PROGRESS OF THE LARGE INTERFEROMETER AT C E R G A

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Summary

The coude beams from a pair of 1.5 meter telescopes are recombined to achieve coherent aperture synthesis. The spherical telescopes move along a 70-meter baseline, expandable to 300 meters. For the VLT, a grid of railway tracks with 2-D carriages meets the requirements for incoherent and coherent observing.

Steps in the design and construction of a coherent telescope array have been described previously (Labeyrie, 1982, 1984). In 1975, it was first verified that stellar light from two telescopes could be recombined coherently. In 1978, it was decided to develop spherical mounts for 1.5-meter telescopes. Among the expected features were: 1. coude focus with only one flat mirror; 2. wheels for mobility along railway tracks; 3. structural stiffness for interferometric stability, also implying vibration amplitudes inferior to 0.1 micrometer at each reflective surface. This last and most critical requirement implies materials which have to be stiff and also damped.

Since Newton himself, spheres have been employed as telescope substrates, but no satisfactory way of driving the spheres had been found. The published attempts made in the direction of motorizing spherical mounts had involved fittings or clamps holding the sphere, and thereby restricting its three natural degrees of angular freedom. The standing problem was to design a sphere-walking mechanism with no priviledged axes and yet three degrees of freedom. Only two angles are enough to point conventional telescopes, but a third degree makes it possible to simplify the optical train of the coude focus. With the limited engineering support available, it took a long time to go through all the stages of building successive prototypes until a working mount resulted. The spherical mounts now behave as expected. They are a lot more compact than altazimuth mounts, lower in cost, and more easily equipped with wheels for a movable telescope.

Also, their coude output can be aimed in any direction, although it has a single flat mirror. In most respects, spherical mounts are superior to alt-az

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mounts, and their adoption for the large telescopes of the next generation will further enhance the capabilities of these powerful instruments. One such design for a large array is described by Grundmann and Odgers (1983). The interesting "versatile array" concept proposed by Angel et al. (1983), while based upon alt-az mounted telescopes could probably become even more versatile if equipped with spherical mounts. Also, space-adapted versions of the spherical mount are studied for the telescopes expected to participate in the proposed TRIO space array, studied by the ESA. We therefore believe that the time spent in developing spherical drives has been worthwhile, although alt-alt mounts could possibly have been adopted for 1.5 m apertures.

Performance of spherical telescopes

Reproducing the natural walking motion of animals requires very sophisticated software. Even the simplified mechanical configuration which "walks" a smooth sphere required a good deal of programming to achieve a tracking motion of sufficient accuracy.

In their current version, our spherical telescopes have a pointing accuracy of 0.02 degree and drive accuracy of 0.5 arc-second in the best cases. Considerable improvements can be obtained with fine-pitch encoders and more accurate actuators. Screws driven by electric motors may prove preferable to the hydraulic pistons currently utilized.

The optical path length is not very much affected by the angular deviations of the telescopes, but critically affected by translations of the mounts or parts of them. Critical parts are the spider structures supporting the mirrors N2 and N3. These spider's legs are made of 3 fiberglass boards, 8 mm thick and 300 mm high in the beams direction. Their stiffness and damping factor are marginally adequate. Indeed, a laser interferometer which monitors the motion of one spider does show certain resonance modes during which the fringes become invisible to the eye. It is expected that 10 mm thick spider arms made of graphite-reinforced epoxy would solve the problem. 22 mm plywood is also attractive.

Optical train

Each telescope is an afocal parabola-parabola configuration with X20 angular magnification. The collimated coude beam received in the central station has 70 mm diameter, providing a compromise between the large field provided by larger beams and the immunity to seeing in the horizontal arms which narrow beams afford.

On the central table, light is refocused by an achromat onto a reflective slit. The slit feeds star light into a spectrographic arrangement. Because the coude field is unavoidably small, and increasingly so at longer baseline settings, a CCD camera is installed at the prime focus of the telescope, were it receives about 15% of the incident light, transmitted through the partially transparent N2 mirror. This mirror is in fact shaped as a null lens with a silver or aluminum coating, and protective overcoat, the thickness of which is adjusted for reflectivity on the order of 80%. A set of 6 interchangeable mirrors has been made for work in the visible and the infra-red. An auxiliary alignment system helps acquiring the coude beam and maintaining its proper orientation.

It uses a light source located on the central table, and which is seen by the prime-focus camera, together with the star field. This is obtained by having a corner-cube mirror installed between the No. 2 mirror and the camera (Fig. 1). The corner-cube reflector is drilled in the middle, so as not to affect the star beam transmitted through the No. 2 mirror. The collimated light beam coming from the central station is also partially transmitted by the No. 2 mirror, then reflected by the corner-cube, and again reflected by the back side of the coating on mirror No. 2. If a star has its prime-focus image superposed to the light source image, then its coude image is necessarily superposed to the light source itself. In addition, if the prime-focus image of the light source is maintained at a fixed position on the camera, by constantly adjusting the telescope's position angle and the elevation angle of mirror No. 3, then the pupil is seen in a fixed position from the central station. Among the 4 parameters defining the telescope attitude and its coude beam, two are controlled from the star's position on the prime-focus camera, and the remaining two are controlled from the star position on the slit jaw camera at coude. In practice, the first two are, as just mentioned, the telescope's position angle and the elevation of mirror No. 3. The other 2 are those which caracterize the star position on the celestial sphere. Two cameras are therefore interfaced to the drive computer in charge of each telescope.

Further details on the central table are shown in figure 1. The collimated coude beams, 70 mm in diameter, are focalized by achromatic lenses on a pair of slits with reflective jaws feeding the coude guiding camera with the two images. Light going through both slits is reimaged onto a single image through cylindrical lenses and a grating. The combined spectrum is either observed visually, or through a photon-counting television camera.

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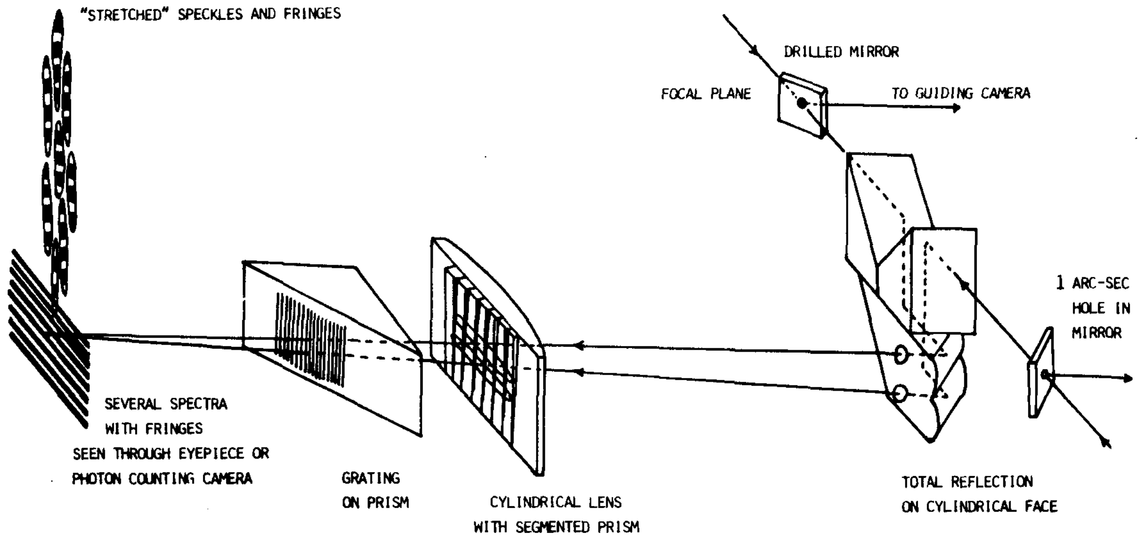

Fig. 1. Central optics in the large interferometer: large achromats (not shown) focus the afocal coude feam onto a field mirror having a 1-second hole. Star light admitted through the hole goes through erecting prisms, cylindrical optics, a segmented wedge plate and a grating. Light from both telescopes is recombined in the spectra thus produced. The cylindrical optics serves to stretch the image vertically, in order to optimize the use of camera pixels. The segmented wedge plate produces several spectra, each from a stripe in the aperture. It avoids the degradation of fringe visibility resulting from the large size of the aperture in comparison with seeing cells. Alternate ways of formatting the fringes can be adopted. Multi-spectral imaging is one of them. In any case, a fairly large number of camera pixels is needed to record all the information contained in the fringed image.

Because the images entering the 1" wide slits contain approximately 10x10 speckles, the contrast of the fringes in the spectrum would be degraded to $1/\sqrt{10}$, i.e. about 30%, of its real value. A slit width covering only one speckle would provide full contrast at the expense of a 10/1 reduction in luminosity. An image slicer could avoid the light losses associated with a narrow slit. However, a set-up equivalent to a slicer, but more flexible in its uses, is obtained by in-

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serting a dozen prismatic plates in the pupil of the spectrograph, as shown in figure 1. This splits the spectrum into a dozen horizontal bands, separated vertically. In each of them, the speckles are enlarged horizontally as a consequence of the pupil width restriction, and full contrast is thus retrieved in the spectrum fringes.

The central table is moved during observation by a micrometric carriage. Its maximum travel length reaches 1.5 meter, and its motion is programmed to vary as a function of the hour angle in order to exactly cancel the variations of the optical path difference. The stepping motor used initially caused excessive vibrations. It is now replaced by a continuous motor equipped with optical encoders for 2-micron positioning accuracy. Below the table, and attached to its supporting pier, there is also a fringe simulation bench which can be flipped in operating position by rotating the bench around its axis. When rotated upwards to become active, it projects into the table's optical system a pair of coherent beams of white light simulating the telescope's stellar light beams. The simulator helps developing the table's optical system, the image processing electronics and software, and also training observers to look for fringes visually. It includes simulated seeing for realistic fringe displays.

Image processing system

Pending the availability of powerful array processors at reasonable cost, a "modest" fringe processor having useful characteristics has been developed by F. Vakili. Because fringe information is concentrated in a peak when dealing with Fourier transforms of the television frames, Fourier transforms are better adapted to fringe processing than the autocorrelations utilized for speckle observations. The video signal, either in photon-counting form or digitized to one bit, is first fed into the "old" speckle correlator of A. Blazit, capable of computing the outcorrelation of 256x256 pixel frames on-line if these contain less than 110 bright pixels or centroided photon events. Autocorrelations, featuring 128x128 elements and 16 bits, are integrated during 4 seconds and then transferred to "Microfrangine", the 68000 microprocessor card programmed by F. Vakili to compute fast Fourier transforms. When searching for the fringes, their slope in the recorded spectrum is not known. Therefore, Microfrangine searches the presence of a significant peak of unknown position in the Fourier pattern. Pattern recognition routines attempt to find it amidst the noisy background generated by photon statistics. If the peak is found, its position may be fed back to the table drive, in order to stabilize the optical path difference.

Microfrangine can also provide fringe visibility measurements, although no effort has yet been made at pushing the accuracy by calibrations and statistical refinements. F. Vakili has successfully utilized Microfrangine on the small interferometer, where it has shown encouraging sensitivity, even beating the remarkable performance of a trained human eye for detecting fringes (the comparison is made with the eye observing the video image, not the direct star light). It is also performing well with the fringe simulator of the large interferometer. The stellar fringe simulator flips into active position and projects coherent beams towards the central table. Seeing may also be simulated with plastic sheets. The simulator trains observers for fringe searching. It also serves to evaluate image processing hardware. If used for finding the fringes, the table has to be displaced by 50 microns every 4 seconds, with the coherence length adjusted to 250 microns. With 1 mm uncertainty on the system's geometry, a typical fringe search time is therefore on the order of 3 minutes.

Desirable improvements concern the speed of the Fourier computations, the pixel count, which is currently insufficient to work in all colors simultaneously, and the possibility of determining fringe visibility and phase in each spectral channel independently. The latter possibility and its potential interest have been nicely illustrated by the fringe processor utilized at the MMT by J. Beckers.

Proposed VLT array

Reasons why a coherent array of spherical, mobile telescopes provides the best architecture for a VLT were previously described in Dugué, Labeyrie and Schumacher (1983). For maximum versatility, the telescopes participating in a coherent array should be able to move anywhere in the horizontal plane surrounding the central station. Air bearings may prove adequate for moving the telescopes on a smooth concrete platform covered with aluminum foil, but ways of pushing the telescopes need to be developed. An alternate possibility involves railway tracks arranged as shown in figure 2. Telescopes can move as needed along the North-South tracks and the East-West tracks if their carriage has 8 wheels (Fig. 3), 4 of which for North-South motion and the other 4 for going East-West. Only half of the wheels can be active simultaneously: if the telescope is going East-West the wheels serving for North-South displacements are retracted.

The zig-zag path, with about 10-meter pitch, allowed by such carriage systems is suitable for long-baseline interferometry. Indeed, the desired telescope positions at any time are along an ellipse having the central station at one of

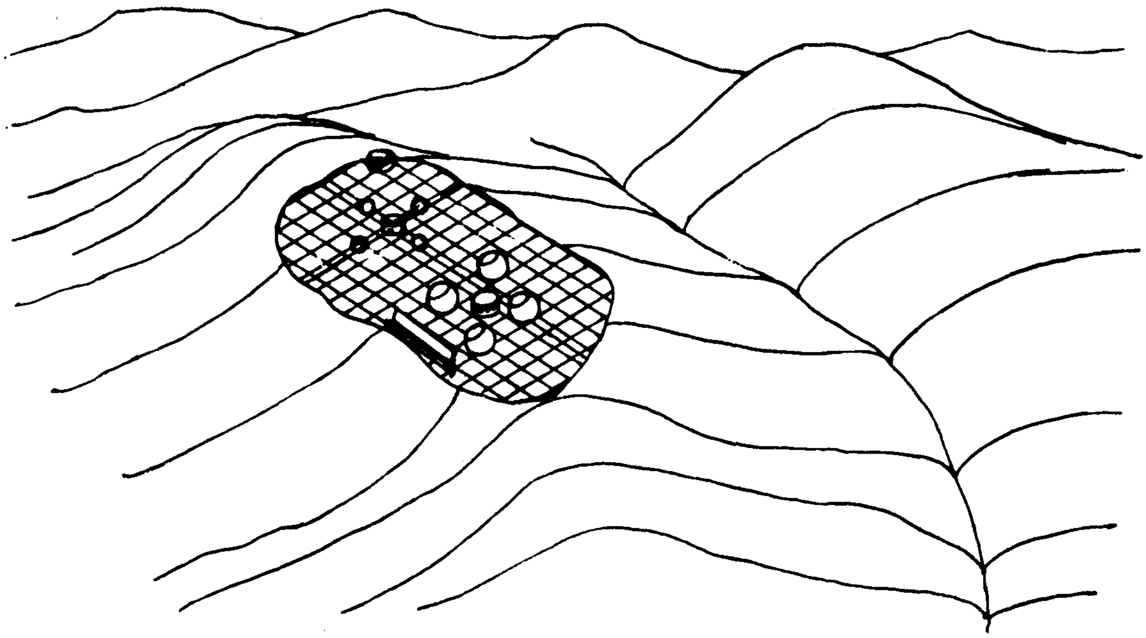

Fig. 2. Concept of VLT with telescopes mobile on track grid. Wind deflectors may be utilized if they prove useful. Several coude labs, such as an infra-red coude lab, a spectroscopy lab, and one for interferometry, contain different types of instrumentation. Smaller telescopes are also present for full-time use of the interferometry lab.

its foci. This ensures equal optical paths and makes it unnecessary to have large delay line systems. With the bidimensional pattern of railway tracks, all telescopes can manage to remain on the ellipse, which keeps deforming itself as a function of the hour angle. If the accuracy of the wheel drives cannot be made to meet the typical 0.01 mm requirement for temporal coherence, it is possible to install small corrective elements in the central station.

In terms of cost, the tracks remain quite manageable: a 200x200 meter square grid with 10 meter pitch requires 8 linear kilometers of tracks, costing approximately $200,000 (not including the concrete piers). Several telescopes and several mobile laboratories can move on the tracks like the elements of a chess-board game. The option of having several coude labs, themselves mobile on the grid, is likely to enhance the VLT's efficiency: while a dozen compact instru-

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ments can be permanently installed inside each of the spherical telescopes, the more bulky spectrographs or Fourier spectrometers, as well as instruments which must remain at a fixed angle with respect to gravity, should be installed in coude labs, located as close to the telescope as possible for maximum field and minimal degradation of the coude beam by seeing.

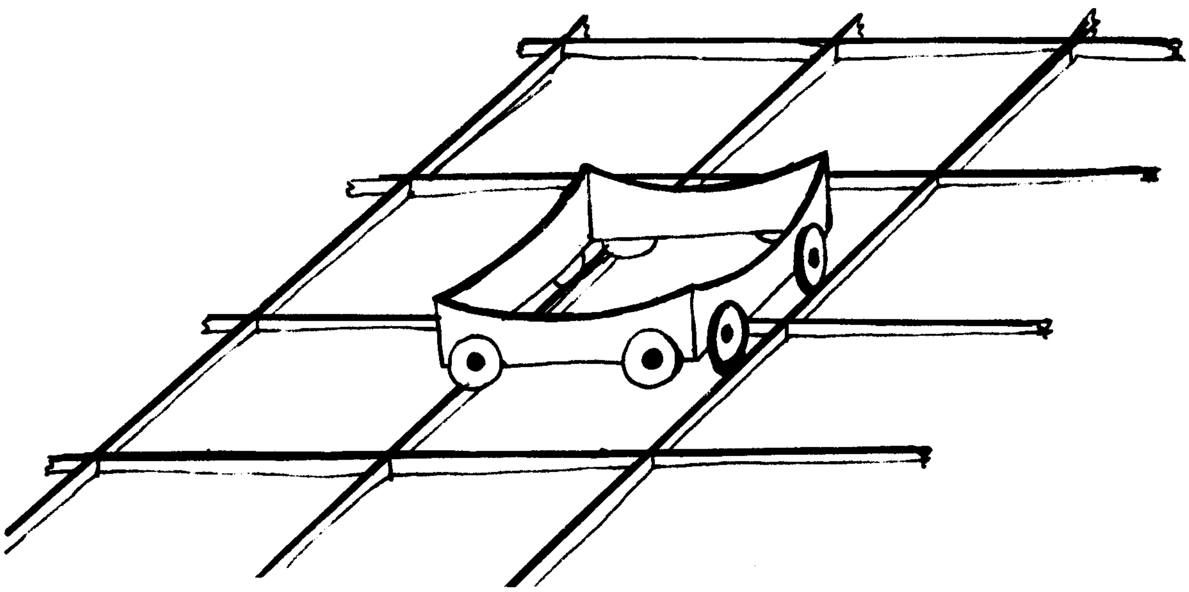

Fig. 3. A square array of railway tracks allows all the telescope displacements required for aperture synthesis. Telescope carriages equipped with 8 wheels can move in both directions on the grid if groups of 4 wheels are retractable. Although the motion cannot be continuous in both directions simultaneously, the telescopes can follow the deformation of the "coherence ellipse", ensuring equal optical path lengths from the star to the central station.

At minimum spacing (fig. 4), the coude field can be quite large, i.e. 10 minutes at least and possibly one degree. Grazing incidence on mirror N3 can always be avoided by locating properly the telescopes with respect to the coude lab, as shown in figure 4B.

If a wall-type wind screen such as proposed by the VLT study group should prove desirable, it would be installed at the North edge of the platform, assuming that winds from the North are dominating, and telescopes could be aligned along this edge when used for non-coherent observing. However, the wall concept for a wind screen requires careful aerodynamic study before being too much advertised. The supposedly "isothermal" turbulence which it generates is in fact adiabatic. It should be investigated whether it can create distortions of the

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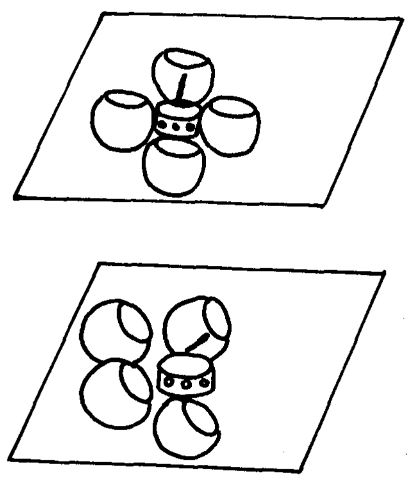
optical wave through a first order effect. Also, the velocity of the deflected wind is increased, and much more so with a wall-shaped deflector than with a conventional dome or a spherical mount structure. Because the spacing of the tracks needs to be about equal to the size of the main mirror in each telescope, in order to keep the carriage and mount design simple, the cost-efficiency of the array is reduced if telescopes of very different sizes are utilized. Therefore, a cautious technical approach is to first build a small extent of the track system, and one telescope on its carriage. Two coude labs may be installed initially, one fixed at the edge of the future platform, and one mobile.



CLOSE PACKED COUDE CONFIGURATION

for

A - high elevation

B - low elevation

Fig. 4. The square arrangement of tracks provides considerable operating flexibility for moving the telescopes, as well as mobile coude labs, to the optimum positions for various observing modes. For coude spectroscopy or photometry with the combined beams, the separation of the telescopes can be less than with an array of fixed telescopes. Example of closely packed configurations for high elevation (A); low elevation (B).

Should there be smaller telescopes dedicated to interferometry? At least one of the coude labs will be dedicated to interferometry, and could certainly be employed permanently if two or more smaller telescopes are available. It is our belief, however, that the large telescopes should be available once in a while for the interferometric programs if the future allocation committee finds it useful. Indeed, certain problems requiring spatial and spectral resolution will require a lot of aperture. Chances are that the interferometric coude lab can be designed for compatibility with both the large and small telescopes. The grid-of-tracks arrangement allows such reconfigurations, if the smaller telescopes can be made to ride the same tracks as the larger one.

Algorithms for aperture synthesis

Should the visibility phase be measured in addition to its modulus? If the Fourier plane is densely sampled, Fienup's algorithm generates images from modulus-only information. Increasing evidence shows the practical value of such algorithms (Dainty, 1984). However, there is one type of phase information which is easily obtained and quite powerful: the "multicolor" phases relating the fringe systems at adjacent wavelengths. These suffice to reconstruct maps if the object function is not color-dependent. In the general case, there are reasons to hope that multicolor maps can be obtained by helping the Fienup algorithm with the available multicolor phase information. Studies in this direction should be encouraged since they have huge potential implications for aperture synthesis, both from the ground and in space.

Conclusion

Exciting new observational possibilities are within reach for coherent arrays of large telescopes. We hope to illustrate some of them with the CERGA array, and thus encourage members of the VLT study team to incorporate the coherent option in their work.

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DISCUSSION

J. Beckers: The 1° field of view which you mentioned must refer to the geometrical imaging of your array. The wave/interferometric imaging field of view must be much smaller. I guess from your optical layout that the interferometric field of view equals about one arc second. Is that correct?

A. Labeyrie: 1° is a rough estimate of the field available at the combined focus for non-coherent observing, assuming suitable aberration correctors. The interferometric field is much less, about 20 arc seconds. Its extent depends on whether one is talking about the phase-conserving field, or the atmospheric aplanetic field. With the split-coudé system studied for TRIO, it may prove possible to obtain simultaneous fringes on 2 stars spaced by 1°.

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D. Enard: I don't understand how it is possible to obtain a field of view as large as 1° at the Coudé focus even in a close-packed configuration. Our investigation has shown that only a few minutes could be obtained unless the size of the third mirror is considerably larger.

A. Labeyrie: A 12m long Coudé beam, 1m in diameter and afocal, diverges into an 8° cone for a 1° field on the sky. A collecting mirror, 1.5m in size, in the central station, does collect most of the light. The third mirror has to be about the same size. Aberrations must also be considered.

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