Current Status of COAST

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ABSTRACT

This paper reviews the current performance of the Cambridge Optical Aperture Synthesis Telescope as an imaging array. Tests of the hardware and methods of measuring fringe visibility and closure phase are described in the context of prospects for a Large Optical Array.

Keywords: COAST, optical interferometry, imaging

1. BACKGROUND

The Cambridge Optical Aperture Synthesis Telescope (COAST) has been designed as an optical/near-infrared imaging array of four telescopes on interferometric baselines up to 100 m. There were three principal aims:

1. to show that imaging using arrays at these wavelengths can be achieved;
2. to explore what kinds of astronomical programmes are practical;
3. to act as a precursor to a much larger array.

The first aim was realised in 1995 with the first images of Capella.[1] The second has led to images of the resolved stellar disk of Betelgeuse and discussion of its limb darkening,[2] the first direct measurement of the variation through its cycle of pulsation of the angular size of a Mira variable, R Leonis,[3] and further programmes still in progress. This paper addresses the third aim by giving a critical assessment of the performance of COAST. It provides the essential basis for the design of a large array, which would give access to images of many types of object and be used by a wide community of astronomers.

2. COAST HARDWARE

Table 1 summarises the components of COAST which are currently in operation and those extensions expected to be implemented during the next few months. A recent view of the array is shown in figure 1. The layout is a Y with one telescope on each arm, moveable to a number of fixed stations, and one telescope at the centre of the Y. When the fifth telescope is installed, it will be used as an alternative to the telescope on the same arm of the Y, with provision for rapid changes between these two telescopes. This arrangement gives a total of 9 baselines which can be used sequentially, with a maximum of 4 telescopes being combined to give 6 baselines at any one time.

The output beams from the telescopes pass through white–painted aluminium pipes, containing air at ambient pressure, into the beam– combining laboratory. The choice of a large beam compression factor ($\times 16$) at the telescopes results in output beams only 25 mm in diameter. This makes the effects of atmospheric fluctuations in the beam pipes and the optical laboratory insignificant, as discussed in section 3. There are two adverse effects of this choice.

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Table 1. COAST hardware.

	Current	Near future
Telescopes (40 cm siderostats)	4	5
Baselines	5–20 m	30 (up to >100 m)
Finder		
Acquisition		
Guider	4 telescopes, tip-tilt correction, 4 ms update	
Delay lines	4 (max delay 37 m)	48 m
4–way beam combiner	Visible 650–1000 nm IR 1.3–2.2μm	
Detectors	4 APD's NICMOS III CCD spectrometer	

Figure 1. The Cambridge Optical Aperture Synthesis Telescope.

Firstly, the maximum useable baseline is limited to about 200 m due to diffraction of the beams. This is unimportant since the maximum baseline is limited by the length of the delay lines. Secondly, the field of view of the telescopes as seen at the detector is small (3 arcsec at 100 m baseline). This second problem is overcome by the use of a video camera, fed by an insertable beam-splitter, just behind the telescope primary mirror.[4] This finder has a limiting magnitude of about +10 and enables the star to be centred in the field of view of the CCD which is used for both acquisition and fast guiding on all four telescopes as described earlier.[5] The fast guider provides tip–tilt corrections to piezo–controlled mirrors at the telescopes with a fastest update time of 4 ms. The limiting magnitude of the guider is approximately +8.5, for which integration times of 15 ms are necessary.

Each of the four telescope beams is provided with a variable delay line, the maximum delay being currently 37 m. We expect to increase that soon to 48 m, which is the limit set by the size of the building.

The 4–way beam combiner for visible wavelengths (650–1000 nm) is as described previously. A separate beam combiner of similar design has been constructed for the near–infrared (1.3–2.2 μm) and is described by John Young in a separate paper.[6] The detectors now in use with COAST comprise the original avalanche photodiodes together with a NICMOS III camera for the near-infrared[6] and a CCD used in a spectrally–dispersed mode.[7]

3. HARDWARE PERFORMANCE

The criterion against which the performance of the COAST hardware has to be judged is the same as that for any instrument. It should provide no degradation of the measurement of a physical quantity beyond the unavoidable limits set by the nature of the system under study. We now have good measures of most of the important aspects of COAST. They are also useful in assessing whether the technology currently in use can be employed safely in the construction of a much larger array. We deal in turn with the baseline stability, delay line performance and overall optical behaviour.

The interferometer baselines appear to be quite stable even though the telescope foundations are only 4 m deep in clay and far from any bedrock. The baseline solution remained the same to about 100 μm over a year and better than 50 μm over periods of weeks. These values are easily good enough for an imaging array.

The delay line trolleys use roof mirrors rather than cats-eye reflectors and hence there is a strong requirement on the straightness of the rails so that angular deviations in azimuth are not translated into significant pupil shifts. The measured deviations of the rails are 2.5 arcsec rms (except at rail joints) which correspond to pupil shifts of $<$1 mm for all baselines up to 100 m. The jitter in the trolley position along the rail relative to that demanded depends on the speed of tracking on the rails. It increases smoothly from 6 nm rms when the trolley is almost stationary to 20 nm rms (about $\lambda/40$) at speeds corresponding to the maximum which would be needed for a 400 m baseline. This implies that the trolley performance is certainly not a limiting factor in COAST and that the present design would be suitable for a larger array with little modification.

The optical train and the long air paths to the telescopes introduce distortions in the optical wavefronts which need to be small if the fringe visibilities are not to be reduced significantly. Measurements of these effects are carried out using a source consisting of a small pinhole illuminated by a filament lamp. The precision is improved by the fact that all the light paths are traversed twice, using the instrument in auto–collimation. The observations show fringe visibilities which are independent of the pupil size up to 14 mm (corresponding to 224 mm at the telescope pupil) and lie in the range 0.90 to 0.95 for a single pass through the optical train. This reduction in visibility is very small compared with that due to the atmosphere above the telescope, since the array is operated with pupils of 2-3 r_0 at visible wavelengths.

A separate effect of the atmosphere within the instrument is to introduce variations in the differential optical paths between any two beams. Extensive measurements of this within the optics building show variations of 0.18 μm rms over timescales of 100 s, with most of the variation occurring on timescales $>$10 s. Similar measurements including paths out to the telescopes, which are typically 20 m at present, gave 0.45 μm rms on the same timescales. These values may be compared with those expected for the atmosphere above the telescopes of 10 μm rms at a 10 m baseline for 1 arcsec seeing conditions. Such good seeing is rarely experienced at our site. The overall conclusion is that atmospheric fluctuations affecting either wavefront shape or optical path are entirely negligible within COAST. It is noteworthy that the values obtained inside the building refer to the standard observing conditions in which there is no additional screening round the optics or delay line and the observer are sitting (quietly!) at terminals in the same building.

A last but important instrumental parameter is the overall optical throughput of the system. At present it is about 6 per cent detected photons at 830 nm. It is the least satisfactory aspect of COAST's performance and arises largely because of the use of aluminium coatings for the mirrors. Attempts to use several different types of protective overcoating on silver have proved unsuccessful in our climate. With dehumidifiers running in the optics building at all times, except when observing, the relative humidity sometimes falls as low as 40 per cent! For the future we may decide to sacrifice the short wavelength performance and use gold coatings. With this exception the performance of COAST approaches that of an ideal instrument though not yet in its convenience in use.

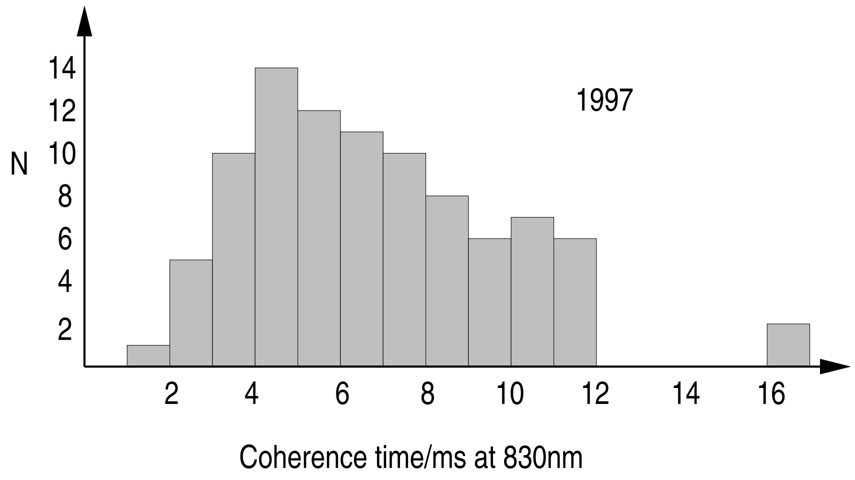

Figure 2. Histogram of coherence times at COAST in 1997.

4. STELLAR FRINGE VISIBILITY MEASUREMENTS

COAST differs from other interferometer in that it normally operates with apertures that are 2–3 r_0 in size. This is important for reaching the best sensitivity and hence will be absolutely essential to the operation of any future large ground-based imaging array. An attractive aspect of a site with only moderate seeing is that this regime can be explored without the need to build large telescopes. The 40 cm apertures of COAST are 2–3 r_0 at wavelengths as long as 1 μm. A direct consequence of this is that COAST is not a fringe–tracking interferometer. The limiting magnitude for fringe-tracking an interferometer in which small apertures ($\simeq r_0$) are used is set both by the seeing (r_0) and by the coherence time of the fringes. The former is usually given emphasis whereas there has been much less discussion of the equally important coherence times. Very little or no data is available for most observatory sites. To encourage measurement and publication of such data we present in figure 2 a histogram of coherence times observed at COAST on a 6 m baseline in 1997. Since these times are a function of wavelength and interferometer baseline, it would be desirable that observations be converted to a standard wavelength and baseline to facilitate comparison of sites. For the present argument the only conclusion to be drawn from the histogram is that the interval of time available for coherent integration to determine the phase of a fringe is very short, so the limiting sensitivity is poor.

In any case, the limiting magnitude for detection of fringes will always be fainter than that for phase–tracking of a fringe. The use of 2–3 r_0 apertures introduces the further difficulty that they give rise to large fluctuations in instantaneous visibilities in addition to the well-known reduction in average visibility for tip-tilt corrected wavefronts of this size. The importance of this effect is displayed in figure 3, which shows a histogram of the observed visibilities taken at 100 ms intervals on a bright star, for which noise fluctuations are negligible. The wide spread of values of visibility (0.35 ± 0.1) is wholly due to wavefront fluctuations.

Since the fringes cannot be tracked either because of the faintness or the star or the occurrence of periods of very low fringe visibility, it becomes necessary to modulate the path delay so that the fringes are scanned, preferably over the whole of the coherence length of the fringe packet. Typical scans on COAST consist of a linear scan with a peak-to-peak amplitude of 60 μm in a time interval of 100 ms. The amplitude is chosen to be larger than any atmospheric excursion in path delay at the baseline in use and the rate of scanning to give fringe frequencies of several hundred Hz, well above the upper limit of the scintillation spectrum in most conditions.

The scatter in visibilities shown in figure 3 suggests that, if a precision in visibility of 1 per cent is required, then 1000 scans (= 100 s) of data must be taken. This procedure is satisfactory provided that the atmospheric statistics are stationary, so that the cumulative average visibility converges to a fixed value as the overall integration time is increased. In some circumstances this works well. An example of a 50 s observation on 12/03/98, the last night on which observations were made before this meeting, illustrates this well (figure 4). The visibility after 50 s has

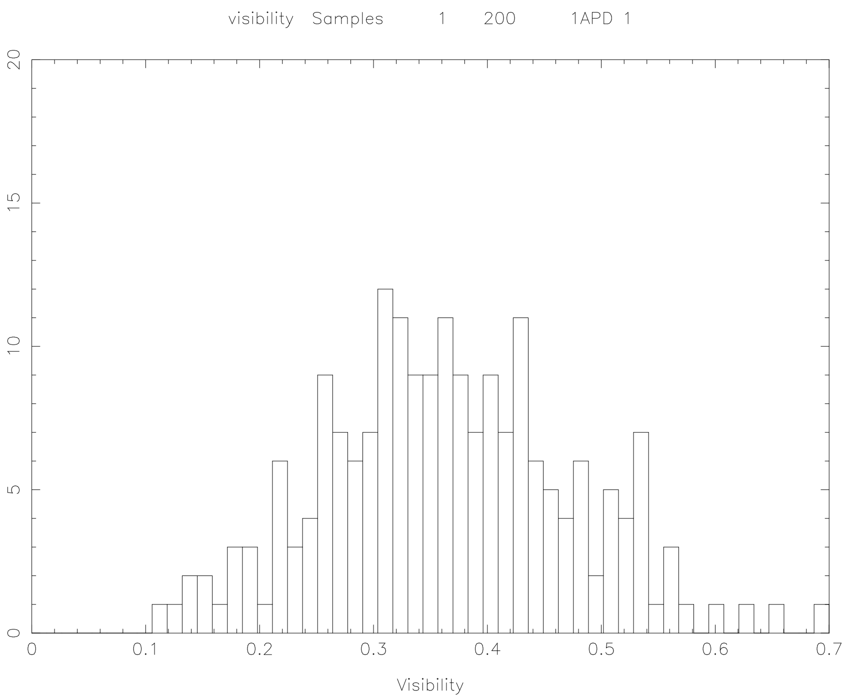

Figure 3. Histogram of visibilities from 100 ms integrations.

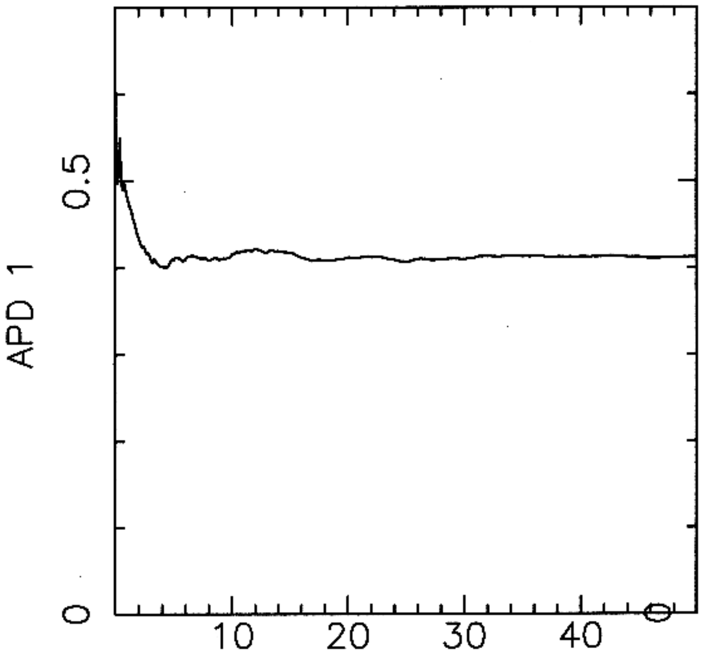

Figure 4. Cumulative average visibility during one observation.

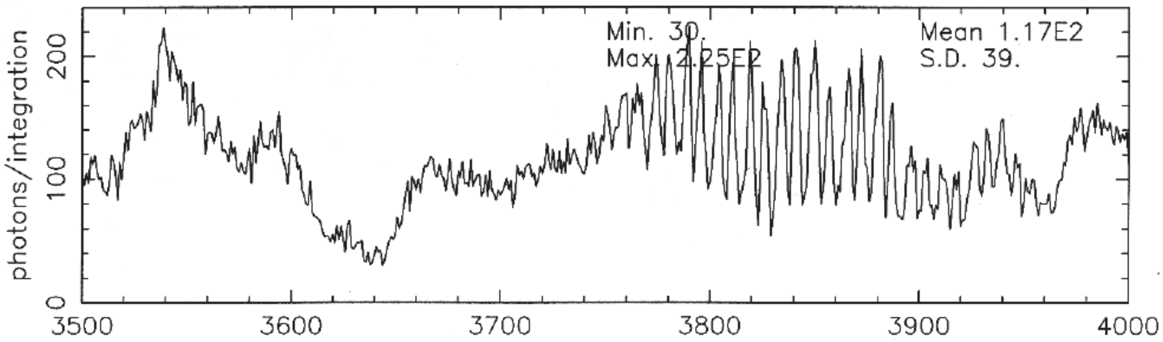

Figure 5. Photon count during one 100 ms scan.

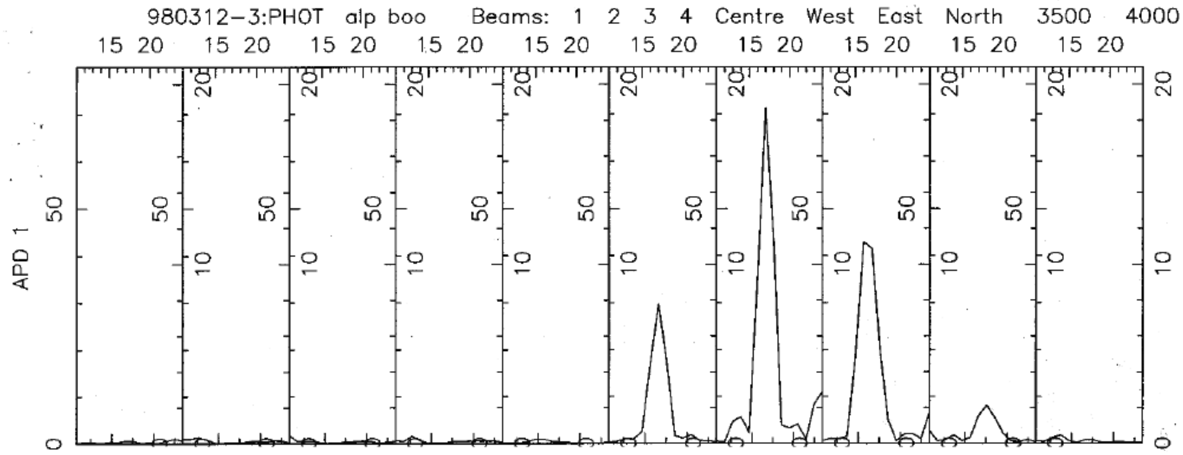

Figure 6. Power spectra of the same data in 10 ms windows corresponding to 6 microns in path.

converged to a value of 0.418. Successive runs of the same duration gave values of 0.418, 0.418, 0.413. 0.414. However, on some nights the values do not converge well. This sets a limit to the accuracy of the calibration procedure. It has led us to investigate spatial filtering of the beams as has been used elsewhere, for example in the IOTA interferometer. David St-Jacques discusses this in a separate paper.[8]

Whilst tracking of the fringe phase is not normally possible with COAST, it is still very desirable to track the position of the fringe packet and correct for its path wander on a slower timescale. It reduces the length of scan needed to ensure that the fringes are scanned, which otherwise is expected to increase with interferometer baseline, d, as $d^{5/6}$. The procedure we have adopted in COAST is to divide the data stream from a single 100 ms scan (figure 5) into ten 10 ms windows and to take the power spectrum of the data in each window. They are displayed in figure 6. The peak of the fringes and of their power spectra evidently coincide in time. The position of the peak in the power spectrum can be determined in real time and used to correct the position of the delay line trolley. In practice, the average power spectrum over one or more seconds of data is used to determine these corrections. We have only recently closed the loop in this slow servo system . Experience so far suggests that 1 s integrations can be used for stars a little fainter than magnitude +4 and correspondingly longer integration times for fainter stars. Figure 7 shows one example of the path excursions measured in a 200 s observation. As expected, the largest fluctuations occur on long timescales so that their correction does not present a difficult problem. For the fainter stars correction only on very long timescales will be possible. The faintest object which we have detected so far is the star Lalande 21185 (see figure 8). It is well known as one of the nearest stars. It is the first M dwarf to be detected interferometrically and has V = +7.6.

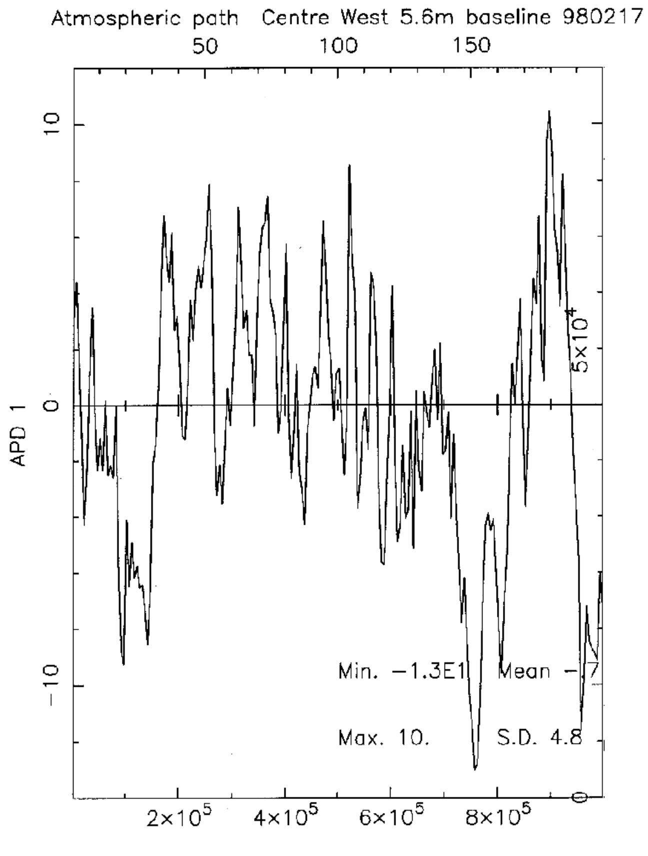

Figure 7. Fluctuations in atmospheric path (in μm) during a 200 s observation at 5.6 m baseline.

5. CLOSURE PHASE MEASUREMENTS

Closure phases of fringes on three or more baselines are measured on COAST by combining beams each of which is modulated by a scan in path delay at a different rate. The fringes associated with any baseline then have a distinctive temporal frequency. With 4 telescopes, 6 baselines can be observed simultaneously. Figure 9 is example of the power spectrum of such an observation. The maximum baseline in this observation was 10 m and the star α Tau is well resolved on two of the baselines.

More commonly we use only three baselines at any one time. The reason for this practice is that large triple product amplitudes and hence precise phases are obtained only if the path delays for all the telescope beams are well centred in the scans. Real–time corrections for this more complicated set up have not yet been implemented. The type of power spectra which would be used is very similar to that shown in figure 6 but with three separate frequencies present in each window. Figure 10 shows one such observation in which the three sets of fringes have widely differing visibilities but are individually quite well centred.

An interesting question is whether closure phases measurements require calibration. It has often been said that they do not, including by some of the present authors. It would be surprising if this were true of any physical measurement. Specific circumstances in which incorrect closure phases will be generated are those in which both of the following conditions are met:

- the shape of the pass band of the light reaching the detector is asymmetric in either amplitude or phase;
- the path delays of the three beams are not accurately matched.

These circumstances may occur potentially in any interferometer, so there is a need to be able to measure observed closure phases of a source for which the theoretical closure phase is known. An unresolved source having a closure

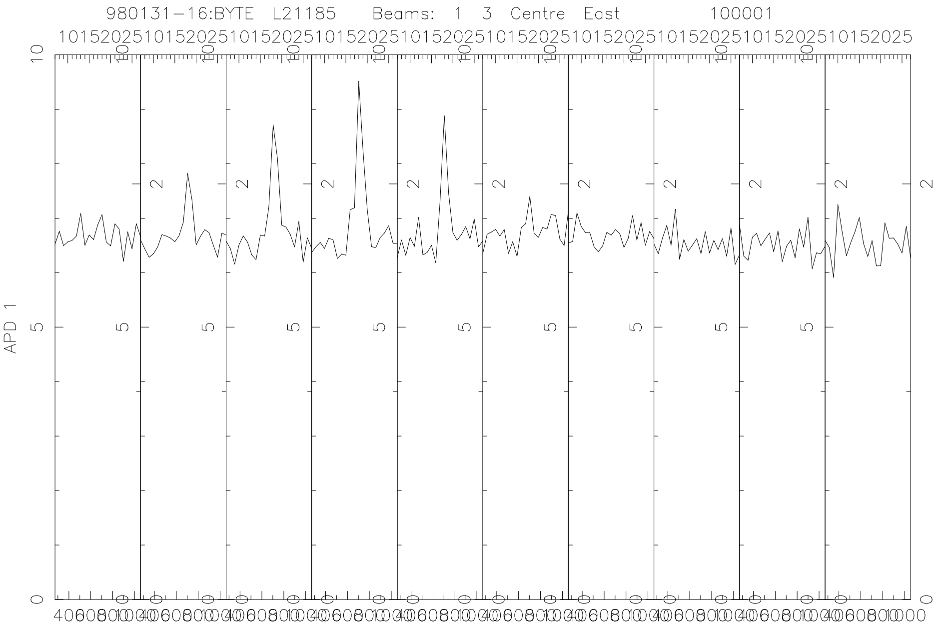

Figure 8. Power spectra of fringes from Lalande 21185, 60 s integration.

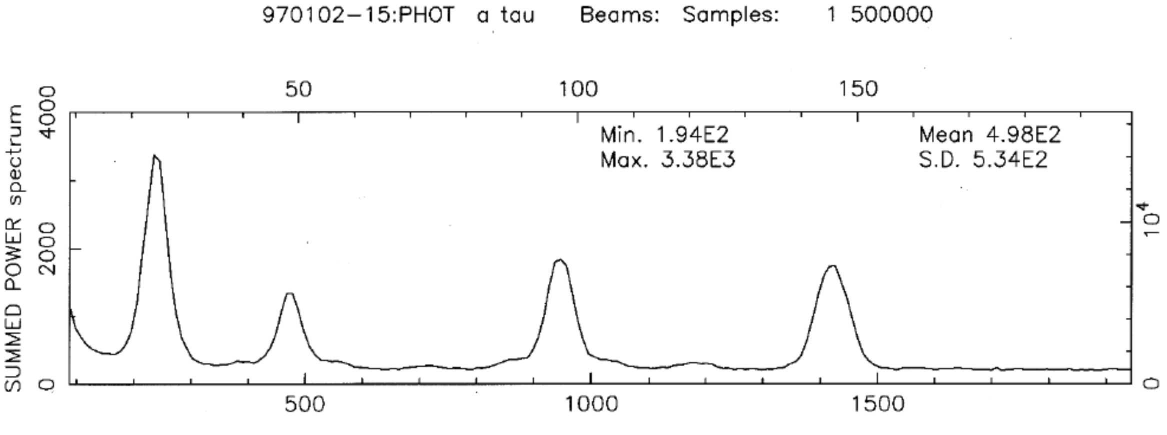

Figure 9. Power spectrum of fringes on 6 baselines on α Tau.

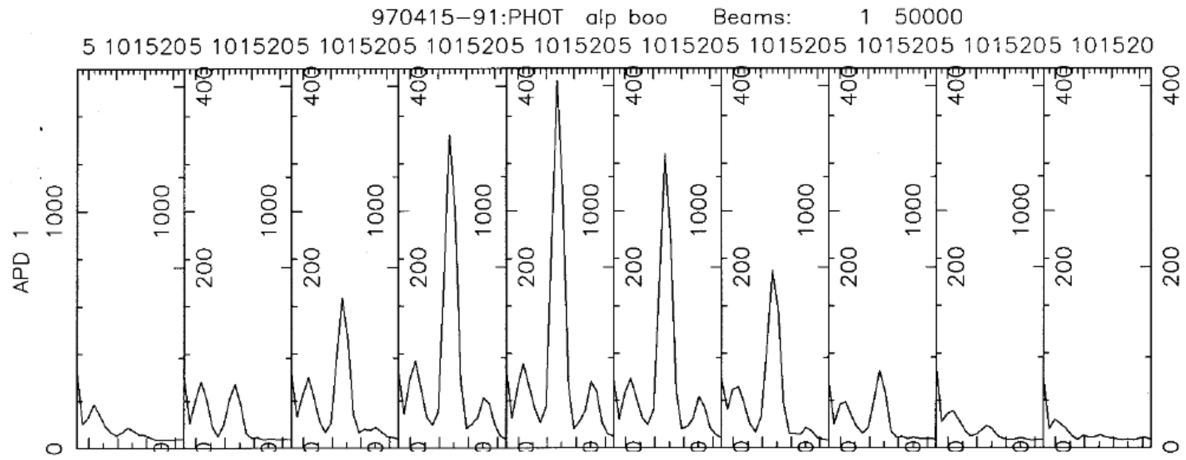

Figure 10. Spectrum of fringes on 3 baselines on α Boo in 10 ms windows, used for measuring the path delay of the centre of the fringe packet on each baseline.

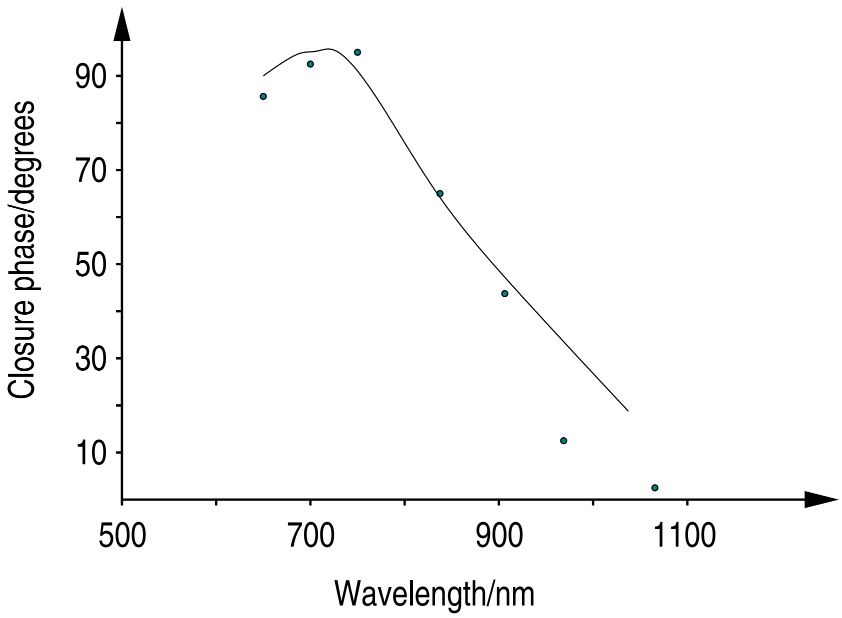

Figure 11. Closure phases measured at different wavelengths for an artificial asymmetric double star. The points are observed values and the full curve is the theoretical expectation.

phase of 0° is useful but of restricted value. We have therefore devised an artificial source comprising two narrow slits whose relative intensity and separation can be varied precisely over a range of separations up to 30 μm. When installed at one end of the optics laboratory, light from it is intercepted by mirrors mounted on the optical axis of each of the delay lines. These act as 4 fixed elements of an interferometer with separations of 300 mm between successive elements. A range of resolutions can be made conveniently by varying the wavelength of observation. First tests (figure 11) show that the measured closure phases match the predicted curve well. However, detailed comparison at the level of $\pm 1°$ will require a more precise adjustment of the source at the sub–micron level. The source already provides an important method for examining closure phase measurements when one or more of the baselines gives very low visibility fringes.

6. THE FUTURE: THE LARGE OPTICAL ARRAY (LOA)

One main conclusion from the preceding discussion is that current observations with COAST are not limited by the instrumental performance, except for the problem of low optical throughput. However, the main limitation of COAST for imaging is the small number of telescopes in the array. With three telescopes (three baselines and one closure phase, imaging was restricted to binary stars with unresolved stellar disks; four telescopes (six baselines and four closure phases) enables low resolution studies of simple stellar disks. High resolution imaging of complex objects requires a much larger number of telescopes. On a site with good seeing, larger aperture telescopes would be useable and give a substantial improvement in sensitivity. Since most of the technology used in COAST would be equally applicable at longer baselines, we now plan to design and construct the Large Optical Array (LOA), whose principal characteristics are:

- 20×1 m–class telescopes for rapid imaging of complex targets.
- 500 m baselines to give sub–milliarcsecond resolution.
- 0.6–3.5 micron operations, with moderate–resolution spectroscopy.
- 14–magnitude limiting sensitivity between R and K.
- Automated operation for efficiency and low running costs.
- $ 12 M capital cost over 5 years for the full array.

The principal astronomical problems which it is planned to attack are those of active galactic nuclei, stellar disks and close interacting binaries. It is likely that many other important areas will be opened up as a result of observations with the current generation of interferometers.

REFERENCES

1. J. E. Baldwin, M. G. Beckett, R. C. Boysen, D. Burns, D. F. Buscher, G. C. Cox, C. A. Haniff, C. D. Mackay, N. S. Nightingale, J. Rogers, P. A. G. Scheuer, T. R. Scott, P. G. Tuthill, P. J. Warner, D. M. A. Wilson, and R. W. Wilson, "The first images from an optical aperture synthesis array: mapping of Capella with COAST at two epochs," *Astron. Astrophys.* **306**, pp. L13–L16, 1996.
2. D. Burns, J. E. Baldwin, R. C. Boysen, C. A. Haniff, P. R. Lawson, C. D. Mackay, J. Rogers, T. R. Scott, P. J. Warner, D. M. A. Wilson, and J. S. Young, "The surface structure and limb darkening profile of Betelgeuse," *Mon. Not. R. astr. Soc.* **290**, pp. L11–L16, 1997.
3. D. Burns, J. E. Baldwin, R. C. Boysen, C. A. Haniff, P. R. Lawson, C. D. Mackay, J. Rogers, T. R. Scott, D. St-Jacques, P. J. Warner, D. M. A. Wilson, and J. S. Young, "Large amplitude periodic variations in the angular diameter of R Leonis," *Mon. Not. R. astr. Soc.* **296**, 1998. In press.
4. P. R. Lawson, D. M. A. Wilson, and R. C. Boysen, "Retroreflector target for co-aligning a pair of counter-propagating optical beams: or how to find a star while looking down a very long pipe," *Optics and Photonics News, Engineering and Laboratory Notes* **9**(2), 1998.
5. J. E. Baldwin, R. C. Boysen, G. C. Cox, C. A. Haniff, J. Rogers, P. J. Warner, D. M. A. Wilson, and C. D. Mackay, "Design and performance of COAST," in *SPIE Conference on Amplitude and Intensity Spatial Interferometry II, Kona, HI, USA*, vol. 2200, pp. 112–117, 1994.
6. J. S. Young, J. E. Baldwin, M. G. Beckett, R. C. Boysen, D. Burns, C. A. Haniff, P. R. Lawson, C. D. Mackay, J. Rogers, T. R. Scott, D. St-Jacques, P. J. Warner, and D. M. A. Wilson, "COAST in the near–infrared: solutions for infrared interferometry." These proceedings.
7. P. R. Lawson, J. E. Baldwin, R. C. Boysen, D. Burns, C. A. Haniff, C. D. Mackay, J. Rogers, T. R. Scott, D. St-Jacques, P. J. Warner, D. M. A. Wilson, and J. S. Young, "Multi-wavelength fringe measurement with a CCD spectrometer at COAST." These proceedings.
8. D. St-Jacques, J. E. Baldwin, R. C. Boysen, C. A. Haniff, P. Lawson, J. Rogers, P. J. Warner, D. M. A. Wilson, and J. S. Young, "Spatial filtering using pinholes at COAST." These proceedings.