Future optical interferometer design

Peter R. Lawson, John Rogers, Christopher A. Haniff, John E. Baldwin,
Roger C. Boysen, David Burns, Peter J. Warner, and Donald M.A. Wilson.

MRAO, Cavendish Laboratory
Madingley Road, Cambridge CB3 OHE, UK

ABSTRACT

The Cambridge Optical Aperture Synthesis Telescope (COAST) has now been developed to the point where stellar images with a resolution of 20 mas can be produced in a routine manner. Based upon our experiences in the design and commissioning of COAST this paper will discuss the possible design of a next generation interferometer.

Keywords: astronomy, interferometry, imaging, optical, infrared

1. INTRODUCTION

In 1995 our group at the Cambridge Optical Aperture Synthesis Telescope (COAST) demonstrated that synthesis imaging of stellar sources was possible by long-baseline optical interferometry.[1] The images were produced using visibility amplitude and closure phase measurements, together with self-calibration methods,[2] a method that had previously been demonstrated by aperture-masking large optical telescopes[3,4] and that has had a longer history of use in radio interferometry. The first image from COAST, showing the two components of the binary star Capella, represented a very simple object and had an effective resolution of only 20 mas—using the the closest configuration of baselines. Clearly, much work remains to be done with this interferometer, as its observation program is still in its infancy. However we can now contemplate future directions in this field and suggest an improved design based on our experience.

The design of COAST itself has been described previously,[5] and its current status is reviewed in these proceedings.[6,7] In this paper we outline the context for a new program, emphasise some important areas of development, and discuss possible design parameters for a future optical/infrared interferometer.

The methods of stellar interferometry, its history and current trends, have been reviewed elsewhere.[8,9] Here we will limit ourselves to discussing imaging interferometers and outline what could be done today with existing technology. Furthermore, we will assume that laser guide stars are not available, and that light from the source itself must be used to cophase the array. We will further restrict the discussion to consider only the technical issues involved in building a new instrument, with the understanding that certain vital aspects of the array, for example the longest baseline, would be determined by the science one would hope to do with the instrument. These issues are not considered in this paper.

2. CONTEXT FOR A NEW ARRAY

If we were to consider designing a new imaging interferometer, the *fundamental* aspects of the design would be similar to those of COAST. The beam combination and delay lines and trolleys would be essentially the same and based on proven technology. The interferometer would be located at a site with high incidence of clear skies and excellent seeing conditions, preferably within the European Community, providing easy access from Cambridge. Because of the scope of the project, it would likely be a collaborative program, and would be developed concurrently with existing European programs such as

COAST itself, the GI2T,[10] and the VLTI.[11] The necessary funding for the project would be less than for a 4-m class telescope, approximately £ 5–10 million. For the instrument to be competitive it would aim at seeing first light within the next 5 years, and preferably before the turn of the century.

3. PARAMETERS FOR THE DESIGN

This prospective interferometer would be designed primarily for imaging. It would image with measurements of visibility amplitudes and closure-phases, using perhaps 6 telescopes at any given time. This number of apertures is thought to be near optimum, offering improved phase-closure constraints whilst maintaining sufficient light for combination in each output beam.[4] The total array would be composed of 12–18 telescopes, so that the configuration of the six-telescope subarray could be changed rapidly, simply by switching relay mirrors. This facility would allow more efficient sampling in the Fourier plane of the observations—faster than would be possible with earth-rotation synthesis alone, and permit more flexible choices of the instantaneous baseline coverage.

Evacuated beam transport would be used to relay the light from the telescopes to the main beam combining area. This would eliminate any additional phase aberrations introduced by ground seeing. In addition, vacuum delay lines would be used, obviating the need of dispersion compensation that is required with air delay lines, and thereby allowing simultaneous fringe measurements across the visible and near-infrared spectrum.

The interferometer would be designed to observe up to wavelengths of 20 μm, although for simplicity the instrumentation would likely first be operational at wavelengths of up to 3.5 μm. Collecting apertures of diameter 1.0–1.5 m would be used with a similar telescope design to those at COAST. The apertures would be stopped down to the appropriate size so that the effective apertures had a diameter no larger than $3r_0$, which is optimum for tilt-corrected wavefronts.[12]

Adaptive optics (AO) would not be essential to the design, as it could not significantly extend the limiting magnitude of the interferometer when the source itself is used as a guide star. Both an AO system and an interferometer would independently cease to function at approximately the same light level, when there are insufficient photons per coherence volume to either sense the wavefront, tilt correct, or fringe track. Conversely, if there is enough light in an interferometer to drive an AO system, then adaptive optics are not strictly necessary—the interferometer would function well even without the adaptive optics, using only tilt correction and $3r_0$ sized apertures. Although not essential, a low-order adaptive optics system could be considered in order to improve the quality of the measurements on sources that were already bright.

The new interferometer would aim from the outset to include a level of automation comparable to that found in radio interferometers. Currently, most interferometers require expert assistance in several routine tasks, for example the alignment of the numerous optical elements. These tasks must be all be automated if the new interferometer is to be as efficient and competitive as possible.

4. AREAS OF DEVELOPMENT AND INNOVATION

4.1. Interferometric site testing

A program of site testing would be necessary, and innovation is possible in the design of a seeing monitor, specifically to evaluate an interferometer's response at long baselines. The performance of an interferometer at baselines less than $\sim$10 m can be inferred, for instance, from interferometric measurements of path fluctuations on scales as short as 40 cm; measurements of the spatial coherence length r_0 and the coherence time t_0 are all that is required. However, the behaviour at longer baselines is less well determined and cannot be simply extrapolated from data at short baselines; an analysis of temporal power spectra of short-baseline data is perhaps not a reliable indicator of an outer scale of turbulence—it is doubtful, for example, that Taylor's frozen-turbulence approximation remains valid over baselines in excess of 10 m.

The full characterization of a site would require measurements of piston phase changes using baselines between 10 and 100 m, only possible with an interferometer. This would show the range of baselines where the path fluctuations begin to saturate.

Unfortunately such measurements would require an interferometer almost as complex as the final instrument. Other indirect methods, such as the measurement of the decorrelation of tilt as a function of baseline,[13] may be a practical alternative.

4.2. Telescope design for larger apertures

The telescopes for a new interferometer would use altitude-azimuth mounts, but would need to be modified from the present COAST design to accommodate mirrors 1.0–1.5 m in diameter. The frames for the telescopes would ideally provide a compact and rigid structure and could usefully benefit from advances in composite material fabrication. Light-weight mirrors would also be an advantage, allowing faster slewing of the siderostats and a major cost reduction in the unit telescope cost. This will be particularly relevant should as many as 12 to 18 telescopes be desired.

4.3. Optimised array configurations

Although much work has been done on optimised array configurations for radio interferometers,[14,15] very little attention has been given to the design of long-baseline optical arrays. In an optical array, significant advantages arise if each baseline that resolves the source is spanned by several shorter baselines that do not. This is because the whole array can be made coherent simply by fringe tracking on the shorter baselines and tying the array together in a piecewise manner. Although this scheme was proposed by Roddier[16] in 1988, and has been discussed on several occasions since,[17,18] no published work has further developed or formalised this approach. The constraints would be different than for a radio interferometer, and the optimization may yield a substantially different result.

4.4. Instrument design

Most existing interferometers have been designed as either technical demonstrators or with limited scientific goals in mind. Any future imaging array would be need to be targeted to a wider astronomical audience, and would therefore require a full complement of multi-wavelength detectors so as to maximize science output. Though the most attractive wavelength range for operational purposes is the near infrared (on account of better seeing and an insignificant thermal background) instruments at both visible and mid-infrared wavelengths will be necessary, both providing at least moderate spectral resolution ($R \sim 100 - 1000$). The role for innovative instrument design cannot be overestimated.

4.5. Automation for efficiency, speed, and comfort

One of the most time-consuming tasks in running an interferometer is the initial alignment of the beams, required prior to observations. Automation of the alignment would be time-saving and reduce the complexity of bringing the system on-line. Moreover, all interferometers have very restricted fields of view, due to the fact that they view stars using afocal beams seen through apertures that are tens or hundreds of meters away from the detector optics. The pointing of the telescopes must be very accurate for the light to arrive at the detectors; acquisition of a new source can occasionally be difficult and again time consuming. The automation of a wide-field acquisition system at each telescope is in principle not difficult, and would make the acquisition of new stars straightforward on even 100 m baselines. Similar automated features leading to a more efficient observing capability would form an essential element of a future array.

5. FUTURE PROSPECTS

Our discussion above is by no means exhaustive, and there are clearly numerous developments ongoing in interferometry that show great promise, but that are still in the early stages of testing: (1) Fibre optics are now being used in the IOTA interferometer as spatial filters to improve visibility measurement and calibration.[19] (2) The dual-star feed of the Palomar interferometer, is being developed for the use of natural guide-stars to provide phase-referencing for observing faint sources.[20] (3) Geometric phase modulation is now being evaluated at SUSI as a possible means of producing accurate broad-bandwidth visibility estimates.[21] Although it would be premature to judge these techniques right now, they may well ultimately change the way optical/infrared interferometry is performed in the long term.

Although, the interferometer design that we have outlined is a conservative one, based on our experience with COAST, it would be straightforward to build and would involve few risks. It would include innovations in some aspects of the instrument, but would incorporate only modest advances in interferometer design. However, the required technology is known and the experience is available to guarantee the success of such a project. Furthermore, with a suitable complement of instruments, such an interferometer would undoubtedly open new vistas onto many areas of astrophysical research.

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