THE VLT INTERFEROMETER: CURRENT STATUS AND EXPECTATIONS FOR THE NEXT 20 YEARS

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ABSTRACT

The layout, optical design and main components of the VLT Interferometer are presented. VLTI subsystems are designed with sufficient flexibility to allow incorporation of new features later. Some parameters, which are of interest for a comparison between ground and space, are also presented :

- Effective aperture diameter, depending on the degree of correction by adaptive optics (for 8 m Unit Telescopes (UT's) and 1.8 m Auxiliary Telescopes (AT's))
- Number of telescopes and (u,v) coverage possibilities
- Maximum size of the array (133 / 202m with VIMA (VLTI Main Array) / VISA (VLTI Sub-Array) respectively)
- Wide field-of-view for off-axis cophasing/coherencing (up to 8 arcsec field), thanks to the "homothetic mapper"

In particular the size of the field-of-view has considerable impact on the scientific use of the VLTI and will be dealt with in more detail. After the year 2005, additional features may be available at the VLTI :

- Four UT's and up to eight AT's and delay lines, with rapid reconfiguration of the array
- Partial adaptive optics at shorter wavelengths
- Blind operation by coherencing or cophasing from sources several arcmin away from axis,
- Full sky coverage using laser guide stars for adaptive optics
- Cophasing of the array using in-orbit artificial sources
- An extension of the VLTI towards the north of Paranal site

Space programmes in interferometry should complement large ground-based facilities which will be operational by the first decade of the next century.

1. INTRODUCTION

By the beginning of the next century ESO will have a visible / IR array of four fixed 8-meter telescopes (VIMA) with a maximum baseline of 130 m, and several movable 1.8m telescopes (VISA) with a maximum baseline of 200 m. A recent review of the VLT Interferometer sub-systems can be found in ref. [1]. This paper presents only the current status of these sub-systems, except for the beam combiner where a more detailed analysis is given. After reviewing how we plan to implement VLTI features up until around 2001, the paper focuses on ultimate modes of the VLTI, especially those that are of importance for a comparison of space and ground.

A prerequisite to the decision to build a 100-m class array in space is to know the limit reached by the large arrays now under construction on the ground, using those ultimate modes. This paper emphasises one of these modes, the so-called "blind mode", where sensitivity performance is seeing-independant and limited only by the total integration time.

2. VLTI SITE, LAYOUT AND OPTICAL DESIGN

Fig. 1 and 7 show a sketch of the VLT Observatory on Paranal in Northern Chile. Compared to the mountainous region surrounding the ESO Observatory at La Silla, the site chosen for the VLT at Paranal is superior -in particular for the interferometric operation- for a number of reasons:

- Average seeing over the year = 0.66 arcsec, including "super seeing" below 0.4 arcsec for 5% of the time for periods exceeding one hour.

- There are 80 more photometric nights per year at Paranal compared to La Silla, of which 58 are in the period March to September. This is an important point since a prime scientific goal for the VLTI is the observation of the Galactic Center and regions around it, visible only during that period.

In addition to the four 8m Unit Telescopes (referred to here as UT's) and two to three Auxiliary Telescopes (referred to here as AT's), the VLTI includes the following sub-systems:

- A 160m long, 8m wide underground tunnel, housing movable Delay Lines (referred to here as DL's),

- An underground laboratory, including an Imaging Beam Combining Telescope (referred to here as IBCT) with associated image, fringe and pupil trackers and two facilities for coherent combined instrumentation (see Fig. 1)

Compared to telescope configurations described in ref. [1], a number of modifications and improvements have been made:

- For sky viewing and clearance requirements, UT1 was moved to the south-west and the DL tunnel moved by 4m to the south, so that UT1, 2 & 3 form a quasi-linear array. The new (u,v) coverage is shown in Fig. 2.

- The configuration of AT stations was slightly modified to provide more flexibility during commissioning and initial operation of the VLTI (see section 5), leading to a total of 30 stations.

The optical design is also described in some detail in ref. [1]. Only the general principles are illustrated here.

The second stage of operation of the VLTI (after ≈ 2003), which involves an 8 arcsec cophased field-of-view for VIMA (3.5 to 8 arcsec for VISA) introduces the most difficult constraints in the design. First,before combining light beams, subpupils must be relayed to a location where at any given time the exit pupil configuration appears as a scaled-down replica of the input pupil configuration projected on the line of sight, with a lateral precision for each subpupil

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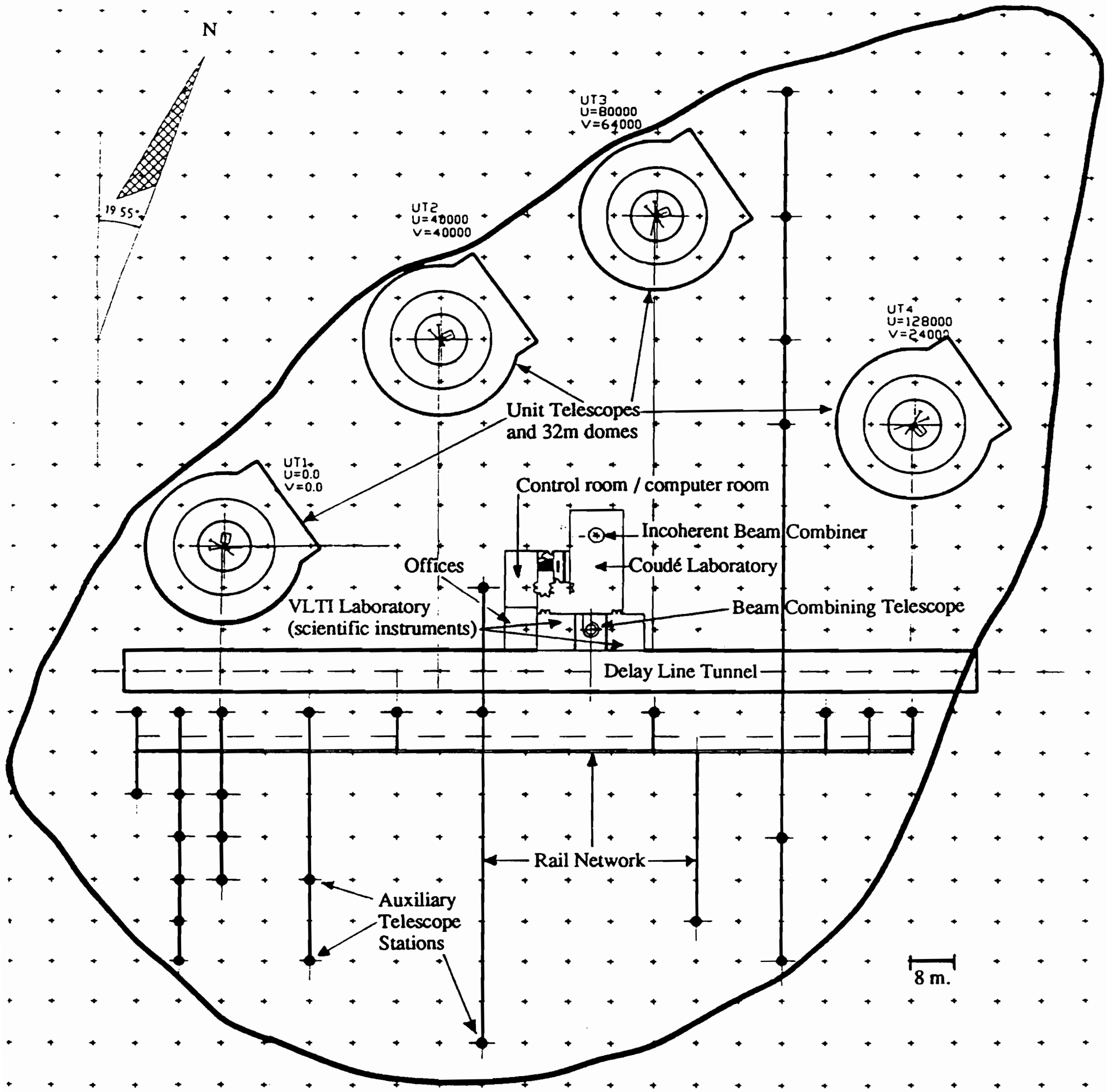


Figure 1: Layout of the VLT Observatory at Paranal (only UT's and AT's are above the ground)

of ≈ 50 µm, a difficult task. Secondly, this operation requires large optics, in particular for DL cat's eyes (see Fig. 4) and for the IBCT (see Fig. 5). The first point calls for a pupil lateral monitoring system at M16 (Fig. 3); this is done by monitoring the image of a pupil beacon located at the center of the telescope pupil, namely the mirror M2 (both for AT's and UT's). Because beam lateral movements near the IBCT will be fast (≈5Hz) due to air motion in the tunnel, each pupil beacon must be shone continuously. Reimaging of pupils in addition removes diffraction effects, which lead to a reduction in contrast (ref. [4]). Fig. 3 shows the mirrors M16 on which pupil images are formed (using variable curvature mirrors in DL cat's eyes, see sec. 3 and fig. 4); a M16 mirror can be fed directly from a M15 mirror, or from the side of the IBCT to maintain equal polarizations or to avoid mutual beam obstruction by M15 mirrors. M15 and the next mirror must move simultaneously during an observation (tracks for M15's are shown in Fig. 3). Finally, the M16's will be on tip-tilt mounts for fine image tracking purposes.

The IBCT, including optics and mechanics, was studied at ESO in more detail recently.It is presently designed as a 2.1 m diameter, F/25 Gregorian looking at zenith (Fig. 3 and 5). Such a large diameter is required for the largest baselines (200m) with VISA, when homothetic mapping will become an option (ref. [4]). To minimize optical aberrations for off-axis rays (maximum field angle in IBCT: 400 arcsec), a Gregorian is superior to a Cassegrain and one must increase the primary focal ratio (→ 3.2) and decrease the demagnification of the secondary mirror (→ 8). Those choices lead to a rather deep pit (10 m). Another combined focus behind the primary mirror is available for sensing purposes (e.g. tilt or wavefront sensor). A fringe sensor, briefly described in the next section, will share the Gregorian focus with scientific instruments (Fig. 5).

The wide FOV operation requires the combination of beams in an image rather than a pupil. This is why an image plane IBCT was selected. Nevertheless pupil plane combination,

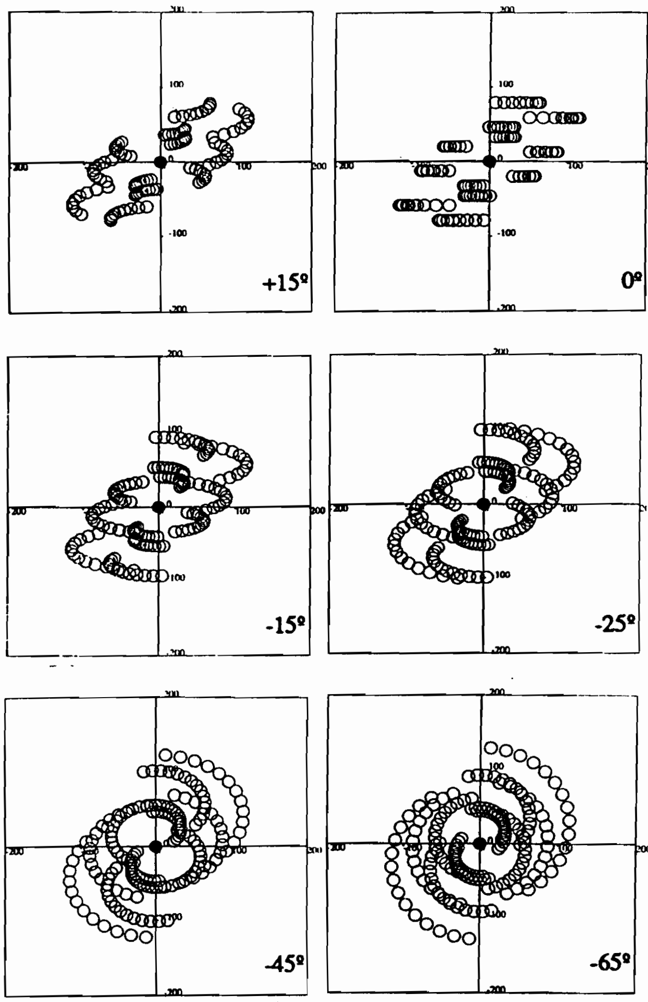


Figure 2: u,v plane coverage of current VIMA configuration for source declinations indicated in (º). Units are given in m

which presents important advantages for IR instruments, can also be accommodated by combining pupil images after M15 mirrors. This is foreseen for VLTI initial operation.

3. VLTI RELATED STUDIES: A STATUS REPORT

The VLTI concept and subsystems were reviewed by external experts in May, i.e. before contracting out the major parts of the VLTI. The basic approach to the VLTI was well received and no significant problem was found. However the control of the whole system was identified as a very critical part of the project and as an urgent matter for the team in Garching (four persons).

This chapter gives a status report on important VLTI subsystems as well as on other critical components. Major subsystems of the VLTI (AT's, DL's and IBCT) have been studied by external contractors and are now ready to be contracted out, except the IBCT for which studies are presently being conducted in-house.

AT's and DL's:

Funding for a third DL and a third AT have just been committed by CNRS (France) and MPG (Germany). This was an essential step to provide VISA with imaging capabilities by itself.Status reports on different options studied for both subsystems can be found in refs. [5], [6] and [7]. Presently, technical specifications are being finalized (for AT transporters too) and calls for tenders for construction are expected to be dispatched by the begining of 1993, the actual construction expected to start at the beginning of 1994.

IBCT (homothetic mapping):

A solution has been proposed to reconfigure the exit pupil (so-called "homothetic mapping") based on extendable arms articulated from the edge, carrying a M16 mirror at its end, and numerical simulations are now starting to check its mechanical performance. At the beginning the M16's will be set and fixed during an observion; later they will be capable of moving continuously to preserve the pupil configuration. The secondary mirror M18 and flat tertiary M19

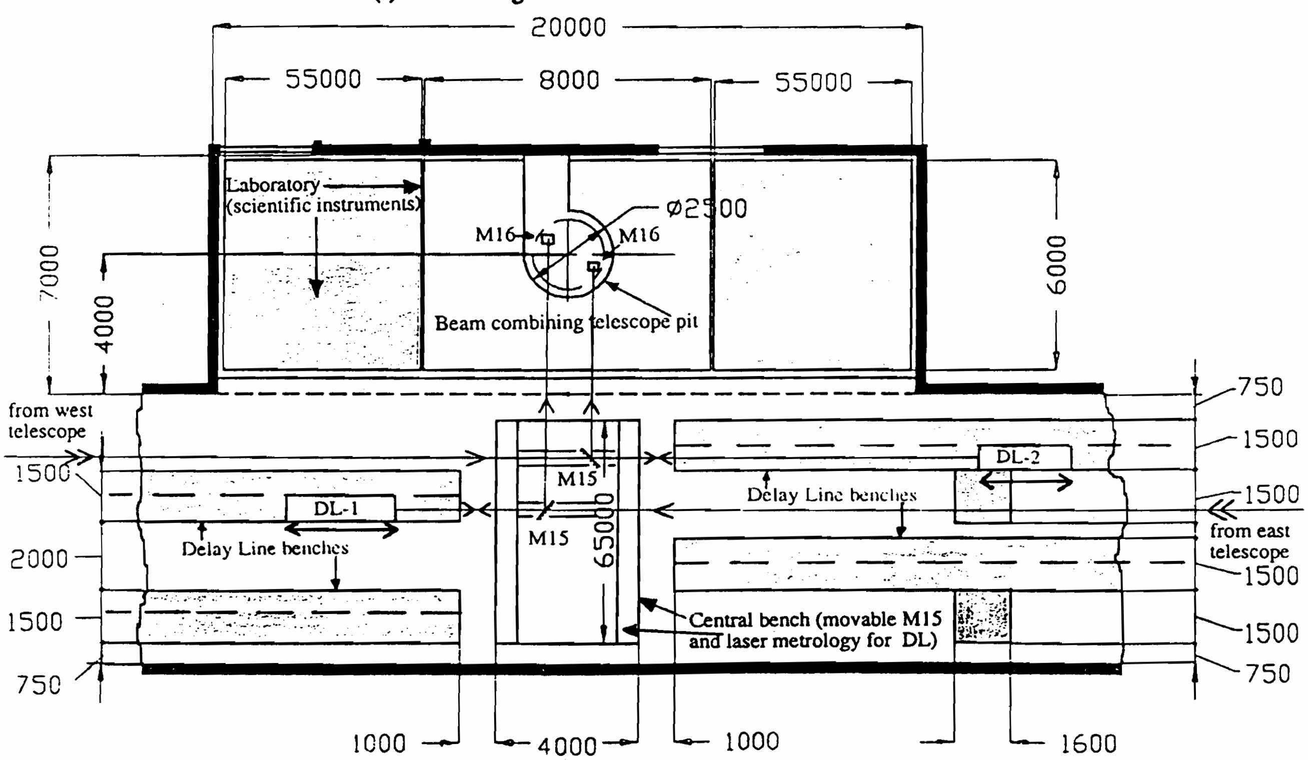


Figure 3. Central part of Delay Line Tunnel, showing DL benches (2 DL per bench) and paths for 2 lightbeams down to M16's

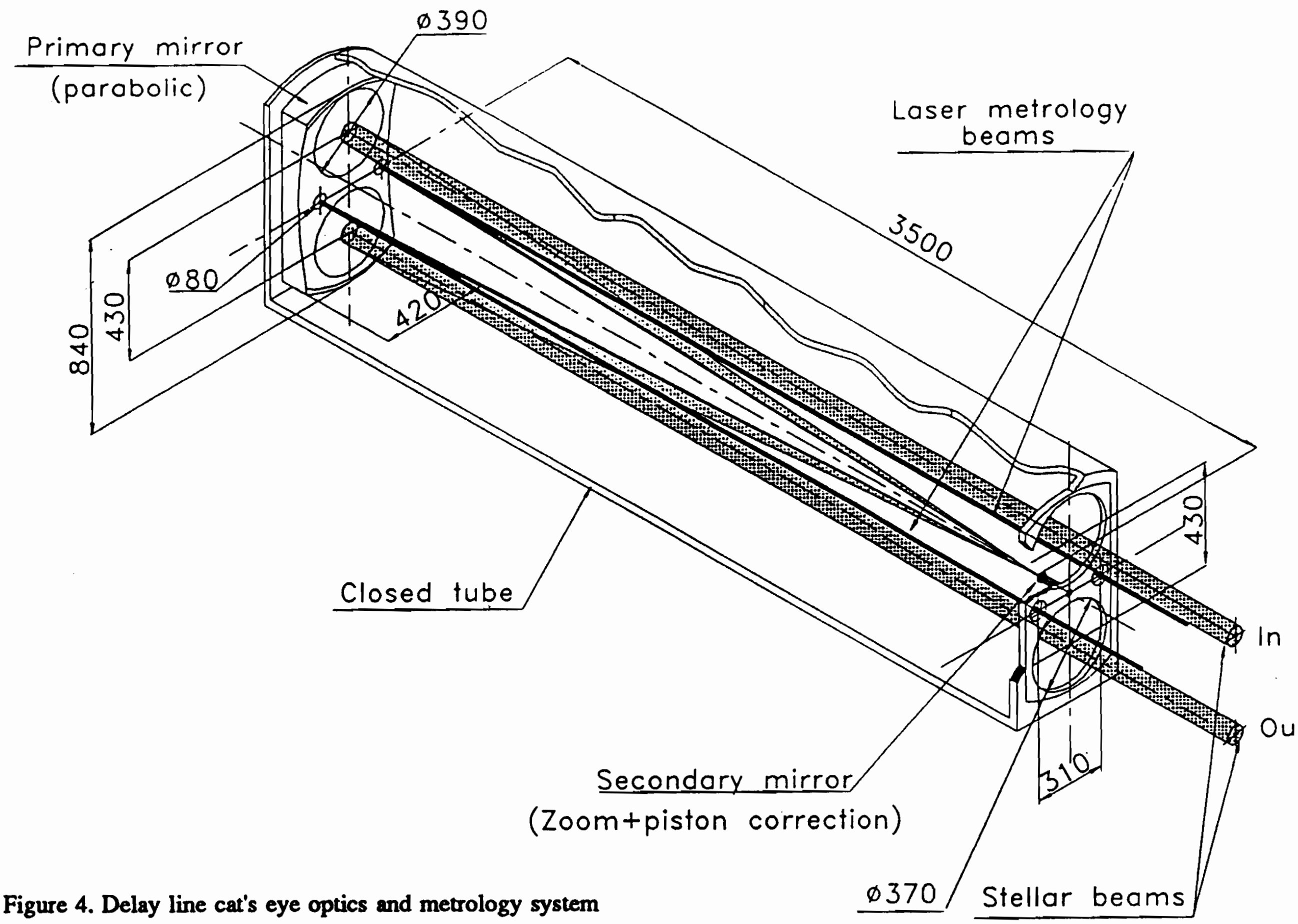


Figure 4. Delay line cat's eye optics and metrology system

are inside a tube which can rotate to feed a given scientific instrument. A final design is expected by the end of 1993.

Fringe sensor:
A concept was selected by ESO, following a study by OCA in Nice. It involves monomode fibers in the near IR (H or K) and two channels for modulation, with amplitudes of λ and $n\lambda$, so as to include a contribution from the fringe pattern envelope in the modulated signal (fringe coherencing). Beams are then combined onto a single pixel detector. OCA shall propose a detailed design to ESO at the end of 1992. A laboratory prototype will be completed by the end of 1994.

Variable Curvature Mirror (VCM, for description : ref. [1]):
The VCM, essential for the wide field mode, fixes longitudinally the position of an exit subpupil at the IBCT entrance, independent of the position of the DL carriage. The construction of a prototype, involving a steel membrane actuated by a pneumatic device has now started at the Observatoire de Marseille;it is expected to be completed by July 1994.

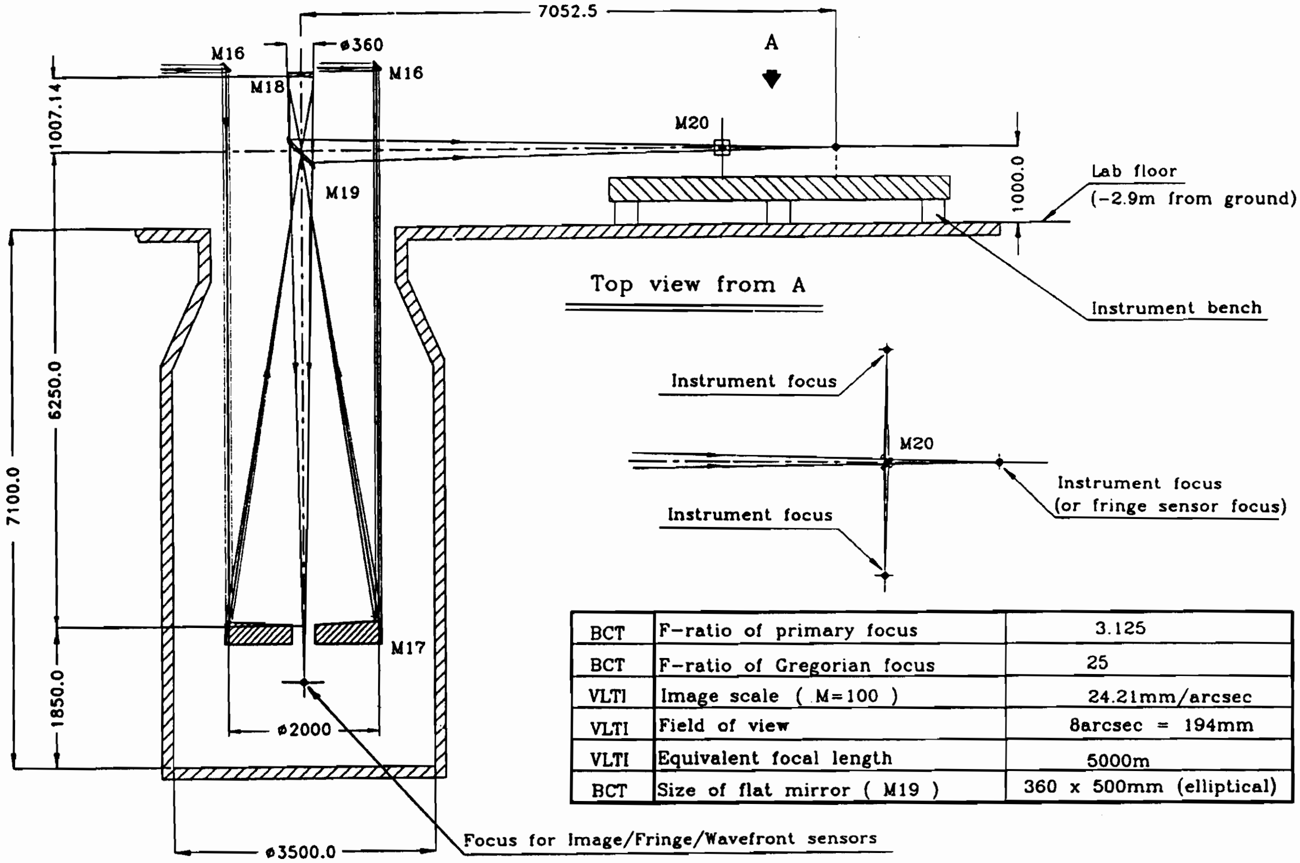
VLTI control organisation:
Following recommendations made during the last VLTI review,the general software architecture is being designed and data critical links identified and specified, especially the links with the VLT. Hardware and software concepts selected for the VLT will be used for the VLTI. The major tasks for ESO will be to ensure compatibility between many subsystems built outside ESO and to manage several complex interfaces (especially related to the homothetic mapper).

Straylight produced by artificial sources in VLTI arms:
Light beams are combined in the VLTI after 20 reflections. It is foreseen to use artificial lights to monitor optical path changes, lateral pupil positions or image scales. A study of straylight induced by microroughness/dust has now started.

VLTI mock-up's:
Simulations of the aperture configuration of the VLTI, with a goal to produce and detect interference fringes, and to reconstruct images of artificial sources, are currently being developed by G. Weigelt in Bonn (for visible light) and by R. Genzel in Garching (for infrared light).

Adaptive optics (AO):
The prototype developed in France was recently upgraded (Come-On-Plus:19 → 54 actuators, see ref. [8]). Its aim is to demonstrate the feasibility of AO, to assess its performance and to carry out an intensive observation programme. The ESO AO programme has two goals: to make Come-On-Plus an ESO standard instrument by developing adequate tools (artificial intelligence) and to pursue the system study by Matra aimed at defining the VLT AO system. AO with > 80% Strehl ratio at $\lambda = 2$ µm is presently foreseen for UT's only. It is foreseen to have at least fast image guiders for the AT's, which should provide them with a wavefront correction approaching that of the UT's. AO on AT's was highly recommended by the VLTI review experts, in particular for keeping visibility losses (≈ 15% in K-Band with only tip-tilt correction) at a minimum.

Scientific Interferometric Instrumentation (I I):
Combined focus instruments will be developed and built outside ESO. I I concepts and the three instruments selected for the VLTI, which cover the visible, near IR and 10 µm regions of the spectrum, are described in a report by the Interferometry Panel (ref. [9]). Following a Preliminary Inquiry by ESO related to the first generation instruments,"I I Science Groups", including both institutes and industries, will be created. The present trend, given the limited budget for II (a resolution to double this budget(2.4MDM) has been submitted to the ESO Council) is to develop simpler versions of at least 2 instruments, initially operated by IISG's.



BCT	F-ratio of primary focus	3.125
BCT	F-ratio of Gregorian focus	25
VLTI	Image scale (M=100)	24.21mm/arcsec
VLTI	Field of view	8arcsec = 194mm
VLTI	Equivalent focal length	5000m
BCT	Size of flat mirror (M19)	360 x 500mm (elliptical)

Figure 5.Present design for the Imaging Beam Combining Telescope, showing possible locations for fringe/wavefront sensors

4. PLANS FOR BLIND OPERATION

After reviewing current R&D activities and studies related to the VLTI, this section analyses the propositions for blind operation and what is needed to implement them. Only when those options are available with VIMA (≈ 200m^2 collecting area -to be compared to 7.5 for VISA with three AT's-) will ultimate sensitivities be reached with the VLTI. Most of these options require a cophased field-of-view of several arcsec, calling for continuous "homothetic mapping" (see section 3). Since this last mode, despite indepth studies at ESO, is not scheduled before ≈ 2003 (see section 5), the present section presents items which will be installed after ≈ 2005 at the earliest. Only at that time can sensitivity limits be approached with the VLTI.

To operate the VLTI "blindly" means to equalize pathlengths between its arms to a fraction of the coherence length of the light without using the light from the object under ob -servation. The phase information is taken from a "bright" channel to synthesize a longer coherence time in the "faint" channel. "Bright" refers to a source giving both enough photons per coherence time and fringes of sufficient contrast, the latter restricting considerably the number of candidates for longest baselines. The goal is often to "maintain" the presence of "science" fringes (so-called coherencing). In the first set of solutions described here, the "bright" channel uses a star while in the second it uses an artificial source, either placed on earth or on a satellite.

4.1 Sources for the "bright" channel:

1) The "science" object itself, if the number of photons per coherence time and the fringe contrast $|\gamma|$ are enough. The spectral bandwidth for the fringe sensor should be as large as possible. The sensor has two possibilities:

- Use the same spectral bandwidth
- Use a different spectral bandwidth (e.g. if $|\gamma|$ higher)

2) An off-axis source within the unvignetted field-of-view at the combined focus (VISA:up to 8 arcsec, VIMA:8 arcsec) with three possibilities :

- The field-of-view is neither coherent nor cophased: an additional variable delay line (max. stroke: 1mm) is required at the combined focus for the off-axis star
- The field-of-view is coherent (homothetic mapping)
- The field-of-view is cophased (homothetic mapping)

3) An off-axis source within the Isoplanatic Patch for coherencing (can reach 0.5° in radius, see ref. [3]) or for CoPhasing (referred to here as IPCP; can reach 20 arcsec in radius in the K-Band, see ref. [10]). We assume that the unvignetted field-of-view at the combined focus is cophased, i.e. that the homothetic mapper is used. Also we assume that a system close to a telescope focus relays the off-axis source into the VLTI field-of-view. In any case, an additional delay line (max. stroke: 0.44 m for 1° angle) is required for the off-axis source. There are two possibilities:

- The off-axis source is distant by more than the IPCP. This calls for a relay to the VLTI path at the Nasmyth focus, proposed in ref. [3]. Faint object fringes can only be acquired and maintained to ≈15 µm rms error.
- The off-axis source is within the IPCP. This calls for a relay to the VLTI path at the coudé focus, see section 4.2. Fringes on the faint object can be cophased externally, thus allowing longer integration times.

4) Artificial sources to monitor internal path differences. Monitor some critical paths or the absolute internal optical path difference (OPD in the following) between telescopes:

- Critical paths (especially inside UT's, where vibrations could possibly blur stellar fringes: see sect. 6)
- The absolute internal OPD, when all laser measurements are referenced to the same point

5) An artificial source to monitor (internal+external) OPD's A high orbit point source close to the target is required, since artificial stars generated by resonant scattering from the mesospheric sodium layer cannot be used (parallax problem). A. Greenaway proposed (PHAROS, see ref. [11] and [12]) shining a multi-coloured laser from a satellite, which can stay at less than 4 arcsec from the target during about an hour. This laser can be used either to phase each telescope or to cophase the array. For cophasing, unlike a stellar reference, the source can be made unresolved at all baselines, a crucial advantage. Even though PHAROS can cover only $\approx(1^{\circ})^2$ per year, it leads to ultimate sensitivities for the VLTI (see ref. [13], sect. 2.1.3.3), provided that the laser light is filtered out. Several PHAROS would be desirable to increase sky coverage.

Although most of the "bright" source propositions can be implemented in the VLTI (see ref. [3]) in theory, the proposed designs need further improvement. It is very unlikely that ESO will study those modes in greater depth before the end of VLTI commissioning (≈ 2001).

We analyse in the next section two propositions to implement the "bright" source concepts developed in item 3).

4.2 Implementation of wide angle pick-up concept (§ 3))

Coherencing of the VLTI by using an off-axis star at each Nasmyth focus (30 arcmin field-of-view) was proposed (ref. [3]) and since then, a mechanical design for a pick-up system has been studied. Interesting here are firstly the large size of the isoplanatic patch for coherencing -which allows us to find a reference source in many cases- and secondly the similarity between this size and the field at the Nasmyth focus. A practical difficulty is the need for the off-axis star delay line to rotate about the axis since the field rotates beyond a telescope (AT's and UT's have Alt-Az mounts).

Unfortunately, the central part of the field (3 arcmin in diameter) is obstructed by mirror M4 which is used for the on-axis target. It is proposed (see ref. [10]) to pick up an off-axis star at the coudé and to reintroduce it into the interferometric field, using fiber optics. This application is particularly interesting for AT's, which have in general a smaller interferometric field than UT's.Indeed one can show that the IPCP is almost as large as the standard isoplanatic patch. For an excellent site like Paranal (0.5" seeing), the IPCP reaches 4 arcsec (V Band), i.e. 20 arcsec at $\lambda = 2.2$ µm or 2 arcmin at $\lambda = 10$ µm, which is the field at the coudé focus.

This is, briefly, the set-up proposed for a UT: a 45° dichroic reflects the off-axis light, assuming it has been corrected by the AO system, to the coudé focus for instrumentation, where the stellar image is then fed to a monomode fiber.The light from the fiber, after compensation of the additional pathlength (pressure drums), is reinjected at a fixed location near the edge of the field mirror M10 (ref. [1], sect. 3) in the interferometric field. Field rotation is compensated by rotating the fiber head. Fiber lengths should be stable in time.

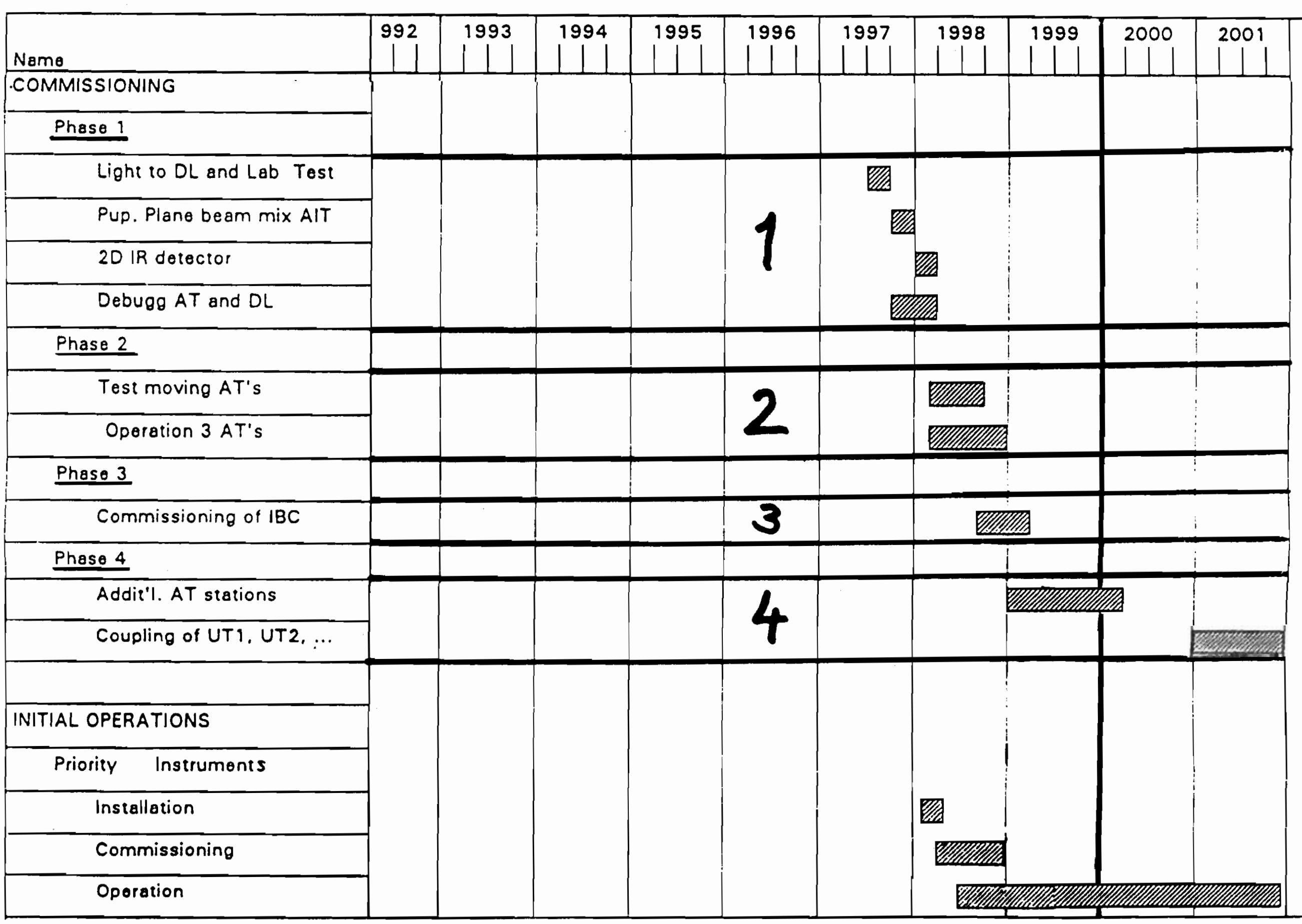


Figure 6. Steps of the VLTI commissioning procedure and initial operation

With solutions described in this section, stars located at an angle from 0 to 15 arcmin angle can be used to cophase or to coherence the array.

5. PLANS UP TO THE YEAR 2001 AND BEYOND

5.1 Commissioning of the VLTI and initial operation

Although the modes described in the previous section are not, strictly speaking, part of the VLTI Implementation Plan (ref. [13]), their study has enabled us to identify related items which should be included in the telescope or IBCT design. Since the beginning of 1992 our group has been focusing on the preparation of the commissioning phase/initial operation of the VLTI. Also more detailed planning up to 2001 for sub-system design and manufacturing, transport to the site, Assembly/Integration/Test (AIT) and initial operation involving the first VLTI instruments, has been set up.

The objectives for the initial operation can be summarized in this way:

- use AT's in pairs, with shortest baselines
- use initially three stations (N-S, then E-W baseline)
- limit seeing effects by observing in the IR
- use simple pupil plane beam combiner (i.e. no IBCT)
- limit number of subsystems to absolute minimum
- gradually upgrade complexity and performance

The commissioning has been split into four phases, which are summarized in Fig. 6 and described in more detail below.

During Phase 1, only the two stations close to the interferometric laboratory, defining a N-S baseline and only one delay line are used. A co-axial combination set-up in the IR (classical Michelson interferometer) is foreseen during this phase (see end of sect. 2). "First fringes" will be acquired using a non-resolved object, and their visibility measured.

Phase 2 involves operation of an east-west baseline, including two AT stations close to the interferometric laboratory, thereby minimizing the optical path to the laboratory. The panoramic near IR detector used during the initial phase will be progressively replaced by the first scientific instruments. Commissioning will rely on them to optimize the VLTI. At the end of Phase 2, the three AT's will be tested in pairs, each using a moving and a fixed delay line.

Phase 3 involves the simultaneous combination of three AT's at the locations used in Phases 1 and 2. The three delay lines are then used simultaneously. Also, the image plane beam combining telescope will be commissioned. Nevertheless the M16 mirrors will only be set and fixed during an observation. First tests of the on-axis coherence / phase tracker will be carried out in conjunction with fringe detection by scientific instruments. The goal is to assess the "contrast performance" of each subsystem in the VLTI.

Phase 4 involves operation of two or three AT's, located on one of the ten stations of the linear array (see Fig. 1). The three delay lines, running now in both halves of the tunnel, are used. Scientific instruments are used at the combined focus of the IBCT to assess the performance of the linear array. When scientific instruments are operational, Unit Telescopes will be involved, one by one, to form a pair with an AT. Fig. 6 shows that the operation with UT's will not start before the year 2001.

The commissioning of the VLTI, described in this section, should produce valuable scientific results during Phase 4. Because the VLTI has been designed for *flexibility*, new features that we will now review can be incorporated later.

5.2 Plans beyond 2001

The modes described now are of interest for a comparison with a 100m-class visible/IR array in space. The first years of the next century will be dedicated to scientific observations with VISA and to the interferometric combination of UT's with/without VISA. Then tests of the IBCT in conjunction with the homothetic mapper will probably start after 2003. Only after 2005 can one think of testing blind operation systems on UT's. Therefore the components, namely the four UT's in a coherent mode and blind operation tools, which are needed for a comparison with the above defined array cannot be realistically operational before 2010. This is comparable to the time scale needed to define and build the space array, if it were decided today. In 2010, additional features may become available:

Combination of four UT's and up to eight AT's and DL's
The interferometric tunnel and the IBCT can accommodate up to eight stellar beams (see Fig. 3).

Addition of new AT stations to improve (u,v) coverage
A maximum of 30 is planned at the moment.

Rapid reconfiguration of VISA
It is already planned to be able to move AT's, including all operations, to another station in just one hour.

Partial AO at short wavelengths and UV/visible exploration
Active mirrors with many actuators (2500 needed for operation in the visible) and faster wavefront sensors may be available ten years from now.

Blind operation using stars several arcmin away from axis
Those modes are described in section 3.

Full sky coverage using laser guide stars for AO

Cophasing of the array using in-orbit artificial sources
see section 4.1-5.

An extension of the VLTI to the north of Paranal
The Cerro Paranal slope in a northerly direction, is quasi constant. Starting 100m from the N edge (UT3) it amounts to ≈26º over a distance of ≈700m. Since the latitude at Paranal is -24.6º, we have a potential extension for the VLTI in a direction which does not deviate by more than a few degrees from the earth's axis. A dedicated AT, transported to a number of selected stations placed along the axis shown in Fig. 7, could be coherently combined with UT's and/or AT's (UT's preferred for sensitivity and (u,v) coverage, see Fig.7) through either a light duct connecting those stations with the DL tunnel, or an optical fiber. One can show that the OPD variation resulting from the earth's rotation remains within the range of a VLTI DL stroke (60 m) for any given star (zenith d.<45º) and for baselines larger than 200m. The remaining OPD, or DC part (up to 260m) can easily be accommodated by putting together several DL's in a trombone arrangement.One difficulty requiring further study comes from the difference in seeing behaviour to be expected between two AT stations, due to a difference in altitude which reaches 320m for a 700m distance. The area covered by such an extension is that of a triangle, 130m X 800m in size.

6. A 100M-CLASS VISIBLE/IR ARRAY IN SPACE: WHEN ?

Theoretical predictions of VLTI performance (ref.14) show that VIMA equipped with a blind operation mode and full sky coverage AO at short wavelengths would be more sensitive in the visible for relatively "bright" objects, compared to an equivalent array on the Moon with 1m telescopes.

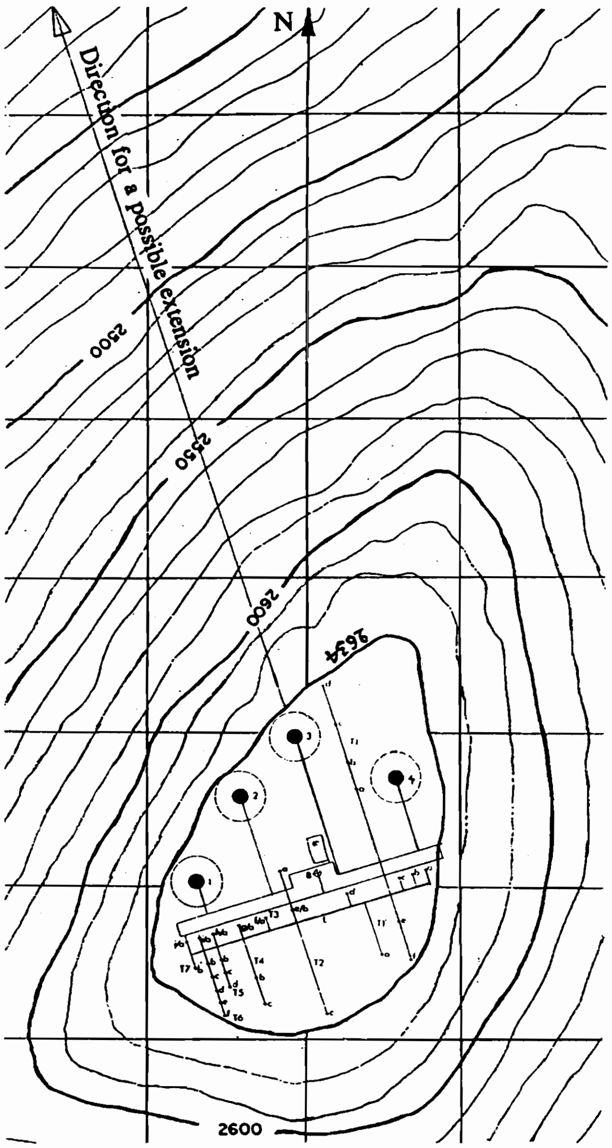


Figure 7: Map of Paranal with the VLT (scale:23mm≡100m)

This assumes the smooth running of features which are not in the VLTI Implementation Plan. A key issue in the "space vs ground" debate is the technical feasibility (we have not yet identified limitations by laws of physics !) of extensions which can only be included after 2005. Although we have reason to be confident about the initial operation involving AT's -they were designed for interferometry, especially regarding OPD stability-, we have reservations about the following:

- UT's have not been specified for interferometry, making the use of laser metrology probably unavoidable (but, before including UT's in the VLTI, time will be available to measure pathlength stability and to derive a strategy)
- Homothetic mapping is a real mechanical and control challenge (calls for robotics) and not a proved concept
- It is too early to assert that proposed designs for coherencing using off-axis stars at Nasmyth or coudé will work
- The VLTI control will be complex, in addition because many parameters must be controlled. Compatibility between subsystems and reliability are major issues.

We should also keep in mind that the imaging capability of VIMA will be poor ("parameters" rather than images). But can Europe afford to have a visible/IR 100m array in space, more sensitive than VIMA, with good imaging capability ? We must wait until the beginning of the next century before taking a decision to build a 100m class array in space. By then we will be well versed in the extended VLTI performance limitations.

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