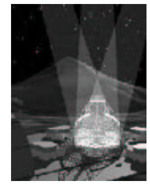
Adaptive optics for ground-based hypertelescopes

Venice 2001
Beyond Conventional Adaptive Optics



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ABSTRACT

Large Earth-based hypertelescopes will require adaptive optics using specific wavefront sensors. Most challenging is the formation of high-resolution images on very faint objects. MCAO approaches are of interest, as well as satellite-based laser guide stars. For wavefront sensing, we present an extension of dispersed-fringe algorithms, using tri-dimensional Fourier analysis.

1. INTRODUCTION

The prospect of building large hypertelescopes, i.e. "multi-aperture densified-pupil imaging interferometers", combining hundreds or thousands of mirror elements across a square kilometer (CARLINA concept of "Exploded Extremely Large Telescope") or even 10 km (Optical Very Large Array), demands adaptive optics to exploit the high angular resolution achievable. The high limiting magnitude, matching in principle that of a compact mosaic mirror having the same collecting area, also demands that the faintest sources be imageable with the adaptive system (Labeyrie *et al, this conference*).

The actuator problem is similar to that for compact mosaïc mirrors, with inter-element piston corrections and tip-tilt corrections needed for each mirror element; and intra-element corrections also needed if the elements are larger than r_0. Typically, one must restore the spherical figure of the sparsely sampled wavefront reflected from these elements of a large diluted primary mirror.

The wavefront sensor however has to differ from those serving for compact mosaic mirrors. Indeed, the large gaps between elements here destroy the wavefront continuity exploited in wavefront sensors such as Shack-Hartmann's tilt sensor, the curvature sensor, and pyramid sensors. One approach, described by Pedretti *et al* (2000), involves a hierachy of sub-aperture triplets. Another approach (Labeyrie *et al*, 2000), currently explored by two of us (VB & AL), involves a tri-dimensional Fourier analysis of the image, recorded as a data cube in the x,y, lambda spectro-imaging mode.

2. THE CHALLENGE OF MCAO FOR KILOMETRIC APERTURES

Diluted apertures of kilometric size raise challenging problems for adaptive optics. On bright stars, the method already utilized by Michelson at Mt Wilson remains applicable: fringes from pairs of apertures can be dispersed to extract information on path difference and phase. This can be extended to three apertures , and then to any number of them if considered as a hierachy of triplets (Pedretti *et al*, 1999). Another algorithm is presented below.

These methods give the piston errors, while the "local" errors, tip-tilt and seeing within the sub-apertures, are measurable like in ordinary telescopes.

Faint stars are more difficult to deal with. The MCAO approaches discussed at this conference are of interest. The tomographic modelling of the atmosphere is here made more difficult by the gaps between apertures, but can be helped by the broad primary field in instruments such as CARLINA (Labeyrie *et al, this conference*). Several focal stations located 5°-20° apart can observe bright stars and provide useful tomography data on the local and high-altitude atmosphere (Labeyrie *et al*, 2000).

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3. LASER BACK-SCATTER GUIDE STARS

This approach, using Rayleigh scattering or sodium resonance has been explored in considerable depth by different groups for monolithic apertures since the description of Foy and Labeyrie (1985). In diluted interferometric arrays, this cannot provide information on piston errors among the elements. However, a challenging variant conjectured by C. Townes (private communication, 2001) may provide such information. A significant limitation of laser shooting arises from safety regulations for aircraft pilots.

With large sub-apertures, 8 to 10 meters for example, it is of interest to use Rayleigh or sodium Laser Guide Stars to correct each sub-aperture separately. This can intensify a faint object observed, and thus increase the limiting magnitude for piston correction.

4. SATELLITE-BORNE LASER GUIDE STARS

The idea of using satellite-borne laser sources as artificial stars for adaptive optics on Earth-based telescopes has been considered for several decades. Unfortunately, a satellite seen fixed with respect to the constellations has no orbital velocity around the Earth and therefore falls towards it. The feasibility of using a highly excentric orbit as an approximation to a free-falling body has been explored by A. Greenaway (private communication). He found that such orbits could maintain a satellite for an hour within the visible isoplanatic patch of a bright star, but with little flexibility in selecting the stars.

We have further explored the matter by considering a flotilla of nano-satellites equipped with small solar sails for orbital control. Rather simple spaceships, presumably of low cost, can suffice for this use. For continuous availability when switching objects, inactive satellites have to be driven in advance to the apparent location of the next object to be observed. Pending space-based hypertelescopes, for which adaptive phasing will likely be a lot easier, such driven space-ships may prove to be efficient carriers of artificial stars. A more detailed study would be of interest.

5. WAVEFRONT SENSING ALGORITHMS FOR DILUTED APERTURES

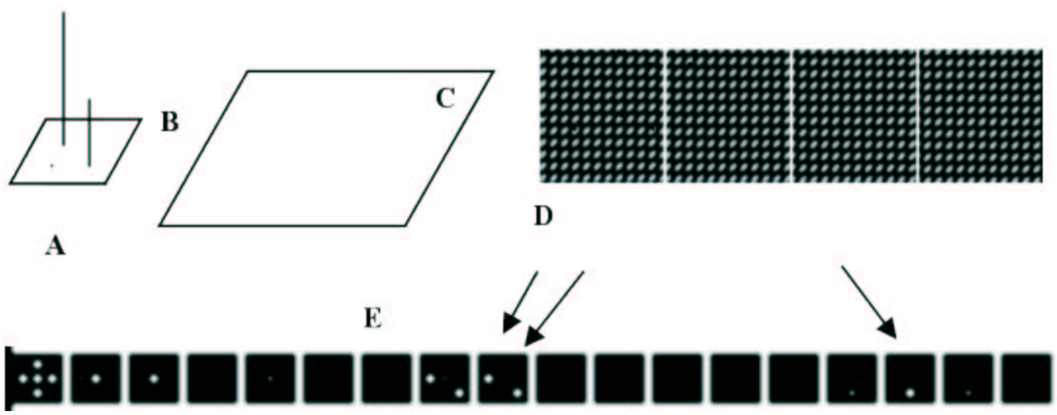

Figure 1. Simulated wavefront sensing with tri-dimensional Fourier analysis, shown with only 3 apertures for simplicity. B- pattern of 3 apertures; A- piston errors delta, indicated by vertical bars; C- autocorrelation of aperture (modulus); D- sections of spectro-image data cube, i.e. interference patterns at adjacent wavelengths. 40 sections are recorded in the (x,y, lambda-1) data cube; E- calculated (X,Y) sections of the cube's tri-dimensional Fourier transform. Delta values are increasing from zero, at left. For faster computing, only those columns corresponding to the pupil's autocorrelation shown in C are calculated The 3 peaks (arrows) appearing at certain delta values indicate the piston errors for the triplet of apertures. With N apertures, there are N(N-1)/2 peaks, several of which can be in the same column of the output cube if there is.

In addition to the triplet hierarchy algorithm of Pedretti et al. (1999), mosaic apertures, whether diluted or not, can be analyzed in different ways:

1. by extending the Shack-Hartmann method with dispersion;
2. by extending curvature sensing (Cuevas 2000).

Another possibility for large hypertelescopes , briefly described by Labeyrie et al. (2000), involves the tri-dimensional Fourier analysis of spectro-images (figure 1). Simulations are pursued by one of us (VB) to assess the method and its limiting magnitude. The spectral resolution determines the coherence length, which can be adjusted to match the maximal piston errors expected , well beyond the seeing-induced bumpiness of the wavefront, to accomodate the positioning errors of mirror elements in large diluted mosaïc mirrors. Several types of "integral field spectroscopy" devices among those developed at Marseilles by G. Courtès and his group, provide "spectro-images" directly usable for both science and wavefront sensing. Among these, the field-grating arrangement can provide hundreds of monochromatic images and is perhaps most efficient. The prospect of CCD’s capable of direct photon counting is particularly promising.

6. CONCLUSIONS

Adaptive techniques can be extended to diluted apertures as large as one kilometer, and perhaps ten kilometers on Earth when dealing with bright stars. Direct images having diffraction-limited resolution are then directly obtainable at the focus of interferometric arrays built according to the hypertelescope architecture.

A challenging problem is the access to faint sources, with a significant sky coverage, in such instruments. Possible solutions are foreseen with laser guide stars in two different ways: 1- Towne’s idea of a scheme using laser backscatter ; 2- laser sources aboard a flotilla of mobile spaceships. Pending space hypertelescopes, such instruments can extend general astrophysical imaging to high resolution on deep-Universe galaxies.

REFERENCES

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