Astronomical Results From COAST

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ABSTRACT

In September 1995 the Cambridge Optical Aperture Synthesis Telescope (COAST) became the first optical interferometer to produce an image of a stellar source from phase-closure and visibility amplitude measurements. These observations demonstrated for the first time the feasibility of operating long-baseline optical/near-infrared interferometers for high dynamic range high-resolution imaging. Here we present these and subsequent observations made with COAST and describe the methods used to analyse such data.

Keywords: astronomy, interferometry, telescopes, optical, stars, imaging, closure phase, data analysis.

1. INTRODUCTION

The idea that interferometry at optical wavelengths can be used to provide high resolution information is not a new one: measurements of visibility amplitude have been used for over a century since Michelson's first application in 1891.[1]

However, the visibility amplitude contains only a part of the information in interference fringes, the rest being contained in their phase. Unfortunately, the *astronomical* phase of optical interference fringes is too badly perturbed by the atmosphere to be measured. It is this inability to measure the astronomical phase of interference fringes that prevented, until recently, the further development of imaging optical interferometry. Without phase information inferences about source structure are only possible within symmetric or other very simple models.

A solution to a similar phase problem in the, then emergent, field of radio astronomy was put forward by Jennison[2] in 1958. Jennison suggested that if the astronomical phase on an interferometer baseline d_{ij} between the i^{th} and j^{th} elements was ϕ_{ij} , and if there were phase errors θ_i and θ_j associated with the elements, due for example to atmospheric perturbations, then although the observed phase ϕ_{ij}^{obs} would be:

$$\phi_{ij}^{obs} = \phi_{ij} + \theta_i - \theta_j \tag{1}$$

the sum of the observed phases ψ_{ijk}^{obs} around a loop of three baselines d_{ij}, d_{jk} and d_{ki} would be:

$$\begin{aligned} \psi_{ijk}^{obs} &= \phi_{ij}^{obs} + \phi_{jk}^{obs} + \phi_{ki}^{obs} \\ &= (\phi_{ij} + \theta_i - \theta_j) + (\phi_{jk} + \theta_j - \theta_k) + (\phi_{ki} + \theta_k - \theta_i) \\ &= \phi_{ij} + \phi_{jk} + \phi_{ki} \end{aligned} \tag{2}$$

This quantity is independent of the atmospheric perturbations and is known as the *closure phase*. Today the closure phase is used routinely as a constraint in the production of very high quality radio maps.[3]

Despite a revival of interest in optical interferometry pioneered largely by Labeyrie[4] (1975), little attention was paid to the phase problem in optical interferometry until Baldwin *et al*[5] (1986) succeeded in measuring the closure phase of a number of stellar sources using a non-redundant aperture mask in a the pupil plane of a large telescope. These measurements demonstrated for the first time the practicability of optical aperture synthesis, even if only via aperture masking.

Since 1986 there have been numerous applications of this technique, using existing 4m class telescopes, for imaging – see for example Buscher *et al*[6] (1990), Wilson *et al*[7] (1992) or Tuthill *et al*[8] (1996). However, the resolution obtained is still limited by the diameter of the mirror used, and while larger telescopes are under construction or proposed, they will offer relatively small increases in resolution. In order to avoid this problem, and thereby to increase the range of astronomical sources open to the observer, it is clear that a separated element interferometer is needed.

The Cambridge Optical Aperture Synthesis Telescope (COAST) was conceived as the simplest possible separated element array for optical closure phase imaging. When designed in 1987 it was not clear that the technical difficulties associated with co-phasing multiple elements simultaneously could be overcome. However, we have found that the problems associated with building such an array are not insurmountable, and in September 1995 the first images from COAST were produced. In this paper we present these and subsequent observations, and describe the methods used to analyse such data.

The design and current status of COAST are described by Warner *et al*[9] elsewhere in these proceedings. The lessons learned in the construction of COAST are incorporated into our ideas for future interferometer design, and are described by Lawson *et al*,[10] also in these proceedings.

2. DATA CAPTURE AND PROCESSING

At COAST, beams from each unit telescope are combined to form interference fringes, which are then measured by focusing the combined beams onto single-element photon-counting Avalanche Photodiode detectors (APDs). During an observation the optical path delay in each beam is modulated by a sawtooth wave-form in order that the fringes are scanned past the APD detectors. An example of some stellar fringes, together with their power spectrum is shown in figure 1.

The visibility amplitudes are first measured on each baseline separately by combining light from the telescopes in pairs. Short segments of the data stream corresponding to single sweeps of the fringe packet across the detector are Fourier transformed, and mean power spectra are obtained by averaging these over 100 second sequences of data.

The resulting spectra show a peak centred at the mean scan rate of the fringes, which was 715 Hz in the case of the 830nm observations described below. This peak is substantially broadened by the atmosphere and also superposed on a "white" background due to photon noise. A second peak due to the mean photon level, also broadened by atmosphere, is observed at low frequencies. In order to estimate the mean squared fringe visibility the power beneath the fringe peak, but above the background noise, is integrated. This quantity is normalised by the mean photon rate squared in order to give an uncalibrated estimate of $\langle V^2 \rangle$

This quantity is computed for both the science source and a nearby unresolved calibrator source, and the ratio of these is the adopted value of $\langle V^2 \rangle$. This method requires only that the statistical properties of atmospheric variations are approximately the same on the time-scale of the observation/calibration cycle (minutes) as they are on the time-scale of data capture from a single baseline (100 seconds). The final visibility amplitudes typically have errors in the range 2% to 10% of their value, the quality of the data being limited primarily by calibration.

Closure phase measurements are then made by combining the light from all three telescopes. This ensures that simultaneous measurements can be made of fringes on all three baselines. The optical path modulations are chosen so that the fringes from each baseline are well separated in frequency. For example, for 830nm observations fringe scan rates are typically selected to give frequencies on the three baselines of 238, 477, and 715 Hz.

In making observations there is an important characteristic (coherence) timescale. Operationally it is important for two reasons: firstly, it is useful in providing a log of seeing conditions, and secondly, it defines the longest useful integration time in

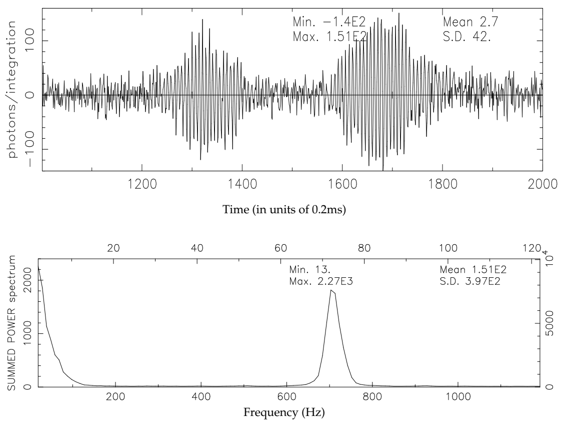

Figure 1: Interference fringes measured from Capella at 830nm on 1995 September 13th (top) together with the power spectrum obtained from 100 seconds of such data (below). The mean level has been subtracted from the fringes and two sweeps of the fringes past the APDs are shown. Notice that the signal to noise is very high in the power spectrum, indeed, it is difficult to see the "white" background due to the photon noise. The scale on the vertical axis of the power spectrum is arbitrary and the zero frequency is not plotted.

closure phase measurements. We define a coherence time, τ_c, to be the time taken for the autocorrelation of a data stream containing fringes to fall by a factor of 2. In practice τ_c is estimated from the autocorrelation of segments of data corresponding to a single sweep of the interference fringes (figure 2). τ_c is determined largely by the atmosphere, although an upper limit is imposed by the coherence length set by the passband of the filter. In the case of a periodic function and a linear phase ramp our definition corresponds to a phase lag of $60°$ and is therefore closely similar to Buscher's[11] definition of t_o where the lag is 1 radian. In order to make closure phase estimates the data stream is divided into short sequences of about τ_c and each is integrated coherently, with sine and cosine weighting functions, in order to give estimates of the complex visibility on each baseline. The triple product of these complex visibilities is formed and this procedure is repeated for each segment of length τ_c. The argument of the average of this quantity is the adopted estimate of the closure phase. Typical errors on the closure phases are $\pm 2°$. Data from unresolved sources, for which the closure phases are expected to be zero, typically give values of $0° \pm 2°$ in 100 seconds. This indicates that there is a only small degree of crosstalk between the three baselines and a low level of systematic error.

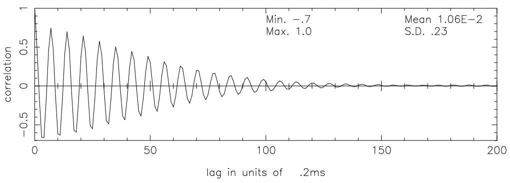

Figure 2: The autocorrelation function of some mean-subtracted and scintillation-corrected fringes from Capella on 1995 September 13th. Notice that the amplitude decreases by a factor of 2 in roughly 7.5ms.

Visibility amplitudes and closure phases are entered into a file for use with a standard VLBI mapping package[12] designed for use in radio astronomy. It is noteworthy that the mapping algorithms in this package have required no modification for our purposes, that they converge quickly, and that no assumptions about the source structure need be made.

3. THE FIRST IMAGE FROM A SEPARATED ELEMENT OPTICAL INTERFEROMETER

On 1995 September 13th observations were made of the binary star Capella (α Aurigae) at 830nm (see figure 3). Three elements of the COAST array were employed, each being stopped down to 14cm via a mask on the primary in order to match the seeing conditions. The seeing was estimated, based on corrections sent to the fast tip-tilt autoguiding system, to be 1.4 arcseconds, and τ_c was 7.5ms. Calibration of the instrument was achieved via observations of ι Aurigae which were interleaved with observations of Capella. The star ι Aurigae is known to have a diameter of 7 mas (Benson *et al*[13] 1991), and hence was only slightly resolved on our longest baseline of 6.1m. In total, 30 visibility amplitudes and 10 closure phases were measured. The corresponding uv coverage, or that portion of the synthesised aperture actually sampled, is illustrated in figure 4.

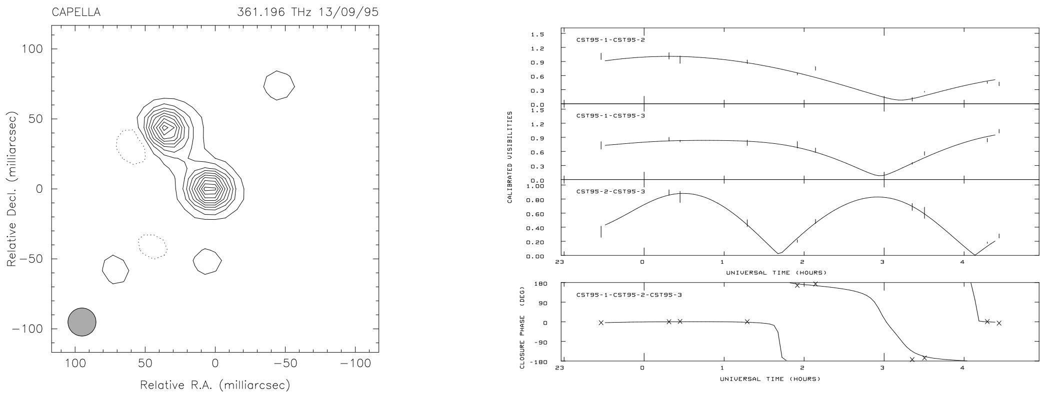

Figure 3: The map of Capella obtained with COAST on 1995 September 13th. The beam used in the reconstruction is illustrated in the bottom left corner. The contours are drawn from -5% to 95% of the peak flux with an interval of 10%. There are no noise features higher than 5% of the peak flux, as expected from the number of uv measurements made. The fit of the map to the data is also illustrated on the right of this panel, where the measured data are plotted as a function of time.

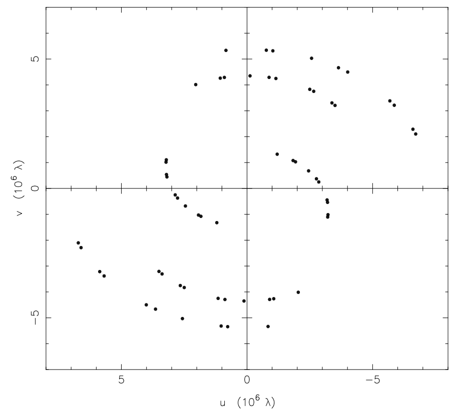

Figure 4: The uv coverage obtained on 1995 September 13th.

4. THE SECOND IMAGE

On 1995 September 28th the observations of Capella were repeated. Despite somewhat poorer atmospheric conditions (the seeing was 1.6 arcseconds, τ_c was 2.3ms) the typical errors in the data are comparable with those of September 13th, that is, $\pm 2^\circ$ in closure phase and $\simeq 5\%$ of the visibility amplitudes. In total 24 visibility amplitudes and 8 closure phases were measured, again calibrated via interleaved observations of ι Aurigae.

Figure 5 shows the map obtained from this data. On both September 13th and September 28th the measured position angles and separations of the two component stars are in excellent agreement with those predicted from the best currently available set of orbital elements (Hummel *et al*[14] 1994). Figure 6 shows the agreement between our observations and the predicted positions from these orbital elements.

A more complete account of the observations described here may be found in Baldwin *et al*[15] (1995).

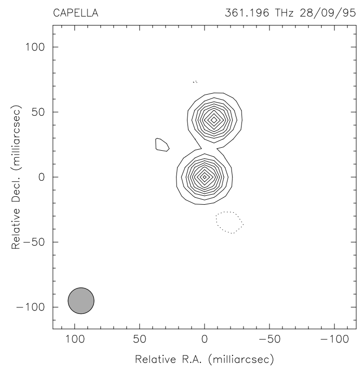

Figure 5: The map of Capella obtained with COAST on 1995 September 28th. The beam used in the reconstruction is illustrated in the bottom left corner of the map. The contours are drawn from -5% to 95% of the peak flux with an interval of 10%.

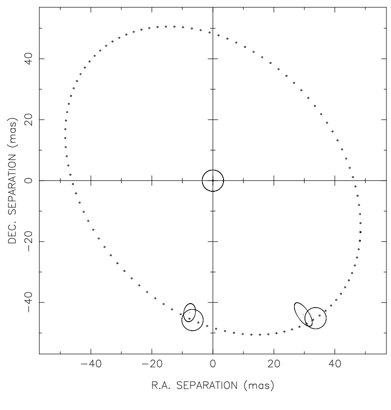

Figure 6: The agreement between the maps presented here and positions predicted from the orbital elements of Hummel *et al* for our observational epochs. The circles are centred at the predicted positions, and have a diameter equal to the average of the component stellar diameters measured by Hummel. The ellipses represent the 1σ errors in the component positions estimated from the COAST maps.

5. THE SURFACE STRUCTURE OF BETELGEUSE

Between 1995 October 20th and 1995 October 31st four-colour observations were made of the M2Ib star Betelgeuse (α Orionis) using COAST in a 3 element configuration with a maximum baseline of 9m. The map shown in figure 7 was produced using 63 visibility amplitude measurements and 21 closure phase measurements, which were made at 830nm. Due to the low declination of the source the uv coverage is somewhat poorer than in the images of Capella presented above, and the beam is therefore elongated. Whereas all previous studies of Betelgeuse (such as those by e.g. Wilson *et al* referred to above) have shown strong asymmetries or hot-spots, our closure phase data preclude the presence of any such features at the time of observation.

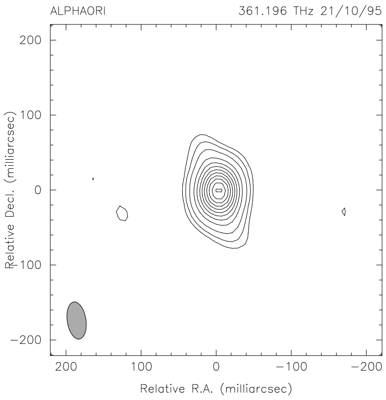

Figure 7: A map of Betelgeuse obtained during late October 1995. The contour levels are 2.5, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 & 99% of the peak flux. The apparent elongation in position angle $9°$ is due entirely to the beamshape shown in the bottom left corner of the map, arising from the uv coverage. Our closure phase data suggest that the source was in fact highly symmetric.

When plotted as a function of baseline length the visibility amplitude is first observed to fall and then, on baselines longer than 5m, to rise again. Contemporaneous measurements of the closure phase and additional measurements of the visibility amplitude show that observations have been made *beyond* the first null in the transform. This is the first time that such confirmation has been possible. Our measurements are indicative of a strongly limb-darkened disk.

A detailed account of these observations is in preparation.[16]

We are currently engaged in a programme of observations of other nearby K and M-type stars. The array is configured to give baselines up to 9m and the first results are very encouraging.

6. ACKNOWLEDGEMENTS

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