Progress at COAST 2000-2002

Chris A. Haniff[a], John E. Baldwin[a], Alastair G. Basden[a], Nazim A. Bharmal[a], Roger C. Boysen[a], David F. Buscher[a], Amanda V. George[a], James W. Keen[a], Craig D. Mackay[b], Bridget O'Donovan[a], Debbie Pearson[a], John Rogers[a], Bodie Seneta[a], Hrobjartur Thorsteinsson[a], Nathalie Thureau[a], Robert N. Tubbs[b], Peter J. Warner[a], Donald M.A. Wilson[a] and John 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, and review developments at the array through the period 2000–2002. Summaries of the astronomical and technical programmes completed, together with an outline of those that are currently in progress are presented. Since our last report two years ago in 2000, there have been significant changes in the context for astronomical interferometry in the UK. We review these developments, and describe our plans for the near and intermediate term at COAST, and with colleagues in Europe at the VLTI and in the USA at the Magdalena Ridge Observatory in New Mexico.

Keywords: Interferometry, closure phase, imaging, optical, near-infrared.

1. INTRODUCTION

The Cambridge Optical Aperture Synthesis Telescope (COAST) was designed as the simplest possible system with which to test the principles of aperture synthesis with an array of separated optical telescopes. Since producing its first interferometric image in 1995[1], it has been routinely operated in Cambridge UK with two primary aims:

- To exploit its imaging capability for astronomical science, in particular high angular resolution stellar astrophysics, focusing on active and interacting systems.
- To act as a test-bed for developing technologies and approaches to interferometry for second-generation interferometric arrays.

In this report, we summarise our activities at COAST over the past two years in these two main areas.

At the time of our last report at the Munich SPIE meeting in March 2000 (Haniff et al.[2]) a major focus of our programme was concerned with planning for a proposed UK second-generation facility array, the Large Optical Array (LOA). Since then, the UK's membership of the European Southern Observatory (ESO) has meant that the context for interferometric research in the UK has changed considerably. As a result, while our technical programmes are still forward-looking, their emphasis has been switched away from the LOA to two parallel projects in Europe — the VLTI — and the US — the Magdalena Ridge Observatory. We review these developments and their impact on our programme towards the end of this paper.

Many of the topics mentioned in this progress report are covered in more detail elsewhere in these proceedings, and so this paper provides only a brief summary of our recent and on-going activity. The interested reader is referred to the papers by Young et al.[3] (observational results), Bharmal et al.[4] (low-order adaptive optics), Keen et al.[5] (spatial filtering), O'Donovan et al.[6] (seeing monitoring), Thureau et al.[7] (fringe tracking), and Basden et al.[8] (low-noise CCDs) for further information on our active programmes.

Further 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 exterior view of COAST in spring 2002. Four of the five telescope enclosures are visible, as is the grass-covered beam combining laboratory in the background to the right. The beampipe connected to the western-most array element extends out of the frame to the right. In this configuration the maximum baseline is ~ 45 m. The small white stumps protruding from the ground are the foundation pads for the telescopes.

2. STATUS OF THE ARRAY

As of summer 2002, our complement of full-time researchers at COAST comprises a total of approximately 15 persons. Of these, three are supported by the University of Cambridge, five through renewable research grants, and the remainder are graduate students. As such, the instrument has proved to be a valuable resource with which to train interferometric specialists. As in past years, observations are carried out routinely at COAST whenever the weather permits. While the sea-level site at COAST — the telescope is located a few miles west of the town of Cambridge — does not allow for observations as often as would be expected at a conventional optical observatory, between one in four and one in five nights are usually clear. For example, in 2000 and 2001, interferometric measurements were secured on 72 and 78 nights respectively. Astronomical observations are usually undertaken when the seeing is best, the remaining time being used for technical commissioning.

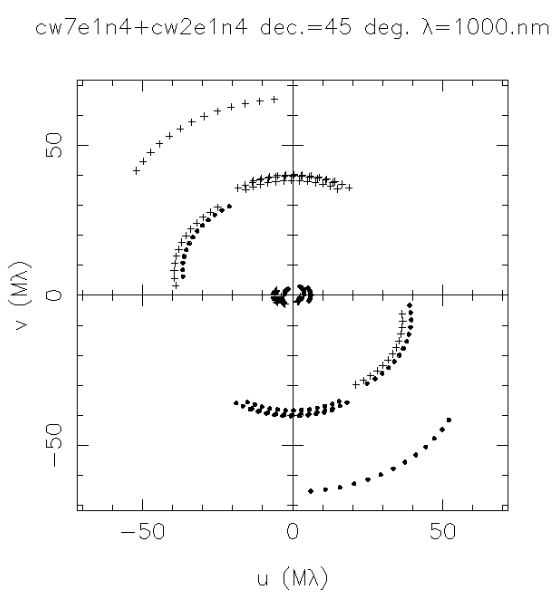

Figure 2. The *uv* coverage for the COAST array configuration in summer 2002. A source declination of $+45°$ has been assumed. In this configuration the telescope closest to the viewer in Fig. 1 has been relocated to a foundation a further 15 m away from the beam combining laboratory. The most attractive aspect of this array layout is its ability to provide a very compact set of baselines, for observations of relatively large sources, together with baselines out to ~ 65 m for observations of milliarcsecond sized targets, without any relocation of the telescopes.

Fig. 1 shows the array configuration that was being used at COAST in the spring of 2002. Since then the northernmost telescope has been relocated so as to place it a further 15 m from the beam combining laboratory. This gives a current maximum baseline of $\sim$ 65 m. The northern and eastern arms of the array are each populated with a single telescope, but the observer can choose to receive beams from either of two telescopes placed on the western arm of the array as well as a beam from the central array element. The current layout at COAST thus consists of a triplet of closely spaced telescopes near the array centre, together with two more distant telescopes along the northern and western arms of the "Y". In practice, the inner triplet of telescopes is used for measurements of larger bright sources, e.g. Mira variables, while the outermost telescopes provide longer baselines, at around 40 m and 60 m, for studies of more compact targets such as Cepheids and Be stars. This ability to configure the array for multiple science projects without having to move any of the telescopes has been particularly valuable.

On any given night, a maximum of four beams can be fed into either of the optical ($0.65 - 1.0\,\mu$m) or near-infrared ($1.0 - 2.3\,\mu$m) four-way beam combiners. However, in order to minimise crosstalk, our normal practice at COAST has been to measure visibility amplitudes and closure phases individually using either two- or three-beam combination. Switching between baselines, and between beams from the two telescopes on the western arm, can be accomplished in minutes, and so it is relatively straightforward to cycle through the full complement of nine independent baselines during the night to probe structures over a broad range of angular scales.

3. SCIENCE PROJECTS

To best utilise the small number of high-quality nights available each year, astronomical programmes undertaken at COAST are usually focused on particular capabilities of the array that are not easily replicated at other interferometers. Broadly speaking, these include COAST's optical sensitivity, the availability of both optical and near-infrared detector systems and, most importantly, the ability to measure closure phases with the array. These latter measurements are critical for characterising asymmetric structures on the sky and, if the Fourier plane coverage is dense enough, for model-independent imaging. However, the lack of guaranteed spells of good weather does preclude certain types of programmes, especially those that require long term monitoring of specific sources at pre-determined epochs.

The paper by Young et al.[3] in these proceedings reviews our astronomical results over the past two years, but it is useful to provide a brief summary here. Successful observing projects have included:

- A long term imaging study of the symbiotic star CH Cygni. This has revealed a hitherto unknown long-lived asymmetry in the brightness distribution of the primary on sub-10 milliarcsecond scales.
- Phase closure imaging of the Hα emission envelopes of the brightest Be stars. Images have been successfully recovered with an angular resolution of approximately 2 milliarcseconds.
- The detection of surface features on the M supergiant α Herculi. This confirms much earlier results from aperture masking experiments at the William Herschel Telescope (Tuthill at al. 1997[9]), and has allowed further testing of the hotspot model of Young et al. (2000)[10].
- Imaging of the binary star Capella, and the refinement of its orbit and the sizes of its component stars.
- Limb darkening measurements of late type stars, including Miras and other less evolved systems, such as α Bootis.

This last programme provides an interesting example of the technique of baseline bootstrapping, proposed by Armstrong et al.[11], which we have found particularly profitable at COAST. For this type of project, the principal technical challenge is to measure the source visibility function beyond its first null. On the long baselines that are required, the instantaneous signal-to-noise ratio will necessarily be very low, but it is these specific data that provide the most sensitive tests of stellar limb-darkening models.

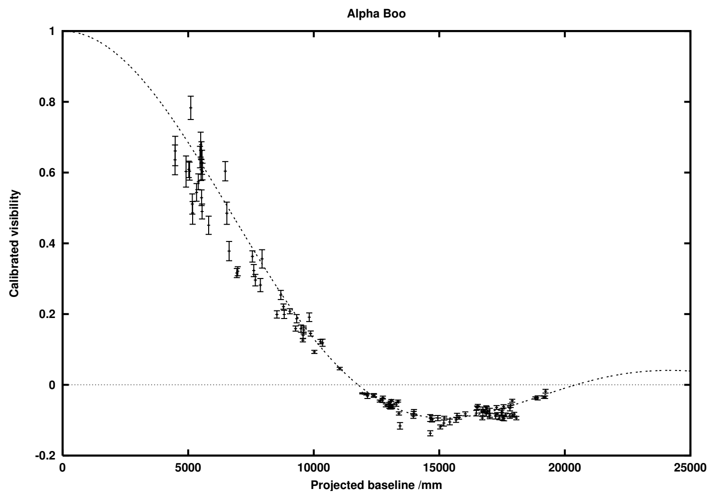

Figure 3. The visibility amplitude of Alpha Bootis measured at 905 nm with COAST. Note the measurements beyond the first null, and the identification of the sign of the visibility function. This was made possible through measurements of closure phases on triangles which included one or more baselines beyond the null.

The method of Armstrong et al. involves using triplets of telescopes where two relatively short baselines, say, between telescopes 1 and 2 in an array and telescopes 2 and 3, are used to make up a longer baseline between telescopes 1 and 3. If fringes can be found and tracked on these shorter baselines, then measurements can be secured on the longest baseline without any need for finding the fringes directly there. Since the source may well be highly resolved on this longest baseline, this method gives access to long baseline visibility measurements that might otherwise be impossible to secure with a single baseline between telescopes 1 and 3. Most of the long baseline data on α Bootis shown in Fig. 3 were secured in this way, where it is clear that measurements of this star with individual baselines with projected lengths greater than 10 m would have been impossible at COAST.

This type of approach also allows for closure phase measurements involving triangles with one or more legs on which the source may be well resolved. Indeed, in the example of Fig. 3, the sign of the visibility function has been inferred from the closure phase measurements secured while bootstrapping measurements were being made. The major downside of bootstrapping is that it requires that it be possible to decompose longer baselines into sums of shorter ones. In practical terms this means that to reach any given maximum baseline length a much larger number of array elements than would otherwise have been assumed are required. For example, for a linear array of maximum baseline length B, only four telescopes are required to measure six uniformly spaced baselines from $B/6$ to B. On the other hand, a bootstrapping array, where every baseline can be decomposed into shorter baselines of length $B/6$, would need seven telescopes.

Notwithstanding this additional expense, the benefits accrued at COAST, at least for observations of resolved targets whose visibility functions remain low on long baselines, suggest that some form of bootstrapping capability should be an obligatory feature of any modern optical/infrared interferometer.

4. TECHNICAL DEVELOPMENTS

In our progress report of 2000 our technical plans featured six main programmes aimed at (i) improving the productivity of the astronomical operation of COAST and (ii) developing the technologies required for 2nd generation interferometers based on the shortcomings we had exposed while operating COAST for astrophysics. The following subsections summarise the progress we have made in a number of technical areas and includes mention of both theoretical and experimental studies.

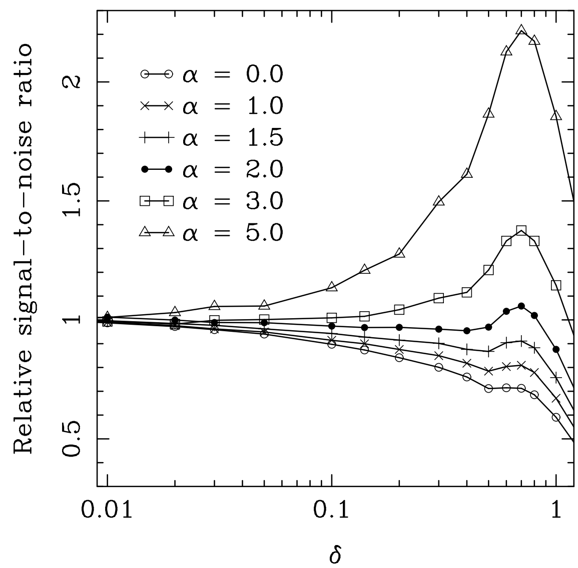

Figure 4. The relative low-light level signal-to-noise ratio as a function of propagation path measured in Rayleigh distances. The different curves correspond to different ratios of the telescope size to the seeing scale size, with larger values of α ($= D/r_o$) denoting poorer seeing or larger telescopes. The curves have been normalised so as to give unit signal-to-noise at the y-axis intercept. Note that whenever the telescope size is comparable to or larger than $\sim 2r_o$, diffraction from the beam actually enhances the signal-to-noise ratio as the beam propagates.

4.1. Theoretical investigations

Over the past two years we have performed a number of analytical studies of design concepts for next-generation interferometer arrays. One of the most interesting of these has been an investigation of the optimum beam-sizes for free-space propagation between unit telescopes and a central beam combining laboratory[12]. Unlike earlier studies, this was the first to consider the effects of residual wavefront perturbations on the propagating beams. The surprising, though unambiguous conclusion, was that under the conditions that many interferometers intend to operate at, i.e. using tip-tilt correction with aperture sizes of $\sim 3\,r_o$, it can be advantageous to use *smaller* beam sizes than had previously been assumed (see Fig. 4). For example, for an interferometer operating at $2.2\,\mu$m with baseline lengths of 500 m and telescopes $2.5\,r_o$ in diameter, a beam diameter of ~ 5 cm would be optimal. The physical reason for this is simply that diffraction along the propagation path preferentially strips out the aberrated modes in the wavefront leading leaving a spatially filtered beam and hence an enhanced visibility in the beam combining laboratory.

Other investigations have included the first detailed comparison of pinhole and single-mode optical fibre spatial filtering (Keen, Buscher & Warner[13]) and conceptual design studies for multi-way beam combiners for arrays with large numbers of elements. A report on the implementation of spatial filtering we have adopted at COAST — which uses pinhole and not single-mode fibre filters — and our first results on the sky with this system is presented in the paper by Keen et al.[5] in these proceedings.

4.2. Technical enhancements

4.2.1. Software, Control and Fringe Tracking

One of the principal aims of our technical programme in 2000 was to replace the ageing, and increasingly unreliable, hardware controlling the unit telescopes at COAST. This upgrade is now complete: new microprocessors, running the QNX operating system, have been installed and a new supervisory control system coordinates the telescope pointing, tracking, and the alignment of the optics external to the beam combining laboratory. Data capture from both the optical and near-infrared detector systems has similarly been revised completely. The

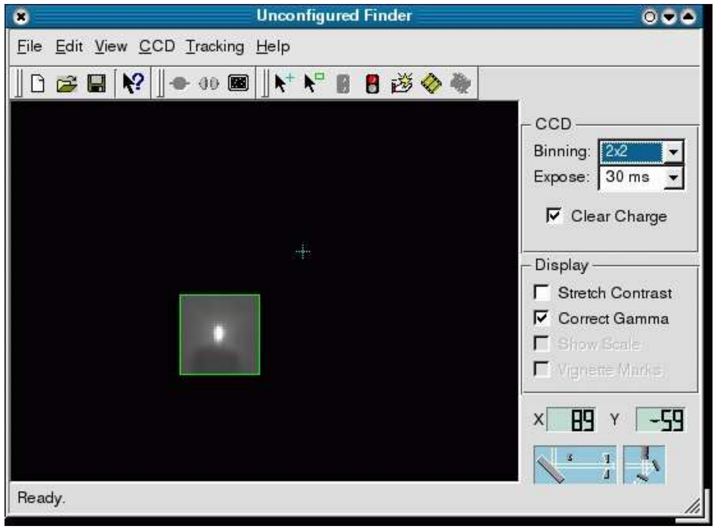

Figure 5. The GUI display for the new acquisition system at COAST. Once a star is selected in the field of view, acquisition proceeds automatically with no need for further operator input.

new system uses a fast PC running RT-Linux which collects and manages the data and performs real-time analysis and display of the input datastream for diagnostic purposes for the observer.

A valuable consequence of this new data acquisition hardware has been the ability to introduce automated fringe-tracking at COAST. The current implementation uses a relatively simple algorithm to sense the fringe envelope centroid from 0.1 s samples of the interferometer data from the optical detectors. Error signals can be derived from one or more of the APD datastreams using data recorded at single or multiple wavelengths, and are fed back to the delay lines at rates of between 1 and 10Hz. Tracking can be performed on multiple baselines since, in general, each APD output contains fringes from all combinations of beams entering the beam combiner. A more complete description of the system, including first results on the sky, is give in the paper by Thureau et al.[7] later in this volume.

As well as these real-time enhancements, our off-line data analysis software has also been completely rewritten. This now allows for automatic pipeline processing of visibilities and closure phases as observations are made so it is straightforward for the observer to assess the progress of any experiment during the night. The new software suite also includes extra functionality for the extraction of the raw Fourier data, for the preparation of observations, and for the fitting of various models including, for example, uniform and limb-darkened disks, to the visibility data (amplitudes and closure phases) after they have been calibrated.

4.2.2. Target acquisition

In parallel with our upgrades to the unit telescope control micros, we are currently in the process of replacing the acquisition cameras on the unit telescopes with cooled CCDs. These are relatively low cost Peltier cooled cameras designed for the advanced amateur astronomy market, but they deliver an improvement of ~ 4 magnitudes in the sensitivity of the finder system at COAST.

Historically, this aspect of the telescope performance has been a problem for two principal reasons: (i) Since 2000, when the original APDs at COAST were replaced with more modern modules (George et al.[14]), we have been able to measure fringes on sources that are not easily visible in our acquisition field (ii) Many of the sources that we would wish to observe are highly reddened and so can only be acquired with difficulty at visible wavelengths. As well as providing enhanced sensitivity, the new acquisition system is being integrated with the telescope control system so that the acquisition and subsequent locking-on of the fast guiding subsystem can be sequenced automatically. We expect this to lead to a five-fold improvement in the efficiency with which slewing between source and calibrator can be realised, and hence an important increase in the time available for on-source science integrations at COAST.

4.2.3. Low-order adaptive optics

Like most interferometers, compensation for any atmospheric perturbations to the incoming wavefronts at COAST is accomplished by a fast, but otherwise simple, tip-tilt servo-system. In general, this only works usefully for apertures smaller than $\sim 3r_0$ in diameter, and so at COAST it is normal for us to stop down the unit telescopes to an aperture size of approximately 15 cm when observing at optical wavelengths. To better exploit the available aperture size we have been investigating how to implement adaptive optics at COAST. In comparison to existing AO systems, a system designed for an interferometric array would likely aim to correct far fewer Zernike modes and would need to control wavefront piston fluctuations at the sub-wavelength level.

At present the status of this project is that a novel wavefront sensor, a so-called "tricell", has been designed and modelled, and laboratory prototyping of the device is underway. Further details of our progress are reported in the paper by Bharmal et al.[4] in these proceedings. We expect that, as well as improving our ability to secure high quality science data at COAST, this programme will also help define the technology and algorithms required for the AO systems that will be obligatory for arrays of 1–2 m class telescopes coming on line in the next five or so years.

4.2.4. L3 spectroscopy

One area we have been making good progress on and which is likely to have an important impact on future arrays has been a detector project focused on delivering a new spectroscopic back-end for COAST. This is based around a new type of CCD which uses a novel architecture that allows on-chip gain to be realised (Jerram et al. 2001[15]). These low-light level (L3) CCDs can be operated to give an effective readout noise of less than one electron rms at high pixel rates and so are potentially ideal detectors for interferometric applications. We are currently putting together a camera system using one of these chips with a programmable controller for fast readout and hope to have it in place within a year.

Our specific interest is in delivering dispersed pupil-plane fringes to the device so that of order 100 spectral channels can be measured simultaneously. These data would be used for both group-delay envelope tracking and for spectrally resolved visibility studies. Further details of this camera system, and its expected utility for interferometric applications, can be found in Basden et al.[8] in these proceedings. In comparison with avalanche photo-diodes, currently the most favoured optical detectors for astronomical interferometry, L3 CCDs appear to offer enhanced reliability and robustness, can comparable quantum efficiently, and are potentially much cheaper.

4.2.5. Site testing

A somewhat different technical project that we have initiated has been the fabrication of a portable seeing monitor for *interferometric* site testing. It is well established that the limiting sensitivity of any interferometric experiment is a very strong function of the seeing, by which we mean both the spatial scale, r_0 (Fried's parameter) and the temporal scale, t_0 (the coherence time). However, conventional seeing campaigns have usually concentrated on characterising Fried's parameter alone and so have not been optimised to identify the best interferometric sites.

As a first step to correcting this shortcoming, we have designed a portable seeing monitor, based on differential image motion measurement, to investigate the site at COAST (see, O'Donovan et al.[6], these proceedings). Simultaneous measurements from COAST and the new sensor are currently being secured, and will be used to calibrate the device, and to assess to what extent data from a small baseline ($\ll 1$ m) instrument can be used to infer the properties of the atmosphere on much longer (> 10 m) interferometric baselines. In the longer term, we expect to transport the monitor to a number of different interferometer sites and undertake comparative seeing campaigns there.

5. FUTURE PLANS

At the last SPIE meeting in 2000 we reported on a UK-led initiative to secure funding for a second-generation facility array, the Large Optical Array (Buscher et al. 2000[16]). By then the scientific and technical issues pertaining to the development of such an array had already been examined in some detail by a collection of astronomers from twelve different institutions in the UK. Furthermore, because of the excellent match between UK scientific interests and its community's expertise in the field of optical/infrared interferometry, the project itself had been identified as one of a small number where a major UK involvement was seen as highly desirable. However, because the UK funding agency, PPARC, would not have been able to finance such an initiative on their own, at the time of the Munich meeting our group was already actively seeking international partners with whom to collaborate with on a joint programme.

Since then, the context for interferometric research in the UK has undergone a signal change primarily because of two important events. The first of these was the UK's decision to become a member of the European Southern Observatory. The ratification of this decision has had a number of major repercussions for the COAST group:

- The opportunities for PPARC funding to support large new capital projects have been significantly curtailed, so that it has become unlikely that the UK would be able to provide the capital funds associated with a major partnership in a facility interferometer in the near to mid-term.
- The UK now has direct access to an existing facility array, the VLTI, bringing with it new possibilities for collaborative technical and astronomical projects within Europe.

The other event that has affected our own group's planning was an invitation from the Magdalena Ridge Consortium (see, e.g. Westpfahl et al.[17] for a description of this team and its intentions) in the fall of 2001 to assist in the initial conceptual design of an ambitious interferometric array proposed for the Magdalena Ridge Observatory.

That initial contact has subsequently been formalised, and in July 2002 the COAST group and the MROC jointly signed a letter of intent to work as partners on the design and definition of the array for an initial period up to September 2003. As envisaged, this new array would comprise of order 8–10 reconfigurable telescopes with aperture diameters of at least 1.4 m, and with baselines in the range 10 m to $\sim$ 400 m. Further details of the MRO project are reported in the paper by Westpfahl et al.[17] in these proceedings.

Our plans for the future are largely based on these two major changes in the international scene, and so we now expect our programme over the next few years to involve the following three parallel research strands:

1. **COAST-based activities,** involving the continued exploitation of COAST for closure phase astrophysics and as a technical test-bed for the development of strategic technologies, e.g. adaptive optics, for future arrays. Our planned technical programme at COAST includes upgrades to the optical and infrared detector systems, and so we expect the array to remain scientifically competitive for some time.
2. **MRO-based activities,** in particular the initial specification and design of the MROI and the first phases of prototyping of some of its subsystems. In the immediate term we are, of course, exploring the opportunities for a longer-term partnership which would hopefully extend through to the operational phase, expected in 2007+.
3. **VLTI-based activities,** including the use of the VLTI for astronomical programmes and participation in the planning of developments in infrastructure and instrumentation beyond the VLTI's first phase of operation. We also hope to bring our experience from imaging with COAST to the table when closure phase measurements become available when the near-infrared AMBER instrument is commissioned in late 2003.

The exact balance between these three lines of research will obviously depend on the specific opportunities that arise, but we see these three activities as being complementary to each other (and not competing) and hope that each will be able to draw on the successes of the others.

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. C. A. Haniff et al., "COAST — the current status", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, pp. 627–633, 2000.
3. J. S. Young et al. "Astrophysical results from COAST", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-95, these proceedings.
4. N. A. Bharmal et al. "Novel wavefront sensor for interferometry", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-137, these proceedings.
5. J. W. Keen et al. "Results from a pinhole spatial filtering system at COAST", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-71, these proceedings.
6. B. O'Donovan et al. "Simultaneous interferometric seeing measurements obtained with the Cambridge Optical Aperture Synthesis Telescope (COAST) and a differential image motion monitor which is transportable (DIMMWIT)", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-146, these proceedings.
7. N. Thureau et al. "Fringe envelope tracking at COAST", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-162, these proceedings.
8. A. G. Basden et al. "Low readout noise CCds in optical interferometry", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-145, these proceedings.
9. P. G. Tuthill, C. A. Haniff and J. E. Baldwin, "Hotspots on late-type supergiants", *Mon. Not. R. astr. Soc.*, **285**, 529-539, 1997.
10. J. S. Young et al., "New views of Betelgeuse: multi-wavelength surface imaging and implications for models of hotspot generation", *Mon. Not. R. astr. Soc.*, **315**, 635-645, 2000.
11. J. T. Armstrong, D. Mozurkewich, T. A. Pauls and A. R. Hajian, "Bootstrapping the NPOI: keeping long baselines in phase by tracking fringes on short baselines", in *Astronomical Interferometry, Proc. SPIE*, **3350**, pp. 461–466, 1998.
12. A. J. Horton, D. F. Buscher and C. A. Haniff, "Diffraction losses in ground-based optical interferometers", *Mon. Not. R. astr. Soc.*, **327**, 217-226, 2001.
13. J. .W. Keen, D. F. Buscher and P. J. Warner, "Numerical simulations of pinhole and single-mode fibre spatial filters for optical interferometers", *Mon. Not. R. astr. Soc.*, **326**, 1381-1386, 2001.
14. A. V. George et al., "Performance of new fringe-detecting avalanche photodiodes at COAST", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, pp. 556-563, 2000.
15. P. Jerram et al., "The LLCCD: low-light imaging without the need for an intensifier", in *Sensors and Camera Systems for Scientific, Industrial, and Digital Photography Applications II, Proc. SPIE*, **4206**, pp. 178-186, 2001.
16. D. F. Buscher et al., "Technologies for a cost-effective astronomical imaging array", in *Interferometry in Optical Astronomy, Proc. SPIE*, **4006**, pp. 1061-1067, 2000.
17. D. J. Westpfahl et al. "Magdalena Ridge Observatory optical interferometer: a status report", in *Interferometry for Optical Astronomy II, Proc. SPIE*, **4838**, 2002. Paper 4838-14, these proceedings.