Technologies for a cost-effective astronomical imaging array

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ABSTRACT

We discuss the design of the Large Optical Array, an optical/IR interferometer optimised for rapid imaging of complex astrophysical sources.

Keywords: Imaging arrays, array geometry, beam combination, adaptive optics

1. INTRODUCTION

The COAST and NPOI interferometers[1,2] have demonstrated the potential for ground-based imaging using interferometric arrays. The time is now ripe for a successor instrument, which uses the same fundamental idea of closure-phase imaging, but extends the performance dramatically, from a prototype array to one capable of being used as a facility instrument. To be astronomically competitive, such an array must allow the investigation of a wide range of important astrophysical questions. We discuss here the rationale behind the design of one such array, the Large Optical Array (LOA).

2. CONTEXT

Astronomical interferometry is now ready to take the next big step, moving from a technical/experimental phase to one where it is seen as an important astrophysical tool by many astronomers. The next generation of interferometers will not be cheap, and a project to build an interferometer which is capable of observing a wide range of astrophysical sources will gain more support in the mainstream astronomical community than a more limited instrument. On the other hand, an interferometer which tries to do everything will be too expensive, and may be so complex it can do nothing well. The balance is somewhere in the middle, an instrument which is optimised for investigating a moderate number of key astronomy topics.

With this in mind, a consortium has been set up in the UK to look at the astronomy that could come from a new array, and the ways that such an array could be constructed. The consortium consists of four universities interested in the construction of the array (Cambridge, Durham, Imperial College London and University College London), together with a further eight universities interested in the defining the scientific priorities for the array. The major conclusions that have arisen from the consortium meetings are that imaging is more important for the UK community than astrometry, and that rapid imaging of complex targets is a priority. Milliarcsecond resolution at wavelengths between 0.6 and 2.2 microns is seen as the minimum for tackling high priority targets such as star and planet formation and active galactic nuclei. The major constraints on the wavelength regime were the need to access the Hα line at the short-wavelength end and the need to penetrate dusty regions at the long-wavelength limit. A limiting magnitude faint enough to allow imaging of a significant number of prototypical sources of each class is essential. Spectroscopic resolutions of order a few hundred is the minimum useful resolution for understanding many of the astrophysical phenomena at which the array is targeted: higher spectroscopic resolutions are desirable but may not be practical for faint sources.

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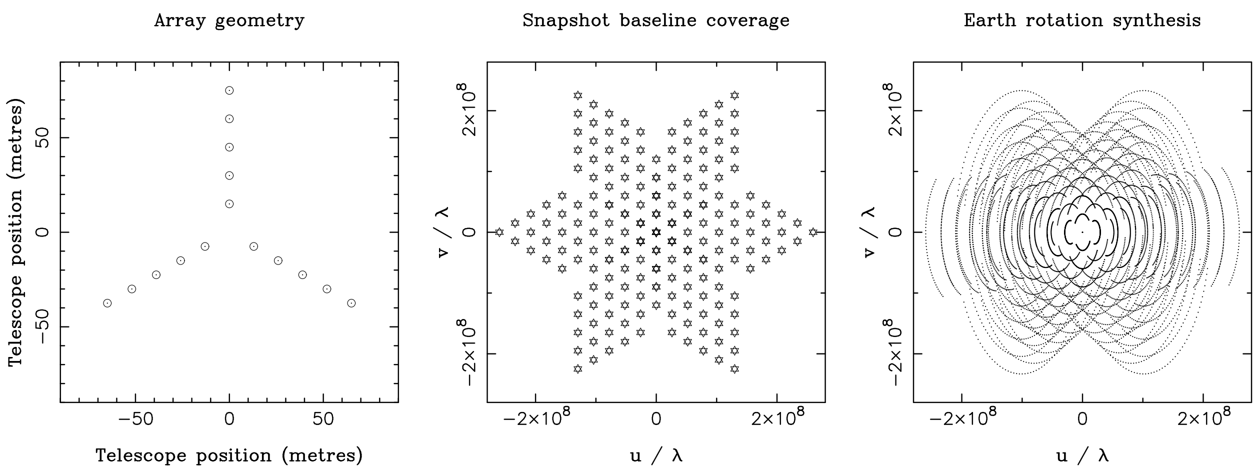

Figure 1. An example array configuration in a 'Y' geometry with good phase-bootstrapping properties. The figures from left to right show the array geometry, its instantaneous Fourier-plane sampling for a source near the zenith, and the sampling after allowing for a moderate amount of Earth-rotation synthesis.

3. CHALLENGES

The astronomy priorities outlined above lead to a number of fundamental design choices. The angular resolution specification leads to a maximum baseline requirement of order 500m. The limiting magnitude requirement is probably the hardest to reach: primarily it drives the need for a site with good seeing, but it also drives the telescope aperture diameter. A figure of 1.2m diameter on a site with median seeing better than 0.7 arcsec gives a fringe-tracking limit at around K=14, sufficient to access a large number of AGN and YSOs. Sites with good enough seeing and enough flat land to reach the required baselines are rare, but a site which appears to meet the requirements has been identified in Tenerife.

The requirement for rapid imaging of complex sources is one which is not met by any currently existing array. Rapid imaging is defined here as imaging on timescales of order 1 night or less. This means that the amount of array reconfiguration which can be allowed for the observation of a given source is relatively small. For complex objects, a large number of U-V points is required for good imaging fidelity. The work of Tuthill et al in these proceedings[3] illustrates the sort of array size needed for imaging relatively complex astrophysical sources: sources such as AGB dust shells and Wolf-Rayet stars are imaged using arrays with between 10 and 20 apertures.

A further implication of source complexity is that the source visibilities will be low on the longest baselines. This will have a detrimental effect on the limiting magnitude unless we use "phase bootstrapping"[4]: using phase information derived from short baselines where the source is less resolved to acquire fringes on longer baselines. To do phase bootstrapping, the longest baseline must be made up of a 'chain' of many short baselines. As a result, a large number of telescopes is needed, even larger than implied simply by U-V coverage.

This combination of requirements drive the design towards an interferometer with a large number of large apertures on long baselines: this is a potentially complex and expensive array. The following sections sketch out how some of the difficult requirements of the Large Optical Array can be met. We describe the basic elements of the design which has been used as the basis of cost estimates for LOA. It is expected that as a more detailed design for LOA is developed, some aspects of the design will change, but we believe that the overall design is now fairly well determined from the science goals of the array.

4. ARRAY LAYOUT

As explained in the previous section, the array design is to some extent dictated by the need to do phase bootstrapping. Roughly speaking, to get a 1-D map with 10 resolved pixel elements across it we need a linear equispaced "chain" of about 10 telescopes: to get a 10×10 pixel map, we can use a 3-armed 'Y' array with 15 telescopes, 5 on each arm (see figure 1), which can be thought of as a superposition of 3 approximately-linear 10-element arrays at 3 different orientations. These telescopes must be arranged in a near-redundant configuration in order to maintain high visibilities on the shortest baselines.

Although 15 telescopes will be sufficient to obtain a fairly complex map of a source of an appropriate angular size without needing to reconfigure the array, several different array configurations will be needed to access different sources of very different angular scales. For example, an array of 15 telescopes where the maximum baseline is 30m would be appropriate for imaging nearby red supergiant stars, whereas a scaled version of the same array with a maximum baseline of 500m will be needed to look at more distant and bluer stars. Another reason for needing to reconfigure the array is that arrays with different angular resolutions will be required to match or dovetail with the spatial scales accessible to other instruments with complementary capabilities, e.g. NGST, ALMA, VLBA and so on. Reconfiguration of the array is planned as a relatively infrequent occurrence, similar to the VLA, where reconfigurations take place every 6 months or so.

A 'Y' design appears to be the best layout: it gives excellent 'snapshot' U-V coverage as shown in figure 1 and with Earth rotation synthesis the coverage is further improved as shown in the figure. In the redundant configuration shown, only 87 different U-V points are sampled instantaneously; this design could be adjusted slightly to make more of the 105 possible baselines distinct, while still retaining the short spacings necessary for array cophasing. Other array geometries such as circles are possible, but the 'Y' has several practical advantages: it is easy to match the angles of incidence for the reflections in different arms of the interferometer, thereby equalising the polarisation states of all the beams; beam transport from the telescopes has to be in vacuum pipes for an array of this size and the number of vacuum pipe supports is minimised with a Y configuration; the array can be easily scaled, reusing telescope and pipe support foundations from smaller arrays in the larger arrays.

5. ADAPTIVE OPTICS

The most important form of adaptive optics for an imaging interferometer is that for correcting atmospheric piston variations between the array elements: at the faintest magnitudes only correction to within a fringe coherence envelope can be achieved, and this sets the ultimate limiting magnitude of the system (it has to be emphasised that, as with any adaptive optics system, the limiting magnitude refers to the flux unresolved on the relatively coarse angular scales corresponding to the shortest interferometer baselines: within the interferometric field of view, objects 5-6 magnitudes fainter can be easily observed). At brighter magnitudes, real-time correction to better than a radian is possible, and this can be used to take long-exposure interferograms at high spectral resolution.

Given that the fringe-tracking limit of a 1.2m-telescope interferometer is around K=14, it is not cost-effective to use a "dual-feed" system to allow fringe-tracking on a reference source a few 10s of arcsec from the target source, since the increase in fractional sky coverage resulting from such a system would be less than 1%. Instead, efficient use must be made of light from the source itself for array cophasing.

An array design with separate fringe-tracking and 'science' beam combiners is essential for achieving the faintest magnitude limits and hence the most science: the fringe-tracker design can be separated from the needs of the science instruments so that these two functions can be separately optimised. Fringe-tracking can be done with pairwise beam combination, whereas imaging requires larger numbers of beams to be combined, requiring the light from each telescope to be split more ways and hence reducing the instantaneous fringe SNR. The array design must be optimised to allow maximum throughput to the fringe-tracking combiner, since this sets the limiting magnitude of the system; we have preliminary optical designs with only 11 reflections between the incoming stellar beams and the fringe-tracking detectors, but 17 reflections for the science combiners.

Considering fringe-tracking as the lowest order of adaptive optics, the higher-order levels of AO involve correction of the wavefronts at each telescope. As shown in figure 2, tip-tilt correction provides nearly perfect wavefront compensation for 1.2m apertures in the K-band, where $D/r_0 < 2$ in typical seeing. This is the most important waveband, since it sets the fringe-tracking limiting magnitude. It is clear however that for shorter wavelengths, higher-order adaptive optics has the potential to substantially improve the fringe SNR, and only a moderate order of AO is required. Any AO system which has to work on 15 separate telescopes must be both cheap and robust. We are beginning work on an AO system optimised for interferometry. The system may use micromachined deformable mirrors (figure 3), which are both cheap and reliable, and the Mozurkewich hybrid tilt/focus wavefront sensor which can be used to sense up to 5 wavefront modes with high sensitivity.

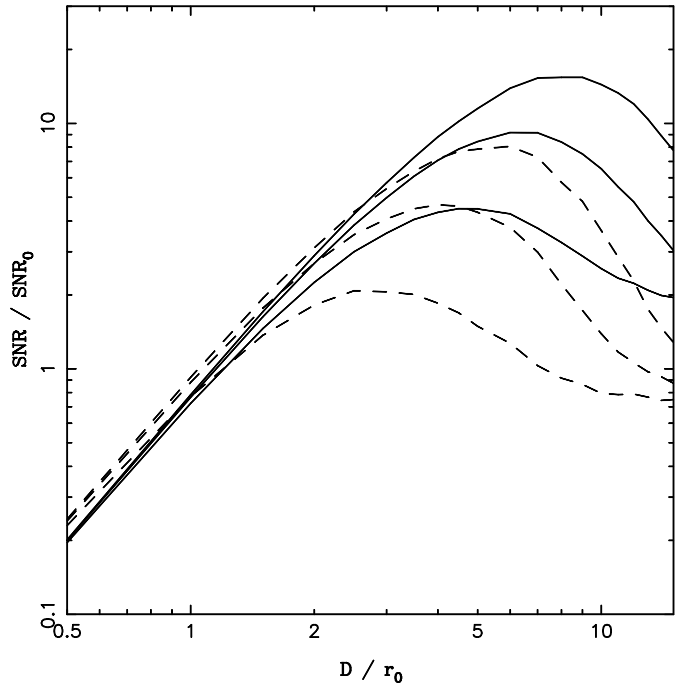

Figure 2. The fringe amplitude signal-to-noise ratio at low light levels with 1st, 2nd and 3rd radial order adaptive correction. The solid lines are with monomode fibre spatial filtering, and the dotted lines without. The figure is taken from Buscher and Shaklan 1993[5]

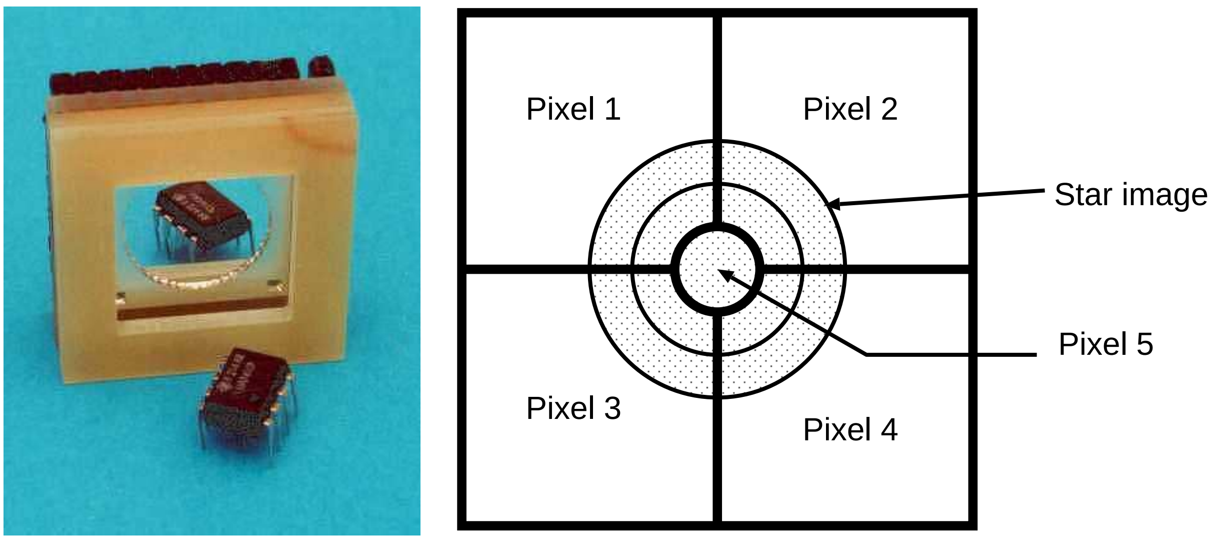

Figure 3. A micromachined deformable mirror from OKO Technologies (left) and the geometry of a hybrid tilt/focus sensor (Mozurkewich, private communication). The shaded circular rings represent the diffraction pattern of a star falling on the 5 pixels of the detector.

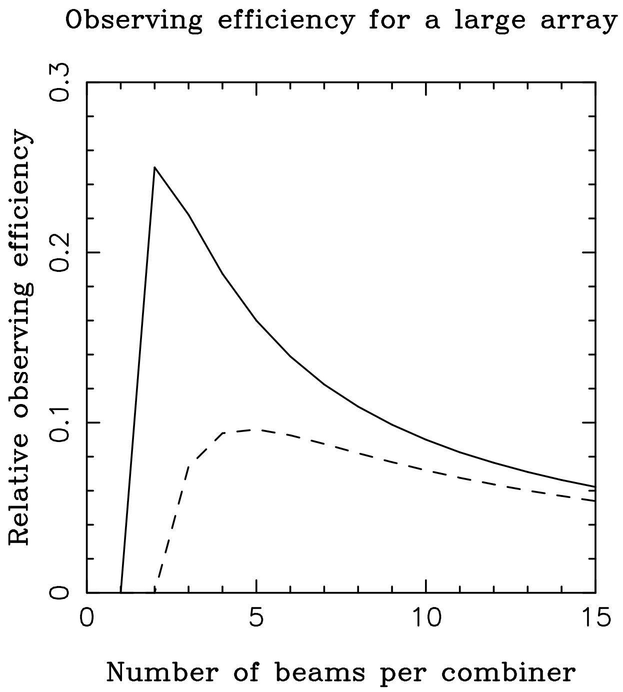

Figure 4. The amplitude (solid line) and closure phase (dotted line) observing efficiency of a fixed number of telescopes, as a function of the number of telescopes which are combined simultaneously in parallel sub-arrays. It can be seen that the optimum sub-array size is either 2, if amplitudes only are being considered, or 4-5 if the closure phase observing efficiency is more important. More details of this calculation can be found in Buscher.[6]

6. BEAM COMBINATION

With 15 telescopes and 105 possible baselines, beam-combining is a potential nightmare. However it is important to realise that not all baselines need to be measured simultaneously to make full use of the array: the minimum number of telescopes that need to be combined simultaneously for imaging purposes is 3 (to derive a closure phase), and as long as one can switch rapidly (i.e. on timescales of minutes) between baselines, one can in principle derive all the phase closure and visibility information that the array can produce using only a single 3-way beam combiner. Phase bootstrapping can take place on a separate set of fifteen 2-way combiners so that all the baselines can be phased, regardless of which triple of telescopes is being used for science observations.

In order to maximise observing efficiency, several sub-arrays of telescopes must be combined in parallel, using for instance five 3-way combiners or four 4-way combiners (with one position unfilled). In fact, we can show that large numbers of small beam-combiners is an optimal configuration: if we divide a large number M of telescopes into M/m sub-arrays of m telescopes each (M is presumed divisible by m) and combine each sub-array in an m-way beam combiner, then we can show that the observing efficiency is best for $m < 5$ (see figure 4). The observing efficiency is defined as the inverse of the time required to measure a given number (assumed large) of visibilities or closure phases to a given SNR, in the photon-noise-limited regime.

Efficient 3-way pupil-plane combiners are in use at NPOI,[7] efficient 4-way pupil-plane beam combiners have been demonstrated at COAST, and efficient 5-way Fizeau combiners have been used for aperture synthesis experiments at the William Herschel Telescope[8] and the Anglo-Australian Telescope[9]; work remains to be done to reduce the crosstalk in the 4-way combiners by increasing the pathlength modulation rate. More stable and compact 4-way combiners are under development at COAST, and the current miniaturised designs will allow four 4-way combiners to be built on a single optical breadboard.

7. TELESCOPES

The LOA preliminary costing shows that more than 30% of the total cost of the array is in the fifteen 1.2m telescopes. These are currently specified as scaled-up versions of the COAST siderostat/beam compressor system. This design has the advantage of having a compact and stiff moving element and only 3 reflections from sky to vacuum pipe, but the sky coverage is limited by vignetting and the cost is dominated by having to have two large mirrors. Possible

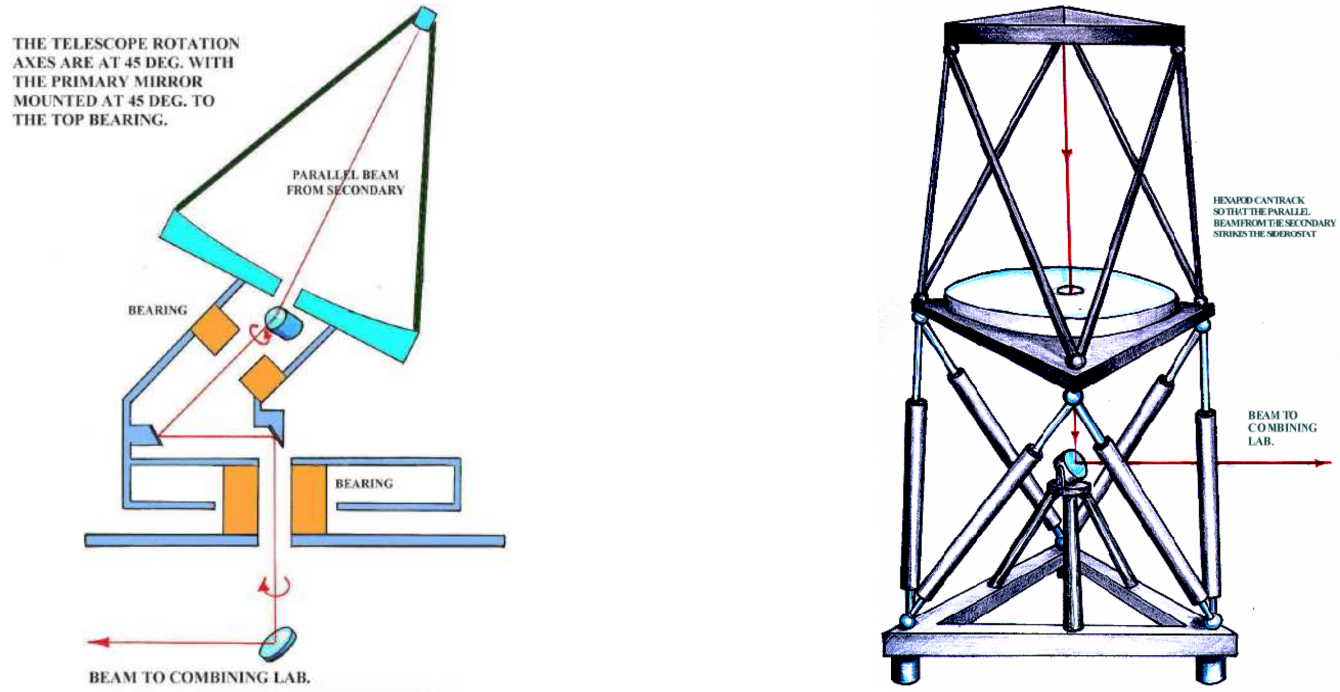

Figure 5. Possible alternatives to a siderostat/beam compressor arrangements for the unit telescopes. The figure on the left uses the 'goniometer' arrangement, which uses industrial bearings of the type used on the COAST siderostat, the figure on the right shows the use of an industrial hexapod mount to move a telescope about a centre of rotation which is coincident with that of a small fixed siderostat.

alternative designs include conventional alt-az telescope mounts or more exotic arrangements as shown in figure 5.

8. CONCLUSIONS

We have presented the outlines of a design for a next-generation optical/infrared imaging array. We have argued that the array design should be based on a science-driven specification, and have shown that, although the technological requirements are challenging, an array can be built that meets the specification using proven technologies.

The Large Optical Array proposal as submitted to the UK-only Joint Infrastructure Fund (JIF) was costed at about US$18M at 1999 prices. Although highly rated, it was ultimately unsuccessful in the JIF competition. The plan now is to take the design forward as an international project, with the UK taking a ~50% share. The prospects look good that LOA will be funded in the near future; it represents a timely opportunity to exploit the advances that have been made worldwide in the technology of optical and infrared aperture synthesis, and it has strong and growing backing from the scientific community.

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