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Forty Years of Progress in Long-Baseline Optical Interferometry: 2005 Robert Ellery Lecture

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Abstract: The development of long-baseline optical interferometry in Australia from the Narrabri Stellar Intensity Interferometer (NSII) to the Sydney University Stellar Interferometer (SUSI) and the resulting technical and scientific achievements are described. Three examples of results from the SUSI programme, for a single star, a double-lined spectroscopic binary, and a Cepheid variable, are presented to illustrate the advances made in the past four decades. The leading role that Australia has played in the development of the field worldwide is discussed from a personal viewpoint. Long-baseline optical interferometry has promised much, has been slow to deliver, and has been restricted to black-belt interferometrists, but it has now matured to the point where it is becoming an observational technique for astronomers in general.

Keywords: instrumentation: high angular resolution — instrumentation: interferometers — techniques: interferometric — stars: fundamental parameters — binaries: spectroscopic — Cepheids

Preamble: Personal Remarks

The award of the biennial Robert Ellery Lectureship for 2005 cited 'my contributions to the field of Long-Baseline Optical Interferometry'. I therefore chose as the topic for my lecture the advances made in the field and its applications over the more than 40 years that it has been my primary research interest. The main theme is the developments in Australia that I have been directly involved in from the Narrabri Stellar Intensity Interferometer (NSII) through to the Sydney University Stellar Interferometer (SUSI). A brief summary of the current capabilities of long-baseline optical/IR interferometry and the scientific observations that are being made with them is included. In an Appendix I have added some personal remarks on my career and contributions to the field of long-baseline optical stellar interferometry.

1 Introduction

The first measurement of the angular diameter of a star was made with Michelson's stellar interferometer attached to the 100-inch telescope on Mount Wilson, California, in 1920 (Michelson & Pease 1921). A 50-foot (15.2-m) interferometer was subsequently built on Mount Wilson (Pease 1931) but did not produce any new angular diameter measurements. The extreme tolerances on mechanical stability and control, plus the effects of atmospheric seeing, could not be overcome with the technology then available.

The field lay dormant until Hanbury Brown had the idea of intensity interferometry (Hanbury Brown & Twiss 1954). An intensity interferometer developed for radio astronomy was found to be insensitive to radio scintillation (Hanbury Brown, Jennison, & das Gupta 1952) and Hanbury Brown and Twiss realised that an optical version would be insensitive to scintillation at optical wavelengths. After a series of laboratory experiments which generated considerable controversy, but which clearly demonstrated the viability of the technique, Hanbury Brown measured the angular diameter of Sirius from the Jodrell Bank Experimental Station of the University of Manchester with what might be regarded as the prototype stellar intensity interferometer (Hanbury Brown & Twiss 1956). Hanbury Brown borrowed two World War II searchlights to use as the light collectors of his interferometer (Figure 1). The final value determined for the angular diameter of Sirius from these measurements was 7.1 ± 0.55 mas (Hanbury Brown & Twiss 1958) which, although not of great accuracy, is in reasonable agreement with more recent measurements. In this remarkable demonstration of the technique Sirius was never more than 20° above the horizon and was observed to scintillate strongly.

An intensity interferometer differs significantly from a conventional optical interferometer in which light beams are brought together to produce interference fringes. In an intensity interferometer the light is detected at the foci of the light collectors and the correlation between fluctuations in the resulting electrical signals is measured. A theoretical analysis shows that the normalised correlation is equivalent to the square of the fringe visibility, as defined by Michelson, that is measured in a conventional optical interferometer.

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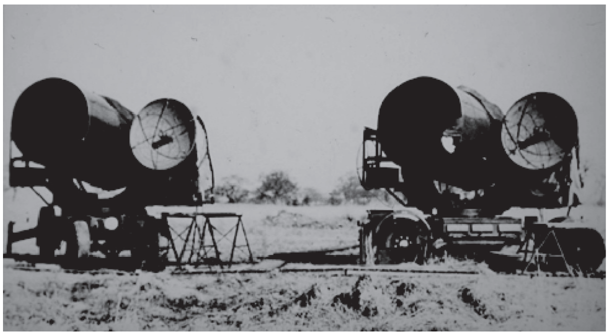


Figure 1 The first stellar intensity interferometer at Jodrell Bank (University of Manchester) in 1956.

A major advantage of the intensity technique is that the tolerance in matching the paths to the point at which the correlation is measured is set by the upper limit of the bandwidth of the correlation measurement. For example, in the NSII (see below) the upper limit was set by the photomultipliers used as detectors at about 100 MHz. The paths were matched to within 30 cm, one tenth of the corresponding wavelength of 3 m. The other major advantage, already mentioned, is the fact that the technique is insensitive to 'seeing'. These two factors overcame the problems that had prevented the development of Michelson's 'amplitude' stellar interferometer.

2 The Narrabri Stellar Intensity Interferometer

The successful measurement of the angular diameter of Sirius with the prototype intensity interferometer led to the design and development of a large dedicated intensity interferometer. This instrument became a joint project between the University of Manchester in England and the University of Sydney and a site near Narrabri in northern New South Wales was chosen for its location. The construction of what became known as the Narrabri Stellar Intensity Interferometer began in 1961 and the first result, the measurement of the angular size of Vega (α Lyr), was published in 1964 (Hanbury Brown et al. 1964).

2.1 The Instrument

The NSII is shown from the air in Figure 2. Starlight was collected by two 6.5-m diameter reflectors mounted on trucks running on a circular railway track 188 m in diameter. The surface of each reflector was made up of a mosaic of hexagonal mirrors that reflected the starlight to a photomultiplier at their common focus. An advantage of the intensity interferometer is that it is not necessary to form an image in the conventional sense — only to get the light onto the detector with path differences within the tolerance set by the electrical bandwidth of the correlation measurement. In operation a line joining the two reflectors, the baseline of the interferometer, was kept constant and the reflectors moved around the track to keep the baseline perpendicular to the direction of the star. Cables suspended on catenaries carried the signals, via a tower at the centre of the circular track, to the control building where the correlation between the signals was measured.

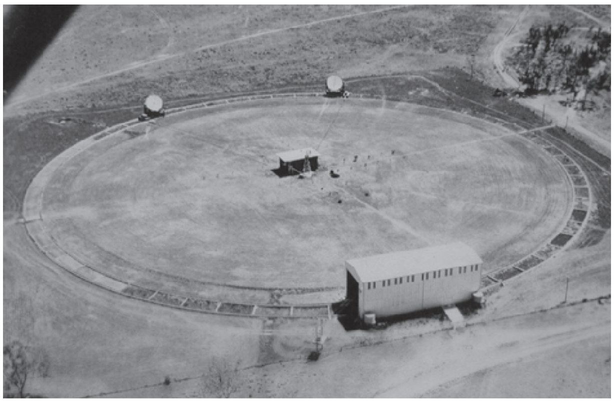


Figure 2 The Narrabri Stellar Intensity Interferometer from the air. The two reflectors can be seen at the top of the picture.

2.2 The Achievements

The major achievements of the NSII programme were:

- The measurement of the angular diameters of 32 stars leading to the effective temperature scale for early-type stars (Hanbury Brown, Davis, & Allen 1974a).
- The first combined interferometric–spectroscopic study of a double-lined spectroscopic binary (α Vir; Herbison-Evans et al. 1971).
- Several exploratory experiments that demonstrated the potential of optical long-baseline interferometry.

Among the exploratory experiments were observations to measure the limb-darkening for α CMa (Hanbury Brown et al. 1974), to measure rotational distortion for α Aql (Lake 1975), to measure the relative size of the CIII–CIV emission region around γ^2 Vel (Hanbury Brown et al. 1970), and to measure the electron scattering corona around β Ori (Hanbury Brown, Davis, & Allen 1974b). Unfortunately the sensitivity of the NSII was insufficient to obtain significant astrophysical results in these experiments but they demonstrated the potential of long-baseline optical interferometry.

A by-product of the programme was the discovery that several stars, previously thought to be single, were in fact double. This will be discussed further in Section 4.2.

2.2.1 The Temperature Scale for Early-Type Stars

The empirical effective temperature of a star can be determined by combining its angular diameter with the flux received from the star integrated over the entire spectrum. The emergent flux at the surface of a star ($\mathcal{F}_\lambda$) is given by

$$\mathcal{F}_\lambda = \left(\frac{4}{\theta^2}\right) f_\lambda \quad (1)$$

Table 1. Major parameters determined for the double-lined spectroscopic binary α Vir

Parameter	Value
Mass of primary, M_1	$10.9 \pm 0.9\ M_\odot$
Mass of secondary, M_2	$6.8 \pm 0.7\ M_\odot$
Radius of primary, R_1	$8.1 \pm 0.5\ R_\odot$
Effective temperature of primary, T_{e1}	22400 ± 1000 K
Luminosity of primary, log $L_1/L_\odot$	4.17 ± 0.10
Distance, d	8.4 ± 4 pc

where θ is the angular diameter of the star and f_λ is the flux received at the Earth from the star at wavelength λ, corrected for extinction. The effective temperature of the star (T_e) is then given by

$$\sigma T_e^4 = \int_0^\infty \mathcal{F}_\lambda \, d\lambda = \frac{4}{\theta^2} \int_0^\infty f_\lambda d\lambda \qquad (2)$$

where σ is the Stefan–Boltzmann radiation constant.

In the case of the 32 stars, whose angular diameters were measured with the NSII, the flux distributions were assembled from three spectral ranges:

- The ultraviolet flux distributions (λλ110–350 nm) from the University of Wisconsin's Orbiting Astronomical Observatory (OAO-2; Code et al. 1970).
- The visual flux distributions were derived from spectrophotometric observations (λλ330–808 nm) made at the Mount Stromlo Observatory (Davis & Webb 1974) calibrated with monochromatic magnitudes (λ550 nm) measured at Siding Spring Observatory (J. Davis 1974, private communication).
- The infrared flux distributions were assembled from narrow and broad-band photometry.

For the hottest stars there is significant flux short-ward of 110 nm and allowance for this was included from theoretical model atmospheres. The resulting flux distributions were used to derive effective temperatures for the 32 stars using Eqn (2) and hence to establish the effective temperature scale for stars hotter than the Sun (Code et al. 1976). It is worth noting that the angular diameter measurements made with the NSII have only been superseded recently for some of the A- and F-stars and for none of the O- and B-stars, some 30 years since they were made.

2.2.2 The Double-Lined Spectroscopic Binary α Vir

The binary star α Vir was observed with the NSII and the results were combined with spectroscopically determined parameters for the system to demonstrate, for the first time, the power of combining interferometric and spectroscopic observations of double-lined spectroscopic binaries for the determination of fundamental properties of stars (Herbison-Evans et al. 1971).

The two techniques allow the determination of some of the orbital parameters in common, namely the period P, the longitude of periastron ω, and the eccentricity e. However, there are also complementary parameters: interferometry can provide the inclination of the orbit i, the angular size of the semimajor axis θ_a, and the angular size of at least the primary component of the system θ_1, whereas spectroscopy can provide $a \sin i$, $M_1 \sin^3 i$, and $M_2 \sin^3 i$, where a is the semimajor axis and M_1 and M_2 are the masses of the component stars.

The masses of the components M_1 and M_2, the distance to the system, and the radius of the primary R_1 can be found from the interferometrically and spectroscopically determined orbital elements. The effective temperature T_{e1} can be derived from the angular diameter of the primary θ_1 combined with the flux distribution, and the luminosity L_1 can be found from T_{e1} and R_1. The physical parameters M_1, R_1, and L_1 can be directly compared with the predictions of evolutionary models. The key parameters determined from our study of α Vir are listed in Table 1. The distance derived from the interferometric and spectroscopic data (the 'orbital parallax') has significantly better accuracy than the parallaxes available at the time, and is in good agreement with the more recent Hipparcos value of 80.4 ± 5.6 pc (ESA 1997).

3 A Successor for the Narrabri Stellar Intensity Interferometer

In 1970, as the observational programme with the NSII was nearing completion, Hanbury Brown was already thinking about the next project and initially, with Harry Messel, Head of the School of Physics at the University of Sydney, the idea of obtaining a 2-m class telescope to exploit the possibilities of new array detectors was considered. However, the NSII programme had demonstrated the enormous potential of long-baseline optical interferometry. It therefore made sense to develop a more sensitive interferometer and it was decided to follow that path.

3.1 Intensity or Amplitude Interferometer?

Initially a larger, more sensitive intensity interferometer was considered as the successor to the NSII because the technique was understood, there were no unknowns, and the commissioning of such an instrument would be quite straightforward. The only reservation was sensitivity and it was not clear in 1975 what maximum electrical bandwidth would be possible with photodetectors for use in the new instrument. At the time it seemed unlikely that the sensitivity required for some of the proposed astrophysical programmes could be reached. Thoughts turned to resurrecting the technique developed by Michelson using modern technology in the form of laser metrology, adaptive optics, computer control, etc. to overcome the problems that had prevented its development. After a thorough investigation it was decided to build a prototype modern Michelson, or amplitude, interferometer. At this point Hanbury Brown

Figure 3 The SUSI Prototype Stellar Amplitude Interferometer.

Figure 4 SUSI seen from the northern end of its 640 m north–south baseline array.

decided to hand over the development of the project to me. Nevertheless he retained a close interest in the project and helped raise the funds for the construction of the Sydney University Stellar Interferometer.

3.2 The SUSI Prototype Amplitude Interferometer

The initial stage in the development of the prototype amplitude interferometer was the design and testing of the various sub-systems in the laboratory. This was followed by the assembly of the sub-systems into an interferometer for testing the complete system on the sky. The characteristics of the prototype amplitude interferometer were chosen with the following considerations in mind:

- Specification of the optical components so that they could be used subsequently in a major interferometric instrument.
- To allow testing of sub-systems that could be transferred into a major interferometric instrument.
- Demonstrate the successful performance by measuring the angular diameter of a star.

The prototype instrument (Davis & Tango 1985), which is shown in Figure 3, was located in the grounds of the National Measurement Laboratory at West Lindfield. It had a fixed north–south baseline of 12.4 m and 15-cm diameter input siderostats. It featured wavefront tip–tilt correction, dynamical optical path length compensation, and rapid signal sampling and processing. It operated at the blue end of the visual spectrum and its successful performance was demonstrated with the measurement of the angular diameter of Sirius at 442 nm (Davis & Tango 1986).

4 The Sydney University Stellar Interferometer

In parallel with the commissioning of the prototype instrument the design of a major interferometric instrument was developed. The success of the prototype instrument led to the commencement of funding in 1987 for the major instrument now known as SUSI. An aerial view of SUSI is shown in Figure 4. It features a 640-m long, north–south array of input stations which each house a 20-cm diameter siderostat that steers starlight into the central building via fixed mirrors and evacuated pipes. The long tunnel-like section of the central building houses a 70-m long path equalisation system that precedes the beam-combining optical systems. A detailed description of SUSI and the commissioning of its ‘blue’ beam combination system ($\lambda\lambda$430–500 nm) has been given by Davis et al. (1999a, 1999b).

It is not appropriate to dwell in detail on the problems and difficulties faced in bringing a pioneering instrument like SUSI into operation. However, it should be noted that, after the majority of the mechanical and optical installation had been completed by 1990, major delays in commissioning were experienced due to problems outside our control — with the metrology system that monitored and provided control of the path equalisation system, with the initial mirror coatings that required the development of a refined coating technique, and to multiple failures of the blue reference HeCd laser used for alignment of the blue system. As a result some three years were lost before the real commissioning could commence. For technical reasons associated with the detection technique originally adopted, the blue system was limited to narrow spectral bandwidths ($\leq$4 nm). In addition, the predicted reflectance of the mirror coatings was significantly less than we had been led to expect and, with some 20 reflections in each arm of the instrument, the sensitivity was limited to a B-magnitude of ~+2.5.

Techniques were developed during the commissioning of SUSI for measuring the spatial and temporal scales of the wavefront distortion caused by atmospheric turbulence — respectively r_0 (Davis et al. 1999b) and t_0 (Davis & Tango 1996). A measurement was also made of the outer scale of turbulence using the ability to switch rapidly between the baselines of SUSI’s unique linear array (Davis et al. 1995).

A fundamental difference in operation between the NSII and SUSI is that the intensity interferometer, being unaffected by seeing, measured the correlation without need for external calibrators. For an amplitude interferometer like SUSI, it is necessary to interleave observations of programme stars between observations of calibrator stars — stars that are essentially unresolved, or only partially resolved and of known angular diameter. Experience with SUSI has shown that, at least at blue wavelengths, it is essential for the calibrators to lie within approximately 5° of the programme star and to be observed close in time if satisfactory calibration is to be achieved. With the bright limiting magnitude of B ~ +2.5 it is impossible to find calibrators close in the sky to programme stars except for a few cases. As a result, much of the observational programme with the blue system has been devoted to the study of binary systems and an example is given in Section 4.2.

Given the relatively low sensitivity of the original blue system, a red beam combination system ($\lambda\lambda$500–950 nm) has recently been commissioned in SUSI. This system uses a fringe scanning detection system similar to that used in COAST (Baldwin et al. 1994). It has a significantly improved sensitivity mainly due to the fact that much wider spectral bandwidths can be used, the detectors are avalanche photodiodes with improved quantum efficiency compared with the photomultipliers used in the blue system, and the reduction in the deleterious spatial and temporal effects of atmospheric turbulence at the longer wavelengths. The limiting magnitude of the red system at 700 nm is ~ +5. An upgrade of the blue system to improve its sensitivity and to provide rapid wavelength switching for spectral line observations is being implemented. Dichroic beamsplitters will divide the spectrum between the blue and red systems and it is planned to run the two systems simultaneously.

Three examples are given to demonstrate SUSI's capabilities compared with those of the NSII and to illustrate the advances made. These are the results for a single star (δ CMa), for a double-lined spectroscopic binary (β Cen), and for a Cepheid (ℓ Car). Observations are also being made for a range of other studies including the distortion of rapidly rotating stars, limb-darkening in absorption lines, and the relative sizes of emission regions around hot stars.

4.1 A Single Star

The F8 supergiant δ CMa was the faintest star measured with the NSII and an accuracy of only ±14% was achieved in spite of a total of over 50 h of signal integration. It has been measured twice with SUSI, first with the blue system at λ442 nm (Davis et al. 1999b) and subsequently with the red system at λ700 nm. The results showing the improvement in the accuracy of the angular diameter determination are illustrated in Figure 5.

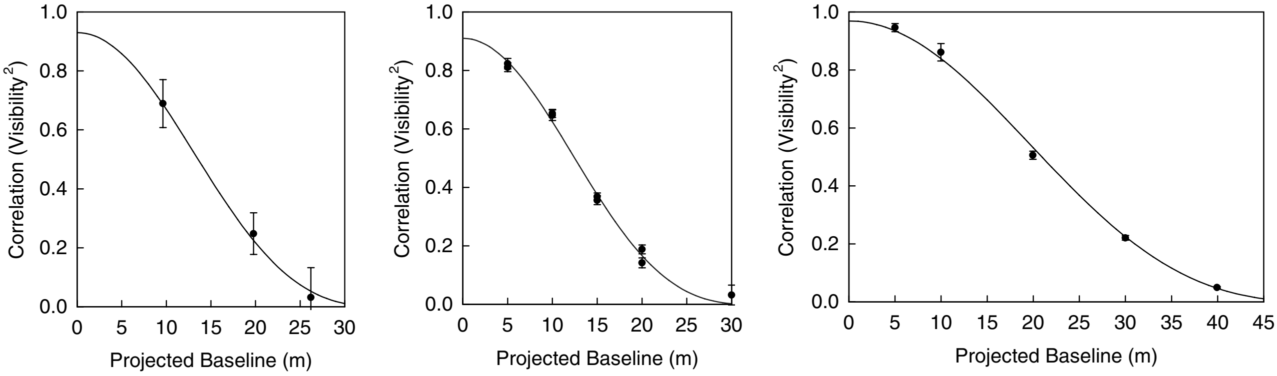
Combination of the angular diameter, corrected for limb-darkening, with the flux received from the star, following the procedure used by Code et al. (1976), gives the emergent flux at the stellar surface equal to $(1.38 \pm 0.07) \times 10^{15}$ W m^{-2} and the effective temperature equal to 6100 ± 80 K. The effective temperature is in excellent agreement with the value of 6110 ± 430 K determined by Code et al. (1976) but with significantly improved accuracy. The accuracy is now limited by the uncertainty in the integrated flux (±4.5%) rather than by that in the angular diameter.

As shown in Figure 5 for δ CMa the angular diameter of the equivalent uniformly illuminated disk, rather than that of the true limb-darkened disk, is generally determined from correlation (equal to visibility squared) measurements. The reason is that the differences in the shapes of the transforms for a uniform disk and for a limb-darkened disk are almost indistinguishable out to the first zero. It is therefore simpler to fit the transform for a uniformly illuminated disk

$$C_b = \left|\frac{2J_1(x)}{x}\right|^2 \qquad (3)$$

where C_b is the correlation at baseline b and $x = \pi b\theta_{\mathrm{UD}}/\lambda$, where θ_{UD} is the uniform disk angular diameter and λ is the wavelength of observation.

The true limb-darkened angular diameter θ_{LD} is then obtained by making a small correction to the uniform disk angular diameter based on the centre-to-limb intensity predictions of model stellar atmospheres. The



NSII 443 nm
3.29 ± 0.46 mas* (±14%)

SUSI 442 nm
3.505 ± 0.064 mas* (±1.8%)

SUSI 700 nm
3.471 ± 0.022 mas* (±0.6%)

Figure 5 The values of correlation (visibility squared) for the F8 supergiant δ CMa, measured with the NSII and SUSI, plotted against baseline. The curves are uniform disk fits to the observational data and the corresponding angular diameters, marked by an asterisk, are given below the plots together with their percentage uncertainties.

correction factors for the extensive grid of model stellar atmospheres of Kurucz (1993a, 1993b) have been computed by Davis, Tango, & Booth (2000). The grid covers effective temperatures from 3500 K to 50000 K, surface gravities (log g) from 0.5 to 5.0, metallicities ([Fe/H]) from –5 to +1, and wavelengths from 401 nm to 20 μm. The correction factor ρ_λ is defined by

$$\rho_\lambda = \frac{\theta_{\mathrm{LD}}}{\theta_{\mathrm{UD}}} \qquad (4)$$

and ranges from ~1.004 to ~1.14 with an uncertainty dependent on the realism of the models but estimated to be significantly less than 1% for stars with compact atmospheres (that is, atmospheres whose thickness is very small compared to their radius).

The effects of observations with broad spectral bands on the correction factors have been discussed by Tango & Davis (2002).

4.2 A Double-Lined Spectroscopic Binary

In Section 2.2 it was noted that a by-product of the NSII observing programme was the discovery that several stars, previously thought to be single, were in fact double. β Cen was one of these stars. It was the first star to be observed with the NSII, chosen because it is a very bright hot star, and ostensibly an ideal target to use for commissioning the instrument. It had a known companion but this was too faint to significantly affect the expected correlation. However, β Cen gave only half the correlation expected. After a thorough check of the instrument and the theory on which it was based failed to reveal any problem, the instrument was turned to Vega (α Lyr). Vega gave the expected correlation and it was realised that the primary component of β Cen was itself a binary system with components of nearly equal brightness. Nothing further could be determined with the NSII.

The primary of β Cen has subsequently been found to be a double-lined spectroscopic binary and a suitable target for SUSI. Observations of β Cen with SUSI from 1997–2002 have enabled the 357-day interferometric orbit to be determined (see Figure 6) and, in combination with spectroscopic orbital data by Ausseloos et al. (2002), a detailed study has been completed (Davis et al. 2005). The principal parameters determined in this study are listed in Table 2. The mass determinations are the first accurate mass estimates of any β Cep star in a binary system to date and the results constitute a very suitable starting point for asteroseismic modelling of the two pulsating components of β Cen. The Hipparcos value of 161 ± 15 pc for the distance does not agree with the interferometric–spectroscopic value of 102.3 ± 1.7 pc in Table 2 but this is believed to be due to the fact that the binary nature of β Cen was not taken into account in the analysis of the Hipparcos observational data.

A major difference between the NSII and SUSI in the study of binary systems is that SUSI's small apertures enable the determination of orbits not accessible to the NSII because its large reflectors completely resolved the orbital separation of the components as was the case for β Cen.

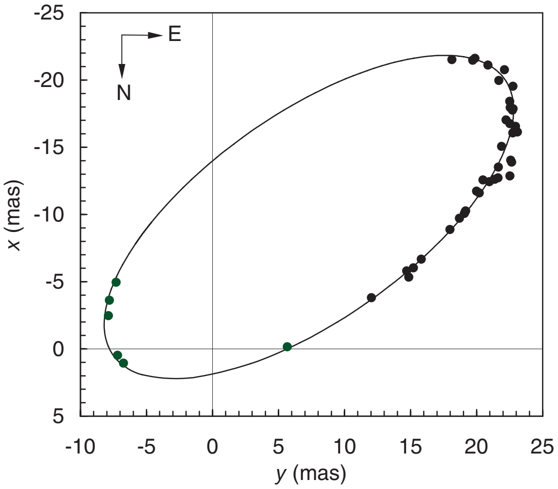


Figure 6 The orbit of β Cen determined with SUSI.

Table 2. Major parameters determined for the double-lined spectroscopic binary β Cen

Parameter	Value
Mass of primary, M_1	9.09 ± 0.31 $M_\odot$
Mass of secondary, M_2	9.09 ± 0.30 $M_\odot$
Distance, d	102.3 ± 1.7 pc

In addition to β Cen, other stars discovered to be binary with the NSII, including λ Sco, κ Sco, and σ Sco, are being observed with SUSI for combination with spectroscopy carried out by Aerts and her colleagues (see for example Uytterhoeven et al. 2004; Harmanec, Uytterhoeven, & Aerts 2004). δ Sco, σ Sgr, γ^2 Vel, and ζ Cen are among other binary systems being observed for orbital determinations.

4.3 A Cepheid

The NSII lacked the sensitivity to measure the angular pulsation of a Cepheid but it was one of the key programmes planned for its successor. Unfortunately, as discussed in Section 4, the initial limiting magnitude of SUSI with its blue beam combination system was not significantly greater than that of the NSII and it was also inadequate for a Cepheid measurement. The increased sensitivity of the red beam combination system has made it possible to commence a programme of Cepheid observations with the aim of determining the distances to the stars by essentially a geometric method. This is achieved by combining the interferometrically determined change in angular size with the spectroscopically determined radial displacement of the stellar surface. Preliminary results for ℓ Car and β Dor were presented at

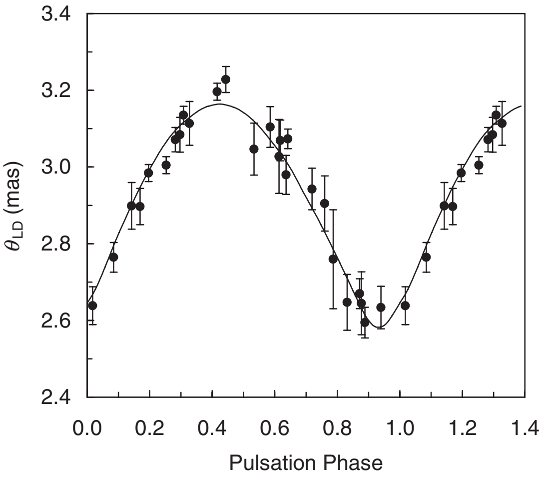


Figure 7 The variation in angular diameter of the Cepheid ℓ Car as a function of pulsation phase determined with SUSI.

Table 3. Preliminary results for the Cepheid ℓ Car

Data Source	Mean θ_{UD} [mas]	Distance [pc]
SUSI	2.873 ± 0.009	525 ± 24
Hipparcos	—	460 ± 100

an ESO Workshop (Davis et al. 2006) and observational data have also been obtained for η Aql. Figure 7 shows the preliminary results for ℓ Car with a curve representing the fit of radial displacements of the stellar surface (Taylor 1999) with the angular diameter measurements to determine the mean angular diameter and distance of the star. The preliminary results are given in Table 3.

5 Long-Baseline Optical/IR Interferometers

Table 4 lists long-baseline optical/IR interferometers and interferometric arrays from the NSII to the present. Interferometers still under construction or development, such as the Large Binocular Telescope and the Magdalena Ridge Array, have not been included in the table. All the listed instruments are amplitude interferometers except for the ISI and its prototype which employ the heterodyne technique. Not all of the apertures listed in Table 4, or the baseline and wavelength ranges, are fully operational for the working instruments.

6 Current Science with Long-Baseline Optical/IR Interferometers

A very few years ago interferometry meetings were highly technical and generally had very few papers with observational results. There were many papers promising what could be done although a few were unrealistic. However, interferometry is now delivering on its promise, is engaged in a wide range of programmes and is throwing up challenges for theoretical astrophysicists. This progress was illustrated at an ESO workshop held in 2005 April, entitled 'The Power of Optical/IR Interferometry'. Topics covered and illustrated with observational results included:

- Accurate angular diameter determinations.
- Double-lined spectroscopic binaries for accurate masses and testing of evolutionary models — including pre-main sequence stars.
- The mean diameters and distances of Cepheid variables.
- The shapes of rapidly rotating stars.
- Limb-darkening studies.
- Circumstellar environs — dust, disks, and winds.
- Multi-wavelength observations of hot massive stars (Eta Car, Be stars, . . .) with closure phase and differential phase for modelling envelopes.
- 10 μm observations of a compact emission region at the Galactic centre.
- Observations and simple modelling of dusty tori in active Galactic nuclei, revealing a hot embedded dust component.

The reader is referred to the proceedings of the workshop (Paresce & Richichi 2006) for details but it is noted that SUSI is contributing to the first five topics in the list.

7 Summary

The Australian contributions to the field of high angular resolution optical stellar interferometry are outstanding. The pioneering work of the NSII re-opened the field after it had lain dormant for some forty years and emphatically demonstrated the potential of high resolution optical interferometry for studies in stellar astrophysics. The development of SUSI continued the Australian leadership in the field and the examples given illustrate the advances in accuracy and capability that have been made since the NSII completed its observational programme in the 1970s. SUSI graduates are in high demand around the world and are represented in the groups at COAST, CHARA, PTI, and Keck as well as at universities, observatories and institutions in the USA, Europe, and at home here in Australia. Many ideas initiated and implemented in SUSI have been adopted by other interferometry groups and the field has rapidly expanded in recent years with several well-resourced groups and international collaborative projects. Scientific applications that were speculative a decade ago are now feasible.

Looking at the development of amplitude interferometry over the past two decades it has obviously taken very much longer to overcome the problems of developing an amplitude interferometer than anyone, including myself, anticipated. The proposed second-generation intensity interferometer would have had some 20 years of operation before being seriously challenged by an amplitude interferometer. However, amplitude interferometry is now achieving its promise

Table 4. Interferometers and interferometric arrays

Acronym	Name	Location	Reference	Number of apertures	Aperture diameter [m]	Maximum baseline [m]	Wavelength range [μm]	Status
NSII	Narrabri Stellar Intensity Interferometer	Narrabri, Australia	Hanbury Brown et al. (1974)	2	6.8	188	0.44	closed
ISI (P type)	Infrared Spatial Interferometer Prototype	Kitt Peak, USA	Sutton et al. (1977)	2	0.81	5.5	11	closed
SUSI (P type)	Sydney University Stellar Interferometer Prototype	Sydney, Australia	Davis & Tango (1985)	2	0.1	12.4	0.4–0.5	closed
Mark III	Mark III Stellar Interferometer	Mt. Wilson, USA	Shao et al. (1988)	2	0.05	32	0.45–0.8	closed
I2T	Interféromètre à 2 Télescopes	Calern, France	Koechlin (1988)	2	0.26	144	Visible	closed
IRMA	Prototype Infrared Michelson Stellar Interferometer	Wyoming, USA	Dyck et al. (1993)	2	0.20	19.5	2.2	closed
GI2T	Grand Interféromètre à 2 Télescopes	Calern, France	Mourard et al. (1994)	2	1.5	65	Visible/IR	closed
COAST	Cambridge Optical Aperture Synthesis Telescope	Cambridge, UK	Baldwin et al. (1994)	5	0.4	100	Red/near IR	working
SUSI	Sydney University Stellar Interferometer	Narrabri, Australia	Davis et al. (1999a)	2	0.14	640	0.43–0.95	working
IOTA	Infrared–Optical Telescope Array	Mt. Hopkins, USA	Carleton et al. (1994)	3	0.45	38	Visible/IR	working
ISI	Infrared Spatial Interferometer	Mt. Wilson, USA	Bester et al. (1990)	2	1.65	70	10	working
NPOI	Navy Prototype Optical Interferometer	Flagstaff, USA	Armstrong et al. (1998)	6 (4)	0.12 (0.35)	437 (38)	0.45–0.85	working
PTI	Palomar Testbed Interferometer	Mt. Palomar, USA	Lane et al. (2000)	2	0.4	110	2.2	working
CHARA	Center for High Angular Resolution Array	Mt. Wilson, USA	McAlister et al. (2000)	6	1.0	331	0.45–2.4	working
Keck1	Keck Interferometer	Mauna Kea, USA	Colavita & Wizinowich (2000)	2 (4)	10 (1.5)	80 (165)	2.2–10	working
VLTI	European Southern Observatory Very Large Telescope Interferometer	Cerro Paranal, Chile	Glindemann et al. (2000)	4 (3)	8 (1.8)	130 (200)	1.0–10	working

and, in the long run, it is the right choice for many reasons including the fact that, by using phase-closure techniques, imaging is possible.

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Personal Remarks

My personal story and how I became involved in optical long-baseline stellar interferometry really starts in England at the Jodrell Bank Experimental Station of the University of Manchester. I earned my Ph.D. there with a combined optical/radar study of meteors and upper atmospheric physics. This was followed by a Turner & Newall Research Fellowship that enabled me to develop instrumentation to carry out early photoelectric studies of meteors. It was while I was at Jodrell Bank that the late Professor Hanbury Brown had the idea of intensity interferometry, first for radio astronomy but, when it was realised that the technique was insensitive to scintillation, Hanbury Brown and Richard Twiss developed its application to the optical regime.

After the successful measurement of Sirius, plans were being developed for what became the NSII and, at this point, Hanbury Brown invited me to join the new project. My fellowship was nearing completion and, as I have said on many occasions, no young post-doc in his right mind would have said anything other than ‘yes please’! The result was that I came to Australia in 1961 to a tenured Lectureship in Physics at the University of Sydney and have remained there for the rest of my career.

My role in the NSII programme, apart from sharing the observing, was to plan the observing schedules and to maintain and improve the optical aspects of the instrument. At the completion of the observing programme I carried out a global analysis of the entire dataset resulting in the angular diameters of 32 stars (Hanbury Brown, Davis, & Allen 1974a). During the course of the observing programme I anticipated the need for spectrophotometry and monochromatic photometry of the programme stars. The former I carried out with a student (R. W. Webb) using the 50-inch telescope at Mount Stromlo (Davis & Webb 1974) and I am indebted to Mike Bessell for his advice and help with operation of the spectrophotometer. The monochromatic photometry I did with the 16-inch telescope at Siding Spring Observatory. On the strength of these telescope observations and the NSII angular diameters I persuaded Art Code and Bob Bless of the University of Wisconsin to collaborate in establishing effective temperatures for the 32 stars. Their contribution was the UV fluxes measured with their OAO-2 satellite. I spent a month in Wisconsin assembling the absolute flux distributions from the UV, visual, and IR data and combining them with the NSII angular diameters. I subsequently wrote some 70% of the resulting paper (Code et al. 1976) which has received 628 citations to date. It is one of the regrets of my career that, in spite of having done the bulk of the work and writing for the paper, which was published in the *Astrophysical Journal*, I had to agree to Wisconsin having first authorship since we were not allowed to pay the page charges.

At the completion of the stellar observational programme with the NSII we modified the detection system and collaborated with scientists from the Center for Astrophysics in Cambridge, Massachusetts, in experiments to detect high-energy gamma rays via Cerenkov light produced in the atmosphere. We detected gamma rays from Cen A (Grindlay et al. 1975) and, on one night, I detected what appeared to be a clear and unambiguous signal from the Crab Nebula. Unfortunately, the signal could not be detected on subsequent nights and it had to be regarded as a highly unlikely but spurious event. Some years later it was discovered by others that the Crab Nebula is a variable source of gamma rays and I am convinced that I was the first to detect gamma rays from the nebula but I will never know for certain!

In 1970, when Hanbury Brown was considering building a 2-m conventional telescope when the NSII programme was completed, I accompanied him on a world tour of telescope manufacturers. During the trip I suggested that rather than building a modest sized telescope to demonstrate the possibilities with the new detectors, work that would be quickly overtaken by astronomers with larger telescopes, we should exploit the potential we had demonstrated for optical stellar interferometry by building a more sensitive interferometer. On our return to Sydney we carried out a detailed study of the astronomical potential of high angular resolution stellar interferometry, including its application to the study of a range of objects including binary stars, Cepheids, rotating stars, emission line regions around hot stars, as well as accurate angular diameters for all spectral types and luminosity classes. Based on this study we prepared a preliminary design for a large intensity interferometer and submitted a proposal to the Australian Federal Government in 1971. In 1974 the Government announced an initial grant of $75000 ‘to make a design study of a large interferometer’.

Hanbury Brown’s first step following the award of the initial grant was to undertake a fact-finding tour of potential suppliers of critical components for the new interferometer in the USA. I accompanied him on this trip but I was concerned that we would not be able to achieve the sensitivity we needed to carry out the programmes we had planned. During the period the Government was considering our proposal several important developments occurred including the demonstration of speckle interferometry and advances in adaptive optics. Our understanding of the effects of atmospheric turbulence had also improved. My concern was that an amplitude interferometer had the potential of significantly greater sensitivity and I continued on to the UK and Europe to gather information on the prospects for the development of an amplitude interferometer and, in particular, I visited Richard Twiss to see the prototype amplitude interferometer he was developing at Monte Porzio near Rome (in 1967 I had spent a three-month sabbatical working with Richard on this project at the National Physical Laboratory in England). On my return to Sydney, Hanbury Brown and I carried out a detailed comparison of the relative merits of intensity and amplitude interferometers and it became clear that an amplitude interferometer appeared more attractive — it would be cheaper to build and, at least on paper, it would be more sensitive. The outcome was a decision to build a prototype amplitude interferometer and Hanbury Brown persuaded the Government to allow us to use the design study grant to explore the potential of amplitude interferometry. Hanbury Brown was approaching retirement and, while retaining a close interest in the project and giving it his wholehearted support, he chose to pass responsibility for the project to me. At this point William (Bill) Tango, who had worked with Twiss in Italy, was recruited and he and I have worked closely ever since on all aspects of the prototype and SUSI programmes.

The remainder of my career has been devoted to directing the development, commissioning and operation of the SUSI programme and I will close with a few comments about the experience. The design and development of the SUSI Prototype Amplitude Interferometer and SUSI itself have already been described along with some examples illustrating the performance of SUSI. When I wrote the proposal seeking funding for the construction of SUSI in 1985 I thought long and hard about the problems that would be faced as it was already clear that the Universities would be facing cuts in staff. I could see that the project was unlikely to be staffed at the optimum level required for efficient development and operation. However, I decided that it was an excellent project and worth pursuing but little did I realise just how difficult it would become. The entire programme has been carried out by a very small team given the size of the project. At no time during construction and early commissioning were there more than four academic staff, two electronic technical staff, and two mechanical technical staff involved. Essentially all the electronics, servo systems, and mechanical components were designed and manufactured 'in-house'. The only system contracted out was the optical delay line metrology system involving stabilised lasers. All the control, data acquisition and data processing software was written by group members. For a large fraction of the operational phase, as a result of staff reductions and increasing teaching loads, the number of staff available for the observing programme at any given time varied between one and zero — assisted by postgraduate students and for only some of the time by a post-doctoral fellow or research assistant.

Although the Australian Research Council has been generous in their support in the form of operating costs it has been a personal disappointment that it has generally been unwilling to meet requests for the postdoctoral fellowships and technical support needed to capitalise on the investment made in the construction of SUSI — which was completed within budget. The scientific productivity has suffered as a result but I am nevertheless proud of the fact that the SUSI programme has to date produced some 71 publications (30 refereed, 22 invited conference papers, and 19 contributed conference papers) plus 10 completed PhDs and 6 completed MScs.