An Interferometric Mode for the VLT

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1. The Emergence of Optical Interferometry

The heart of the VLT concept is the choice of an 8-m thin mirror. As early as 1983 (at the Cargèse Workshop), it was thought that an array of several telescopes, with its great flexibility, might be preferable to a giant Multi-Mirror Telescope. An array concept was presented at IAU Colloquium 79 in April 1984. It immediately appeared obvious then that one had to investigate whether a coherent combination of the array telescopes would be possible. On the one hand, formidable difficulties were expected, on the other it presented an exceptional possibility to greatly increase the scientific potential of the VLT and to give it a unique and long lasting capability among planned instruments. This evaluation became the task of the Interferometry Working Group.[1]

The main questions to be answered were: Which gain can the use of large telescopes in optical interferometry bring? Do acceptable compromises exist between the interferometry requirements and the more conventional use of the VLT, as required by a large fraction of today's European astronomical community? Is interferometry technically feasible with large telescopes, given the limited experience in this field available today? Can the associated costs be identified and accepted?

Fortunately, during the investigation by the Working Group (1984–1986), the interest for diffraction-limited imaging at optical wavelengths rapidly grew within the community. The maturation of speckle techniques led to several discoveries: separation of Pluto and its moon Charon, resolution of the hypothetical supermassive star R 136a, of T Tauri, of the nucleus of NGC 1068. Shells (IRC +10216, OH-IR stars) and disks (MWC 349, IRc2) were identified in the infrared. Moreover, a spectacular image of the α Orionis dusty environment produced by C. and F. Roddier at the 3.6-m CFHT showed that interferometric techniques can also produce images. Two-telescope interferometry also emerged from the prototype to the operational stage (M. Shao, Center for Astrophysics interferometer at Mount Wilson), measuring stellar diameters with an accuracy not achieved since Michelson (R. Foy and P. di Benedetto at Cerga).

The considerable corpus of imaging techniques accumulated by radio-astronomers during the last 40 years became progressively available to optical interferometry: phase closure, a classical radio technique to overcome atmospheric and instrumental phase errors, was demonstrated in the optical in 1986 by J. Baldwin at Cambridge; image reconstruction procedures, in daily use at the Very Large Array or in VLBI, were found to be identical to specific techniques developed by G. Weigelt for optical interferometry, such as speckle masking.[2]

This short report will outline how it has become apparent that a coherent combination mode of the VLT is no longer an unreal dream. Indeed, in the mean time, other projects of large telescopes are exploring similar ideas: among the most advanced, the COLUMBUS (or "twin-shooter") project combines two 8-metre telescopes on a 15-m centre-to-centre baseline. Other large telescopes may be interferometrically combined in the future, but the originality of the VLT is to integrate the coherent mode *ab initio* into its design.

2. What is a Good Interferometer?

The quality of an interferometer may be judged by its angular resolution, its sensitivity and its instrumental profile. Each factor is wavelength-dependent over the broad spectral range (0.32 to 22 μm) observable from the ground.

Next generation telescopes (D = 10 to 15 m) may produce diffraction-limited images at resolutions of 4 to 300 milliarcsec at these wavelengths when operated in speckle mode (visible) or with adaptive optics (infrared). A tenfold increase is obtained with 100–150 m interferometric baselines. This gain, needed to resolve a whole class of infrared sources just unresolved today, remains small enough to ensure continuity in the spatial frequency coverage.

The sensitivity of an interferometer is controlled by three factors: the average number N of speckles present in the image given by individual telescopes – or, in an equivalent manner, the average number of instantaneous atmospheric coherence areas on the telescope pupil; the integration time; the noise of the detector. Each of these is strongly wavelength-dependent, and no single conclusion applies to the whole range under consideration. Broadly speaking, three domains of increasing difficulty appear: beyond 10 μm, where N = 1 in good seeing; between 3 and 10 μm, where adaptive optics appear suitable to actively phase each telescope and obtain N = 1; shorter wavelengths, where N becomes large (>1,000) and difficult to reduce with existing techniques. A detailed analysis shows that the full sensitivity gain brought by a large mirror is only obtained when N = 1. When $N \gg 1$, the large mirrors do not improve the sensitivity limit, but reduce as D^2 the integration time necessary to reach a given signal-to-noise ratio. Only with D = 8 m will active nuclei of galaxies and quasars become observable at infrared wavelengths.

The issue of instrumental profile (Point Spread Function) is a critical one: modern radio-interferometers combine a large number n of movable antennas which sample densely the spatial frequency domain and give a PSF with limited sidelobes. Residual lobes are "cleaned" with a posteriori numerical treatment. Conversely, VLBI images are, *par la force des choses,* produced with a poor, very diluted frequency coverage, but nevertheless recovered at a high degree of quality by suitable algorithms. The recovery from atmospheric phase errors on each telescope requires to increase n at least to 4 and to use phase restoration methods such as phase-closure, not yet tested with multi-telescopes optical interferometry, or an analogous method developed for single telescope optical interferometry (speckle masking). It is on this particular issue of PSF that interferometry with the VLT is most compromising with the rules an ideal interferometer should obey: the large telescopes are fixed, only four will exist, and for aerodynamic reasons their baseline will almost certainly be linear. Depending on the site, the telescope spacing may be uniform (redundant) or cover different frequencies (non redundant): both configurations have advantages and drawbacks with respect to the final image quality. Since a coverage in the direction perpendicular to the baseline is essential, even with reduced sensitivity, the ESO VLT Proposal included two additional interferometric telescopes (ca. 2 m in diameter) movable on tracks perpendicular to the main baseline. Simulations have shown that a good image quality will result.

To summarize, if it appears practical to operate the VLT as an interferometer, this mode will offer an order of magnitude gain in resolution, several orders

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[1] The VLT Interferometry Working Group was composed of R. Citterio (later replaced by P. di Benedetto), D. Downes, A. Labeyrie, P. Léna, J. Noordam, F. Roddier, G. Weigelt, J. Wijnbergen, with the ESO participation of D. Enard, F. Merkle, M. Sarrazin, R. Wilson and numerous outside contributors as the late L. Weliachew, and S. Guilloteau, R. Foy, A. Maeder, J.-P. Swings, etc. The group issued an Interim Report (No. 44), a Final Report (No. 49) and contributed to the ESO VLT Proposal (Chapter 12).

[2] The growing interest is shown by several successive meetings: ESO Conference on High Angular Resolution (Garching 1981); joint ESO-NOAO Workshop (Oracle 1987); ESA Workshops (Cargèse 1984, Granada 1987) and their copious Proceedings, as well as the increasing literature on the subject. A recent review (F. Roddier, *Physics Reports*, 1987, in press) gives over 1,000 references on "Interferometric Imaging in Optical Astronomy".

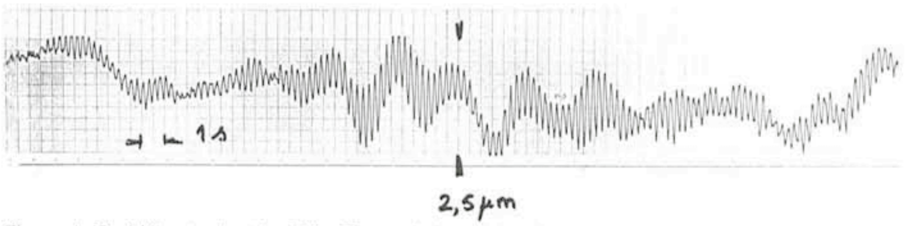

Figure 1: *Stability study at La Silla: The variation of the distance between the tops of the 3.6-m pier and the CAT pier at the base of each telescope, versus time, as measured with a laser interferometer, with a strong wind blowing outside. Horizontal axis: time; vertical axis: distance. A vibration appears at 5 Hz, but the stability of the distance is remarquable.*

of magnitude gain in sensitivity and/or integration time over smaller interferometers, and limited but appreciable imaging capabilities comparable to the ones of VLBI.

3. A Scientific Programme for Interferometry

On the basis of the above conservative performances, and when a factor of 20 in angular resolution is obtained over almost two decades of wavelength, a wide field of new observations and programmes will open. It is probably within the fields of star formation and galactic nuclei that the new contributions will become most important, at least during the first phase of infrared observations and programmes.

Only VLA centimetric observations give today access to the innermost part of the core of an object like L 1551, considered a prototype of a very young object. The high dust opacity of the disk and its temperature make infrared interferometry one of the most powerful tools to investigate the environment of proto- and young stars. Recent indications on the existence of accretion disks around T Tauri stars lead to the same conclusion. Presently, the sample of very young objects embedded in dense molecular clouds is limited to a few dozens, rapidly increasing as IRAS survey data are analysed and followed up by ground-based studies. Although none of these can yet be proven to be a protostar *stricto sensu,* spectroscopy indicates that the regions of accretion or ejection of matter will only be accessible to interferometry. About five disks have been identified with reasonable certainty and more than ten are suspected in nearby associations, all are a few hundred A.U. in size. The relations between disks and large scale mass outflows, local magnetic fields, locally collimated flow and rotation axis all need to be investigated on the 10–100 milliarcsecond scale.

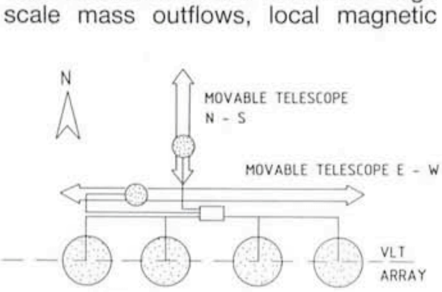

Figure 2: *Schematic configuration of the VLT as a long baseline interferometer, in the redundant (100 m East-West) arrangement.*

Galactic nuclei at infrared and visible wavelengths offer another field of investigation. The structure of the Broad Line Region appears to be close to the available resolution. The small (< 1 milliarcsec) and bright, visible nucleus of a Seyfert galaxy is suitable as point-reference source for infrared interferometry which allows phase control, similar to self-calibration in radio astronomy, and long time integration.

When interferometry progresses toward visible wavelengths, the mapping of the star surfaces will open a new field in stellar physics: convection cells, surface magnetic fields, shock waves in red evolved variables, mass exchanges between close binaries are problems which all fall in the range of resolution and sensitivity discussed above.

4. Technical Feasibility

Since the currently existing optical interferometers are modest in size and recent in completion, the practical experience in interferometry, although growing continuously, is not very extensive. There is nevertheless agreement about the critical issues: they are mainly the vibrational stability and the beam combination.

The vibrational stability set very strict tolerances, never before encountered in telescope design except what concerns the stability of the primary and the secondary mirrors themselves: the longitudinal (i.e. along the optical axis) displacement velocities must remain below 5 to 10 μm/s rms, or certainly smaller than what current mechanical design may achieve. This necessitates the use of active control to cophase internally the array, in the same way as each VLT primary mirror is cophased by active optics. Recent measurements carried out at La Silla (Fig. 1) show that existing large telescopes, although not especially designed for this purpose, have a stability which is not far from interferometric requirements: surprisingly, this stability appears fully adequate to allow coherent coupling between the 3.6-m and the CAT 1.4-m at a wavelength of 10 μm!

The strategy for beam combination, path compensations, and signal detection is an issue that has a number of solutions, depending on wavelength, relative size of the source and field-of-view. The extraction of coherent beams from each telescope has to be considered first. The VLT Proposal relies on classical mirror trains, common to the incoherent and the coherent modes, but the emergence of single mode optical fibers may make this approach obsolete and provide a convenient and economical coupling between each Nasmyth focus and the interferometric tunnel. For the beam combination itself, some common facilities have already been studied (Figs. 2, 3, 4). The progressive construction and operation of small interferometers will bring considerable experience in the next decade. New ideas are emerging, such as the Double Fourier Technique (Fig. 5), applicable at infrared wavelengths and potentially efficient in the use of observing time.

Since the main phase disturbing factors, atmospheric phase distorsions, random time fluctuations and mechanical vibrations, all appear less detrimental and easier to correct when the wavelength increases, it has been proposed to begin the exploitation of the interferometric mode of the VLT at infrared wavelengths ($\lambda > 3\mu m$) and to progressively extend it towards the visible. This step-by-step approach should minimize the technical risks.

5. Operating the VLT as an Interferometer

The availability of VLT observing time in the interferometric mode can only be considered for programmes of the highest scientific value, where the sensitivity and/or time gains provided by the large diameter are justified, when compared with the performances of smaller instruments. This situation is rather similar to the one of speckle programmes on existing large telescopes. Together with the need of frequency coverage discussed above, this led the Working Group to propose the inclusion in the VLT design of two additional, smaller and movable telescopes which are permanently available for interferometry and which can be coupled to the large ones, whenever requested. The design of these telescopes could be derived from the current interferometric programmes underway in France, Germany, the United Kingdom and the United States. For instance, a well engineered Phase A study is now under way at the Institut de Radioastronomie Millimétrique (IRAM, Grenoble), under contract by the French CNRS/INSU for the concept of movable, interferometric telescopes of the 2-m class.

It has already been acknowledged that the VLT operation, even in incoherent mode, shall require more sophistication, more decision aids and more artificial intelligence than is usual in optical astronomy. Interferometry, which gradually adds some complexity to the operations, will also make use of the overall basic flexibility of the VLT design.

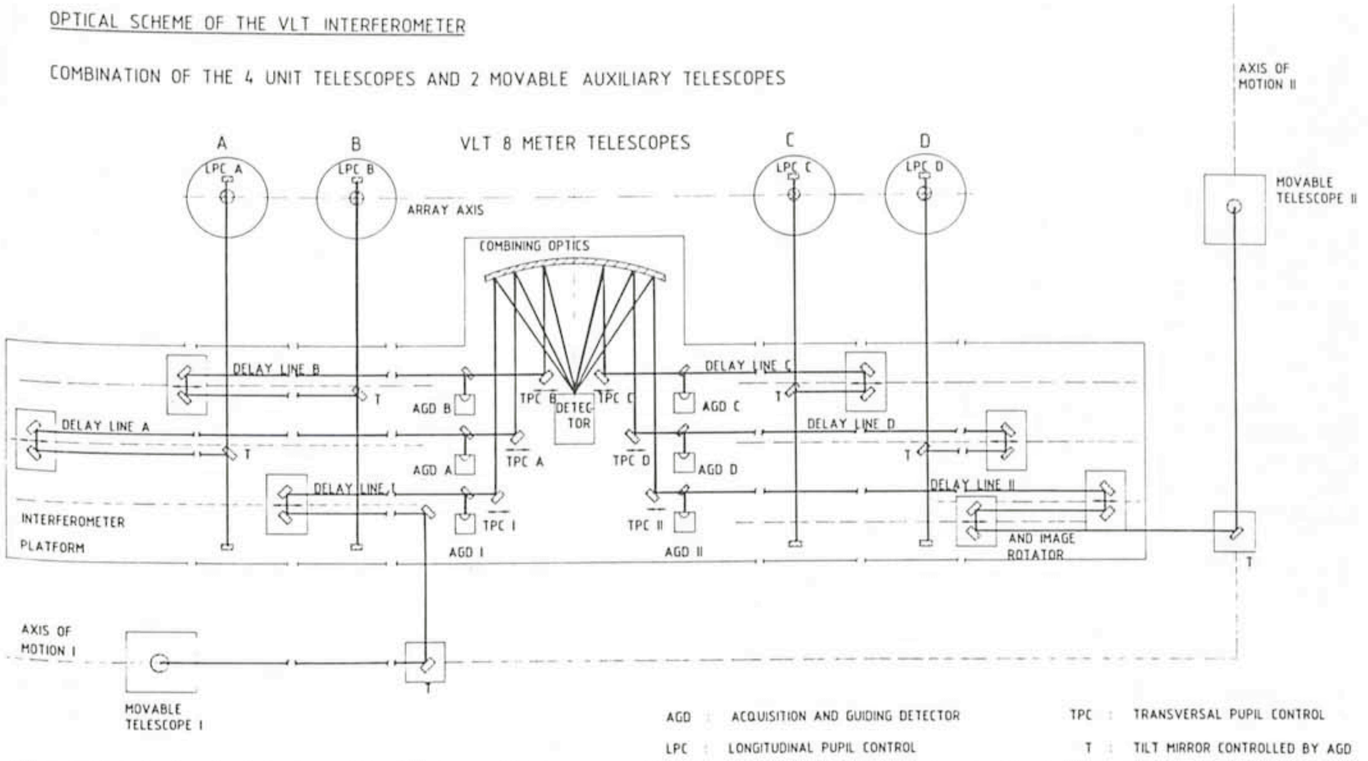

Figure 3: *Detailed optical design of the interferometric beam combination path, schematically showing the beams produced by the 4 large telescopes and the 2 additional ones, their delay lines, the pupil correctors (LGD, AGD and TPC), and a schematic combining optics.*

6. Impact of the Site

The most critical factors for interferometric quality are the seeing and the infrared transparency; these two factors are indeed essential for all VLT purposes. The baseline choice comes next. A compact site like the main Paranal summit would force us to accept a redundant configuration, with a maximum East-West baseline of ~125 m. There would be some difficulties in the North-South baseline implementation but it would nevertheless be acceptable. Some second-order parameters, specific to interferometry, like the microseismicity and the outer scale of atmospheric turbulence, will have to be investigated in the future.

7. Conclusions

In this short review we have summarized the main lines of thought which led to the inclusion of interferometry into the VLT Proposal. Subsequent cost estimates will have to be refined as the project progresses and several items deserve construction of laboratory models as well as research and development.

If the technical difficulties are solved, and it indeed appears that they are less formidable than initially thought, then the implementation of the interferometric mode will add a great and unique scientific capability to the VLT. It will represent long-term investment and put European optical astronomy in a leading position.

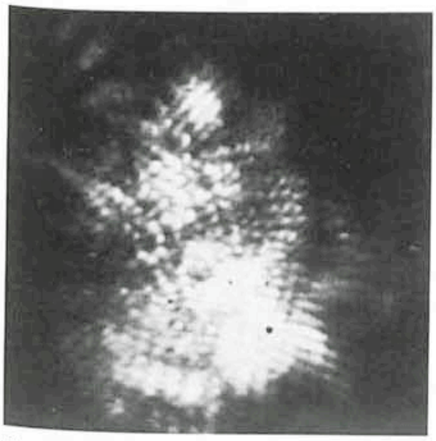

Figure 4: *An example of an interferometric combined image: the six mirrors of the Arizona Multiple Mirror Telescope (MMT) have been cophased at visible wavelengths to produce this instantaneous exposure. Many speckles are obvious (N is large for 2.4 m single pupils), and interference fringes appear for each baseline (Courtesy of J. Beckers and K. Hege).*

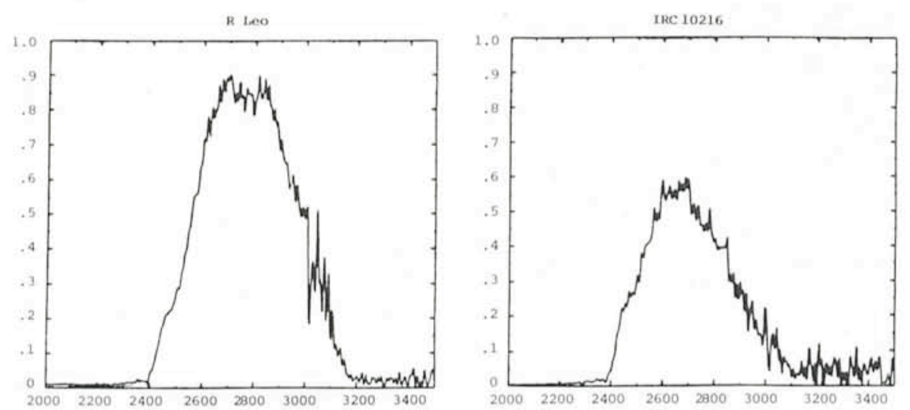

Figure 5: *The Double Fourier technique applied to the bright circumstellar envelope of the star IRC 10216 at 3.5 μm. (a) The spectrum of an unresolved star (R Leo) between 2,000 and 3,400 cm-1, chosen as a reference. (b) The spectrum of IRC 10216, obtained with a conventional Fourier Transform Spectrometer. The two interfering beams are issued from two subpupils of the 4-m KPNO telescope mirror, D = 1 meter apart, instead of being conventionally separated by a beam splitter. The ratio of the two spectra immediately gives the visibility V (σ) of the resolved source versus the wave number at a spatial frequency D σ, keeping the multiplex advantage of the FTS. The spectral resolution only depends on the FTS excursion and the source intensity (J.M. Mariotti and S. Ridgway;* Astron. Astrophys; *in press).*