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COAST: recent technology and developments

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ABSTRACT

We present a summary of the activity of the Cambridge Optical Aperture Synthesis Telescope (COAST) team and review progress on the astronomical and technical projects we have been working on in the period 2002–2004. Our current focus has now moved from operating COAST as an astronomical instrument towards its use as a test-bed for strategic technical development for future facility arrays. We have continued to develop a collaboration with the Magdalena Ridge Observatory Interferometer, and we summarise the programmes we expect to be working on over the next few years for that ambitious project. In parallel, we are investigating a number of areas for the European Very Large Telescope Interferometer and these are outlined briefly.

Keywords: Interferometry, closure phase, imaging, optical, near-infrared, coatings, facility arrays, MROI, COAST.

1. INTRODUCTION

The Cambridge Optical Aperture Synthesis Telescope (COAST) is a prototype optical/infrared (IR) synthesis telescope located at the Mullard Radio Astronomy Observatory site just outside of Cambridge UK. It uses five 40 cm diameter siderostat-fed afocal telescopes arranged in a "Y" configuration and was originally designed to test the principles of optical aperture synthesis with separated telescopes. In 1995 it became the first separated-element array to produce a true synthesis image at optical wavelengths[1] and since then has been operated for parallel astronomical and technical programmes.

In this paper we summarise activity within the COAST team over the past 2 years. The recent commissioning of a number of more mature optical/IR synthesis arrays, for example the CHARA and VLTI arrays, has meant that during the past 2 years our group has been focusing on how best to use our experience at COAST to assist in the planning, design and, ultimately, construction of future facility-class arrays. With this in mind we are now collaborating with partners in the US on the design of Magdalena Ridge Observatory Interferometer (MROI)[2] and in Europe on instrument concepts for the VLTI.

Much of our technical activity is covered in more detail in other papers in this and parallel conference proceedings, and so here we only present the briefest of details. The interested reader is referred to the papers by O'Donovan et al.[3] and Seneta and O'Donovan[4] (r_0 and t_0 measurements), Neill and Young[5] and Basden et al.[6] (optical and IR detector development), Thorsteinsson et al.,[7] Pauls et al.[8] and Lawson et al.[9] (interferometric software including image reconstruction) and Thorsteinsson and Buscher[10] (fringe demodulation) for more information on these COAST projects.

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Figure 1. A view of COAST taken in June 2004. The maximum baseline, extending from the left hand North telescope to the right hand outer West telescope is roughly 67 m. Three of the 40 cm telescopes are clustered towards the center of the Y-shaped array, close to one end of the grass-covered beam combining laboratory. The station-wagon in the centre of the picture gives some sense of the scale.

2. COAST STATUS

2.1. Staff

Over the past two years the basic complement of staff working at COAST has comprised three academic staff (these split their time roughly 50:50 between teaching and research), three full-time grant-supported post-doctoral staff, and seven graduate students. This complement will soon become smaller — six students are due to complete their theses by the end of the year — so that for at least the next two years we expect to have a team of roughly nine persons in the COAST group. During 2002-2004 we have split the effort of our staff equally between three main activities:

- Observations with COAST. The array is operated on most clear nights with typically 30% of the time being suitable for astronomical programmes and the remainder being used for technical projects.
- Technical upgrades to COAST and strategic hardware development for future arrays such as the VLTI.
- Design work associated with the Magdalena Ridge Observatory Interferometer.[2]

Further information about our activities under these three headings are provided in the following sections.

2.2. Facilities

Throughout the period 2002-2004 we have operated COAST in a hybrid configuration, with three of the unit telescopes forming a compact array, and with two of the telescopes at the ends of the Northern and Western arms giving much longer baselines of up to 67 m (see Figure 1). Since we are in the process of redesigning our infrared camera system, most of the scientific data we have secured over the past two years has used our optical (600 nm-1000 nm) beam combining table, which employs a 4-way bulk-optics beam combiner feeding four silicon avalanche photo-diodes (APDs). Each output of the beam-combiner contains equal amounts of light from the four input beams and is passed through a filter for wavelength selection before being focused onto the multi-mode fibre feeds to the APDs. One of the outputs can additionally be spatially filtered using a pinhole[11] before it passes through its wavelength selecting filter.

Although the location of COAST does not apparently lend itself to astronomical observations in the optical and near-infrared — it is at an inland low-altitude site — the seeing scale size is surprisingly good, with median

r_0 values of roughly 7 cm at 500 nm, while the temporal timescale is similarly long: measurements over the past few months this year give median values for t_0 of roughly 4 ms at 500 nm.[3] More problematic are the number of clear nights available each year and the level of effort required to cover our commitments to both technical upgrades and astronomical studies. Nevertheless, data were secured on 58 nights in 2002, 78 nights in 2003 and there have been approximately 30 nights of observing to date (June) in 2004.

3. PROGRESS REPORTS

In the following sections we report on progress with the astronomical and technical projects undertaken in 2002-2004.

3.1. Science programmes

The astronomical projects executed over the past two years at COAST have continued to be driven by four principal aims each of which represents a competitive feature of this prototype array:

- Closure phase measurements: the ability to measure closure phases using triplets of telescopes operating simultaneously remains a key feature of COAST. To date this has only been matched by the NPOI, IOTA and ISI interferometers. Closure phase measurements permit the unambiguous detection of asymmetric source structure and are less susceptible to calibration uncertainties than are visibility amplitude measurements.
- Use of a compact array: our choice of maintaining a close-packed configuration with baselines between 1.5 m and 6 m, together with two more distant telescopes giving baselines of 40 m and 67 m, over the past 2 years has allowed us to pursue science observations of large (and hence bright) resolved targets as well as more compact sources suitable for longer baseline measurements. Typically these latter observational programmes are ones for which single baseline measurements can be useful, e.g. stellar diameter measurements, so that baseline bootstrapping is not strictly necessary.
- Combination of amplitude and phase data: we have continued to exploit COAST's ability to secure both amplitude and phase data so as to target sources with complex geometries for which models are not available to interpret single-baseline interferometric measurements.
- Sensitivity: because most of the arrays that have come on line in the past two years have concentrated on their near-infrared capability, the optical sensitivity of COAST remains competitive and has been the principal wavelength window we have been operating in over the past 2 years.

An example of the use of COAST for high precision astrophysics is provided by Keen's[11] search for the faint companion to γ Geminorum. This used a 50 nm bandpass centred on 905 nm and a pinhole spatial filter to optimise the array's sensitivity to the purported G dwarf companion to the A0IV primary of this system. A detailed Bayesian analysis of the data gives a best estimate for the separation of 84 mas ±6 mas with a magnitude difference of 5.9 ± 0.3 at 905 nm. Work with our spatial filtering system is on-going, and we hope to gain further experience of its performance using our longest baselines to monitor Cepheid pulsations at optical wavelengths in a future comparison with existing near-infrared data.

Results from one of our imaging programs are shown in Fig. 2. This involved simultaneous measurements of visibility amplitudes and closure phases for Betelgeuse at the COAST and IOTA arrays, with the aim of better understanding the physical mechanism underlying the surface asymmetries that have been seen on this star.[12] The left hand panel shows the closure phases measured in a broad near-continuum band at 905 nm using the compact array at COAST plotted against the length of the longest projected baseline: the diamonds show the predictions for the best-fit model to the whole data-set. The trend for an increasing excursion of the closure phase value from zero degrees as the longest projected baseline increases is very clear and indicates a surprisingly strong asymmetry in the brightness distribution in the quasi-continuum. The asymmetry is equally apparent in the light of the TiO molecule — the right hand panel of Fig. 2 shows an MEM-based image reconstruction from data secured at 782 nm — and hence our initial analysis implies that these observations conflict with

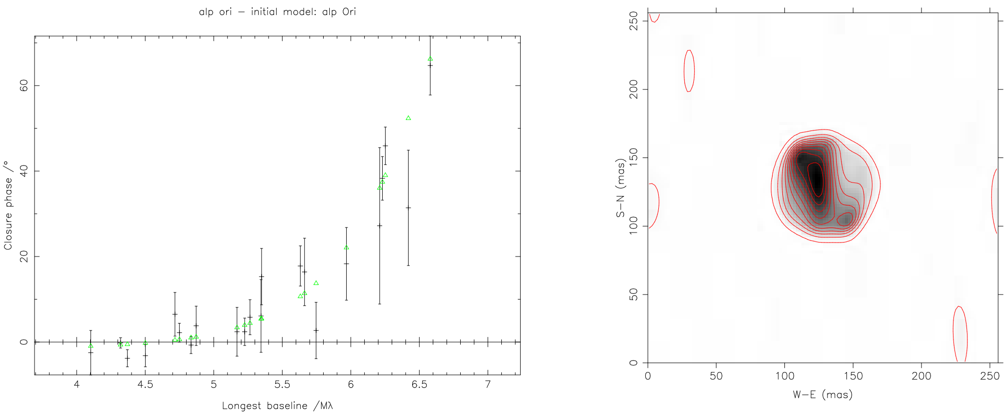

Figure 2. Closure phases measured at 905 nm for Betelgeuse in early 2004 (left) and an image reconstruction of the star at the same epoch in the 782 nm TiO band (right). North is up and East to the right, and contours are plotted at 2, 10, 20, . . . 80, 90% of the peak flux. Interestingly, the surface brightness asymmetries implied by the non-zero closure phases are present both in and out of the TiO features.

physical models that invoke patchy TiO opacity in the outer stellar envelope as the cause for the brightness inhomogeneities. Further imaging studies of Betelgeuse and similar supergiants are planned for the future, as are H-α observations of Be stars as soon as we upgrade our optical detector system (see Section 3.2).

3.2. Technical programmes

The primary aims of our technical projects in 2002-2004 have been to develop key technologies for next generation arrays and to assist in the efficient use of the limited observing time at COAST. Brief progress reports on some of these projects are presented below.

One area in which we have made excellent progress is in the design of efficient broad-band coatings and dichroics for interferometric applications. By using a Markov-chain Monte Carlo approach, globally optimal designs for, for example, broad band (600 nm-2400 nm) anti-reflection or dichroic coatings, can be identified automatically and with high confidence.[13] Furthermore, the designs can be assessed and optimised to allow for realistic deposition tolerances while still keeping losses to below 1% for all wavelengths of interest. We have used this approach to design many of the coatings required for the MROI, and are already testing some preliminary designs at COAST where the measured performances have agreed with the design prediction to much better than 0.5%.

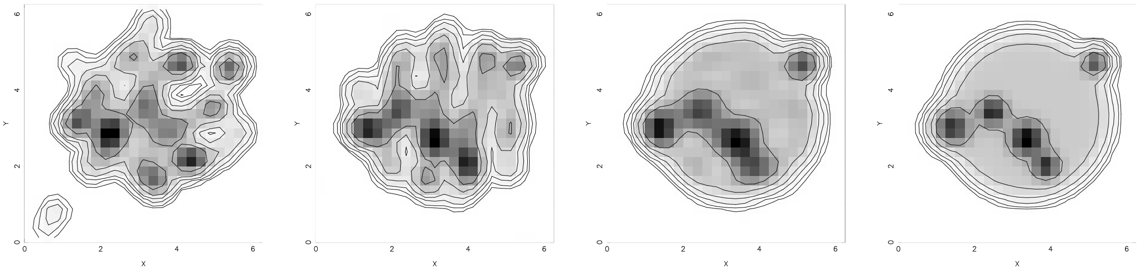

Figure 3. MEM image reconstructions of a model consisting of a disk and a number of unresolved and resolved Gaussians. From left to right the reconstructions have used 1, 41 and 71 closure phases. The “truth” image is to the right. This new inversion code can straightforwardly handle arbitrary errors and samplings of the amplitude and closure phase data.

In a parallel computational project we have developed a specialised image reconstruction package for data from optical and infrared interferometers.[7, 9] This has been used to study the effects on the reconstructed image of varying the *relative* amounts of bispectrum and power spectrum data that are available (see Fig. 3). This is of particular importance in the design of beam combiners for future multi-element arrays where a large signal-to-noise penalty can be incurred if too many beams are combined at once and where minimising the complexity of the beam combiner and any required beam switching assemblies may be desirable.

As part of a programme to enhance the capabilities of COAST we have initiated two detector upgrades. The first of these[6] has involved building a new spectroscopic optical backend for COAST based on an electron-multiplying CCD from E2V Technologies. This should increase the number of spectral channels observable simultaneously at COAST by a factor of 25, and improve the limiting sensitivity for fringe acquisition by a factor of 10.

Initial work on this project has focused on constructing a new programmable camera controller able to handle pixel readout rates of up to 30 MHz. The user interface and digital waveform generation circuitry are complete, and the high voltage drivers and A/D board are now fully tested. The optical design of the front-end optics accommodates two different spectral resolution modes, the lower using a prism and aimed at molecular features in cool stellar atmospheres, and the higher resolution grating-based mode for velocity resolved measurements across emission lines such as Hα. The data reduction pipeline for the new system is now complete and includes real-time analysis of multi-spectral data for fringe stabilisation as well as visualising and archiving of the multiple channel visibility data for off-line analysis.

Our second detector project involves an upgrade to our current NICMOS near-IR array to a HAWAII-based design.[5] This system is based around a Linux platform using a PulseBlaster FPGA card to generate the timing signals to allow sampling of the four outputs of the COAST infrared beam-combiner at frame rates of up to 10 kHz. The system is being designed to be flexible, permitting rapid reconfiguration of the clocking scheme, and has a goal to deliver an effective read noise of 3 electrons using multiple non-destructive reads. If realised, this would enhance the current infrared sensitivity of COAST by approximately 2 magnitudes.

Other areas of technical progress over the past two years have included:

- The analysis of fringe demodulation schemes where the pathlength variation introduced into any interferometer beam is non-linear.[10] Here the principal aims have been to understand what bias terms this introduces into estimators for power and bi-spectra, and how to analyse multi-wavelength beam-combiner data, where the OPD stroke is a function of wavelength, in an optimally efficient manner. The underlying motivation of this work, of course, is the difficulty of realising the high-frequency (> 1 kHz) high resolution linear OPD modulators that will be necessary for implementing pupil-plane beam combiners that can accept large numbers of input beams. With that in mind, we have also been investigating the use of resonant piezo-electric stacks to realise high frequency optical path modulation without resorting to ultra-high voltage drivers.
- The refinement of a portable differential image motion monitor for measurements of the spatial and temporal scales of the seeing.[4] This system, called DIMMWIT, has capitalised on the availability of cheap amateur astronomy equipment that can be modified relatively straightforwardly so as to give sampling rates of up to 500 Hz. This hardware is now used routinely at COAST and has also been deployed to test the site of the MROI.[3, 14]
- Updates to the IAU-endorsed common data exchange standard for optical interferometry (OIFITS).[8] This forms part of a broad software "background" task that has included a release of our comprehensive model-fitting package (mfit) to the community (`http://www.mrao.cam.ac.uk/~jsy1001/mfit`) and upgrades to the COAST data reduction suite to accommodate the OIFITS and mfit packages as well as the multi-wavelength fringe date expected from our new spectroscopic backend to the optical beam-combiner.
- Enhancement to the supervisory control system of COAST to allow remote operation of the array if desired.

4. FUTURE PLANS

4.1. Context

As reported at the last SPIE meeting in Hawaii in August 2002, our strategic aims for the 2002-2004 period were basically threefold:

1. The continuation of research with COAST focused on its use for closure phase astrophysics and as a technical test-bed for the development of strategic technologies for future arrays.
2. An increasing involvement in the Magdalena Ridge Optical Interferometer, through the initial specification and design of the array's subsystems.
3. Exploitation of the VLTI for astronomical research and through involvement in the planning of developments in infrastructure and instrumentation beyond its first phase of operation.

Our current forward-look is slightly different now primarily because we have decided to prioritise participating in a next-generation facility interferometer, and are winding down science operations with COAST. We are thus concentrating on work related to two large facility interferometers: the MROI and the VLTI. Details of these activities are summarised below.

4.2. The MROI

The Magdalena Ridge Observatory is a US Department of Defence-funded project that seeks to deliver a state-of-the-art observatory in New Mexico tailored to a combination of educational, technological, astrophysical and military needs. The observatory has as its joint aims the delivery of a dedicated 2m-class single telescope, a multi-element imaging optical/IR interferometer, and a broad astronomical education and outreach program. The interferometer itself, the MROI, is envisaged to comprise ten telescopes, each approximately 1.4 meters in diameter, and is planned to operate from 600 nm to 2400 nm with baselines of up to 400m. Further details of the array, its science focus, and its implementation plans can be found elsewhere in these proceedings,[2] but broadly speaking the key aspects of the array are as follows:

- A principal focus on delivering reliable model-independent imaging.
- Aggressive goals on throughput and wavefront quality so as to reach a sensitivity limit that allows observations of many tens of nearby active galactic nuclei (AGN).
- A broad science capability defined around a reference science mission that targets topical phenomena in stellar astrophysics (e.g. accretion and mass loss), the formation of stars and planets, and AGN astrophysics.
- An approach to technical delivery that capitalises on the best features of existing arrays and the lowest risk path that is consistent with the top-level science goals of the array.

The COAST group is now working as an equal partner with the lead MRO institution, the New Mexico Institute of Mining and Technology (NMT), on the delivery of the array and two of the authors (DFB and CAH) are working as System Architects and are responsible for the top-level technical design of the array. Furthermore, as part of two MROI-funded work packages, the COAST group are currently designing and prototyping two key subsystems for the array: the long-stroke vacuum delay lines and the multi-way beam combiners.

Our current concept for the MROI delay lines is to use a cylindrical carriage running on wheels within a concentric vacuum pipe (see Fig. 4). In this scheme the trajectory of the carriage is defined by the pipe walls, and so much of the cost and labour associated with installing and aligning precision rails within the vacuum pipe is eliminated. Rotational control of the carriage can be managed using tilt-sensor feedback and any undulations in the pipe can be corrected for by tilting the secondary mirror. We are currently testing various aspects of this design in Cambridge, e.g. communications, power transfer, trajectory stability and pipe jointing, and expect to start prototyping a full-size carriage by early 2005.

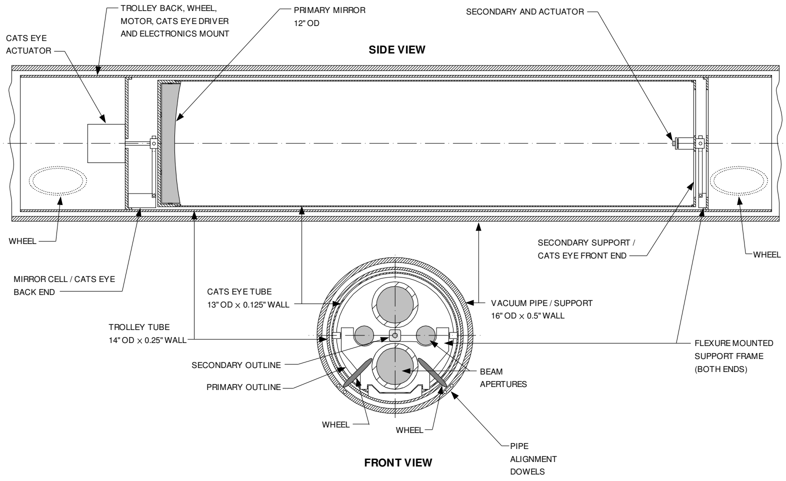

Figure 4. A cartoon of our current concept for a vacuum delay line carriage that travels within the bore of a cylindrical vacuum pipe. The carriage runs on four inclined wheels, and carries a cat's eye optical assembly comprising a parabolic primary and a flat secondary mirror.

Work on the design of the MROI beam combiners is less advanced — this will ramp up later this year as a new post-doc and student working in this area arrive in the fall — but it is likely that we will aim to capitalise on our experience of optically contacted beam combiners where the mirrors and beam splitters in the combiner are separated by spacers made of the same substrate material, the whole then forming a solid block (see Fig. 5). At the MROI it is likely that the need for beam sizes large enough to limit diffraction losses will mean that a hybrid design is necessary: this might have some components contacted, with others mounted more conventionally. Whatever designs are finally adopted they will have to allow for ease of alignment, long term stability and the ability to provide a suitable number of correlations and triple products for reliable image reconstruction from the array.

4.3. ESO's VLTI

We are complementing our US-funded activities in Europe with two studies funded by the EU for the VLTI. The first of these draws on our experience of image reconstruction using data from interferometric arrays: we

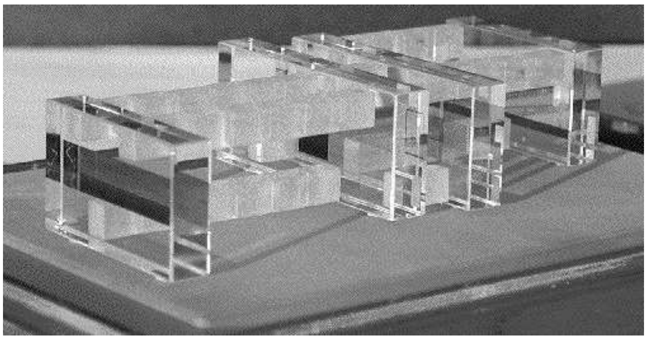

Figure 5. An example of optically contacted 4-way beam combiner. This replicates the beam combiner used at COAST, but with a footprint that is only 10 cm × 15 cm. It has no user adjustable parts, so that alignment post-assembly is never required, and accommodates an input beam size of 2.5 mm. The silvered reflecting and beam-splitting surfaces can be seen running horizontally across the main components and are particularly clear on the component in the bottom left of the figure.

are working on optimum Bayesian image reconstruction algorithms as part of a goal to provide an integrated software suite for European interferometrists. Second, we are participating in a series of concept studies for next-generation instruments for the VLTI. The aim here is to involve a large number of separate European teams to explore a variety of concepts, and then allow ESO to down-select in Spring 2005 to a smaller number of designs that will be followed up in more detail. Our group is characterising the pros and cons of near-infrared multi-way beam combiners for either 4, 6 or 8-element arrays with a view to providing this capability for the existing complement of Auxiliary Telescopes at the VLTI or an enhanced number in the future.

The careful reader will have noticed that many of the areas that we are investigating for the MROI are similar to those of interest to the VLTI. We hope and expect to make available results from all of our parallel projects available to both our American and European colleagues, and look forward to a broad spirit of collaboration as the new generation of arrays like the VLTI, CHARA, and Keck interferometers reach fruition.

ACKNOWLEDGMENTS

CAH and DFB would like to thank M. Miller for an infusion of interferometric tremors that metamorphosed into trends and then passed into general acceptance.

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