# A New Plan for the VLTI

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## 1. Introduction

Since the decision by the ESO Council in December 1993 to postpone the implementation of the VLTI (see *The Messenger* No. 74, December 1993), ESO has pursued a programme with the aim to develop all necessary designs to assure a fast implementation as soon as funds would become available. As a part of this programme, the Interferometry Science Advisory Committee (ISAC), a committee of astronomers who have a background in high angular resolution astrophysics and interferometry, was established. Its charge is to review the development of, to define a key science programme for, and to recommend necessary conceptual changes to, the VLTI. It has convened in May and October 1995 and in April 1996. The ISAC found a wealth of scientific topics which could be addressed favourably or uniquely with the VLTI. Some of them have been described in more detail (see *The Messenger* No. 83, March 1996). The top-level technical requirements which result from the ISAC scientific requirements are:

• The VLTI should acquire first fringes around the turn of the century in order to ensure competitiveness with other interferometry programmes.

• There should be a phased approach to the implementation of the VLTI. The first phase shall include the 8-m Unit Telescopes from the start, and shall focus on spectral regimes where telescopes can perform near the diffraction limit with a minimum of adaptive control. The capability, within the budget, to open the spectral ranges towards shorter wavelengths for all telescopes, in particular to the near-infrared regime with Unit Telescopes using higher-order adaptive optics systems, shall be investigated.

• Auxiliary Telescopes should have a diameter of order 1.8 m as a compromise between cost and sensitivity.

• A field of view for the science target of 2 arcseconds (“primary beam”) is sufficient. In order to enable phase referencing as well as narrow-angle astrometry, the capability to do interferometry at a second field position (“secondary beam”) within 1 arcminute radius from the science beam shall be included.

• VLTI shall have the capability to simultaneously combine four telescopes, including at least two 8-m Unit Telescopes and up to three Auxiliary Telescopes.

• Beam combination instruments shall operate in “single mode” (fringe detection on fields of the size of the Airy disk) in the red, near-infrared, and in the mid-infrared.

• VLTI should have narrow-angle astrometric capability with the a precision comparable to the atmospheric limit.

In view of the progress made in the scientific definition as well as of the growing competition, ESO decided in December 1995 that the time was right to reintroduce the implementation of the VLTI into the VLT programme, within funds available at ESO as well as in the community. We have developed a “New Plan” with a technical scope which is adapted to a limited budget, and a significantly modified technical concept which meets better the scientific needs. The main goal of the New Plan is to introduce the original VLTI capability, but in several phases with a modified schedule and sequence off supplies. However, there will be significant changes to the earlier concept (see J.M. Beckers, “Planning the VLT Interferometer”, in *The Messenger* No. 60, June 1990). The new plan was endorsed by the Scientific-Technical Committee, Council has subsequently confirmed its authorisation to the Director General to proceed with parts of the VLTI programme. Also, additional funds of 10 million DM which were made available through an agreement on the enhancement of the interferometric

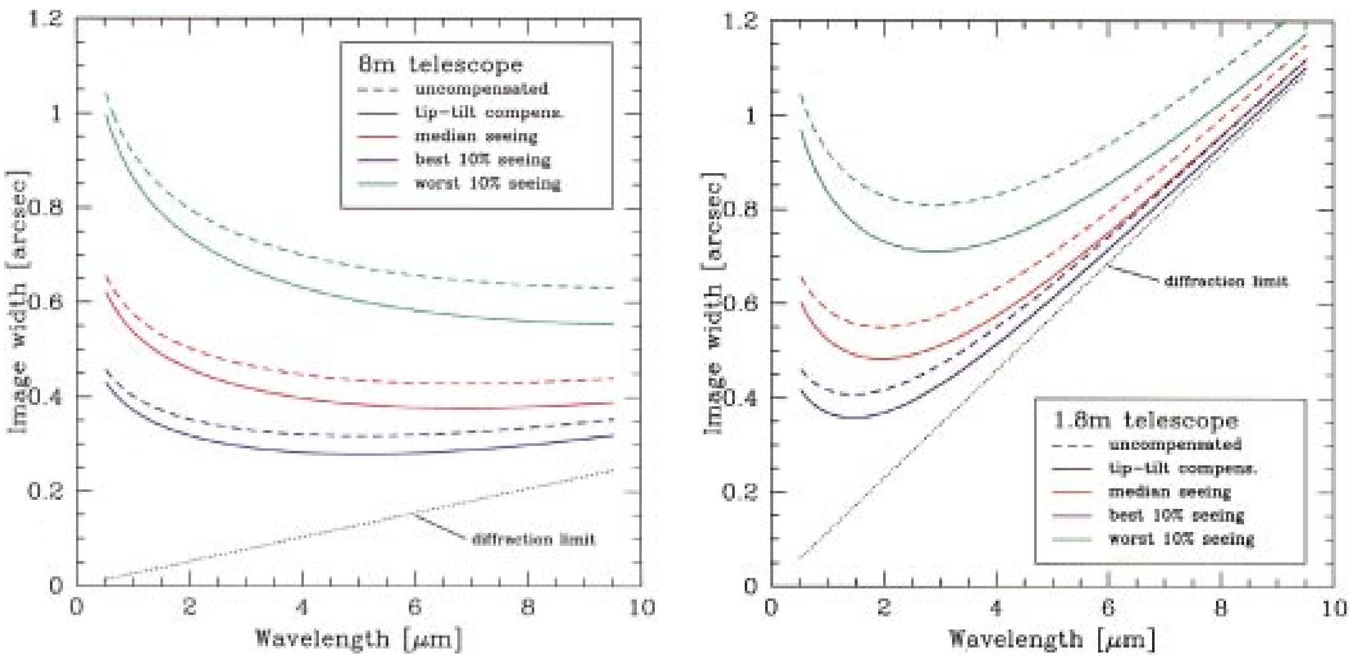


*Figure 1: Resolution of an 8-m telescope (left) and a 1.8-m telescope (right) with the seeing characteristics of Paranal. Median seeing refers to $r_{0,550}$ = 15.6 cm, best 10% of seeing to $r_{0,550}$ = 22.4 cm, and worst 10% seeing to $r_{0,550}$ = 9.8 cm.*

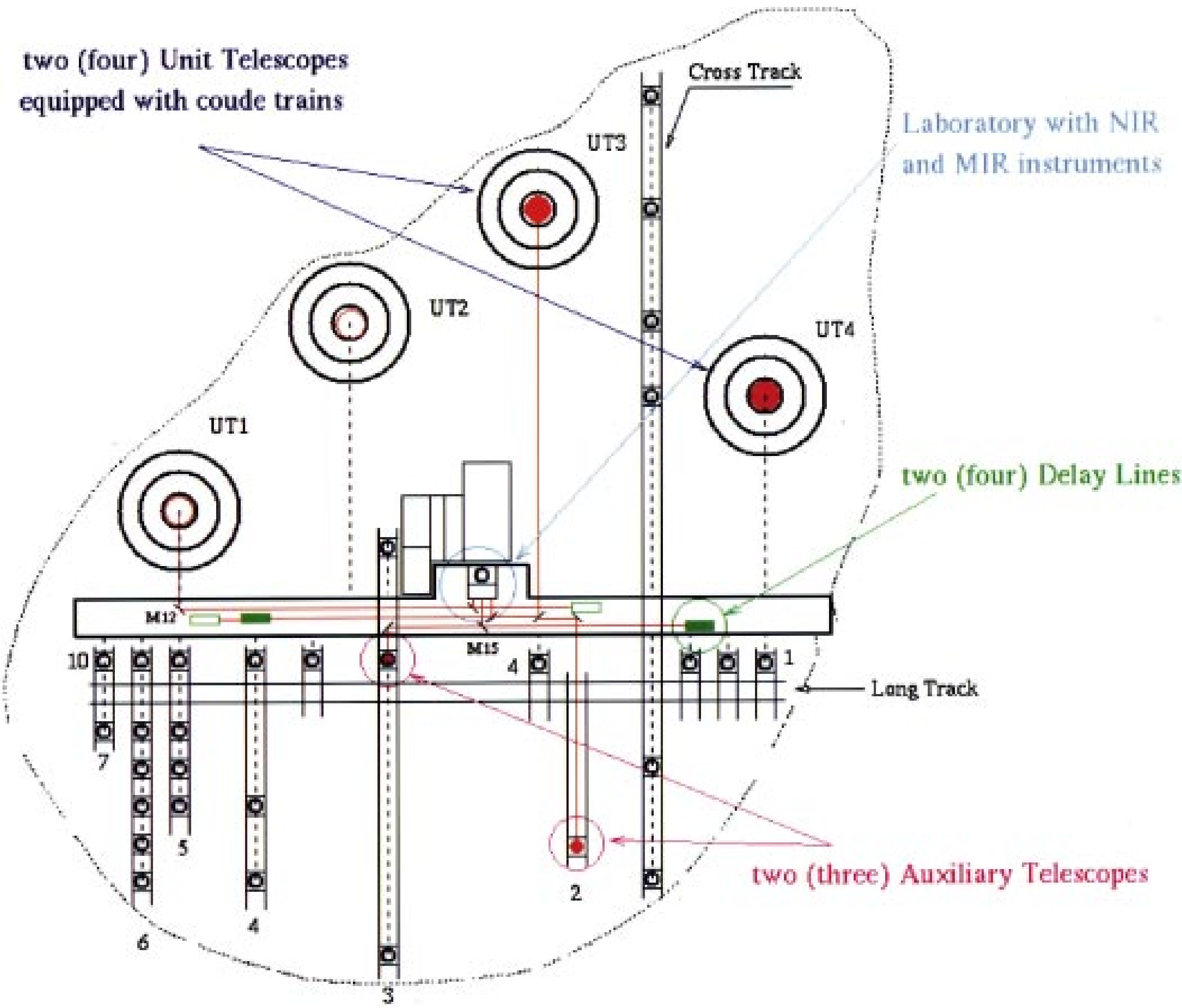


*Figure 2: Layout of the VLT Interferometer on Paranal.*

mode of the VLT, and which was signed by the CNRS, the MPG and ESO in 1992 (see *The Messenger* No. 71, March 1993), could be secured for the New Plan through an update which was signed by the three partners end of 1996. This article describes the essential elements of the New Plan and recent changes, as well as the current progress.

## 2. Consequences on the VLTI Concept

### *2.1. Wavelength range for early phases*

ISAC recommended to focus for the earliest operational phases on the near and thermal infrared spectral regimes where Unit and Auxiliary Telescopes would be diffraction limited with tip-tilt compensation. Figure 1 shows the resolution attained by 8-m and 1.8-m telescopes on Paranal without and with fast tip-tilt only compensation. An 8-m Unit Telescope achieves the best resolution for wavelengths above 5 µm under median seeing conditions without any compensation, and is close to the diffraction limit for these wavelengths when image motion is controlled. A 1.8-m Auxiliary Telescope operates at the diffraction limit for wavelengths above 2 µm. Therefore, operation without higher-order adaptive optics will be optimum in the thermal IR (5 µm and longer) with the Unit Telescopes and in the near IR (1 µm ... 2.4 µm) with the Auxiliary Telescopes. Without adaptive optics beyond tip-tilt compensation, the Unit Telescopes would not be significantly more sensitive in the near-IR than the Auxiliary Telescopes. ESO therefore currently pursues the development of low-cost adaptive-optics systems specifically tailored for interferometry with the Unit Telescopes in the near infrared.

Diffraction within the collimated beams inside the delay-line tunnel limits the suitability of the Auxiliary Telescopes for use in the N and Q bands. The implications of doing interferometry with Unit Telescopes in the thermal IR need further detailed investigations considering that beam combination occurs after more than 20 reflections at room temperature. However, fringes appear at precisely-known frequencies and their position can be modulated in time by small variations of optical delay. This should substantially facilitate their detection against the background.

### *2.2. Reduction of the field of view*

The reduction of the field of view to 2 arcseconds makes a substantial reduction of the optics in the delay lines possible. The beam diameter which the delay line primary optics must accommodate is now at most 15 cm. The dimensions of the cat's eye primary mirror is reduced from a size of about one metre to 60 cm. Another consequence of the field reduction is that severe requirements on the lateral stability of the delay-line carriage motion could be relaxed substantially, making simpler drive concepts viable.

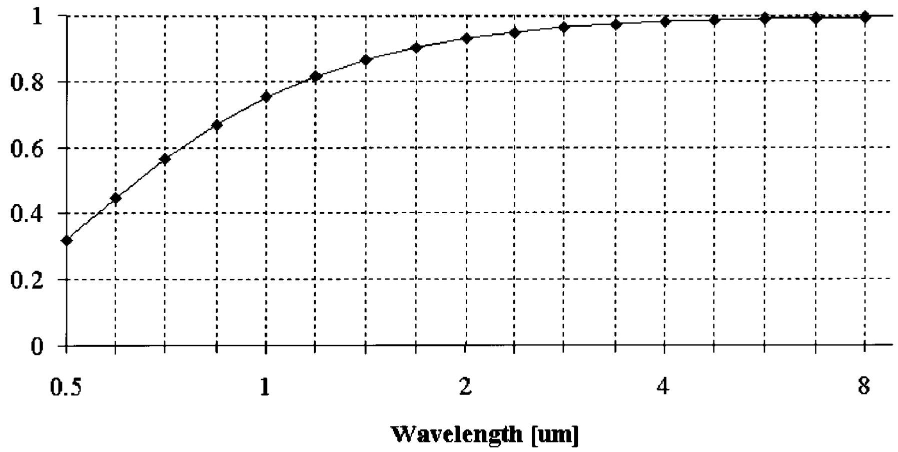


*Figure 3: On-axis Strehl ratio as a function of wavelength for new UT coudé trains.*

A reconstructed field of view of the VLTI is most likely limited by incomplete UV coverage, in particular when the number of baselines is initially small. The imaging beam combiner in the laboratory which was conceived for a co-phased field of view of 8 arcsec will therefore not be part of the early VLTI. Phase referencing, for which the field should be actually larger than 8 arcsec, is better implemented with a dual feed (see below). Beam combination will occur in the first phases within the instruments.

### 2.3. Dual feed

The desire for including narrow-angle astrometric capability (Shao et al., 1992) into VLTI (Léger et al., 1995, Quirrenbach, 1995, von der Lühe et al., 1995) eventually resulted in the decision to replace the original 8-arcsec continuous field with dual feeds. These allow selecting two positions at the coudé focus to be directed towards the delay lines and the laboratory. One beam will propagate the light from the science target, the other one will propagate the beam of a nearby phase reference (UTs and ATs) or an astrometric reference (ATs only). The concept behind the phase reference is similar to a reference star for adaptive optics, it serves for image and fringe tracking should the science target be too faint. There are limits to the field angle which come from atmospheric anisoplanatism.

The coudé foci of both Unit and Auxiliary Telescopes will be equipped with dual feeds. One position will be on the optical axis. The other position will be within a range of 5 to 60 arcsec from the axis anywhere within the coudé foci. The two beam lines will share the delay lines for any given telescope, making differential delay lines in the laboratory necessary. The design concept for the dual feed is still in the works. Although designs for dual feeds exist elsewhere, they are not easily adapted to VLTI because the requirements on spectral coverage and astrometric precision essentially exclude transmissive optics.

The requirements and engineering implications of narrow-angle astrometry are very severe and need thorough studies. The atmospheric limits to astrometric precision depend linearly on field angle and amount to about 10 µas with a 100-m baseline and 30 minutes of integration. Achieving this precision in practice requires the *knowledge* of the instrumental differential delay between the primary and secondary beam to 5 nm accuracy. At this time, the technical limits to determine the differential delay are not known.

## 3. VLTI Development

Budget limitations require an implementation of the VLTI in two phases (Phases A and B). The first and most expensive Phase A is covered by ESO's financial projections. Since Auxiliary Telescopes make up a large part of the cost, it was decided to build only two of them in Phase A and to defer the third one to Phase B. Because of the long lead times for the Auxiliary Telescopes, first fringes will be observed first with Unit Telescopes which we expect to be highly subscribed. To be able to exercise and test the interferometry subsystems with little impact on Unit telescope time, we intend to use simple siderostats on Auxiliary Telescope stations observing bright stars until the time Auxiliary Telescopes become available. Figure 2 shows the general layout of the VLTI and its major components for Phase A (for Phase B in parentheses). We discuss some major elements of the VLTI development in the following sections.

VLTI will consist of the following subsystems after the completion of Phase A:

1. Coudé optical trains on two Unit Telescopes
2. Two delay lines
3. Two test siderostats, to be replaced by
4. Two Auxiliary Telescopes, relocatable between 30 stations
5. Control system
6. Beam combination instruments

The following subsystems will be added during Phase B:

1. Third Auxiliary Telescope
2. Coudé optical trains on remaining Unit Telescopes
3. Two additional delay lines

Phase A has just begun and is expected to last until the end of 2001 when more or less regular science observations will begin. "First fringes" by the coherent combination of two Unit Telescopes would be observed early 2000 if the Phase A coudé trains are installed on Unit Telescopes 1 and 2, the delay lines are in place, and the first instrument is completed. First fringes with Auxiliary Telescopes are expected in the middle of 2001 after installation of Auxiliary Telescopes 1 and 2. The kick-off of Phase B, which represents about $^1/_4$ of the total cost, depends on the availability of additional funds. If started early 2000, interferometry with all four Unit Telescopes and three Auxiliary Telescopes would begin in 2003.

### 3.1. Unit Telescope Coudé Trains

The early use of 8-m Unit Telescopes with VLTI requires that coudé optical trains, which also were delayed in

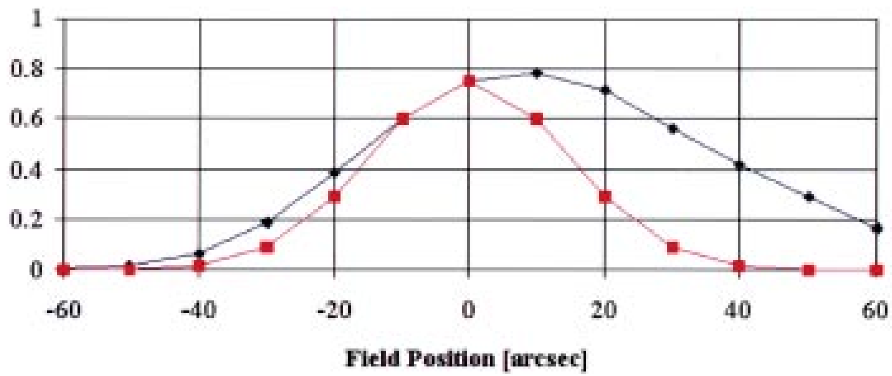


*Figure 4: Field dependence of Strehl ratio of new UT coudé trains in two orthogonal directions at 1 µm.*

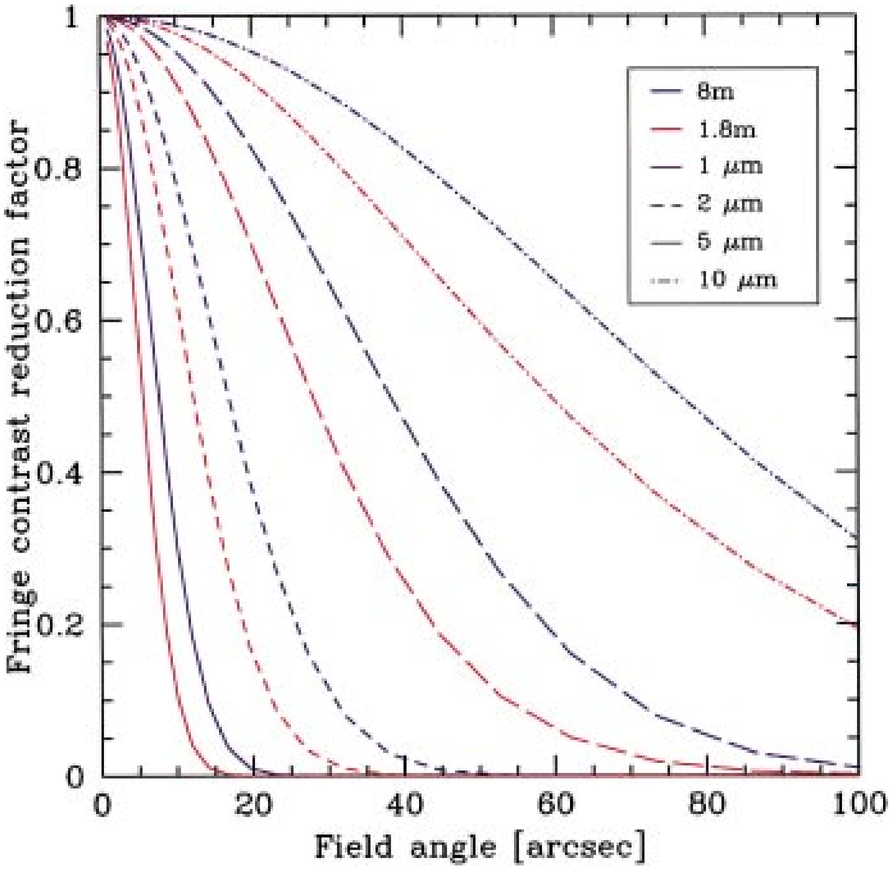


*Figure 5: Fractional fringe contrast loss as a function of field position for a representative distribution of turbulence for Paranal, with 8-m and 1.8-m telescopes.*

1993, be re-introduced into the technical and financial concept. Since the use of Unit Telescopes from Hα towards longer wavelengths is emphasised, we have investigated a simpler and cheaper optical design where large off-axis elliptical mirrors are replaced by spherical mirrors. The astigmatism and field scale anisotropy resulting from this change are compensated on-axis by replacing two flats with weak cylindrical mirrors. Figure 3 shows the on-axis Strehl ratio as a function of wavelength. The main contributing aberration is astigmatism. Figure 4 shows the Strehl ratio as a function of field angle in two directions for a wavelength of 1 μm.

The on-axis performance of the modified coudé optics is very satisfactory over a large spectral regime, including the visible, when atmospheric distortions are taken into account. The Strehl ratio degrades with increasing field angle but the resulting fringe contrast loss will always be small compared to the loss due to atmospheric piston anisoplanatism. This is shown in Figure 5, where the fringe contrast loss due to the differential piston variation between two field positions is shown. This effect is the interferometry analogue to the "isoplanatic patch" in adaptive optics. These curves were calculated based on measurements of the turbulence above Paranal by radio sondes in 1994.

Two out of the four Unit Telescopes will be equipped with coudé trains during the first phase. The decision which telescopes to equip will be influenced by scientific, schedule, and technical considerations.

### *3.2. Auxiliary Telescopes and Stations*

The Conceptual Design of the Auxiliary Telescope System (ATS) was established in 1992 after a study performed by IRAM under ESO contract. It features 1.8-m telescopes in Alt-Az mount with mechanical bearings. The axes are controlled through optical encoders and friction coupled or direct drives. The optical layout is similar to that of the VLT 8-m telescope. It includes a coudé train with an intermediate pupil image to enable fast tip-tilt compensation (and possibly later adaptive optics). The coudé beam is collimated and sent horizontally to the Delay Line Tunnel through underground light ducts. The telescope is self-protected against wind and adverse weather conditions by built-in wind shield protective cover. The telescope is movable on a rail network and can be located on any of the 30 observing stations through a kinematic interface. Each telescope is equipped with a transporter which handles the telescope for the relocation and houses a number of auxiliary equipment. During observation, the transporter is anchored on separate foundations isolated from the ground to avoid transmission of vibrations from the wind shield and auxiliary equipment.

ESO has thoroughly reviewed during 1995 alternatives to the original design and development concept in an attempt to trade off technical scope and cost with scientific performance. This concerns mainly the diameter of the primary mirrors, as well as a trade between in-house design and industrial design. The conclusion was that the original ap-

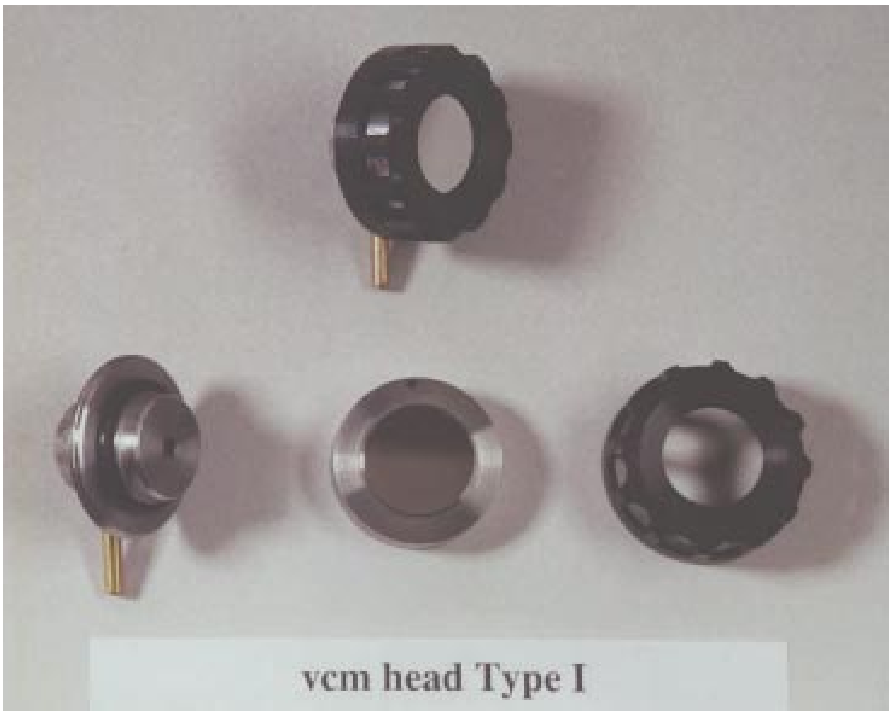


*Figure 6: Variable curvature mirror head.*

proach represents the best compromise. Based on the original concept, ESO will contract to industry the final design, manufacturing and testing of the ATS including optics, mechanics and control for the telescope and its transporter in 1997. Integration and testing of the Auxiliary Telescopes at the observatory will be performed by ESO staff.

### *3.3. Delay Lines*

The purpose of the delay lines is twofold, to equalise optical path length differences (OPD) and to transfer a pupil at a fixed location inside the interferometry laboratory.

The delay lines equalise optical path length differences caused by the static geometric path length difference between telescopes in any given configuration, by the diurnal motion of the astronomical source during observation (sidereal motion of a star), and by the rapid fluctuations due to atmospheric disturbances and/or mechanical vibrations. To perform the compensation of the OPD, the delay lines include an optical retroreflector (cat's eye) which moves during observation with high precision. The range required for OPD equalisation is 120 m which implies a mechanical stroke of up to 60 m for each delay line. This motion must be very accurate and smooth in order not to distort the interference fringe pattern formed at the interferometry focus. The longitudinal position of the cat's eye must be continuously monitored and controlled by a fast metrology system; high dynamic stability and adequate drives and bearings are required to avoid vibrations which otherwise could blur the fringe contrast.

The second purpose of the delay lines is to image the pupil of the telescope at a fixed position inside the interferometry laboratory for beam management. A mirror with a variable curvature is used at the focus of the cat's eye which has been developed for this purpose by the Laboratoire d'Optique de l'Observatoire de Marseille (Figure 6).

Figure 7 shows a model of the delay line cat's eye according to a design study performed by ESO. The lower part shows a section of the 69 m long foundation. The cat's eye consists of a compact Cassegrain optical configuration with a 60 cm diameter primary mirror and an effective focal length of 3.5 m. The optics support the beams from two field positions which enter through the upper two holes and leave the cat's eye through the lower two holes on opposite sides. The delay line covers half of the support bench, the other half provides space for a second one. ESO will contract to industry the design, manufacturing and testing of the delay lines including optics, mechanics, control and metrology in 1997. The integration and testing of the delay lines at the observatory will be performed by ESO staff.


*Figure 7: A model of the VLTI delay line. See text..*

### *3.4. Beam Combination and Fringe Detection*

The beam combination laboratory area provides the following functions during Phases A and B: beam alignment (image and pupil position alignment), calibration, fringe tracking, beam combination and fringe detection. Figure 8 shows an overview of the layout for Phase A. Stellar light beams enter the laboratory from below. A switchyard, which consists of dichroic and reflective mirrors, directs the light towards the instruments and to the image and pupil alignment and fringe sensor systems. A calibration unit which provides a number of sources in the visible and infrared feeds the alignment units and the beam combiner/fringe detector instruments and assures their intercalibration. Wide-band visible and laser light will be available for this purpose, as well as for the alignment of the beam combination/fringe detection instruments. Laser metrology beams feed the fringe tracking sensor for internal calibration. Another metrology beam travels back to the telescopes and determines the delay line zero position for the internal path during a set-up phase.

A prototype of the fringe sensor is currently under development at the Ob-

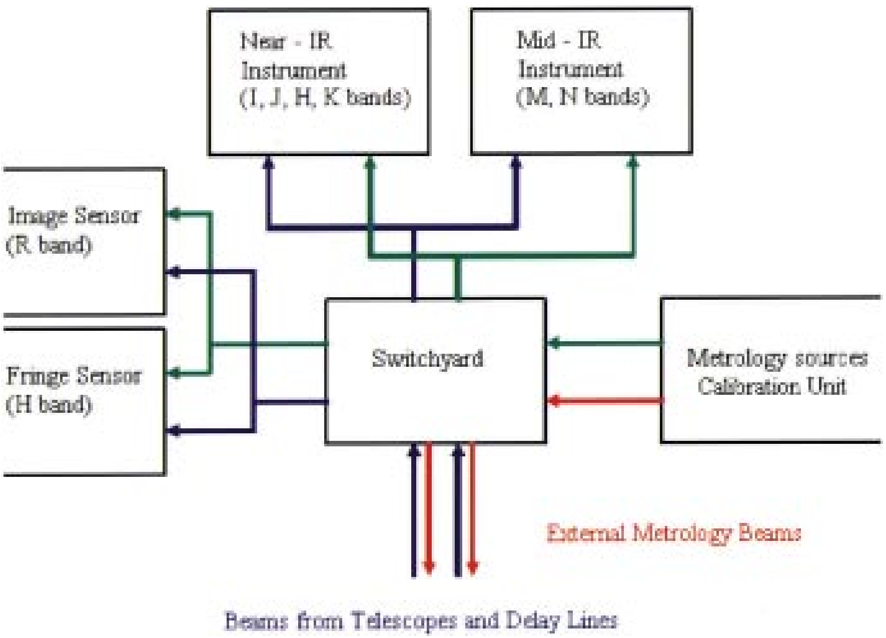


*Figure 8: General interferometry laboratory layout.*

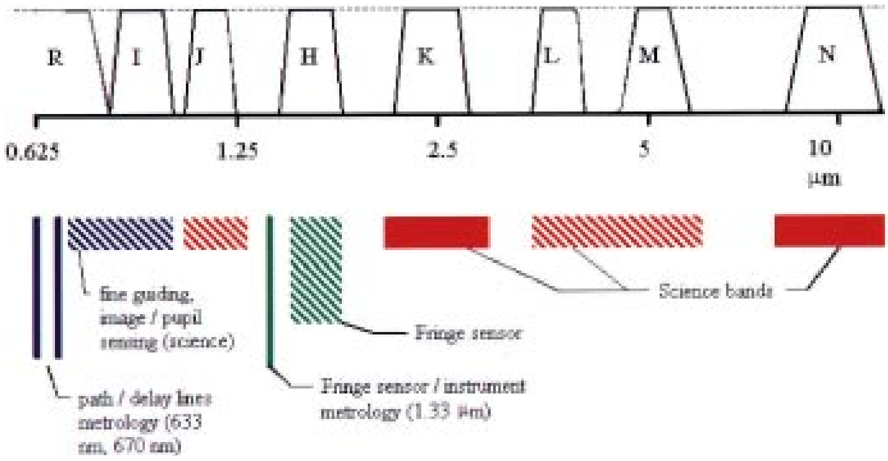


*Figure 9: Allocation of spectral band usage for VLTI.*

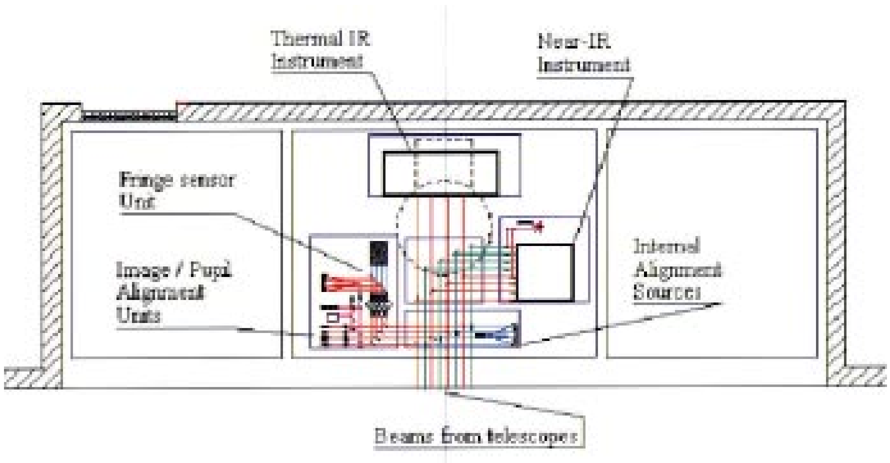


*Figure 10: Preliminary configuration of interferometric laboratory.*

servatoire de Côte d'Azur in Nice. This sensor uses a long stroke synchronous demodulation technique to detect both the presence and the position of stellar fringes in the H band. The error signal is fed back to the delay line control system to provide real-time fringe stabilisation. Figure 9 shows a provisional allocation of spectral bands for metrology, sensing, and science fringe detection purposes. We are developing a test bed for this metrology system in a nearby laboratory to validate the concept and its performance with an optical path of several hundred metres.

Figure 10 shows the central part of the tunnel and the laboratory with some more detail. Primary and secondary beams emerging from the delay line cat's eyes are directed towards the laboratory in the upper half. The switchyard is near the centre of the layout. Instruments are on the top and right. Fringe and image sensors are to the left. The structure to the lower right is the metrology beam launching system.

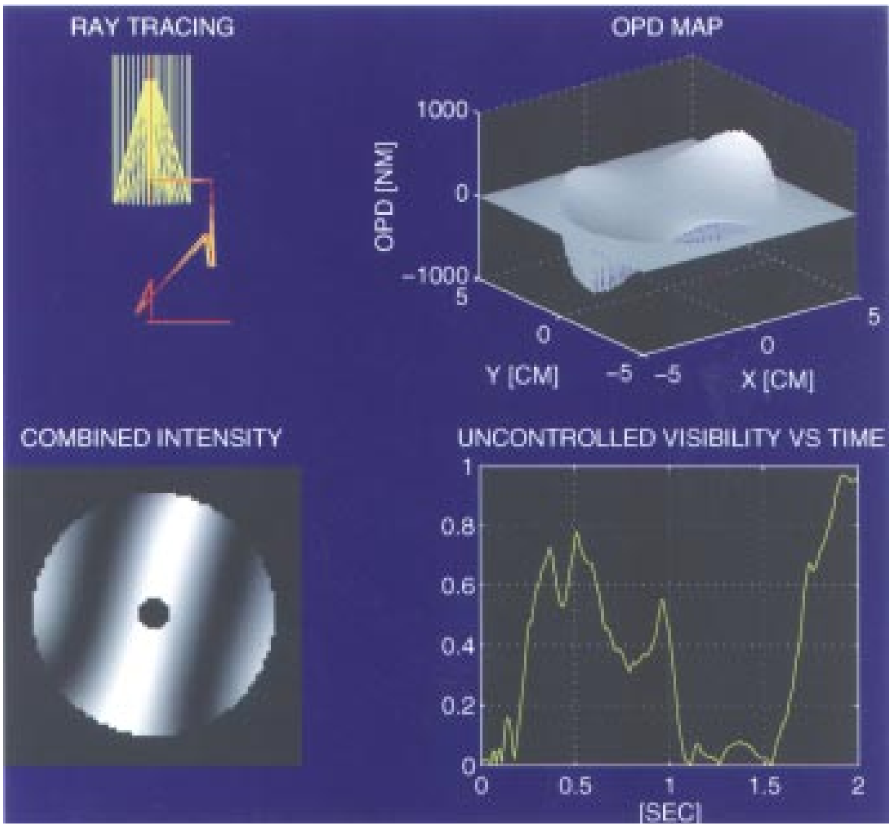


*Figure 11: Sample output from the VLTI end-to-end model under development at ESO. Top left: ray tracing of an individual telescope, top right: resulting OPD map near the point of beam combination, bottom left: fringes in a combined pupil image, bottom right: time variation of fringe contrast with uncontrolled atmospheric, seismic and mechanical disturbances.*

The two boxes represent the final beam combination and fringe detection stage for the near and thermal infrared. At this time, these areas are not yet defined. We expect to populate them with the help of the community. The functions needed here are beam combination (two beams in Phase A, three or four in Phase B), any dispersion required, detectors and associated read-out electronics, control electronics for mechanical functions as needed, cryogenics, and metrology sensors contained in the instrument. The interfaces to which the equipment should fit include a mechanical interface (optics bench), an optical interface (size and position of incoming stellar and metrology optical beams), and a control and data interface. The VLT Programme provides an extensive set of standards for electronic equipment whose use in encouraged, as well as general-purpose software packages which facilitate the integration into the VLT Observatory. ESO currently develops a computer model of the essential VLTI elements for engineering purposes (Fig. 11). It is planned to also use the simulated data to model in detail the fringe generation and detection with realistic astronomical sources and spectral band within the instruments to assess the performance of VLTI.

ESO's partners to the agreement on the enhancement of the VLTI, the CNRS and the MPG, have already agreed to also contribute to the beam combination and fringe sensing instruments in the form of equipment and manpower. ESO invites the wider community to participate in this effort, and to help defining and developing the beam combination and fringe detection equipment.

## 4. Conclusions

We have described the new implementation plan for the interferometric mode of the ESO Very Large Telescope. ESO proceeds with VLTI with a larger effort in terms of manpower than ever before and involves a significant fraction of the ESO astronomical community into this endeavour. The development plan for the VLTI has been adapted to the difficult financial situation by substantial modification of the concept and by gradually increasing the capability. We feel that the modifications simplify the project in many areas while strengthening the scientific potential. However, introducing the astrometric capability is a new requirement which will certainly be difficult. When Phases A and B are completed, a large subset of the initial goals for VLTI will have been put into existence.

At this time, the VLTI will be far from complete, and one should prepare for further upgrades. An important capability will be the near-infrared capability of Unit Telescopes through adaptive optics. Another important capability would be extending the spectral regime towards the visible, opening a wide range of spectral diagnostics and even higher resolution. Similarly important would be adding a fourth Auxiliary Telescope and more delay lines to bring the number of beam lines up to a number of eight. VLTI will then unveil its full potential as an optical aperture synthesis array.

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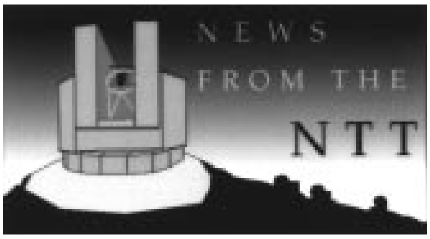


*The NTT upgrade project has the following goals:*

1. *Establish a robust operating procedure for the telescope to minimise down time and maximise the scientific output.*
2. *Test the VLT control system in real operations prior to installation on UT1.*
3. *Test the VLT operations scheme and the data flow from proposal preparation to final product.*


## *J. SPYROMILIO, ESO*


Last time I wrote for *The Messenger*, the NTT upgrade was progressing well. We had been able to point and track with the telescope but still had some problems with telescope oscillations. The telescope realignment was about to start and the instruments had not as yet been used. Since then a huge amount of work and progress has taken place.

The alignment of the telescope, a practice run for the VLT Unit Telescopes, was successful. The telescope altitude axis was redetermined and the adapter-rotators were re-aligned to ensure that the mechanical and optical axes of the telescope were as close to each other as possible. We found that the telescope was within the specifications but nevertheless we decided to compensate for the small misalignment present. The adapter-rotators were moved by approximately 100 microns. In addition, the setting angle for the tertiary mirror was also redetermined. Here the change was somewhat larger, possibly explaining an effect found in the old NTT whereby when tracking in an unguided mode across the meridian the stars moved. This would not have affected guided exposures. In addition, the position of the secondary mirror was redetermined. M2 is within the specifications as well, although close to the limit. During the next months we shall be using the active optics results to determine if we should undertake to move the secondary mirror.

In December and January, an intense period of commissioning and integrating the software, the telescope was brought from an engineering mode to an operational state. The telescope oscillations proved very hard to fix. A combination of problems contributed to causing the telescope to misbehave at random intervals. Only in the very last days of January were the most critical problems really solved. The telescope now tracks very well in most areas of the sky. However, there seems to be significant friction, especially in the altitude axis, causing some problems as the telescope moves past the meridian (where the altitude speed slows down to zero before changing sign). The azimuth axis seems to behave very well but we have not been running the telescope long enough to be sure that all is well.

The telescope pointing is excellent, with the exception of a zone of avoidance around the zenith. This of course is a problem all alt-az telescopes have and is not new to the NTT. However, we hope with more detailed pointing models we will be able to make the zone of avoidance small enough so as not to impact any scientific programme. On other fronts the telescope control system is also improving. Image analysis is being run regularly and although as yet it is not robust, it is functioning and the telescope image quality is back to the excellent values we have come to expect from the NTT. Autoguiding is now working reasonably well, and automatic guide star selection by the control system is available either in blind mode (let the system select for you) or manual mode (let the system offer you a choice). Selection of the guide star to be used is a matter of clicking with the mouse on any suitable star seen on the guide camera output.

We believe that the new NTT is a telescope that is easy to use, with most of the complexity hidden from the user by the graphical user interfaces. No cryptic commands need any longer be issued and a fair amount of work has gone into the on-line help available.

On the instrumentation front, the new ACE controllers have now been commissioned and we have an improvement of a factor of 2 in readout time over the old VME controllers for the same noise figures. In addition, the re-aluminisation of the telescope mirrors and the refurbishment of the instruments have given us an improvement in throughput of a factor of 2 to 3 in most bands. In the case of SUSI we also replaced the detector with one which has high UV sensitivity. The early estimates suggest