole programme was abandoned in 1937.

3. The stellar intensity interferometer at Narrabri observatory

The next successful attempt to measure the angular size of a star was made at Narrabri Observatory in New South Wales (Australia) between 1962 and 1972. The instrument (Hanbury Brown 1974)—an intensity interferometer—was based on a novel principle. It measured the correlation between the fluctuations in the output currents of two separated photoelectric detectors, one at each end of the baseline. These detectors were mounted at the focus of very large (6.7 m diameter) reflectors whose separation could be varied up to a maximum of 188 m. The instrument was capable of resolving angles of 2×10^{-4} arcsec and the faintest star which could be measured had a magnitude of + 2.5.

An intensity interferometer has the interesting and valuable property that the precision with which the paths in its two arms must be equalised is a function of the electrical bandwidth of the fluctuations and not, as in Michelson's interferometer, of the optical bandwidth. For example, the electrical bandwidth of the instrument at Narrabri was 100 MHz and therefore the two paths had only to be equalized with a precision of about 10 cm. This has two practical consequences, firstly it is comparatively simple to construct a very large instrument which will meet this tolerance; secondly atmospheric scintillation cannot affect the measurements significantly because the fluctuations in the pathlength of the starlight which they introduce are very much less than 10 cm. But we must pay heavily for these advantages by a loss of sensitivity; an intensity interferometer needs an enormous lot of light and is therefore limited to measuring bright stars.

In a programme lasting about 10 years the interferometer at Narrabri measured the angular diameters of 32 single stars in the spectral range O5 to F8. Several of these 32 stars are main sequence stars and are the first main sequence stars ever to be measured.

The measurements made at Narrabri were combined with photometric measurements of the flux f_λ to find the effective temperatures T_e of these 32 stars using the relations given by Equations (1) and (2). For this purpose the ultra-violet fluxes in the range 110–330 nm were measured by the Orbiting Astronomical Observatory (OAO-2) in collaboration with the University of Wisconsin and the longer wave fluxes were measured on the ground using conventional spectrophotometry. The results gave the first temperature scale for hot stars to be based entirely on measurements.

The interferometer at Narrabri was also used as a pilot instrument to explore and demonstrate the possible uses of an interferometer with very high angular resolving power. However, because we were limited by its low sensitivity to measuring stars brighter than magnitude + 2.5, the number and variety of the objects on which we could work was severely limited. Nevertheless we managed to make some very interesting observations. For example, by observing α Vir (Spica) we showed how it is possible to find all the orbital parameters, and the distance, of a spectroscopic binary star. To explore the interesting, and potentially valuable, application of interferometers to the measurement of the angular size of stars in the light of narrow spectral lines, we measured the angular size of the Wolf-Rayet star γ Vel in the light of the continuum and in an emission line of ionised carbon. The results showed us that the angular size of the emission region surrounding the star is about 5 times that of the star itself. To demonstrate the application of an interferometer to the many problems of stellar rotation we measured the distortion in the shape of the rapidly rotating star α Aql (Altair). We also did a number of other experiments, including an attempt to measure the limb-darkening on α CMA (Sirius) and to observe a corona surrounding the hot star β Ori (Rigel).

We also did our best to understand as completely as possible the limitations of intensity interferometry. As one of the major advantages claimed for the technique is that the measurements are not significantly affected by atmospheric scintillation, we set out to test this claim using the light from α CMa (Sirius). We showed that the measurements of correlation were not noticeably affected by scintillation even when the star was scintillating violently at an angle of only 15 deg above the horizon.

When we had finished the programme of observing stars brighter than magnitude + 2.5 the intensity interferometer was dismantled and the observatory at Narrabri was closed. Regrettably it was not possible to modify the instrument to improve its performance by an amount which would have made the cost and effort worthwhile, and we needed all our resources to develop a new instrument. Too many observatories continue to exist largely because they are already in existence!

4. The next step

Long before the programme at Narrabri was finished we had started to think about the next step. First we made a detailed study of several possible astronomical programmes and reached the conclusion that—for stellar astronomy—any new instrument should be built to reach stars of magnitude +9 with an angular resolving power of about 10^{-5} arcsec. As it was obviously impossible to modify the existing instrument at Narrabri—even to approach the performance which we wanted—we designed a completely new intensity interferometer, making it as large as we thought anyone who was likely to finance it could afford.

The layout was radically different from that used at Narrabri. Four fiat coelostat mirrors were mounted on a straight railway track and reflected the light from the star into four fixed paraboloids each with a diameter of 15 m. The instrument was designed to operate simultaneously in 10 separate optical bands and the overall electrical bandwidth of the electronic correlator and phototubes was 1000 MHz. Based on our experience at Narrabri we estimated that it would reach stars of magnitude + 7.3 in an exposure of 100 h. Such an instrument would have cost about $A3 m to build (in 1972 dollars) and we could see no way of increasing its sensitivity to approach our ideal of + 9 without increasing its cost unreasonably.

There is little doubt that, had we built this larger intensity interferometer, it would have made and would still be making, a substantial contribution to stellar astronomy. Nevertheless it would have been very large and expensive and would not have reached the sensitivity that we really wanted. And so, before committing our small group to the many years' work which it would have taken to build such an instrument, we set out to find out whether there was a better way of doing the job.

At that time there were three contemporary developments which made us think. A small double-star 'Michelson' interferometer, which used 'active optics' to minimize the effects of atmospheric scintillation, was being developed by Richard Twiss at Monteporzio in Italy (Tango 1979). A 'speckle interferometer' was being developed by Antoine Labeyrie (1978) in France. The technique of using the Moon to occult visible stars was being developed by David Evans (1957) and his colleagues in the USA. We looked carefully at all these things and came to the conclusion that, although speckle interferometry is extremely interesting and offers superior sensitivity, and lunar occultation offers superior economy, neither of these techniques looked to us to be promising ways of making measurements with the high accuracy which we were seeking for our programme of stellar astronomy. We already know from our experience at Narrabri that the answers to many of the interesting questions about stars call for observational data of high precision; observations with an uncertainty of 10 per cent are of limited use, one really needs to achieve an accuracy of 1 or 2 per cent.

To cut a long story short, we decided that the most promising possibility was to modernise Michelson's stellar interferometer. In theory it offers a higher sensitivity than an intensity interferometer and it looked to us as though it should be significantly cheaper to build. The major uncertainty is, of course, whether or not it is possible to overcome the effects of atmospheric scintillation and the need for very high mechanical precision. As far as we could estimate it should be possible to overcome both these difficulties, at least to an adequate extent, by the use of some of the modern techniques which were not available to Michelson, such as narrow-band optical filters, photo-electric detectors, 'active optics', laser distance-measuring equipment and so on. But there was, of course, only one way to find out and that was to build an experimental model. And so, rather sadly, we put the designs of a larger intensity interferometer on one side and started to build a modernized version of Michelson's stellar interferometer.

5. A modernized version of Michelson's stellar interferometer

As a first step we are building, and have almost completed, a small, experimental, interferometer in the grounds of the National Measurement Laboratory in Sydney (Davis 1979). The general layout is shown in Fig. 1. All the components are mounted on reinforced concrete plinths which are anchored in a monolithic layer of sandstone about 1 m below the surface of the ground. The mirrors which collect the light from the star are two small coelostats (C) (150-mm zerodur fiats) which are mounted on concrete plinths 1.35 m high and are separated by 11.4 m in a north-south direction. These coelostats are directed at the star by a computer which is corrected by a photoelectric star-guiding system. They reflect the starlight, via periscopes, into pipes which carry it

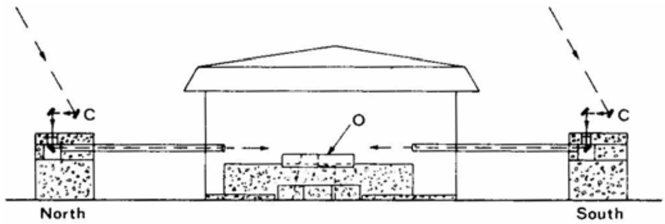

Figure 1. Cross-section of the pilot model of a modernised Michelson interferometer looking east.

to a central laboratory. The pipes are thermally insulated and can, if necessary, be evacuated.

In the central laboratory there is an optical table (O) mounted on a large concrete block. This table carries the optical system outlined in Fig. 2. The incoming beams of light from the coelostats are first reduced in diameter by a factor of 2.5 by the beam-reducing telescopes (BRT) which consist of two off-axis paraboloidal segments. The reduced beams then pass into the optical path compensators (OPLC) which consist of the retro-reflectors (R1, R2). These retro-reflectors are mounted on a very precise track and move under the control of a computer and a fringe-counting interferometer using a laser so that the pathlengths in the two arms of the equipment are equalised to a few microns. The beams then pass through the beamsplitters (G) which reflect roughly 5 per cent of the light into a lens which forms an image of the star on the quadrant detector (Q_g). Error signals from this quadrant detector are used to correct the pointing of the coelostats with a time-constant of several seconds, so that the beams are accurately

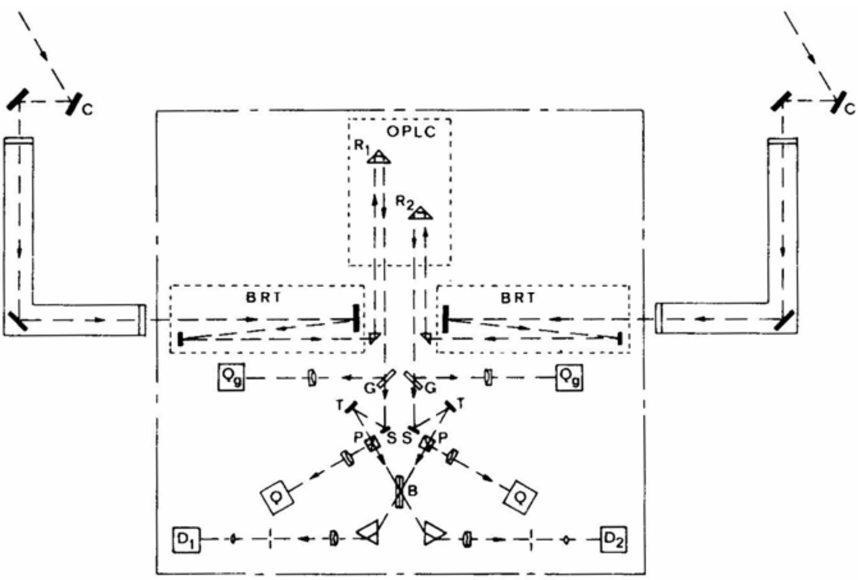

Figure 2. Outline of the optical system of the pilot model of a modernised Michelson interferometer.

aligned with the optical axis of the instrument except, of course, for the rapid angular variations of 1 or 2 arcsec due to atmospheric scintillation.

The beams are then reflected by the mirrors M and T into the polarizing beamsplitters P. The mirrors M are each mounted on a single cylinder of piezo-electric material so that, as discussed later, the relative phase of the two light beams can be varied at will. The ‘active’ mirrors T are each mounted on three piezo-electric cylinders in such a way that they can be tilted by electrical signals in any desired direction. The polarised beam-splitters P take all the light in one polarization and reflect it, *via* lenses, to the quadrant detectors Q. The error signals from these two quadrant detectors are then used to control the ‘active’ mirrors T so that they cancel, as far as possible, the angular scintillations in the two beams due to atmospheric scintillation. For a loss of 1 per cent in the measured fringe visibility the angular scintillation must be reduced to less than about 0.1 arcsec.

After passing through the polarizing beam-splitters P, the two beams—now polarized in only one plane—are incident on the neutral beam-splitter B where they interfere at zero angle, thereby forming sum and difference beams. These two beams then pass through matched prism spectrometers which transmit the light in a narrow optical band to the photon-counting detectors D1, D2. The spectral bandwidth can be varied over the range 0.1 to 1 nm and the sampling time of the two detectors is expected to lie in the range 1 to 10 ms.

In operation the two photon detectors (D1, D2) will measure the number of photoelectrons n_1 (τ), n_2 (τ) received in the short time interval τ(1–10 ms). A computer will then calculate the quantity,

$$\sum_{M} \{[n_1(\tau) - n_2(\tau)]^2 - [n_1(\tau) + n_2(\tau)]\} = |\Gamma|^2 \langle \cos^2 \phi \rangle \tag{3}$$

where, after normalization, $|\Gamma|$ is the modulus of the fringe visibility and ϕ is the relative phase of the starlight at the two coelostats. Assuming that this relative phase is random, then in a large number of samples we can replace $\langle \cos^2 \phi \rangle$ by 0.5. Alternatively we can, if necessary, drive the two mirrors M in such a way as to ensure that any effect of the relative phase of the light at the two coelostats on the measured value of $|\Gamma|$ is negligible.

6. How well do we expect this new instrument to work?

6.1 *The Need for Mechanical Precision and Rigidity*

The precision with which we must match the paths of light in the two arms of the instrument depends upon the optical bandwidth which we choose and that, in turn, governs the sensitivity. For a rectangular bandwidth $\Delta\nu$ and a path difference Δl, the loss of fringe visibility is given by,

$$\sin(\pi \Delta\nu\, \Delta l/c)/(\pi \Delta\nu\, \Delta l/c). \tag{4}$$

If therefore we wish to limit the loss of fringe visibility to 1 per cent then, at a wavelength of 400 nm $\Delta l \ngtr 2 \times 10^7/\Delta\nu$ and, for a bandwidth of 2 nm, we must keep any path difference between the two arms to less than about 100 μm. Such differential pathlengths may be due to a whole host of factors, such as thermal expansion of the instrument itself, earth movements and so on. We believe that they can be reduced to well below the required level by making the instrument mechanically symmetrical, by controlling its temperature, by mounting it on solid rock, by transmitting the light through evacuated pipes, by monitoring the pathlengths in the instrument with auxiliary interferometers and by calibrating it frequently on bright stars.

A second, perhaps more demanding requirement, is that the instrument should be sufficiently rigid so that the relative phase of the light in the two arms should not change during the sampling time τ of a single observation. This implies that any vibration in the instrument should not change the optical paths by more than a small fraction of the wavelength of light ($\lambda/40$) in a time of about 1 ms. We believe that this requirement can be met by making the coelostats and their associated mirrors massive, by shielding them from the wind and by choosing a suitable site perhaps on solid rock.

6.2 *The Effects of the Atmosphere*

Let us look first at the loss of fringe visibility caused by random fluctuations in the relative time of arrival of the light at the two coelostats. Theory suggests that, for a baseline of a few metres, these fluctuations are largely uncorrelated at the two coelostats and that they are given by,

$$\Delta l_{\mathrm{rms}} = 0.4\lambda\,(d/r_0)^{5/6} \tag{5}$$

where Δl is the fluctuating pathlength, d is the baseline and r_0 is the characteristic length of the scintillations. Taking a typical value of r_0 = 10 cm then, very approximately,

$$\Delta l \simeq 2 \times 10^{-6}\, d$$

and it follows that for an optical bandwidth of 2 nm, and a loss of fringe visibility of 1 per cent, we can use baselines of up to 50 m. At longer baselines it would be necessary either to restrict the optical bandwith, thereby losing sensitivity, or to develop a system of compensating automatically for the varying delay. A preliminary analysis suggests that it should be possible to do this by tracking the ‘white-light fringes’ and that such a system would have an adequate signal-to-noise ratio, although it must be remembered that the magnitude and time variation of these delays at optical wavelengths have never been measured at baselines greater than a few metres.

There are also the spatial fluctuations in the phase and amplitude of the starlight. In general, the wavefront of the light arriving at the coelostats will not be plane nor will it be normal to the direction of the star; it will be tilted and curved and the relative phase and amplitude of the waves at the two coelostats will vary rapidly and at random.

There will be a loss of fringe visibility if the relative phase of the light at the two coelostats varies significantly during a sampling interval τ. If this loss is not to exceed 1 per cent then any variation in the relative phase must not exceed about 10 deg in a sampling interval. It follows that, for wind speeds of a few metres per second and a typical scintillation scale of 10 cm, the sampling time cannot be greater than a few milliseconds. As far as the fluctuations in intensity are concerned, it can be shown that their effect on the measurements can be removed entirely if each elementary observation is normalised by the total number of photons counted in that interval.

The next effect which we must consider is that of the fluctuations in the tilt of the wavefront or, in other words, in the apparent direction of the incoming light from the star. If this tilt is not corrected the two beams of light will not interfere at zero angle in

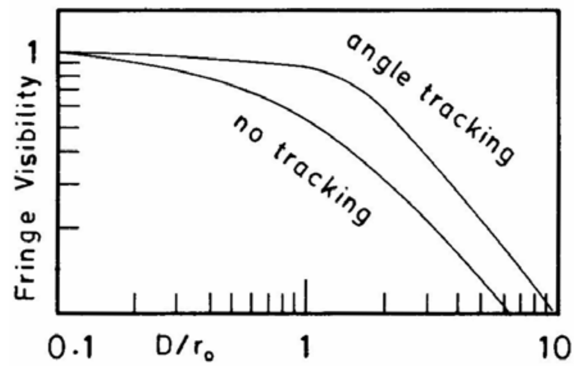

Figure 3. The theoretical loss of fringe visibility as a function of the ratio of the mirror diameter D to the size of the atmospheric scintillations r_0.

the beam-splitter B and the measured value of $|\Gamma|$ will be reduced. Given a theoretical model of the atmospheric fluctuations this loss can be calculated as a function of the ratio of the diameter of the mirror D to the characteristic size of the scintillations r_0. The curve marked ‘no tracking’ in Fig. 3 represents the results of one such calculation and shows how vulnerable this type of interferometer is to atmospheric scintillation.

To a large extent this alarming loss of fringe visibility can, so we expect, be reduced by the use of ‘active optics’. As we have seen in Fig. 2 the two small mirrors T are servo-controlled to maintain the two beams of light at the correct angle relative to the optical axis within a fraction of an arcsec, and to control these mirrors we have taken all the light in one polarization and focussed it on the quadrant detectors. Such a scheme removes the average tilt of the two beams and should greatly reduce the loss of fringe visibility. This is shown by the curve marked ‘angle-tracking’ in Fig. 3 which has been calculated on the assumption that the average tilt of the wavefront has been reduced to zero. The remaining loss of fringe visibility, which increases with D/r_0, is due to the curvature of the wavefront.

The curves in Fig. 3 allow us to choose the size of the coelostat mirrors. They show clearly that if we wish to restrict the loss of fringe visibility due to curvature of the wavefront to 1 per cent then, without ‘angle-tracking’, we are limited to the use of very small mirrors indeed, and therefore to an instrument of low sensitivity. For example, if we take a typical value of r_0 = 10 cm, then without angle-tracking our mirrors must not be significantly larger than 0.1 r_0 in diameter, which means that they must be absurdly small. If on the other hand we use angle-tracking then, for a 1 per cent loss in fringe visibility, the size of the mirrors can be increased to about 0.25 r_0 or 2.5 cm. Even so, the sensitivity of the instrument would be too low and for that reason we propose to make the (projected) diameter of the coelostats mirrors about 10 cm and, as discussed later, to correct for the loss of fringe visibility by using a value of r_0 measured continuously by an independent interferometer. In this way we believe that it will be possible to correct for a loss of fringe visibility of the order of 10 per cent with adequate precision, thereby making it possible to use coelostats of at least 10 cm diameter most of the time.

6.3 *The Sensitivity*

One of the main attractions of a Michelson interferometer is that, compared with an intensity interferometer, it is more sensitive. For the instrument shown in Fig. 2 it can be shown that at low photon rates the signal to noise ratio is given by,

$$S/N_{\mathrm{rms}} = n|\,\Gamma\,|^2\,(\tau T_0/2)^{1/2} \tag{6}$$

where τ is the sampling time, T_0 is the total time of observation and n is the mean counting rate of photoelectrons in one channel. If we take the diameter of the coelostats as 10 cm, τ = 2 ms, the optical bandwidth as 2 nm at a mean wavelength of 550 nm, the overall transmission of the atmosphere and the optics as 0.35, the quantum efficiency of the photodetectors as 0.2, and if we assume that the lowest signal-to-noise ratio with which we can usefully work is 10/1 in one hour, then Table 1 shows the limiting magnitude for an A0 star at the zenith. Column 2 has been calculated for the instrument outlined in Fig. 2, which has only one pair of photon detectors, and shows that the limiting magnitude for that simple configuration is only + 7.6 which falls significantly short of our target of + 9. It should, however, be comparatively easy to increase the sensitivity by adding several pairs of detectors in separate spectral channels and column 3 shows that, by using only 10 separate channels, we should be able to reach stars of magnitude + 9.

It is, however, by no means certain that the sensitivity of the instrument would be limited by the signal-to-noise ratio in the photon-counting process. It seems more likely that it would be limited in practice by the signal-to-noise ratio in the angle-tracking system. The ‘signal’ in that system corresponds to the zero order or average tilt of the incoming light, and the ‘noise’ to a combination of the higher order components of the curvature of the wavefront and the statistical noise in the photoelectron stream at the output of the quadrant detectors. Inevitably this ‘noise’ introduces unwanted ‘dither’ of the tilting mirrors and there is a corresponding loss of fringe visibility. Tango–& Twiss (1980) have made a detailed analysis of this loss and have shown that it will be about 1 per cent for stars of magnitudes + 5 and will increase to about 10 per cent for stars of magnitude + 8.

In principle it should be possible to correct for this loss by measuring the residual fluctuations in the incoming beams after they have been reflected from the tilting mirrors, but how accurately this can be done remains to be found out by experiment. In the meantime it looks as though the sensitivity of the interferometer may be limited, perhaps to stars of about magnitude + 8, by the angle-tracking system.

6.4 *The Precision of the Results*

As we have seen the measured fringe visibility will be reduced by two effects, curvature of the wavefront and angular noise in the angle-tracking system. The final precision and reliability of the results will depend on how accurately we can correct for the losses due to these two effects.

Table 1. The limiting magnitude of a modernized Michelson stellar interferometer for a signal/noise ratio of 10/1 in 1 h.

Optical bandwidth of each channel $\Delta\nu$	Limiting magnitude 1 optical channel	10 optical channels
2 nm	+7.6	+8.9
10 nm	+9.4	+10.6

The first effect, the loss due to curvature of the wavefront, is a function of the ratio of the characteristic size of the scintillations r_0 to the diameter D of the coelostats. In principle it should be possible to correct for this loss if we know r_0 and, to that end, we are building a small auxiliary interferometer to measure r_0 continuously. The curves in Fig. 3 suggest that, if we restrict our observations to atmospheric conditions when $D/r_0 < 1$, then we shall be able to reduce the uncertainty in our measures of fringe visibility to 1 per cent if we can measure r_0 with an uncertainty of about 5 per cent:

The second effect, the loss of fringe visibility due to noise in the angle-tracking system, is expected to be significant only for the fainter stars and may, as noted above, prove to be the principal factor which determines the limiting magnitude. To what extent it can be corrected remains to be determined by experiment.

To sum up, our preliminary analysis suggests that the instrument which we are building will measure fringe visibilities with an uncertainty of a few per cent (less than 5 per cent) for stars brighter than about magnitude + 6. For fainter stars this uncertainty will increase and may reach unacceptable levels for stars of magnitude + 8 or + 9.

7. Conclusion

The observing programme of the Stellar Intensity Interferometer at Narrabri Observatory was restricted to stars brighter than magnitude +2.5 and was completed successfully in 1972. Since then we have been trying to design a more sensitive instrument to carry on and extend this work to fainter stars.

As a first step towards this goal we designed an intensity interferometer with a sensitivity about 100 times greater (limiting magnitude + 7.3) and a resolving power 10 times greater (baseline 2 km) than that of the original instrument at Narrabri. It was both large and costly ($3 m in 1972) and we could see no way of increasing its sensitivity to approach our target of + 9 without unreasonable expense. The only thing which can be said in its favour is that we were confident that it would work!

Before committing ourselves to building such a large instrument we looked carefully at all the possible alternatives and decided to try to improve Michelson's stellar interferometer. We have designed a modernized version of Michelson's interferometer which, so we hope, will be able to measure bright stars with a precision of a few per cent even in the presence of atmospheric scintillation. If all goes well it should reach stars of magnitude +8. We are confident that, if it can be made to work satisfactorily at short baselines, it can be extended to long baselines by the development of an automatic fringe-tracking system. The cost of this instrument will surely be significantly less than that of an intensity interferometer of comparable performance.

Our pilot model of this new interferometer is almost complete and it will be tested during 1984. If these tests are successful we intend to build a full-scale instrument to carry on and extend the work which was started at Narrabri.

References

Davis, J.1979, in *IAU Coll.* 50*: High Angular Resolution Stellar Interferometry*, Eds J. Davis and W. J. Tango, Chatterton Astronomy Department, University of Sydney, p. 14.1.

Evans, D. S. 1957, *Astr. J.*, **62,** 83.

Hanbury Brown, R. 1974, *The Intensity Interferometer*, Taylor & Francis, London.
Labeyrie, A. 1978, *A. Rev. Astr. Astrophys*., **16,** 77.
Tango, W. J. 1979, in *IAU Coll.* 50*: High Angular Resolution Stellar Interferometry*, Eds J. Davis and W. J. Tango, Chatterton Astronomy Department, University of Sydney, p. 13.1.
Tango, W. J., Twiss, R. Q. 1980, in *Progress in Optics XVII*, Ed. E. Wolf, North-Holland, Amsterdam, p. 240.