COAST - the current status

C.A. Haniff[a], J.E. Baldwin[a], R.C. Boysen[a], A.V. George[a], D.F. Buscher[a], C.D. Mackay[b], D. Pearson[a], J. Rogers[a], P.J. Warner[a], D.M.A. Wilson[a], and J.S. Young[a]

[a]Astrophysics Group, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

[b]Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

ABSTRACT

We present a summary of the status of the Cambridge Optical Aperture Synthesis Telescope (COAST). Since our last report we have concentrated on improving both the efficiency of use of the array and its astrophysical capabilities. In particular we have achieved useful improvements in throughput, detector sensitivity and the efficiency of securing measurements of visibility amplitudes and closure phases. With five telescopes fully operational, COAST is now being used routinely for parallel programs of astrophysics and as a technical test-bed for its proposed successor, the Large Optical Array - LOA.

Keywords: interferometry, closure phase, imaging, optical, infrared

1. INTRODUCTION

From the outset our philosophy with the Cambridge Optical Aperture Synthesis Telescope (COAST) was to build the simplest possible optical synthesis array that would work, in the sense of imaging astrophysical sources, and that would allow the proper definition of a more capable second generation facility array. Thus, since its "first-light" image in 1995[1] a major research theme of our group has been to develop COAST to explore the possibilities and limitations of a larger second-generation synthesis array.

In this report we summarise the developments that have occurred at COAST since our last report in 1998[2] and highlight some of the areas in which our effort has been concentrated. Given its location, at the Lord's Bridge site of our radio telescopes just outside of Cambridge, and our desire to capitalise on the array as a tool for astrophysics, we have directed considerable effort towards enhancing the observing efficiency of the telescope. This has been coupled with technical improvements to its astronomical capability so as to take maximum advantage of the relatively small number of clear and stable nights available in Cambridge.

In parallel with our observational programmes, we have now begun to use the array as a test-bed for components for its proposed successor, the Large Optical Array (LOA), and a number of these are discussed here. Further more detailed presentations of our observational and technical programmes are given in the papers by Young et al.[3] (observational results), George et al.[4] (optical detector upgrades), Pearson et al.[5] (spectroscopic performance), and Buscher et al.[6] (concepts for a second-generation facility) in these proceedings.

2. HARDWARE DEVELOPMENTS

2.1. Array configuration

One of the major improvements to COAST over the past two years has been the addition of a fifth telescope giving two telescopes on the array's "Y"-shaped Western arm. Although the path compensation and beam combination sub-systems are unchanged, and so are only capable of accepting beams from four of the five telescopes, the user can now switch between the two telescopes on the Western arm of the array in a matter of minutes during the night. This allows two different 4-telescope arrays to be used on any given night, importantly increasing the number of baselines measurable to nine and the number of closure triangles accessible from four to seven. Some examples of the improvement in the *uv* plane coverage of the array arising from the extra telescope are shown in figure 2.

Other author information:
C.A.H.(correspondence): E-mail: cah@mrao.cam.ac.uk
COAST world-wide-web pages: http://www.mrao.cam.ac.uk/telescopes/coast/

Figure 1. An overall view of COAST in early 2000. All 5 of the housings for the siderostat-fed 40cm afocal Cassegrain telescopes are visible, as is the earth covered beam combining building in the background. The maximum baseline in this configuration is 22 m. Kinematic foundations on which to locate the telescopes have now been installed for all baselines up to a maximum of 100m.

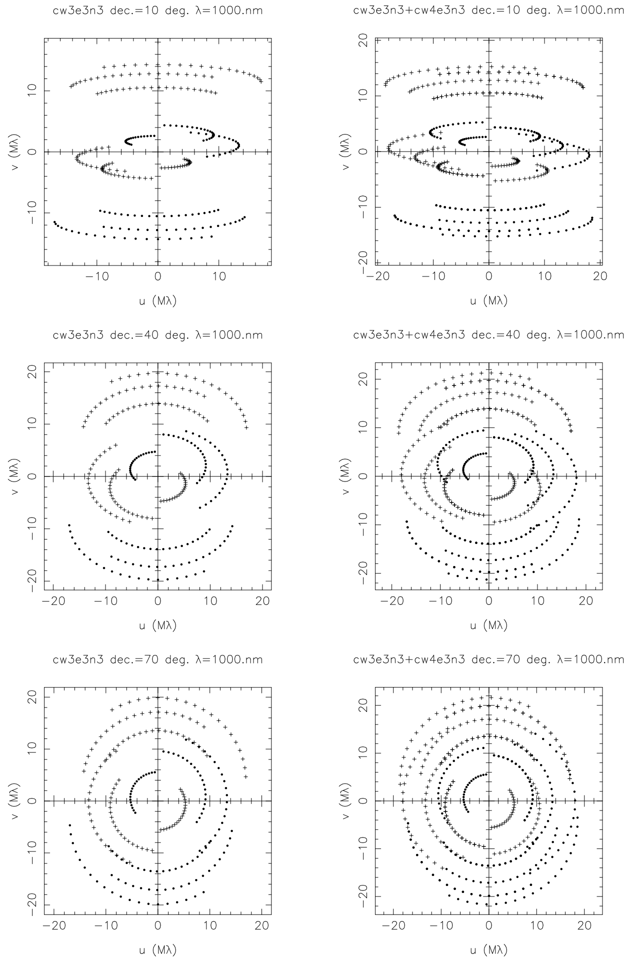

Figure 2. *uv* tracks for simulated COAST observations using either four (left panel) or five (right panel) telescopes. Tracks for source declinations of $+10°$, $+40°$, and $+70°$ are plotted from top to bottom. In each case the *uv* tracks span a range of hour angle from -4 h to $+4$ h, and the points are spaced at 25 min intervals. A wavelength of 1 micron has been assumed.

The ability to switch baselines, in particular to change to a smaller array configuration for resolved sources, with relatively little down-time has been extremely useful for a number of our astronomical programmes. Indeed, whereas in the past certain types of observations would simply have been precluded without complete re-configuration of the array, our observing capability is now much more flexible. The additional short baselines afforded by the fifth telescope most often come into play when we are operating in "blind" mode, i.e. when observations are being made on baselines that have resolved the source. In this case, by ensuring that fringes are visible on a pair of shorter baselines that make up the longer baseline we can be guaranteed to find fringes on the longest baseline. This facility, over and above the simple increase in the *uv*-plane coverage and the rate at which the source can be observed, is perhaps the most important astronomical advantage the extra fifth telescope provides.

Currently we are operating COAST with a maximum baseline of 22 m, giving a resolution of just over 8 milliarc-seconds at 900 nm. Foundations for the telescopes have been installed out to 100 m, though we expect to increase the array baselines to only 60 m over the summer months. This move to longer baselines is principally conditioned on a programme to measure the diameter variations of a number of bright Cepheid variables in an effort to refine their distances and to gain experience of operating with substantially longer air paths than we have to date.

2.2. Optical throughput

Since the limiting magnitude of any telescope, especially an interferometric array, is of particular interest to our astronomical colleagues, we have made strenuous efforts to improve this measure of performance at COAST. Over the past two years we have achieved an increase of a factor of two in the throughput of our optical train, primarily through enhancing, wherever possible, the performance of the reflective coatings used. At present the corrosive atmosphere at our site — there is a cement works located only a few kilometres away — has enforced the use of protected aluminium coatings for all of our external optics, but within the path compensation and beam combining building over-coated silver is used throughout. Recently, we have begun to test gold as a possible coating for the telescope optics since the majority of our science measurements are at wavelengths longer than 700 nm where the reflectivity of newly-deposited gold is greater than 97%. The principal concern here is one of longevity in our harsh external environment and the cost, and subsequent down-time, associated with potentially frequent re-coatings.

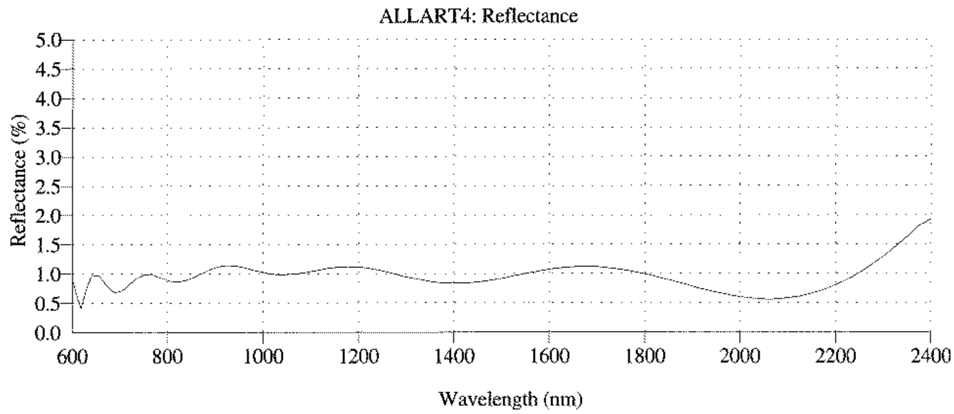

Figure 3. Predicted reflectance of a high efficiency anti-reflection coating designed for use at the operating wavelengths expected for the Large Optical Array. In this case the design has been optimised for both good optical performance and ease of fabrication.

As part of this theme of minimising losses in the optical train, which we see as being crucial to the design of any realistically competitive second-generation interferometer, we have given considerable thought to the anti-reflection coatings required on any transmissive optics in such an array. Typically these would be needed for the optical windows on any pipes carrying light from the telescopes to the beam combining building. Our current specification for LOA suggests that it would initially operate at wavelengths between 0.6 and 2.4 microns, and so we have successfully designed wide-band anti-reflection coatings that have excellent performance throughout this broad window. We expect to take delivery of a set of such windows for installation at COAST very soon so as to replace the original windows to the beam combining building that have anti-reflection coatings designed solely for the optical band.

In a similar vein we are exploring the losses of all of the other transmissive optical components, e.g. dichroics, that we intend to use in LOA. The typical performance of a broad-band anti-reflection coating designed for interferometric use is shown in figure 3

2.3. Detector subsystems

The improvement in the limiting magnitude of COAST, for example from a V magnitude of +7.5 ($I = 4.8$) in 1998 to a V magnitude of +8.5 ($I = 6.4$) in 2000, has been additionally assisted by the replacement of our optical detectors (silicon APDs) with newer higher performance devices. The details of this upgrade are presented in the paper by George et al.[4] in these proceedings, but in short these new avalanche photo-diodes have almost twice the quantum efficiency ($\sim 70\%$) and one tenth of the background noise (100 counts/sec) of our older APDs and exhibit lower after-pulsing rates. The resulting improvement in signal-to-noise ratio for astronomical measurements is demonstrated in figure 4 which compares the signal-to-noise of two accumulated power spectra of the same source obtained with the new and old detectors.

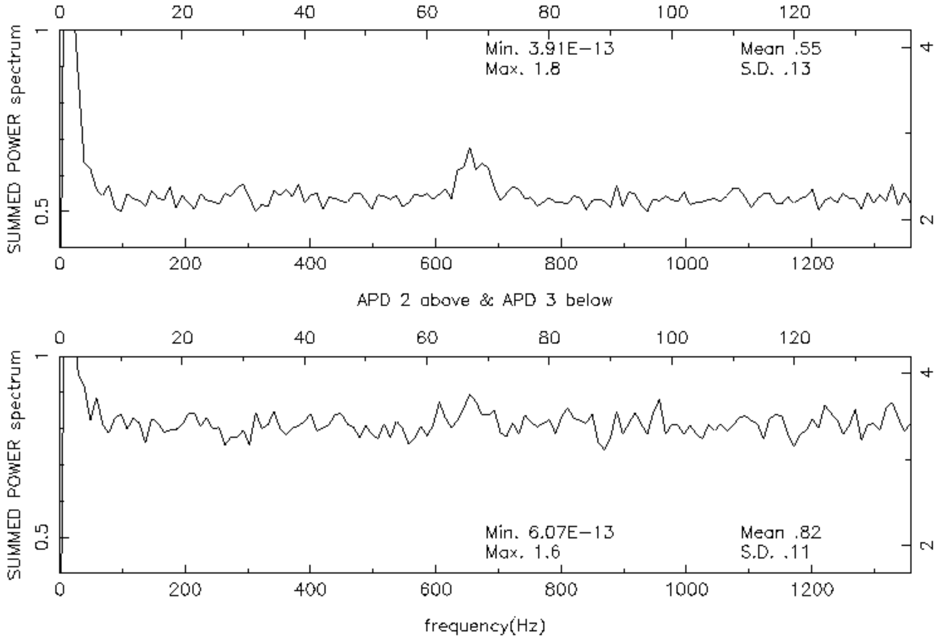

Figure 4. Accumulated fringe power spectra for the star HIP 70899 obtained with the first (bottom) and second-generation (top) APDs at COAST. In both cases the nominal fringe frequency is at ~ 675 Hz. The improvement in signal strength relative to the fluctuations in the photon-noise bias is very clear.

We have also increased the functionality of our infrared detection system, which is based on a NICMOS III chip, by adding a multi-position filter wheel to the ir-camera. This is located within the liquid nitrogen cooled dewar, and uses a external manual drive to change between 5 filter locations. Filter selection is rapid, taking less than a minute in the worst case, and so has significantly enhanced our ability to pursue campaigns that involve contemporaneous measurements in broad and narrow infrared bandpasses: in the past this type of observation would have entailed warming the dewar to room temperature to replace a filter and subsequent pump-down. The infrared and optical beam combination schemes remain identical at COAST, with four pixels of the NICMOS chip being used to sample temporally encoded fringes in the infrared. At a 5 kHz readout rate the typical read noise of the ir-camera is $23e^{-}$ rms.

Auto-guiding at COAST continues to be performed by a fast-readout EEV CCD which has a maximum update rate of 250 Hz. Apart from some minor modifications, e.g. to the dichroic optics feeding the camera, this has seen little change in 1998/99. We do however expect to replace the software controlling the camera over the summer months to allow real-time diagnostic information to be available to the observer during the night, which hopefully will speed up the rate at which astronomical observations can be secured.

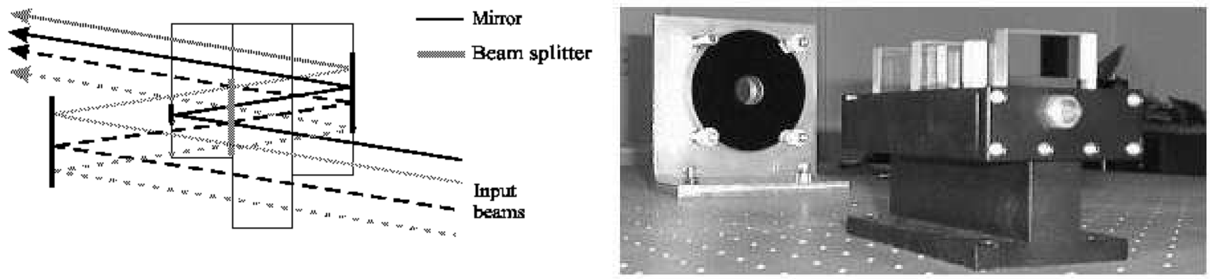

Figure 5. Schematic optical paths (left) and actual implementation (right) of a miniature four-way beam combiner for COAST. In this design, a sandwich of glass slices, all cut from the same "master" block, serves to maintain the relative locations and angles of the reflective/transmissive surfaces. The perforated mirror in the background of the right-hand picture has a diameter of 10 cm, indicating the small size of the whole beam-combining unit.

2.4. Compact beam combiners

As with most other interferometer arrays, maintaining the optical path stability within COAST remains of paramount importance. Fortunately, our current beam combination system, which uses large (approximately 50 mm $\times$ 50 mm) beam-splitter and compensating plates mounted on a conventional optical table, requires manual re-adjustment only on several monthly timescales, and so apart from small adjustments to a single external mirror at each telescope at the beginning of each night, frequent re-alignment of COAST's optics is not usually required.

Nevertheless, as part of our forward planning for LOA we have continued to explore prospects for even more stable optical layouts. At the last SPIE meeting in Kona in 1998 we presented a paper[7] outlining various novel types of beam combiner including monolithic block designs. This approach, which uses small optically contacted components, potentially offered high thermal and mechanical stability, a small physical footprint, and no adjustable components.

In the intervening period we have had three such devices constructed. The first prototype, shown in figure 5, demonstrated the concept, but when tested in the lab gave fringe visibilities for a test source that were no better than our conventional beam combiner layout on its optical table. Furthermore, the measured visibilities were dissimilar between the output ports so that, at best, it was possible to maintain high fringe contrast for only two of the four output beams. We subsequently identified these problems with slight non-parallelism of the substrate faces due to the fabrication and assembly techniques employed. Since this meeting in Munich we have taken delivery of two new miniature combiners for the optical and infrared beam combining tables, that have been designed with tighter specifications and have been assembled under more controlled regimes. Lab testing of these, and subsequent integration into COAST should be complete later this year, and will hopefully pave the way for the designs of the multi-way combiners required for LOA.

3. ASTROPHYSICS PROGRAMMES

As one of only two operational imaging interferometers worldwide, our ongoing astrophysics program at COAST has been designed to take advantage of those features of the array that are unmatched elsewhere. These include the large range of baselines types accessible (i.e. both long and short baseline lengths, and with differing orientations on the sky), the ability to measure phase information through the closure phase, and the possibility of rapidly switching between different observing bandpasses. A summary of our recent astronomical results is included in the paper by Young et al.[3] in these proceedings, so here we will simply outline the range and scope of the projects currently being undertaken. These include:

- The diameter monitoring of Mira variables in broad and narrow bands in the near-infrared. This allows investigation of the structure of the stellar atmosphere, i.e. its extent and stratification etc, as well as testing of dynamical models of stellar pulsation. Importantly, interferometric measurements are some of the only data that can constrain these models directly.

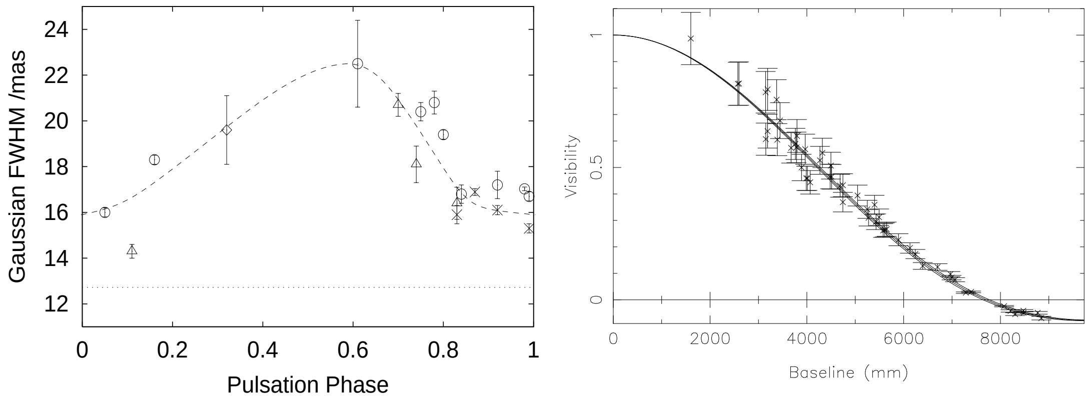

Figure 6. Examples of measurements secured with COAST over the past two years. The left hand panel shows the diameter of the Mira variable χ Cygni as measured at 905 nm during its photometric variability cycle. Note the large increase in apparent size close to minimum light (phase 0.5). The right hand panel shows visibility amplitude data for the M supergiant α Orionis as measured at 1290 nm. The solid curve is a 2-parameter limb-darkening model fit. Closure phase measurements allow the identification of "negative" visibilities beyond the first null in the visibility function.

- Measurement of the limb-darkening of late type giants and supergiants. The longer baselines now available at COAST mean that this can be extended to a larger sample of cool stars than has hitherto been possible. It is useful to note that fewer than 10 stars ever have had their limb-darkening measured, and in most cases these have been very recent interferometric measurements.
- Surface imaging of M supergiants to better understand the physical mechanisms underlying the "hotspots" seen on Betelgeuse and other similar analogues. For this project a range of long and short interferometric baselines are required, as well as the ability to measure closure phases and a multi-wavelength (optical and infrared) capability. The fact that the optical and infrared wavelengths of interest have a ratio of order two has significant implications on the *uv*-coverage required if multi-wavelengths images reconstructed at the same angular resolutions are to be compared.
- Imaging of symbiotic systems, such as CH Cygni, where interferometric measurements can interrogate both the atmospheric structure of the cool primary and any effects due to mass transfer onto, or heating by, the hotter compact companion. Clearly, for these potentially very complex sources the ability to measure numerous visibility amplitudes and closure phases is vital for unambiguous and reliable scientific interpretation.

Some examples of results from COAST for the first and second of these categories are shown in figure 6. Further details can be found in Young et al.[3] and the references therein.

4. UPGRADE PROGRAMME FOR COAST

Over the coming year the main themes of our upgrade programme will continue to be twofold. First, to improve the performance of COAST for astronomy, and second to develop a number of the systems and technologies required for COAST's successor, LOA[6]. Currently our plans for COAST include the following projects:

- Replacement of the unit telescope microcomputers with modern processors of the type proposed for LOA. Not only will this improve reliability, but it will also allow improvements to be made to the telescope performance itself.
- Completing the APD upgrades and replacing their control computers so as to enable active fringe tracking for bright sources, and group-delay tracking for fainter targets.
- Extending the maximum baseline of the array to 60 m for new astrophysics and tests of automated alignment procedures.

- Testing a new low-noise CCD with an expected readout noise level of $\sim 2e^-$. If successful this could replace both the auto-guiding and spectroscopic CCD's in use and might be competitive as a fringe-sensing detector.
- Testing the new compact optical and infrared beam-combiners at COAST.
- Initiating tests using single-mode optical fibres for spatial filtering so as to improve the repeatability of measurements and allow more reliable calibration of visibility amplitude measurements.

With these improvements, we expect to reach the limiting astronomical performance allowed by our site, and hopefully to converge on the most effective strategies for a second-generation array such as LOA.

REFERENCES

1. J. E. Baldwin et al., "The first images from an optical aperture synthesis array: mapping of Capella with COAST at two epochs", *Astron. Astrophys.*, **306**, L13-L16, 1996.
2. J. E. Baldwin et al., "Current status of COAST", in *Astronomical Interferometry, Proc. SPIE*, **3350**, pp. 736–745, 1998.
3. J. S. Young et al. "Recent astronomical results from COAST", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, 2000. These proceedings.
4. A. V. George et al., "Performance of new fringe-detecting APDs at COAST", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, 2000. These proceedings.
5. D. Pearson et al. "Channelled spectroscopy at COAST", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, 2000. These proceedings.
6. D. F. Buscher et al. "Technologies for a cost effective astronomical imaging array", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, 2000. These proceedings.
7. J. Rogers et al., "Miniature beam combiners for optical and NIR interferometers", in *Astronomical Interferometry, Proc. SPIE* **3350**, pp. 1004–1008, 1998.