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Planning the VLT Interferometer

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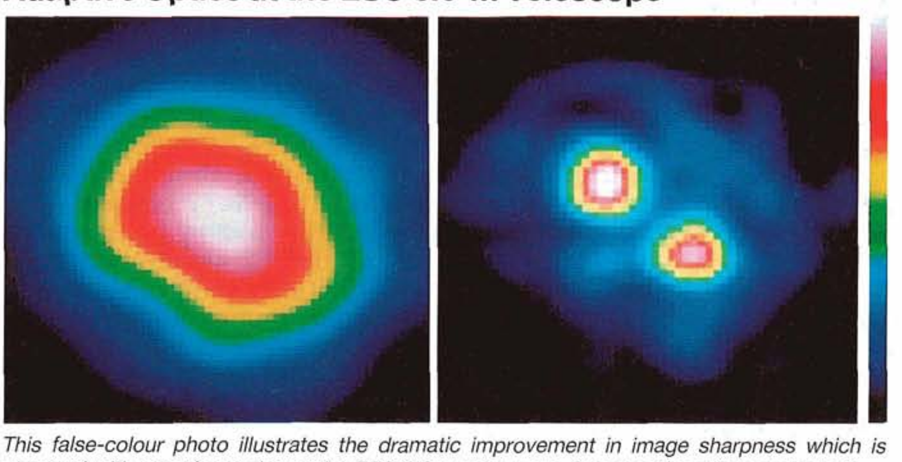
1. The VLT Interferometer: One of the Operating Modes of the VLT

1.1 Its Context

The Very Large Telescope has three different modes of being used. As four separate 8-metre telescopes it provides the capability of carrying out in parallel four different observing programmes, each with a sensitivity which matches that of the other most powerful ground-based telescopes available. In the second mode the light of the four telescopes is combined in a single image making it in sensitivity the most powerful telescope on earth, almost 16 metres in diameter if the light losses in the beam combination can be kept low. In the third mode the light of the four telescopes is combined coherently, allowing interferometric observations with the unparalleled sensitivity resulting from the 8-metre apertures. In this mode the angular resolution is determined by the distance between the telescopes (up to 120 metres), rather than by the resolution determined by the individual telescopes (set by the atmospheric seeing, or by the diffraction limit of single 8-metre apertures while using adaptive optics or speckle interferometry). Following an in-depth study by the VLT Interferometry Working Group under the chairmanship of P. Léna (published in VLT Reports 44 and 49), the interferometric mode of the VLT was included in the VLT proposal, and accepted in the approved VLT implementation. P. Léna described the concept and planning for the interferometric mode of the VLT at

Adaptive Optics at the ESO 3.6-m Telescope



This false-colour photo illustrates the dramatic improvement in image sharpness which is obtained with adaptive optics at the ESO 3.6-m telescope. See also the article on page 9.
It shows the 5.5 magnitude star HR 6658 in the galactic cluster Messier 7 (NGC 6475), as observed in the infrared L-band (wavelength 3.5 μm), without ("uncorrected", left) and with "corrected", right) the "VLT adaptive optics prototype" switched on. The diameter of the uncorrected image is about 0.8 arcseconds, corresponding to the instantaneous "seeing" disk. When corrected, the image sharpness increases nearly fourfold; the diameter is now only 0.22 arcsec. This corresponds to the diffraction limit at this wavelength; the diffraction rings are well visible. The improved sharpness reveals that the star is double; the angular distance between the two components is 0.38 arcseconds.
Although it is not evident on this picture in which the intensity scales have been normalized to the same level, the central intensity of the corrected image is much higher than that of the uncorrected. By concentrating the light better, the efficiency of the telescope is correspondingly increased. This means that shorter exposure times are possible or that fainter objects can be observed than before.

that time in an earlier article in the *Messenger* (P. Léna, *The Messenger* **53,** 53, 1987).

Since the acceptance of the VLT proposal, the VLT final definition and design, including the final site testing which will soon lead to the VLT site choice, has been rapidly proceeding. The implementation planning of the interferometric mode is an essential part of that. Interferometry places its own requirements on the design and location of the 8-metre telescopes, on the site choice and development, and in the definition of the observatory infrastructure. In addition to the 8-metre telescopes, the VLT includes two smaller movable 2-metre-class telescopes (the so-called auxiliary telescopes), whose design and configuration has to proceed in parallel with the others. To aid in this planning a VLT Interferometry Panel was formed, whose members represented the expertise in interferometry in the ESO member countries[1]. This report summarizes the implementation plan of the panel for the so-called *VLT Interferometer* (or VLTI) as proposed to ESO. This plan is out of necessity incomplete since the site for the VLT remains to be chosen.

1.2 Philosophy Followed in the Implementation Plan

Right from the beginning the panel took as the basis for its studies the desire to make use of the unique opportunity provided by the presence on one site of four identical, state-of-the-art 8-metre telescopes to do interferometric imaging. Its definition of the VLTI is thus in the first instance based on the coherent combination of the large telescopes. The sub-array of auxiliary telescopes is truly auxiliary to this goal. It serves two main functions. First, it complements the main-array of 8-metre telescopes to give more interferometric baselines. Second, it provides for an interferometric capability by itself which is available 100 % of the time. This function is of use not only when the full power of the 8-metre telescopes is not needed for the observations being carried out, but also during the important initial phases of the VLTI, for the commissioning and debugging of the interferometer. The latter resulted in the desire to incorporate the VLTI sub-array into the main-array in such a way that the change-over from the use of the sub-array to the full VLTI requires a minimum of steps.

Although such an integrated approach may appear obvious to the reader, it is by no means an uncontroversial, obvious philosophy to everyone in the interferometry community. There first is the skepticism by many about the actual availability of the 8-metre telescopes for interferometric imaging. Certainly, these large telescopes will not be available for a significant amount of the time for interferometric imaging until the astronomy community wants to use them for that. Before their use for interferometric imaging will successfully compete in time with other uses, a "user-friendly" capability for interferometric imaging with the VLTI has to be demonstrated. That will have to be done with the auxiliary telescope sub-array, which will also exploit ways of reaching the maximum possible sensitivity. It is our conviction that this can be done, and that the resulting user demand for the use of the 8-metre telescopes for interferometric imaging will follow. Second, the design of the 8-metre telescopes cannot be optimized for interferometry alone. Therefore, compromises are necessary which ripple through to the design of the entire VLTI, including the sub-array of auxiliary telescopes because of the philosophy described above. Certainly, an interferometer designed without the constraints associated with the VLT (site, fixed telescopes requiring the use of delay lines, alt-az mounts, limited number of telescopes, etc.) would in some aspects be more powerful than the VLTI. These advantages, however, fade in comparison with the power resulting from an interferometer with telescope apertures of 8 metres.

This philosophy is also directly in tune with that of the VLT Proposal in which two movable auxiliary telescopes are "joined" to the 8-metre array with the purpose of giving better (u, v) plane coverage and permanent interferometric usage. It is therefore perhaps not surprising that the panel's implementation plan resembles closely that of the proposal, going mostly into a more refined definition of the array components taking into account the need to optimize performance of the array for both on-axis and off-axis operation. The implementation plan shares such features with the original proposal as the number and size of auxiliary telescopes, the emphasis on long wavelength coverage, a significant (> 3 arcsec) interferometric field-of-view, beam combination in air, use of delay lines with a long stroke, and common usage of beam combiner (and probably delay lines) for 8-metre and auxiliary telescopes. Both implementation plan and proposal view the development of interferometry with the VLTI to be a gradual, step-by-step one. The plan, however, differs from the original proposal in some aspects: (i) it argues strongly for a configuration of the 8-metre telescopes which is more optimized for interferometry (see section 3.1), (ii) it provides for the expansibility of the array with more auxiliary telescopes and delay lines (to be provided by additional contributions by ESO member states), and (iii) it provides for the incorporation of adaptive optics in the auxiliary telescopes.

1.3 Why Large Aperture Interferometry?

In this context the question is sometimes asked on what is really gained by going to large aperture interferometers. Doesn't an array of many small telescopes do as well, or even better? The answer to this question is important because it determines the part of astronomy at which the VLTI will be particularly useful and for which it should be optimized. Although an increase in collecting area in astronomy is generally thought of as giving an increase in sensitivity, this is by no means obvious for interferometric imaging. It has been argued in fact that little is gained in limiting sensitivity by the increased aperture in the case of multi-speckle, broadband observations. This is the case at short wavelengths (up to the Johnson M band without the use of adaptive optics, up to the H band with the use of adaptive optics). The combination of the fact that the number of photons per speckle is independent of the telescope diameter D with the decrease of the maximum spectral bandwidth which can be used with larger apertures results in a very slow increase at visible wavelengths in sensitivity, it being proportional to $D^{1/3}$. The VLTI is therefore not well suited for that kind of observation, unless the larger "pre-resolution" provided by the individual 8-metre telescope apertures is of importance for the astronomical observation. Things change when spectral resolution larger than a few hundred is wanted. In that case the sensitivity of the multi-speckle observations increases as D^2, making it an important goal for the VLTI.

Larger gains with telescope aperture result in the single speckle mode which occurs without adaptive optics in the Johnson N band and above, and with the VLT adaptive optics at wavelengths as short as the H or K bands. In these domains the sensitivity increases proportional to D^4 for any spectral bandwidth. The entire infrared region is therefore an important region for the VLTI. As

[1] The VLT Interferometry Panel is composed of J.M. Beckers, R. Braun, G.P. Di Benedetto, R. Foy, R. Genzel, L. Koechlin, F. Merkle, and G. Weigelt, with A. Labeyrie, P. Léna, J.-M. Mariotti, and D. Downes as consultants, and D. Enard, M. Faucherre, H. van der Laan, and M. Tarenghi as observers.

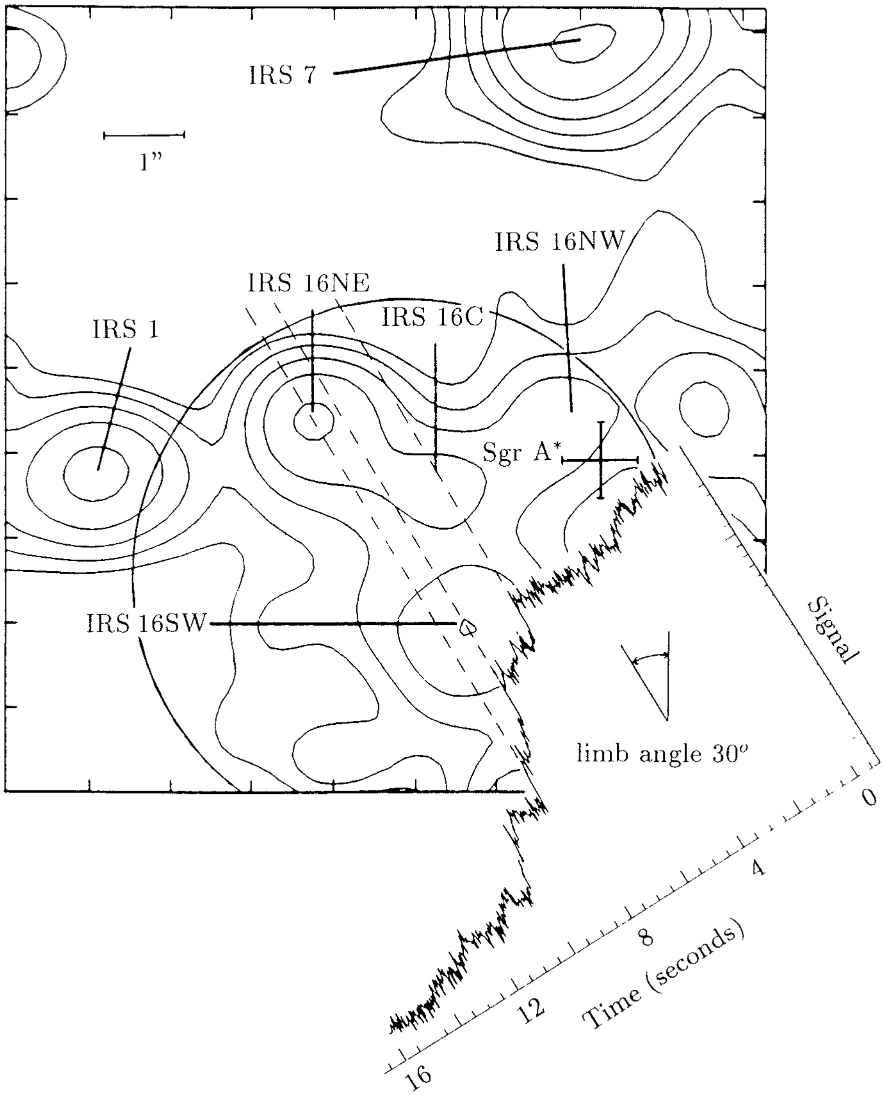


Figure 1: *Contour map of the Galactic Centre in the Johnson K band (2.2 μm) with an angular resolution of approximately 0.7 arcsec. The Galactic Centre is thought to coincide with the location of IRS 16 NW/Sgr A*. Superposed is the light curve due to an occultation by the moon and the resulting reconstruction of the fine structure in the IRS 16 area (shaded areas and dots in the circle). The angular resolution provided at this wavelength by the individual 8-metre telescopes (.055 arcsec) equals half the dot sizes shown at IRS 16NE and IRS 16E. The resolution of the VLTI exceeds that by a factor of 15 (.004 arcsec). Courtesy R. Genzel.*

an example of its potential application, Figure 1 shows an intensity map in the K band of the Galactic Centre, an area of particular interest at the VLT location. The presence of the very bright compact source IRS 7, only 5 arcsec away from the Galactic Centre, allows accurate sensing of the atmospheric wavefront disturbances needed for the VLT adaptive optics. This will result in direct very high angular resolution imaging (.055 arcsec) of the entire IRS 16 region (size of the isoplanatic patch ≈20 arcsec) with the individual 8-metre telescopes. This by itself demonstrates a very important feature of the use of a large telescope for interferometry because it allows the "pre-resolution" of features in a complex target like this one. Starting with the well-resolved images of the individual 8-metre telescopes, the VLTI will increase the angular resolution with another factor of 15 using the very high sensitivity coming from the 8-metre aperture. This sensitivity will be further enhanced by the possibility of real time sensing of the position of the interferometer fringes on IRS 7 which is probably unresolved by the VLTI, or another unresolved object in IRS 16, and subsequent fringe tracking. This allows long exposures, which gives signals exceeding the detector read-out noise even when using high spectral resolution. The Galactic Centre provides perhaps the finest demonstration of the VLTI power, and of the advantages gained with its large apertures. It is however not unique, similar examples can be given for other objects.

2. The VLT Interferometer: Are We Ready for It?

2.1 Current Efforts in Optical Interferometric Imaging

Figure 2 summarizes the properties of existing optical interferometers as well as those in the construction and planning stages. There are at this moment 6 operating interferometers available (GI2T, I2T, MARK III, MMT, Soirdete, Sydney).

The interferometers shown are broadband amplitude interferometers only, and do therefore not include the now discontinued Culgoora intensity interferometer and the 10.6 μm Berkeley heterodyne interferometer. All interferometers, except for the MMT, are non-monolithic interferometers (with the telescopes on separate mounts) requiring pathlength adjustments using e.g. delay lines. All existing interferometers routinely acquire fringes, often within minutes and, when well engineered, shortly after the start of the commissioning of the device. Technically, the viability of optical interferometry has therefore been amply demonstrated. These existing interferometers, generally of a prototype nature, have given us the confidence and expertise needed to go on with the many second-generation machines shown in Figure 2, which are now under construction or on the drawing board.

In contrast to most existing first-generation interferometers, which focussed on stellar size, binary star, and astrometric observations, these second-generation devices emphasize two-dimensional imaging using a number of simultaneous baselines, phase closure techniques, and other imaging methodologies taken from image synthesis efforts in radio astronomy.

2.2 Optical and Radio Interferometry: Similarities and Differences

The VLTI will rely strongly on the expertise gained with interferometric imaging in radio astronomy with interferometers like the Westerbork array, the VLA, MERLIN, the VLBI networks, and the Australia Telescope. Both optical and radio interferometry rely on the simultaneous measurement of the amplitude and phase of interference fringes over a number of different baselines as their basic observable. Algorithms for deriving astronomical images are therefore very similar, if not identical. The ways to arrive at the measurement of the interference fringes are however very different. It is instructive to compare these differences.

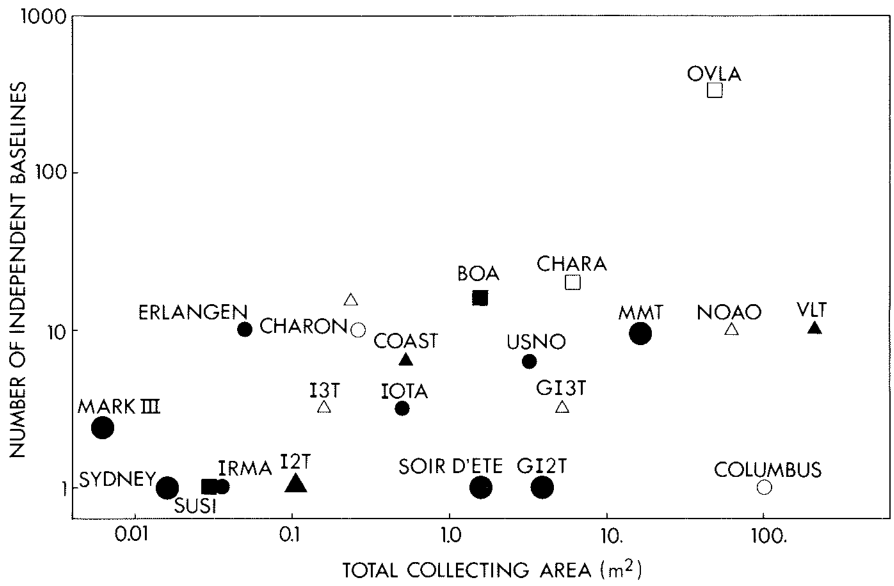


Figure 2: *Properties of Optical Interferometers. Large filled symbols represent existing facilities, small filled symbols those under construction, and open symbols those being planned. Circles for maximum baselines under 100 metres, triangles for maximum baselines between 100 and 300 metres, and squares for maximum baselines above 300 metres.*

The most obvious difference results of course from the very large difference in wavelength or frequency. This difference amounts to about a factor of 10^5. The much shorter wavelengths in optical interferometry places on the one hand a much higher demand on the dimensional stability and dimensioning of the array, but on the other hand allow angular resolutions comparable to that of the VLBI networks over baselines of only 100 metres. The much higher frequency of optical radiation (10^4 to 10^6 GHz) eliminates the use of heterodyne technologies with their limited bandwidth (< 1 GHz), except at the lower frequency end and when high spectral resolution observations ($R > 10^4$) are needed. Also, whereas in radio interferometry heterodyne techniques allow the use of electronic delays to compensate for the varying pathlength differences, optical interferometry has to use optical delay techniques.

Also the effects of the earth atmosphere are very different. Only at the very longest wavelengths will the VLT 8-metre telescopes be diffraction limited, whereas this is the case for all radio telescopes. The VLTI will therefore either work in the so-called multi-speckle mode at the very short visible wavelengths, or use adaptive optics to make the telescopes diffraction limited at the longer near-IR wavelengths. In the multi-speckle mode the fringe phase varies across the seeing image on the speckle scale. Recently developed methods using bi-spectral image analysis (or speckle masking) allow the measurement of the relative phases for the different baselines, needed for phase closure imaging, also in this multi-speckle case. In the diffraction limited, or single speckle mode, the relative fringe phase is well established and can be directly measured. Another difference caused by the atmosphere is the rapid variation of the fringe phase with time, in as little as 10 milliseconds at visible wavelengths. This implies the use of many observations with very short integration times, which sets a serious limit to the sensitivity of optical interferometers.

Then there are differences resulting from the different treatment of the radiation. Detection techniques at optical wavelengths are photon-noise limited except at near-infrared wavelengths where readout noise still dominates. At radio wavelengths detection noise is always detector limited. The difference in noise characteristics necessitates differences in measurement reduction techniques. Another difference is the ability at optical wavelengths to build interferometers with a wide interferometric field-of-view[2], giving interference over a field comprising many (> 10^4) Airy disks, allowing e.g. the use of IRS 7 near the Galactic Centre (Fig. 1) for fringe position monitoring or tracking. Radio interferometers limit themselves generally to one Airy disk using one "feed", although multi-feed systems using a few Airy disks are now in development.

Radio and optical interferometry thus share much, including the intellectual challenges associated with developing high-resolution imaging techniques, but also differ in many aspects. Initial differences relating to the different languages and cultures of the two fields of endeavour have been resolved, and a fruitful interaction and active participation has developed.

2.3 Adaptive Optics: An Important Part of the VLTI

The largest gains in sensitivity of the VLTI will come from the incorporation of adaptive optics which will make the telescopes diffraction limited at near infrared wavelengths (≈ 2 μm). All radiation from an unresolved source collected by the 8-metre telescopes will then be combined in phase, in the area of a single speckle of the size of an Airy disk. The recent spectacular success with the VLT adaptive optics prototype developed in a collaboration of French research institutes and ESO (see F. Merkle et al., in the *Messenger* No. **58,** p. 1, and also on page 9 in this issue) promises the successful incorporation of adaptive optics in the VLT early in its commissioning. Its application will predominantly be determined by the availability of stars within the common-phase field-of-view, or the so-called isoplanatic patch. Wavefront sensing in the visible and near IR (2 μm) will result in full sky coverage at about 5 μm wavelength and above, and major sky coverage at shorter IR wavelengths (e.g. 100 % for the central areas of the Milky Way at 2 μm). Present experiments using artificial, laser-generated stars for wavefront sensing, promise to extend full sky coverage of adaptive optics systems to shorter wavelengths (1 μm).

These lower wavelength limits to the utility of adaptive optics refer to the combination of all the collected radiation in a single speckle. But at shorter wavelengths an adaptive optics system built for e.g. 2 μm (as is planned for the VLT) will not suddenly fail to function, instead it will become a so-called partial adaptive optics system. In this mode, computer simulations show that a fraction of the light (5 to 10 % at visible wavelengths) will still be combined in a single central bright speckle with the rest remaining distributed over the multi-speckled seeing image. Even this minor concentration in the partial adap-

[2] In the following I will distinguish clearly between so-called interferometric and unvignetted field-of-views. For an unvignetted field-of-view the light from the different parts of the entrance pupil arrives at the beam-combining station unvignetted, but not necessarily in a condition to allow interferometry between the different telescopes. An interferometric field-of-view has to be unvignetted, but in addition has to combine the rays from the different telescopes in phase (within a fraction of a wavelength, the so-called "phased field-of-view") or coherently (within the coherence length, resulting in fringes, the so-called "coherent field-of-view").

tive optics case can be shown to enhance the sensitivity of the VLTI at shorter wavelengths very much. As is the case for full adaptive optics at near-IR wavelengths, it is realistic to expect the availability of partial adaptive optics for visible light, covering a major part of the sky, early in the lifetime of the VLT, since they use the same wavefront sensing and correcting systems.

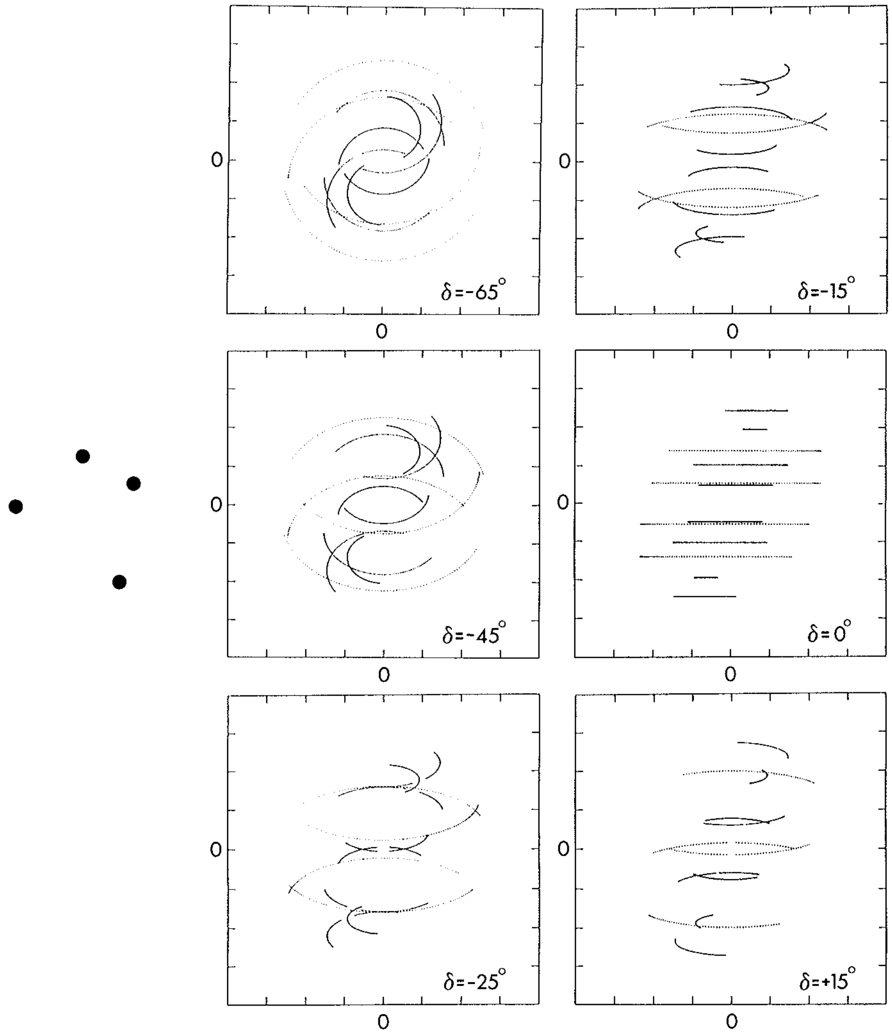


Figure 3: *Proposed configuration of the VLT 8-metre telescopes and the resulting (u, v) plane coverage for different declinations δ and for zenith distance angles up to 60 degrees. The base of the trapezoid has a length of approximately 120 metres. North is up.*

3. The VLT Interferometer: Current Plans

3.1 The Array of 8-metre Telescopes

As described already, the philosophy in the planning of the VLTI focusses on the optimum implementation of the array of the four 8-metre telescopes. Therefore, that's what will be described first.

Telescope Configuration

The quality of full two-dimensional interferometric imaging very much depends on the simultaneous availability of many interferometer baselines in all directions of the compass. It is important for interferometry with the VLTI to optimize the configuration of the 8-metre telescopes in this respect even in the presence of movable smaller telescopes. The reasons for that have to do with both the sensitivity of the VLTI and with its potential for being used in a wide interferometric field-of-view mode.

At infrared wavelengths, where the telescopes will be diffraction limited, the maximum sensitivity in the imaging mode of an interferometer using different aperture telescopes results from matching the size of the Airy disks. That results in different image scales, and results in a "zero" field-of-view (restricted to the size of the Airy disk). The sensitivity for on-axis interferometry becomes in that case proportional to D^2d^2, where d equals the diameter of the smaller telescope. With a d = 180 cm auxiliary telescope this results in a 20 times lower sensitivity as compared with the use of a pair of 8-metre telescopes. When Airy disks are not matched (e.g. when a wide interferometric field-of-view is wanted) and when working at the shorter wavelengths, the sensitivity is much larger (100 times and more).

For observations of the faintest objects, it is therefore very important to have access to the array of 8-metre telescopes optimized for interferometric imaging. The array as described in the VLT proposal is, however, far from optimum. It consists of the four telescopes in an approximate EW line, with very redundant spacings resulting therefore in only 3 or 4 simultaneous baselines in a direction which makes two-dimensional imaging virtually impossible, especially for regions at the lower declinations like the Galactic Centre (Fig. 1). The VLT Interferometry Panel therefore strongly argues for a quadrilateral configuration for the VLTI approximately in the form of an equilateral trapezoid. Figure 3 shows the configuration which is suggested and the resulting (u, v) plane coverage for different declinations δ.

This array has a total of 6 simultaneous, non-redundant baselines and results in a good two-dimensional (u, v) plane coverage for objects anywhere in the southern sky. These properties are little dependent on the precise orientation and baseline length of the array, so that it can be fitted to the VLT site. Site considerations will determine however the final configuration chosen, as will be the estimates of the deteriorating effects of the wind flow of telescopes on its neighbours. More on this later.

How to Get the Light to the Combined Coherent Focus?

Figure 4 shows the way in which the light from the individual telescopes will be combined in the VLTI beam combiner.

At each coudé focus of the telescopes the relay optics create an afocal beam with a diameter demagnification M of 100, resulting in an 8-cm diameter horizontal light beam being sent to the beam-combining system. The combination of the light in an interferometer has to occur according to stringent conditions if the performance of the interferometer is not to be compromised. To maintain maximum fringe contrast, the optics has to be of high quality and the polarization effects (retardation effects and direction changes) have to be identical in all light paths. The requirement that the rotation of the polarization directions have to be identical also results in identical orientations of the combined images as well as of the exit pupils. This

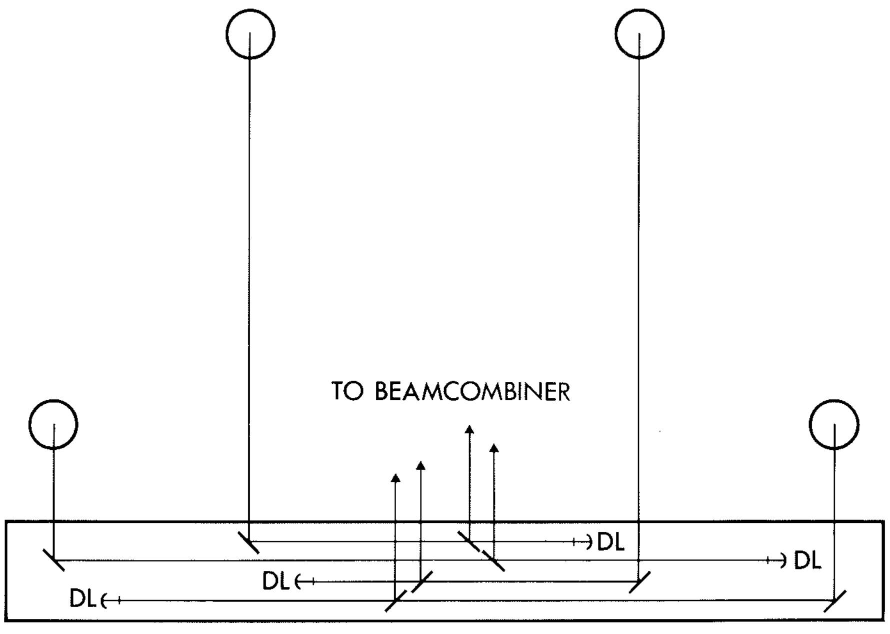


Figure 4: *Beam-combining scheme proposed for the VLTI. The afocal light beams from the coudé foci of each of the four individual telescopes are relayed to the interferometer tunnel (the long rectangular horizontal box) in underground light tubes located at right angles to the interferometer tunnel. The latter contains the delay lines (DL) for pathlength adjustment. The output of the delay lines is relayed to one of two beam-combining laboratories located on either side of the interferometer tunnel.*

is an important condition if the VLTI is to be operated in the wide interferometric field-of-view mode. The proposed beam-combination scheme follows these beam-combination conditions all the way from the telescope Nasmyth focus to the beam combiner.

Beam combination in the VLTI will occur in air. This decision is based both on arguments related to cost and operational complexity of an vacuum system of this size, as well as an evaluation that the effects of air in the light path can be managed at an acceptable level. There are five effects of concern: (i) image deterioration due to seeing for on-axis beams. This effect is lessened because of the large demagnification (M = 100) of the beam diameter making the effective Fried's parameter r_o M = 100 times larger, (ii) deterioration of the isoplanatic patch size due to the increase in angles by M = 100. An evaluation indicates that this effect is just acceptable for the interferometric field-of-views under consideration, provided that the seeing is carefully managed, (iii) pistoning of the light phase due to seeing, even if the effective r_o is large. These phase variations have to be compared to those of the free air above the telescopes, and can be made small and slow enough by shielding the light path from the wind, (iv) scintillation effects, which disappear when the pupil is reimaged onto the beam combiner, and (v) the so-called "longitudinal chromatic aberrations". The latter result in the change of the optical pathlength in the beam-combining optics from the geometric pathlength due to the finite refractive index of air. Lightpath differences in air of 100 metres will occur, resulting in changes of as much as 20 mm, a change which is wavelength-dependent, thus complicating broad spectral band observations. To compensate it, the VLT will use refractive optics of moderate size.

Description of the Delay Lines

Figure 5 shows the optical schematic of the Cat's Eye delay line optics which is envisaged for the VLTI.

The afocal light beam entering from the left is imaged by M_B on M_A, and recollimated by M_B to exit towards the left. Its dimensional and angular characteristics are preserved, and are quite insensitive to tilts and displacements of the Cat's Eye optics. Because the EW distances between the telescopes amount to as much as 120 metres, long tracks for the delay lines will be needed. These 60-metre-long tracks combined with the requirements for the size of the optics, their smoothness and accuracy of motion, as well as their dead reckoning positioning pose a major challenge to the implementation of the VLTI. The size of the Cat's Eye is determined by the unvignetted field-of-view required. Because of the M = 100 times angular magnification 8 arcsec on the sky results in 1/250 radian in the interferometer tunnel. With a pupil image as far as perhaps 75 metres away, this results in a beam size on the Cat's Eye entrance and exit of 38 cm diameter (8 cm inherent on-axis beam diameter, combined with 30 cm beam expansion). For a lower cost alternative, a 2-arcsec unvignetted field-of-view is also under consideration with a 15.5-cm beam diameter.

The small secondary mirror M_A in the delay line can serve a number of other functions. In the MARK III interferometer it is mounted on a piezo-electric actuator so that it can be used for rapid, small-pathlength adjustments. Also for a number of reasons it is desirable to make an image of the pupil at the entrance of the beam combiner. By making M_A curved it can do that without affecting the image relay or the afocal character of the optics. Since the delay line moves in position this curvature has to be variable making it a "zoom mirror". Techniques exist for accomplishing this.

The Beam-combining Station(s)

Interferometric beam combination can take many forms including combination in the pupil plane, in the image plane, and electromagnetic interference in the coupling between single-mode fibers. Each way has its advantages and disadvantages, and the mode chosen depends often on the type of observations wanted. Other forms of beam

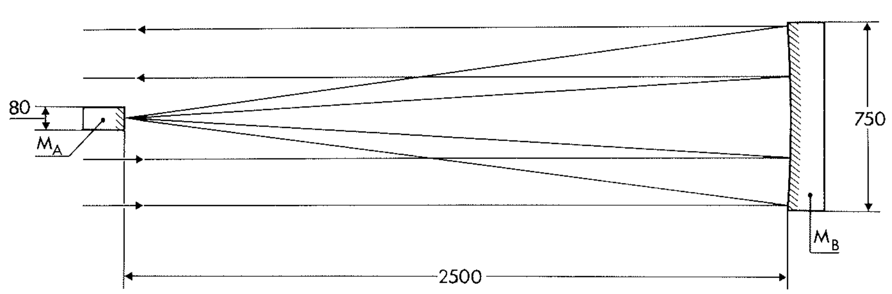


Figure 5: *Optical diagram of the Cat's Eye delay line optics. A Cat's Eye looks very much like a telescope with M_B as the parabolic primary mirror, and the little mirror M_A located in the prime focus as the secondary mirror. The dimensions of this delay line are for an 8-arcsec unvignetted field-of-view. A 2 arcsec field-of-view requires about half the size.*

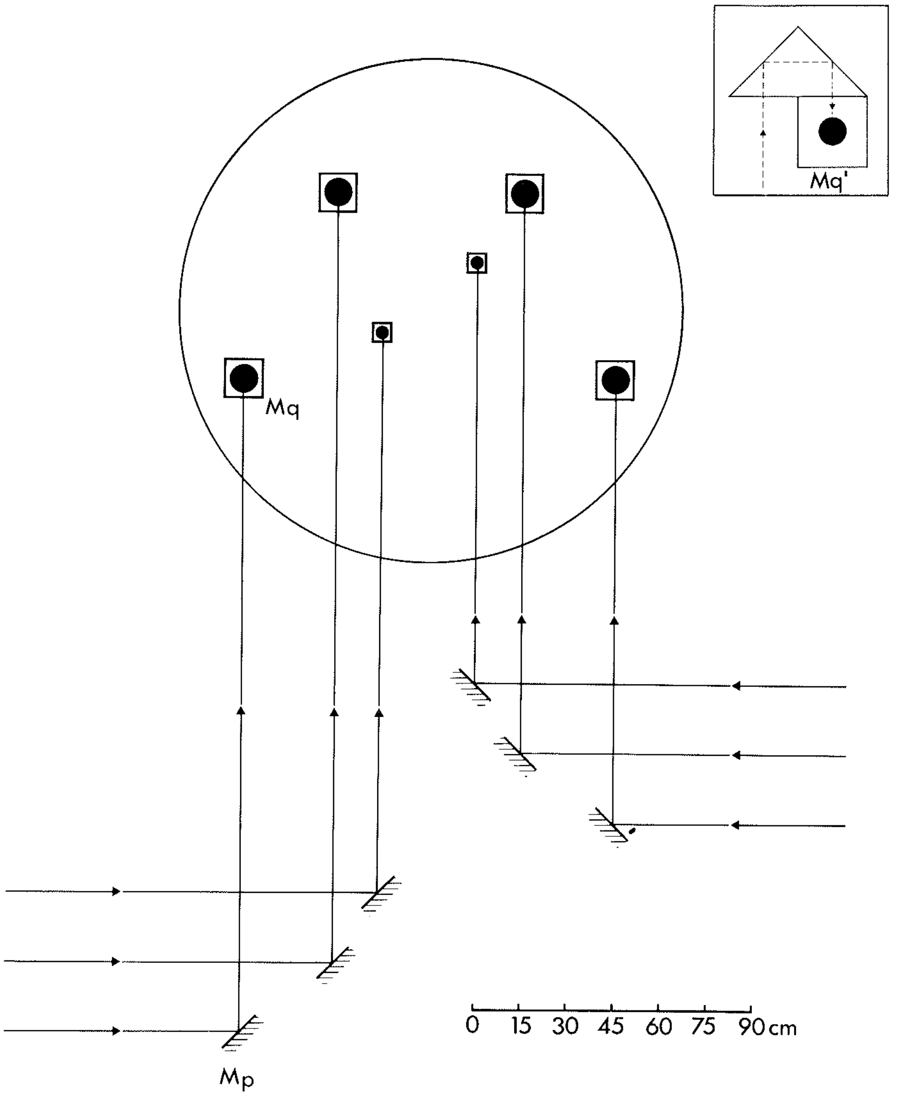


Figure 6: *Possible configuration of the on-axis light beams or pupil images at the entrance of the beam-combining telescope. The four large dark circles are the beams of the 8-metre telescopes, the small ones those of the auxiliary telescopes. The beams/pupil images are positioned by linear movement of the flat mirrors M_p, which send the light horizontally into the beam-combining laboratory, and by movement of the flat mirrors M_q which transfers the light downward into the beam-combining telescope. M_q is replaced by $M_{q'}$ in case it is desirable to rotate the image and/or pupil over 180° (as is the case when combining telescopes located on opposite sides of the interferometer tunnel).*

combination will undoubtedly arise in the future. For the VLTI it is therefore impossible to define the characteristics of the final beam-combining station now. Instead it is proposed that the VLTI provide for two stations, one containing an optical laboratory for experimentation, the other containing a fixed beam-combining telescope with an aperture between 80 and 180 cm. The latter will provide for common user image plane interferometric capability, including the capability for doing spectroscopy and, perhaps, wide interferometric field-of-view observations.

Figure 6 shows a possible combination of the light beams on the entrance of the beam-combiner telescope.

The actual configuration of the beams/pupil images on the beam-combining telescope can be determined by the actual observation wanted. Examples are:

(i) for spectroscopy a linear non-redundant (e.g. spacings 10, 20, and 40 cm of the 8-cm-diameter pupil images) configuration may be optimum. It results in a pattern of parallel fringes in the image plane whose spacing encodes the telescope pair and whose contrast and relative phase can easily be examined with a spectrograph simultaneously for many wavelengths. A configuration like this can use a stationary configuration of M_p and M_q, requires only an 80-cm aperture beam combiner, but suffers in respect to wide interferometric field-of-view operation. Its pupil configuration is not preserved, thus giving a "zero" field-of-view.

(ii) for wide interferometric field-of-view operation it is necessary to preserve the pupil configuration in detail from the entrance to the exit pupil. This places stringent but realizable requirements on the location of the pupil images, a location which changes with time, as the entrance pupil as seen from the star, changes with earth rotation. Motion of the M_q mirrors is more complex now and the beam-combining telescope has to be large enough in aperture to cover the area of the VLTI site demagnified by M = 100, resulting in an approximately 180-cm diameter mirror.

3.2 The Auxiliary Telescopes

So far the use of the 8-metre telescopes has been emphasized and the definition of the VLTI main-array has been based on it. As described in section 1.2, the definition of the sub-array of smaller 2-metre-class auxiliary telescopes (d = 180 cm is assumed here) is based on its incorporation into the main-array. That results both in an ease of change-over from the sub-array to the main-array, in a commissioning and debugging of the VLTI using the always available sub-array, and in a maximizing of the number of affordable auxiliary telescopes given the limited budget available for the VLTI. This results logically in the following definition of the VLTI sub-array (or VISA).

Telescope Configuration

The auxiliary telescopes are movable telescopes. It is proposed that they be relocatable between fixed stations, similar as is the case for the radio Very Large Array and for the IRAM millimetre array. In Figure 7 a possible configuration of stations for the auxiliary telescopes is shown.

In this configuration the auxiliary telescopes share the interferometer tunnel, the delay lines and the beam-combining optics with the 8-metre telescopes. To change over from the 8-metre telescopes to the auxiliary telescopes requires the insertion or turning of a single flat mirror. Change-over can therefore be done within minutes. The add-on cost per auxiliary telescope is limited to the telescope itself and possibly its transporter.

The Auxiliary Telescopes

To simplify the change-over and the coupling to the 8-metre telescopes it was decided to use the same type of coudé optics and telescope mounting as used for the 8-metre telescopes. In doing so one can use again similar or identical control systems, image/pupil/

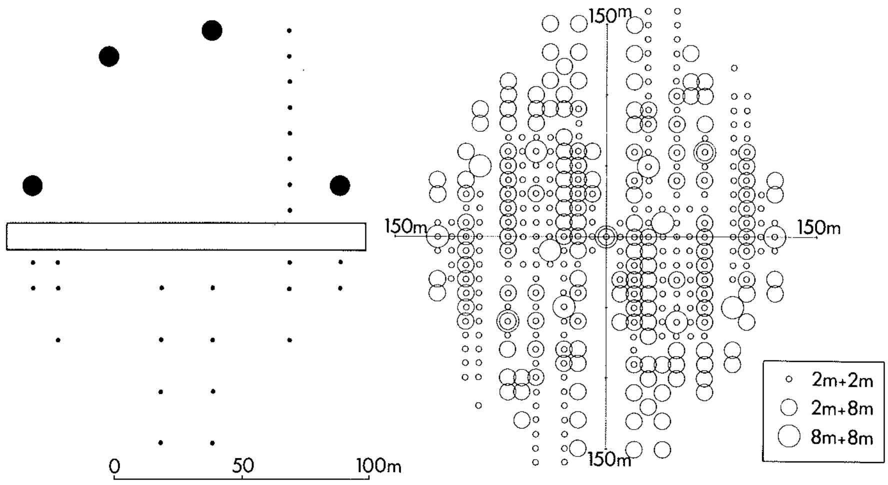


Figure 7: *Left: a possible configuration of the stations for the auxiliary telescopes (small dots). The assumed location of the 8-metre telescopes are shown with large dots (now slightly different from the configuration shown in Figure 4). The light from the auxiliary telescopes travels to the interferometer tunnel along the vertical lines which combines the stations. It anticipates therefore that only one auxiliary telescope can be used per vertical line. Additional stations on the lines connecting the 8-metre telescopes to the interferometer tunnel can also be envisaged. Right: (u, v) plane coverage options for object at zenith with the stations shown left. Note that in this case not all coverage is simultaneous as was the case in Figure 3.*

polarization orientations become the same, and retardation effects are comparable. The auxiliary telescopes include the option for relatively simple (as compared to the 8-metre telescopes) adaptive optics.

Telescope Transporters

Again following the example of the VLA and IRAM array, the telescope transporters will run along railway tracks. There will probably be one transporter per telescope which will lift the telescope from one station and place it on the next with good precision using a kinematic positioning system. The transporter will probably carry a wind shield as well as other telescope support equipment. Initially it is the intention to move the telescopes infrequently, like once per night. As experience with the VLTI develops, and as calibration techniques are refined, more rapid configurations (a number of times during the night) may become feasible.

3.3 Site Aspects

Which Site?

For the configuration shown in Figure 7 a flat plane is envisaged. To keep the length of the delay line as short as possible and to optimize the (u, v) plane coverage it is desirable to have the flat elliptical area with the short axis running roughly EW. This can be done at all VLT sites being considered (Vizcachas, Paranal and perhaps Armazones). The EW dimension of approximately 120 metres will pretty well be set by the need to space the 8-metre telescopes in that direction at right angles to the wind. From the VLTI point of view all three sites look acceptable although Armazones has the advantage of a larger NS extension as compared to the other sites for a given EW extension. This gives higher angular resolutions in that direction without the need for longer delay lines.

For a number of reasons it is advantageous to locate the VLTI on a flat area. On the longer term, large baselines may be wanted, which when located in approximately NS direction, can use the existing VLTI delay lines. In that case the additional telescopes (8 metres or smaller?) will probably be located at different levels, which does not exclude their use for interferometry.

Fitting the VLTI to the VLT Site

Figure 8 shows a drawing of the VLTI on Cerro Paranal following the layout shown in Figure 7.

The actual configuration for the VLTI will be chosen on the basis of the topography of the site chosen for the VLT, on the wind directions, on the seeing effects resulting from the interplay of the wind, the site plateau and the telescope structures, and on other VLT site needs. Interesting questions remain especially concerning the seeing effects which are presently being analysed (L. Zago, *The Messenger* No. **59,** p. 22). Such analysis will have to answer the question on whether the seeing for the 8-metre telescopes on the downwind end of the plateau is much worse than, or comparable to, that on the upwind end (no one expects it to be better!). If it is, the 8-metre telescopes will have to be located upwind, but at the cost of the probably much worse seeing effects for the auxiliary telescopes caused by the wind interactions with the 8-metre telescopes which are now upwind of the auxiliary telescopes.

4. The VLT Interferometer: What Comes Next?

Implementation of the VLTI will start with the site development after the choice of the VLT site. Extended Phase A studies of the major components of the VLTI (auxiliary telescopes, stations, tracks, transporters, delay lines) will be completed early 1991 and will be followed by their construction. It is desirable that interferometry using 3

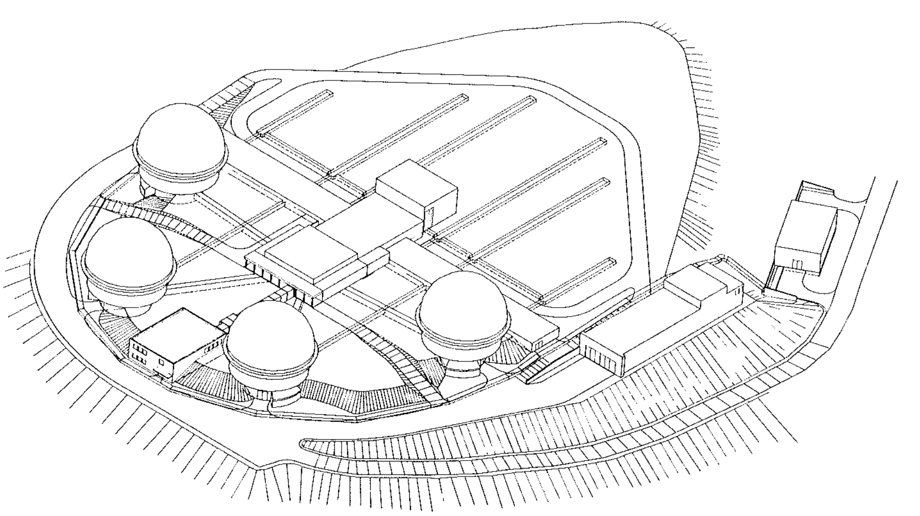


Figure 8: *The VLTI according to the layout shown in Figure 7, shown on Cerro Paranal.*

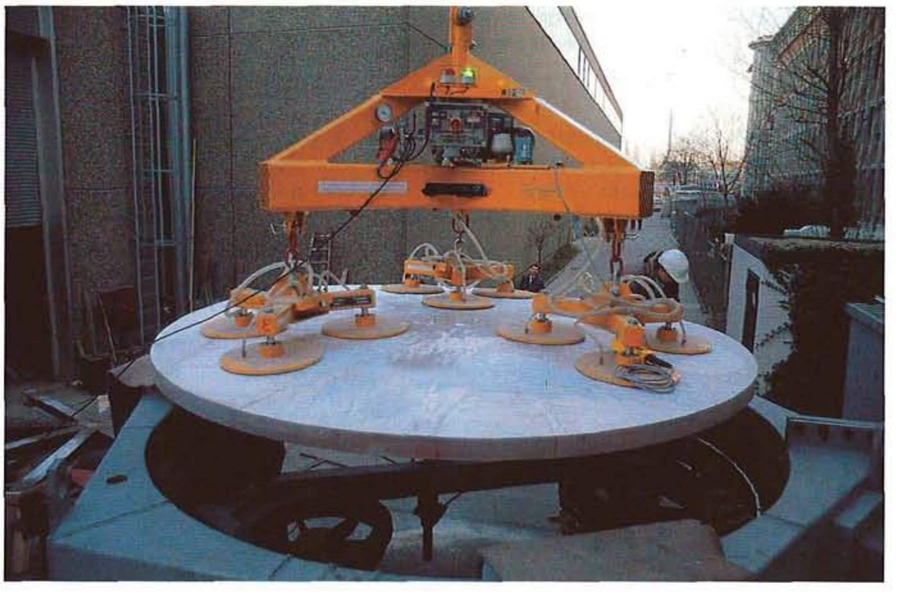
or 4 auxiliary telescopes (2 to be funded out of the VLT budget, the others by additional contributions by research groups in ESO member countries) and limited wavelength coverage (.45 to 25 μm) will start soon after the commissioning of the first large telescope on the VLT site. The full VLTI capability (including such features as the inclusion of the 8-metre telescopes, rapid reconfiguration of the auxiliary telescopes, a non-zero interferometric field-of-view, blind fringe acquisition and maintenance, extended wavelength coverage into the ultraviolet, additional auxiliary telescopes possibly at long NS baselines, additional delay lines) will evolve over a number of years after this, some of it requiring additional resources. The goal will be to provide early on at the VLT Interferometer a facility which will serve both the needs posed by the astronomical programmes of the non-experts in interferometry, as well as the needs of the experts in this rapidly developing field of astronomy. This is a tall task, but as it could be done for radio interferometry, it should also be possible to do it at optical wavelengths. The field is ready for it and the opportunity is here.

How Will the VLT Mirrors be Handled?

Schott is now putting the final touch to the building where the facility to produce the Zerodur VLT mirror blanks is to be installed. Meanwhile Schott is developing the various tools and equipment necessary for the casting, annealing, ceramization, machining and test of the mirror blanks.

Handling in particular is a major concern for Schott. The raw blanks obtained after casting are considerably heavier than the finished blanks and are also a lot more fragile because of the local defects at the surface which have a tendency to behave like perfect crack propagators. An additional difficulty is that after casting only the top surface is physically accessible.

Schott has therefore developed a special handling tool based on suction. The photograph shows a smaller-scale system developed to handle 4-m-diameter mirrors. It is being tested on an experimental thin meniscus realized in the frame of the VLT development programme. This mirror has been produced with the spin casting technology and was originally 4.1 m diameter. It has subsequently been machined down to 3.7 m diameter and to 7.5 cm thickness.



The picture shows the vacuum pumps located at the top and the large sucking cups arranged as a whiffle tree. The triangular structure is used as a vacuum buffer.

The tests have demonstrated the good functioning and the reliability of this type of handling device. Even in case of power failure the system can safely hold the mirror during several hours. A similar system is likely to be used for handling the mirror during its polishing and for its integration into the cell at the observatory. *D. ENARD (ESO)*

Adaptive Optics at the ESO 3.6-m Telescope

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From April 11 to 16, 1990, the VLT adaptive optics prototype system has been tested at the 3.6-metre telescope on La Silla. After the two preceding test periods at the Haute-Provence Observatory in October and November 1989 (see the article by F. Merkle in *The Messenger* **58**, 1989) this was the first test of the adaptive optics prototype system at the telescope for which the system was initially designed.

A description of the prototype system has been given earlier (Merkle, *The Messenger* **57**, 1989). The following table summarizes the major data: