EUROPEAN SOUTHERN OBSERVATORY

VLT REPORT No. 59a

THE VLT INTERFEROMETER IMPLEMENTATION PLAN

Executive Summary

October 1989

Very Large Telescope Project

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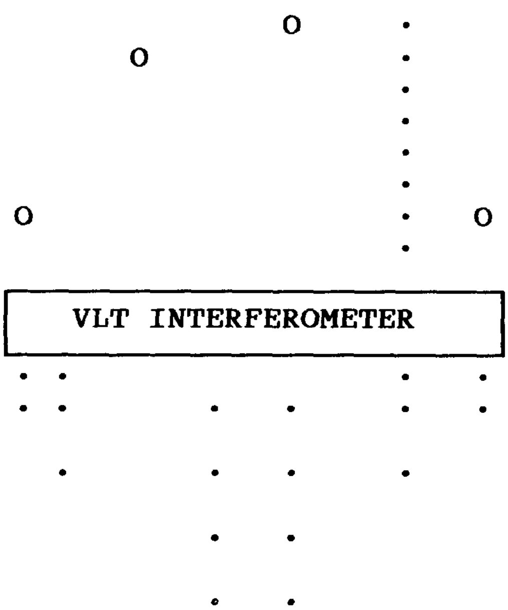

REPORT BY THE ESO/VLT INTERFEROMETRY PANEL

October 1989

Very Large Telescope Project

FOREWORD

In November 1988 I proposed to ESO's Scientific-Technical Committee and in December to the ESO Council the formation of an Interferometry Panel (IFP) with the following assignment:

The Panel will:

(1) develop a plan for the implementation of the adaptive optics interferometric capabilities of the VLT. This plan will define both the optical and mechanical configurations, the data recording and analysis demands, a schedule, and a budget profile needed to accomplish this task;

(2) call on the expertise in the community (both scientific and engineering) to aid itself in the accomplishment of these tasks in the form of ad-hoc working groups, workshops, "tiger teams", consulting and engineering contracts, and other means;

(3) when required, aid ESO in the execution of the design and construction contracts of the components of the VLT adaptive optics and interferometric mode;

(4) develop a plan for the operation of the VLT interferometric and adaptive optics mode;

(5) advise ESO on the merits of the different sites being considered for the VLT from the point of view of the interferometric imaging mode;

(6) encourage the funding and construction of the additional auxiliary telescopes through other channels, in addition to the two which are part of the VLT proposal.

The Panel has the following composition:

J.M. Beckers (chair)	ESO	
R. Braun	NFRA	Dwingeloo (NL)
G.P. Di Benedetto	IFC	Milano (I)
R. Foy	Obs. Paris	Meudon (F)
R. Genzel	MPfEP	Garching (D)
L. Koechlin	CERGA	Caussols (F)
F. Merkle	ESO	
G. Weigelt	MPfRA	Bonn (D)

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.

This team went to work with gusto, starting with a series of meetings and culminating in a labour-intensive retreat to the congenial Observatoire de Haute Provence. Every meeting was prepared by the Chairman, whose enthusiasm as much as profound knowledge of this complex subject egged on the panel members to analyse, to argue and choose; then to draft, redraft and finalize the texts.

In a remarkably short time the Panel has converged on an implementation plan for VLT Interferometry, a plan with options for scope and schedules, but with a singularly ambitious end goal. The result is a voluminous, highly technical report, plus this rich executive summary now in hand.

ESO and our users community are indebted to the members of the Panel, who gave unstintingly of their time and talents as well as to Jacques Beckers, the untiring and prolific Chairman.

The STC has now a substantial proposal to assess, to convey preferences and priorities to the Director General and to the ESO Council. In the inevitable tension between ambitions and resources, the contractual development of the VLT's major systems and the choice of site in 1990 will clarify the pace with which the Advanced Array can be realized. In the meantime engineering studies continue. I trust that the opportunities this report reveals and the challenges it poses, will stimulate institutions and research workers in Member States to contribute resources and ideas. A whole new domain opens up for optical astronomy. It is an exciting and rewarding prospect for the ESO community to get there first.

H. van der Laan
ESO Director General

OVERVIEW

The VLT Interferometry Panel has the broad responsibility to advise the ESO Director General on matters relating to all high resolution imaging with the ESO Very Large Telescope (VLT) involving wave manipulation techniques. It includes speckle interferometry and speckle imaging with individual 8 meter telescopes, interferometric imaging by coherently combining the radiation from the 8 meter telescopes and 2 meter class auxiliary telescopes, as well as the pre-detection wavefront reconstruction involving adaptive optics.

The first major task of the panel consisted in the development of the implementation plan for the VLT Interferometric Mode, here referred to as the VLT Interferometer (VLTI). The result of that effort, undertaken the first 9 months of 1989, are given in the full report, of which this is the executive summary. It includes the definition of the VLTI concept taking into account scientific and imaging methodology requirements, optical and mechanical considerations, site and project constraints, as well as budget and manpower limitations. This plan will form the basis for the realization of the so-called Advanced Array (more ambitious and powerful than the Basic Array described in the VLT proposal, but still restricted in its capabilities) in the second half of the 1990's, followed by an evolution to the so-called Extended Array thereafter.

The development of this plan was urgent. This was not only because of the desire of the interferometric community represented by the Panel to implement the VLTI at an early stage, but also because of the close relation the ongoing implementation of the 8 meter telescopes, and the site choice and development, have to the realization of the VLTI. Waiting would therefore have caused, by default, major incompatibilities.

As a summary this document necessarily has to restrict itself to giving the headlines of the intensive in-depth studies made by the panel. Full details of these studies are available in the full report.

This study grew from the solid foundations laid by the earlier ESO/VLT Working Group on Interferometry described in VLT Report No. 49 (1986). It profited very much also from the work done since then as reported in the ESO-NOAO Interferometry Workshops in Oracle (1987) and Garching (1988) and the 1988 NATO Advanced Study Institute on Diffraction-Limited Imaging with Very Large Telescopes in Cargèse.

1. GENERAL BACKGROUND

1.1 The ESO Very Large Telescope and its Interferometric Mode

The VLT as proposed and approved, consists of four 8 meter diameter telescopes and two 2 meter class telescopes. The large telescopes can be used separately, each one acting individually, each as one of the world's most powerful telescopes in terms of collecting area and angular resolution. They can also be used combined to give either the unequalled collecting area of a 16 meter telescope, in the so-called incoherent combined focus, or to give the very-high angular resolution resulting from interferometry with large baselines, in the so-called coherent combined focus. The two smaller movable telescopes complement the array of large stationary telescopes by allowing much more complete sampling of the image in the (u,v) plane.

Because of the resulting large gains there is a strong desire in the European interferometry community to add to this complement of four large and two small telescopes (which will be referred to as the "Basic Array") additional small movable telescopes. These would be funded by additional contributions from member countries. They would result in (i) many more available baselines, (ii) the option of operating the array of small telescopes (or VISA = VLT Interferometric Subarray) by itself with a 100 % access time, and (iii) a decreased pressure on the combined use with the array of large telescopes which would generally only be required when its much higher sensitivity is needed. Because of these major gains, and because of the resulting likelihood of obtaining these additional small, auxiliary telescopes, the present study includes them in its consideration. The results of the study are, however, not dependent on the availability of these additional auxiliary telescopes.

Finally, we want to emphasize strongly that the prospect of having the VISA, with its 100 % accessibility, in no way detracts from the importance of and need for the interferometric mode of the 8 meter telescopes. The availability of an interferometric capability with four, adaptive optics aided, 8 meter telescopes will make the VLT the world's premier facility for achieving high angular resolution imaging on faint astronomical objects for a long time to come. This capability makes the VLT very unique and leads to the very strong drivers for this study which: (i) want to optimize the array of 8 meter telescopes by itself for interferometry, and (ii) couple the definition of the VISA to its joint use with the 8 meter telescopes, including the beamcombination of light from the large and small telescopes as originally proposed.

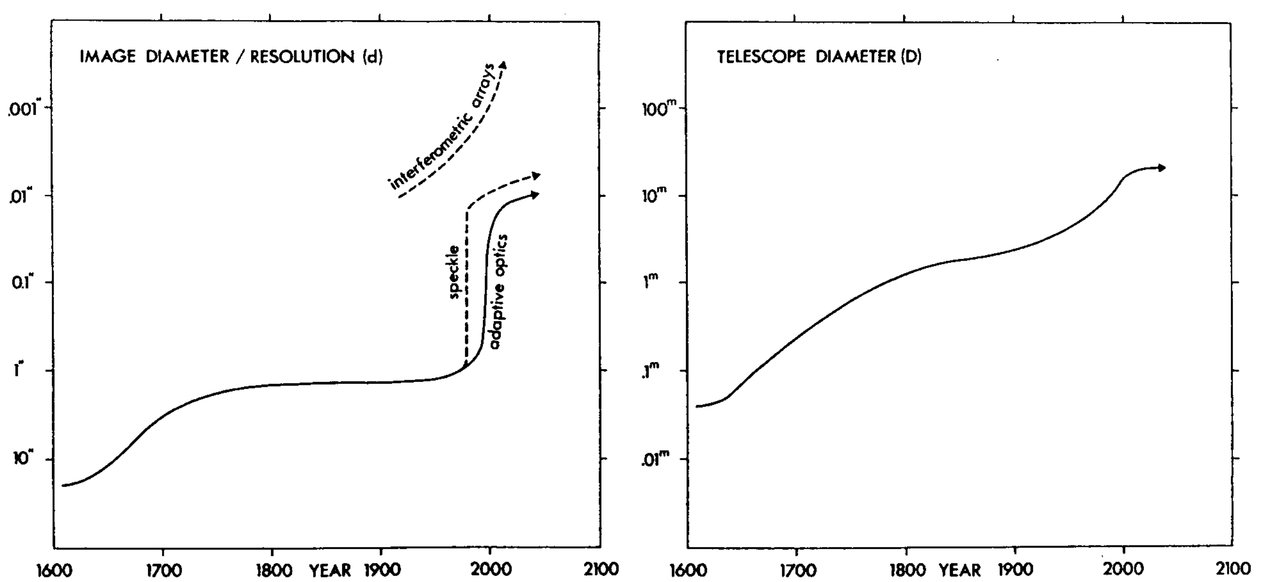

Figure 1.2-1 Evolution of telescope resolution and size

1.2 The VLT and its Interferometric Mode in Historical Perspective

Figure 1.2-1 summarizes the evolution of telescope size and angular resolution from the time of the invention and first use of the telescope in the pre-ESO members states (by Lippershey, a German-Dutchman, and Galileo, an Italian) to the present day, and places the VLT in this context. Even more striking than the improvements in collecting area (diameter) is the recent and predicted improvement in angular resolution resulting from the improvement of telescopes (eg the NTT), the invention of speckle interferometry by A. Labeyrie, the development of speckle imaging methods (Knox-Thompson and speckle masking), the application of adaptive optics to astronomy, and the rebirth of Fizeau/Michelson interferometry also as a result by A. Labeyrie's efforts. With the VLT European astronomy will have the tools available to regain the lead in observational and experimental astronomy which it lost in the beginning of this century.

1.3 The Place of the VLT Interferometer Relative to Other Efforts

A total of 6 optical interferometers are now in regular operation, 5 (including the VLT) are under construction, and at least 12 earth-based arrays are in the planning stage. Figure 1.3-1 summarizes these. Considering that the rebirth of

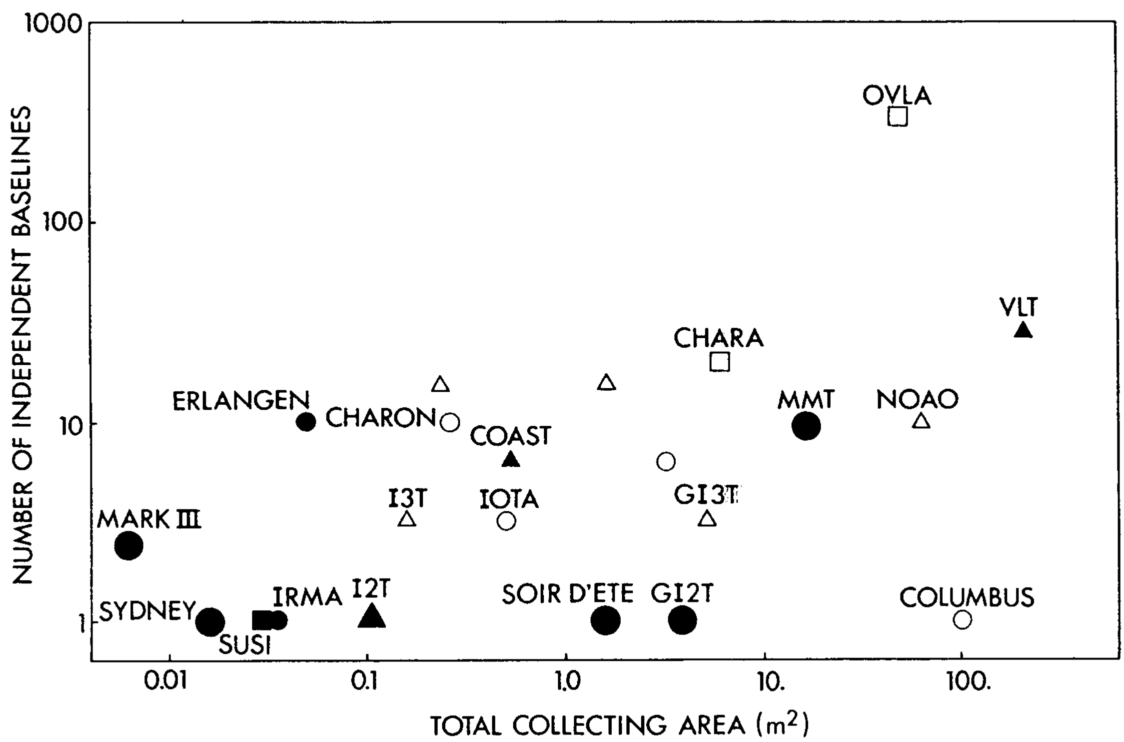

Figure 1.3-1 Properties of Optical Interferometers. Large filled symbols = existing; small filled symbols = under construction; small open symbols = in planning. Maximum baselines: circles < 100 m; 100 m < triangles < 300 m; squares > 300 m.

interferometry occurred only recently, these numbers demonstrate the explosive growth of this challenging technique to obtain very-high angular resolution. It follows the path breaking work in radioastronomy, which has been using interferometry with arrays of telescopes since the early 1960's. The same route is indicated now for optical astronomy. Optical interferometry profits greatly from the developments in radioastronomy, especially in the area of imaging methodology and algorithms, data acquisition and analysis. Optical interferometry has, however, some unique aspects. These are both advantageous (the availability of array detectors/feeds) and more challenging (the need to interfere the light directly rather than after mixing with the signals of local oscillators).

The VLT Interferometer stands out in Figure 1.3-1 as the facility with the largest sensitivity (collecting area of individual telescopes) but with a modest baseline (≈ 120 m) in its original "Advanced Array" configuration. During the subsequent implementation of the "Extended Array" longer baselines could be considered. Existing facilities have taught us a great deal about the unique aspects (technical and operational) of optical interferometry. These, as well as the experience gained with the new facilities and concomitant experimentation, will be closely tracked as the VLTI is being implemented.

1.4 Readiness of Methodology and Technology

The experience gained with the implementation of existing interferometers is very important for the planning of the VLTI. Some devices, like the Mt Wilson (Mark III) and Sydney interferometers, acquired fringes almost immediately and routinely without major problems resulting from vibrations and other causes for fringe contrast disappearance. The Mt. Wilson interferometer works already now at a level where service operation is possible and where remote operation is within reach. Fringe contrast decrease has been studied at most existing systems and has led to the identification of their causes (eg optics, vibrations, detector resolution, polarization) and resulted in a reliable tolerancing analysis of the VLTI components (see section 4.1). The experience with large aperture interferometers gained with the MMT (180 cm aperture), the Soird'ête (100 cm aperture) and the GI2T (150 cm aperture), gives one confidence that their use will not lead to surprises. It is clear that the VLTI as an interferometer can be made to work now provided that it is implemented using sound engineering principles based on our best physical understanding.

The most challenging components of the VLTI implementation probably lie in the area of *systems and control engineering* and in the realization of *adaptive optics*. An array of 6 to 8 telescopes, some of them movable, some of them with active optics, all of them with adaptive optics, all of them with variable delay lines, and all of them with image and fringe trackers, is a very complex system the likes of which is not in existence in optical astronomy. In order for it to be routinely functional, its implementation will require the greatest attention in quality systems and control design and in reliability in its construction. Although the VLTI could operate without it, especially in the diffraction limited 10 to 25 µm wavelength region, only adaptive optics inclusion will result in the full gains promised by large aperture interferometers. An active program aimed at implementing adaptive optics therefore must be pursued in parallel with the implementation of the VLTI.

2. SCIENTIFIC GOALS AND CAPABILITIES

2.1 Some Prime Targets

It is not part of this study to revisit the scientific reasoning behind the VLT proposal which led to its acceptance. Instead we will visit in this section some of the major scientific targets for the VLTI with the aim to identify the required array parameters. The following listing will therefore definitely not be exhaustive, but rather focus on some representative targets important to the definition of the VLTI:

- *THE CENTER OF THE MILKY WAY* is a unique target of special interest for the VLTI both because of the VLTI location in the southern hemisphere and because of its importance for the understanding of galaxies and their evolution. The bright , small IRS7 source, located 6 arcsec away from the galactic center, provides an outstanding opportunity for adaptive optics wavefront sensing and interferometer fringe tracking. It implies a *field-of-view larger than 6 arcsec* and *infrared (2.2 µm) wavefront sensors and IR fringe trackers*.

- *NGC 1068* is the brightest *SEYFERT GALAXY* accessible by the VLTI with a nucleus of extraordinary interest for the study of AGN's. Its narrow line region has been resolved with 4 meter class telescopes. The VLTI will be able to image NGC 1068 with milliarcsec resolution and with *high sensitivity* when *baselines of ≈ 100 m* are used and when the bright (V = 11 to 12) nucleus is used for *photon limited wavefront sensing* and possible *fringe tracking*.

- *3C273*'s broad line region is expected to be resolved with the milliarcsec resolution resulting from a *≈ 100 m baseline*. In addition it may be bright enough (V = 13) for *wavefront sensing* and *fringe tracking*. M.-H Ulrich (1988 NOAO-ESO Conference) predicts also fainter *QSO's and AGN's* to have broad line regions of 10^{-2} - 10^{-4} arcsec, again close to the resolution of a *≈ 100 m baseline* VLTI. The highest *sensitivity* (best limiting magnitude) is again needed.

- Many crucial questions of *PROTOSTARS, GIANT PROTOPLANETS, and CIRCUM-STELLAR DISKS* are addressed by high resolution *far infrared (10 to 25 µm)* imaging. These objects are quite bright and their imaging can be done with now available detectors using diffraction limited images, which are obtained directly under good seeing conditions without the need for adaptive optics.

- High resolution imaging gives access to accretion and fragmentation processes in protostellar objects. Imaging of *YOUNG STELLAR OBJECTS, T TAURI OBJECTS, and STAR FORMATION REGIONS* all require access to the *infrared wavelengths between 1 and 25 µm*.

- A *baseline of ≈ 100 m* will enable the measurement of *DIAMETERS OF MAIN SEQUENCE STARS*. *Larger baselines (≥ 500 m)* are needed for imaging.

- Milliarcsec resolution will allow the imaging of eg the disks of *RED SUPERGIANTS* and the envelopes of a number of stars with as many as 100 to 1000 pixels. *Good (u,v) plane coverage* is essential to accomplish that. Often one can use a nearby companion, for fringe tracking (as is the case for *α SCO* and *α HER with companions at 3 and 5 arcsec respectively)*. *High spectral resolution* will be needed to study physical processes on these stars.

- For *STELLAR ENVELOPE* studies one wants both *high spectral resolution* and *broad spectral coverage*, ranging from chromospheric lines in the blue to the dust shell emissions in the IR. *Polarimetry* is also likely to be important in this case.

- Many stars show temporal variations on the scale of a few days due to INTRINSIC *STELLAR VARIABILITY* or *STELLAR ROTATION*. Imaging therefore requires as *many auxiliary telescopes* as possible combined with the ability to *rapidly reconfigure* the VISA.

- *Imaging of* other *(INTER)PLANETARY TYPE SYSTEMS* (eg *β PIC*) can only be done with low sidelobe observations resulting from *high S/N* and *good (u,v) plane coverage*. Even so, the *dynamic range* may be insufficient for planet detection.

2.2 Required Capabilies of the VLTI

On the basis of scientific goals such as these, combined with the realities of the constraints imposed by site, budgets, technological complexity and operational possibility, we identify the following requirements for the capabilities of the VLTI:

- *Baselines* up to 120 m, possibly to be expanded later to ≈ 1000 m.

- Good *(u,v) plane coverage* with many baselines (implying as many auxiliary telescopes as possible) with some baselines as small as the diameter of the large telescopes (8 meter), extending in all directions.

- *Adaptive optics optimized for near IR wavelengths (≥ 2 µm)*, for the large aperture telescopes as well as for the auxiliary telescopes.

- *Low* signal deterioration by *instrumental fringe contrast loss*, by *transmission loss*, and by *increased thermal emissivity*.

- *Extended wavelength coverage* from the far infrared (25 µm) downwards to include initially wavelengths as short as 420 nm but to be expanded later to shorter wavelengths.

- *Good spectral resolution* (3000 – 60 000 in visible, 200 – 8000 in IR).

- *Fringe tracking* and *wavefront sensing* at both visible and IR wavelengths.

- A cophased or good coherent *field-of-view* of ≈ 1 arcsec to be expanded later to ≈ 8 arcsec.

- *Rapid reconfiguration capability* (≈ 15 minutes) of the VISA.

- *Polarization control* in the beamcombination.

It is proposed that many, but not all, of these capabilities will be provided in the original version of the VLTI (in the so-called "Advanced Array"), with others being included in the later evolution towards the "Extended Array". The Extended Array may also include features not listed above, but which may become feasible in the next decade(s), like shorter wavelength adaptive optics aided by artificial, laser generated stars.

2.3 Sensitivity Estimates

Of interest is primarily the limiting sensitivities for faint object interferometry. It is determined by the number of photons in the so-called coherence volume CV. CV is defined as the product of the area over the telescope aperture over which the wavefront distortion is small (A) multiplied by the atmospheric coherence time (τ_0) and maximum allowable spectral bandwidth (B). Since both A, τ_0 and B are directly dependent on atmospheric seeing (A(:)r_0^2, τ_0(:)r_0 and B(:)$r_0^{5/6}$ for large telescopes), the limiting sensitivity is a strong function of the seeing. Even more than is the case with regular astronomical observations, interferometry therefore depends on outstanding seeing conditions to achieve its full potential. The same holds also for the use of adaptive optics for pupil phasing and for cophasing using a nearby object, since the area of the isoplanatic area also increases like r_0^2. When the use of adaptive optics is an option (by the availability of sufficient flux from a nearby object or from the study object itself but at a different wavelength), the effective value of r_0 is increased to the telescope diameter D, thus vastly increasing the interferometer sensitivity. Other factors entering the sensitivity estimates include atmospheric wind velocities, total observing time, and telescope diameter.

Figure 2.3-1 summarizes the estimated limiting fluxes for the 8 meter VLTI array at infrared wavelengths, with pupil phasing (adaptive optics) and array cophasing on the source itself or on a reference object (eg nearby star,laser generated reference star), and compares them with the fluxes of a number of astronomical objects. In case adaptive optics is not an option, Curve I corresponds to the limiting magnitude for the telescopes diaphragmed down to r_0. The full aperture, giving multispeckle observations, should somewhat increase this sensitivity.

At visible wavelengths the coherence volume decreases rapidly, resulting in fewer photons. To some extent this loss is compensated by better detectors (photon counting and/or low readout noise). In this multispeckle mode, limiting magnitudes are expected to be comparable to those achieved with speckle interferometry with single telescopes (V ≈ 18 for about 10 minutes observing), where the results refer, of course, only to the area of the (u,v) plane sampled. Filling the (u,v) plane will require, of course, additional time, depending on the number of telescopes available in the VLTI. Substantial gains can be

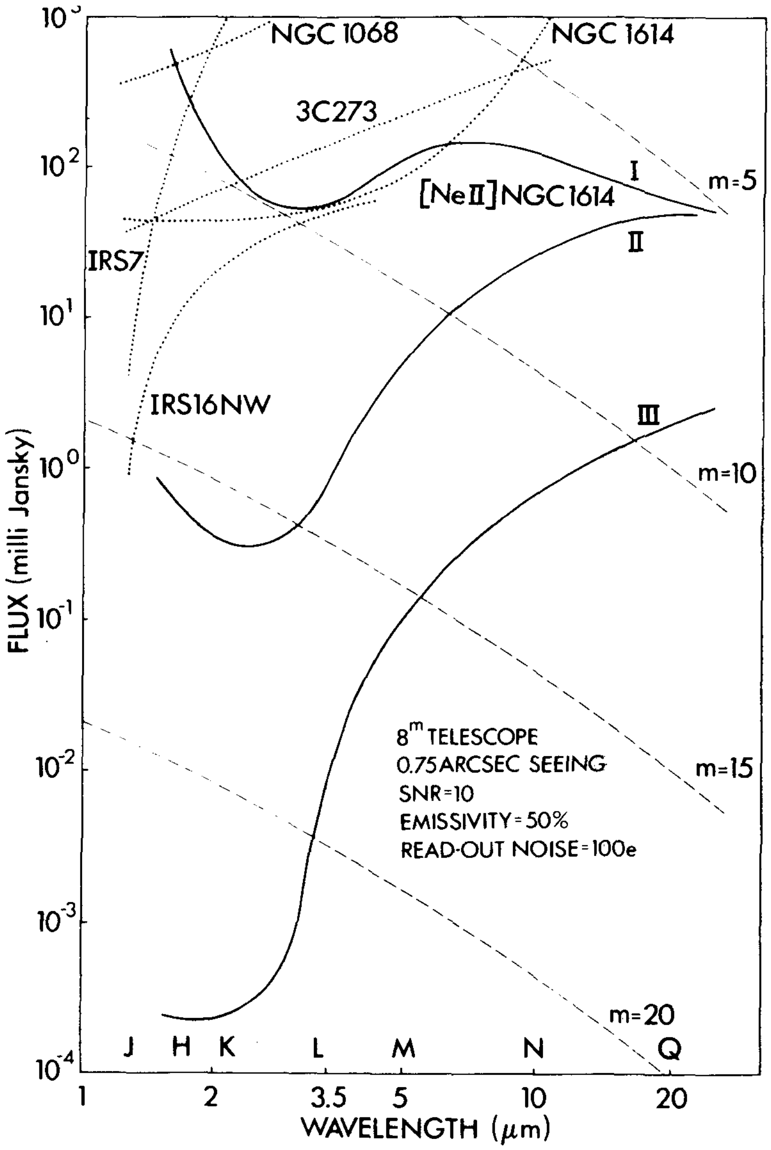

Figure 2.3-1 Limiting sensitivities of VLTI 8 meter array. Curve I gives limiting brightness for on-source pupil phasing (adaptive optics) and cophasing (fringe acquisition). Curve II gives the limiting brightness for off-source pupil phasing, but on-source cophasing. Curve III assumes that cophasing (fringe tracking) is possible on an off-source object, using a 10 minute observing time. Also shown are some objects of interest (dotted lines).

expected in those cases where adaptive optics can be used. Even an adaptive optics system built to work at 2.2 μm will still put ≈ 10% of the photons in an Airy spike which can be thought of as coming from a much larger coherence volume. Such a *"partial adaptive optics system"* would increase the limiting magnitude by 2 to 3. The use of such a partial adaptive optics systems is however limited to a few percent coverage of the sky, until the realization of laser generated reference stars. Large gains will also result from fringe tracking (effectively increasing τ_0) if the scattered light from the sensor star is controlled. Then interferometric imaging down to objects at or below the dark sky background (V ≈ 21) may eventually become possible allowing studies of, for example, high-z galaxies.

3. VLT INTERFEROMETER DEFINITION

3.1 Constraints

The VLTI definition takes into account the following constraints:

3.1.1 Site Constraints

Three sites are under consideration for the VLT: Vizcachas (near La Silla) and Paranal and La Montura (near Antofagasta). All these sites can accommodate an observatory with a baseline of 120 meters and providing space for at least a circular area with the same diameter with a similar effort in soil removal. Except for this similarity, there are substantial differences from the point of view of interferometry. We summarize the advantages of each of the sites (the complement being the disadvantages):

Vizcachas

- Close proximity to La Silla.
- Extended area in the NW-SE direction.
- Very good seeing.
- Well defined wind directions.

Paranal

- Substantially more clear nights than Vizcachaz.
- Very good seeing.
- Low water vapor content, humidity and rainfall.
- Well defined wind directions.

La Montura

- Substantially more clear nights than Vizcachaz.
- Good seeing.
- Low water vapor content, humidity and rainfall.
- Large extended area in the N-S direction.

After examining the pros and cons of the three sites, on the basis of limited information, the panel tentatively concludes:

(a) that it has a preference for the *La Montura* site over the other two sites for the VLTI. This conclusion is based on a combination of sky clarity, low water vapor, and large area availability resulting in a convenient future enlarged baseline option in the NS direction of as much as 1000 meters. If in fact the seeing at La Montura is inferior to that at Paranal, the panel considers a $\geq$ 10 % seeing difference as too high a price to pay for its area advantages.

(b) that, if La Montura is not an option, it feels neutral about the choice between *Paranal* and *Vizcachas* if the seeing conditions are comparable. The advantages of the larger area on Vizcachas compare with the advantages of the better climatic conditions and IR quality of Paranal. If the seeing turns out to be significantly better on one of these sites, then that would be a decisive factor.

3.1.2 Constraints imposed by other VLT Usage

The 8 meter telescopes will be used only a fraction of the time for interferometry purposes, with most of their time going to astronomical observations requiring the large flux (and image quality) of the individual 8 meter diameter telescopes or, at the incoherent combined focus, of the 16 meter equivalent diameter telescope. The amount of time available for interferometry will have to depend on the quality and amount of the observing programs which are submitted for that use. That in turn will depend on the success of the VLTI as a high resolution astronomical facility for the observation of faint objects.

The VLTI definition thus includes the possibility of using all 8 meter telescopes, but anticipates their availability to be restricted. In the beginning emphasis will be on the full 100% use of the VISA for interferometry . The inclusion of even only a single 8 meter telescope will significantly enhance the interferometric capability by approximately doubling the number of baselines (assuming there are enough baselines available) and by giving a substantially higher sensitivity, and wider (u,v) plane tracks, for the baselines which include the 8 meter telescope. The array of 8 meter telescopes will be essential for several of the most interesting applications like the infrared observations of the galactic center. After the success of the VISA capability by itself and with single 8 meter telescopes has been demonstrated, it is therefore expected that the observing pressure for progressively including more 8 meter telescopes, eventually leading to the full use of the VLTI, will become very large because of the opportunities provided to do frontier astronomical research uniquely possible with the VLTI.

3.1.3 Optical Constraints

To maintain high fringe contrast and provide a large field-of-view it is important that the polarization characteristics and the exit image/pupil orientations in all interferometer arms are the same. Although this could be accomplished by correction elements in the beamcombining optics, the panel preferred an approach which included this as part of the optical design of the VLTI. That approach, however, constrains the design by requiring the optical layout of the auxiliary telescopes and associated relay and beamcombining optics to be the same for all telescopes.

3.1.4 Mechanical Constraints

Images, pupils and polarization directions rotate in the coudé beams of telescopes by an amount and at a rate determined by the type of mounting of the optics. Since the 8 meter telescopes have Alt-Az mountings the same philosophy as adopted for the optics implies the need for Alt-Az mounts for the auxiliary telescopes.

3.1.5 Operational Constraints

The VLTI will be the first interferometer which will be implemented as a user facility rather than as a research prototype. This places major requirements on the quality of design and construction and on reliability. Being a user facility, of course does not exclude its use for experimentation. Its remoteness and its user oriented function leaves, however, much of the R&D in interferometric imaging up to other efforts.

3.1.6 Budget and Manpower Constraints

The approved VLT proposal includes 25 MDM (1986) for interferometry with the VLT. This is to finance 2 auxiliary telescopes, simple beamcombining optics, 2 delay lines, path stabilization, 2 telescope transport/tracks and controls. In addition the budget provides for general purpose adaptive optics (12 MDM) and for IR and visible interferometric instrumentation (2 MDM). Additional resources from ESO member countries are anticipated to be forthcoming towards the enhancement of this so-called Basic Array to the Advanced Array described below.

The implementation of the VLTI will be done under contract and at institutes in ESO member countries. This does not eliminate the need for manpower at ESO since ESO has to remain responsible for the implementation of a functioning facility. ESO manpower will be needed for project planning and coordination, interfacing with other parts of the VLT, contracting, contract monitoring, component and system validation, and ultimately operation.

3.2 Requirements to be Satisfied

Following the desire for the capabilities described in section 2.2, the implementation of the large and small telescopes of the VLTI has to satisfy the following requirements:

- Strict Vibration Control
- High Optical Quality Components
- Adaptive Optics
- Internal Seeing Control
- Rapid Guiding and Fringe Tracking
- Operation in which Pathlength Equality is Maintained over Extended Periods (≈ 15 min) without Fringe Tracking. This is a Referred to as "Blind Fringe Tracking".
- High Throughput and Low Thermal Emissivity
- Control of Polarization
- Capability to Reconfigure of the VISA Telescopes within a ≈ 120 m diameter circle
- Control of Pupil Geometry Transfer
- Incorporation of Parameters of interest in the Astronomical Weather Station (AWS)
- Fixed Instrument Complement as well as User Experiment Laboratory

3.3 Implementation Strategy

The primary goal adopted by the panel is the *implementation of a substantial scientific interferometric capability at the VLT soon after the completion of the first 8 meter telescope*. This is considered to be a realistic goal provided that this initial capability is "simple" and limited, and that many of the more complex options are deferred. This then led to the strategy of concentrating on the implementation of the so-called *ADVANCED ARRAY* first, keeping in mind in its definition, design, and construction the desire to evolve from there to the so-called *EXTENDED ARRAY* (which contains many of the deferred complex options) later. Despite its relative simplicity, the *ADVANCED ARRAY* goes in capabilities well beyond that of the so-called *BASIC ARRAY* described in the VLT proposal. It will, however, require additional resources beyond those given in the proposal. The strategy of how to downscope from the *ADVANCED ARRAY* in case these resources do not materialize is described in section 8.

3.3.1 The *VLTI ADVANCED ARRAY*

The VLTI Advanced Array includes:

- The Ability to Use all 8 meter Telescopes
- Four Movable Auxiliary Telescopes
- Transport between a Limited Number (≈ 25) of Fixed Stations
- An unvignetted FOV of 1.5 arcsec
- A coherent/cophased FOV of 1 arcsec, optimized within the constraints of the VLTI

budget

- "Slow" Reconfiguration Capability (once a day, during daytime)
- Four Delay Lines (to be used with any combination of telescopes)
- Progressive Implementation of 2.2 μm Adaptive Optics for all Telescopes
- Protected Optical Paths in Air
- Wavelengths Coverage Using one Type of Coating from ≈ 420 nm through 25 μm
- Operation not Requiring Blind Fringe Acquisition and Tracking
- A Limited Number (2 - 3) of General User Instruments
- A Laboratory at the Beamcombining Station for User Experimentation
- Data Recording and Quick Look Analysis Capability
- The Inclusion in the VLT Astronomical Weather Station (needed generally for flexible scheduling and remote operation) of measurements of Interferometric Parameters

This configuration, although limited, will provide indeed the "substantial scientific capability" wanted. Notwithstanding its limited nature, it will be very challenging to implement and will already be straining manpower and budget resources.

3.3.2 The *VLTI EXTENDED ARRAY*

Not in order of priority, the Extended Array includes:

- Additional Delay Lines
- More Auxiliary Telescopes
- Additional Stations for the Auxiliary Telescopes
- Rapid (≈15 minutes) Reconfiguration Capability
- Hypersynthesis Capability
- A Wide (≈ 8 arcsec) Field-of-View
- Wide Field (> 8 arc sec) Fringe Tracking
- Evacuated Light Paths
- Increased Wavelength Coverage down to at least 370 nm Using Improved Coatings or Exchangeable Optics
- More General User Instruments
- Extended Baselines (≈ 1000 m)
- Blind Fringe Acquisition and Tracking Capability
- Adaptive Optics Optimized for Shorter Wavelengths (≈ 1 μm)
- Laser Generated Reference Stars at each Telescope

The Extended Array will not necessarily include all these features, and it may include others which are not listed. The listing of features above is intended to be indicative of the direction of evolution towards the Extended Array and as such will influence the definition and design of the Advanced Array. It is, however, premature to attempt a firm definition of the features of the Extended Array now. That, and the definition of the priority among the features to be added, will be done as the Advanced Arrays is being completed and made operational. The Extended Array will be a new program. A plan for its implementation will be developed and submitted to ESO's governing bodies at the appropriate time. It is not part of the present implementation plan.

3.4 VLTI Layout

3.4.1 Telescopes

As discussed above the auxiliary telescopes should be of similar design as the 8 meter telescopes. That means Alt-Az mounts and a coudé optical configuration which is analogue to that of the 8 meter telescopes shown in Figure 3.4-1. This will ensure: (i) same image/pupil/polarization direction transfer, (ii) same "handedness" of the image/pupil/polarization, and (iii) same retardation by off-normal reflections. Including the desire to include an adaptive mirror at a similar pupil scale, these conditions resulted in a decision to closely mimic the optical train given in Figure 3.4-1 for the auxiliary telescopes. The exact optical configuration will depend on the mechanical design, and will be firmed up in the Phase A design study of the auxiliary telescopes currently in progress. Because of their sole use for interferometry, the auxiliary telescope design will be optimized to meet the strict tolerance requirements (section 4.1).

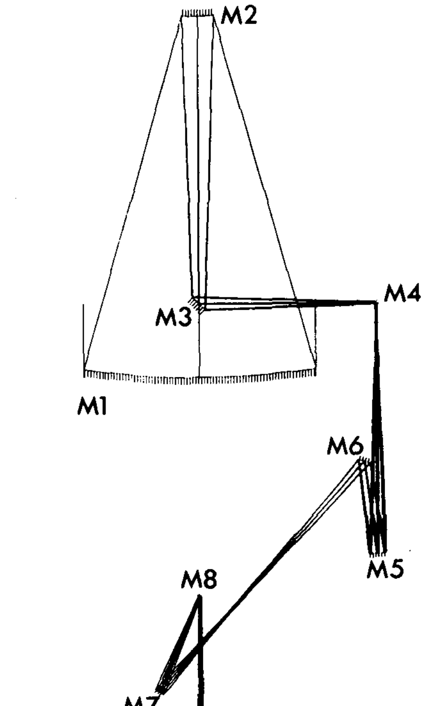

Figure 3.4-1 Optical Layout of the 8 meter Telescope coudé Beam. (mirror M8 is the adaptive mirror)

3.4.2 Delay Lines

It is proposed to use a movable Cat's Eye on a precision linear translation stage. Figure 3.4-2 give the optical layout which is now used in the Phase A design. The diameter of the large mirror M_B is determined by the beam demagnification factor M, by the desired field-of-view diameter Ω, and by the distance L of the Cat's Eye to the nearest pupil image. For M = 100, Ω = 8 arc sec and L = 62 m it equals approximately 75 cm. For the small secondary mirror M_B it is proposed to use a "zoom" mirror with actuators for the rapid fringe tracking. The "zoom" mirror relays the pupil at the delay line entrance to the beamcombiner. The limited FOV (1.5 arc sec) of the Advanced Array needs only a 35 cm diameter Cat's Eye. The delay line has to have a range of motion of ≈ 60 m.

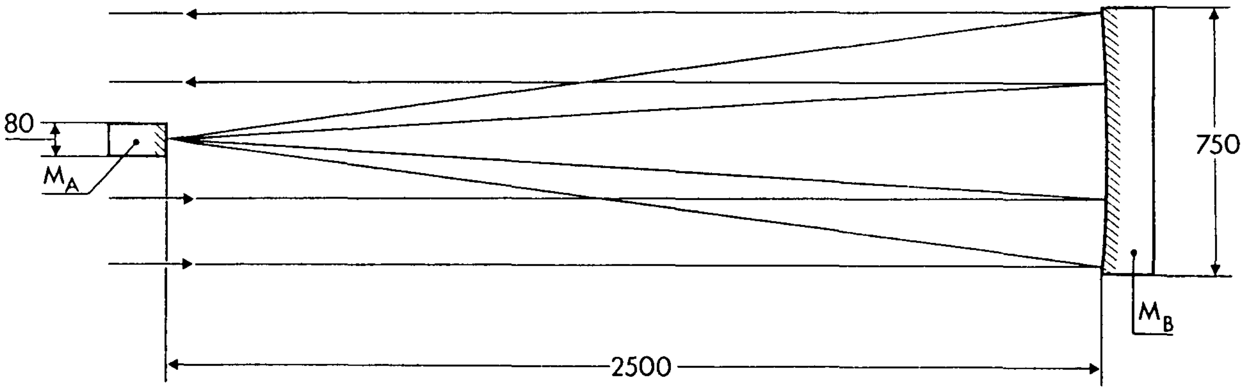

Figure 3.4-2 Optical layout of the delay lines (M_A is the main mirror, M_B the secondary "zoom" mirror).

3.4.3 Configuration of the 8 meter telescopes

The final configuration of the VLTI will very much depend on the site chosen for the VLT. Given that uncertainty, the panel has examined a variety of configuration options for the 8 meter telescopes. The unique opportunity presented by the construction of four identical 8 meter telescopes on the same site make it important to optimize the array of 8 meter telescopes by itself. Configurations studied included both linear, partially redundant arrays relying solely on time synthesis techniques to make images, and 2D arrays with no or partial redundancy (Figure 3.4-3). The panel came out in favor of a 2D

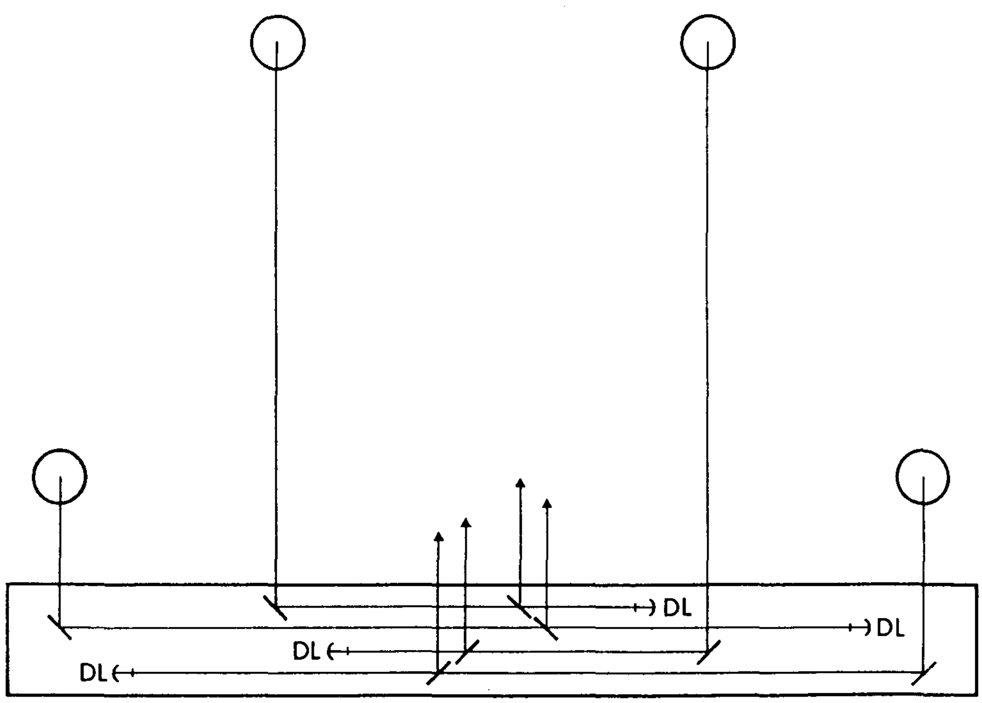

Figure 3.4-4 Lightpaths for 8 meter telescopes. DL = optical delay line.

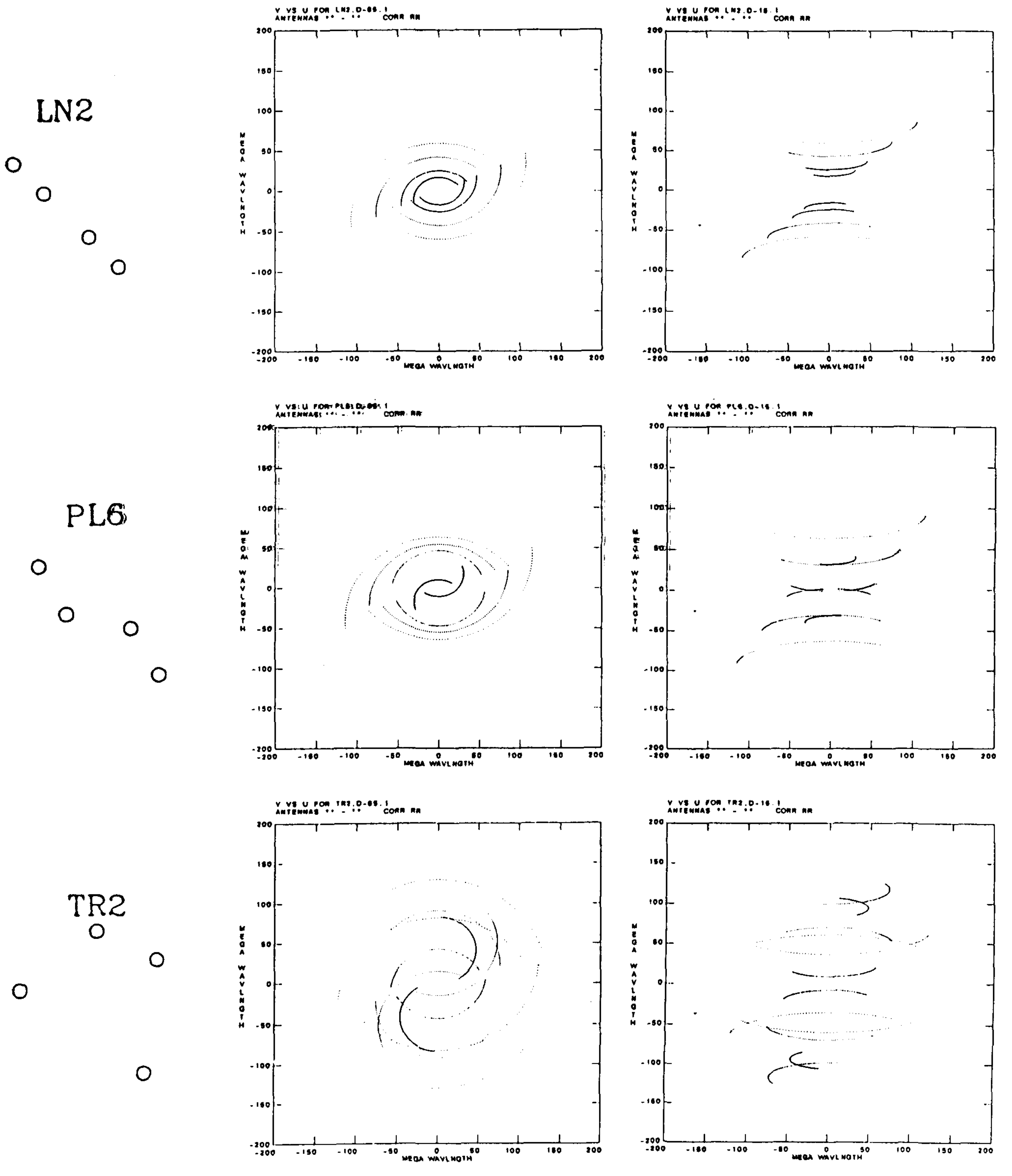

Figure 3.4-3 Layout and (u,v) plane coverage for −65° and −15° declination for the LN2, PL6, and TR2 configurations).

array preferably of the trapezium (TR) type. Second choice is the 2D parallelogram (PL) configuration, third choice the linear (LN), partially redundant array given in the VLT proposal. The orientation of these configurations will have to take into account the site geometry and its wind profile. Although there is a clear preference, all choices are acceptable as giving a powerful interferometric capability.

3.4.4 Relay Optics

It is proposed to bring the light of the 8 meter (as well as auxiliary) telescopes together in a rectangular grid pattern as shown in Figure 3.4-4. Doing so preserves the image/pupil/polarization orientations in a convenient way and equalizes retardation effects due to off-normal reflections. This way of combining the beams is similar to the one described in the VLT proposal in which there is an optical tunnel (parallel to the "rows" of the grid) which is in common to all beams and which contains the delay lines. Figure 3.4-5 shows a possible coupling of the coudé beams of the telescopes to the afocal relay optics. A field mirror in the coudé focus relays the pupil to a place close to the entrance of the delay line. The off-axis parabola collimates the beam with a demagnification ratio of M = 100. When the optical paths in the relay optics, including delay line, are not evacuated, it will be necessary to incorporate a longitudinal atmospheric dispersion compensation device in each interferometer arm.

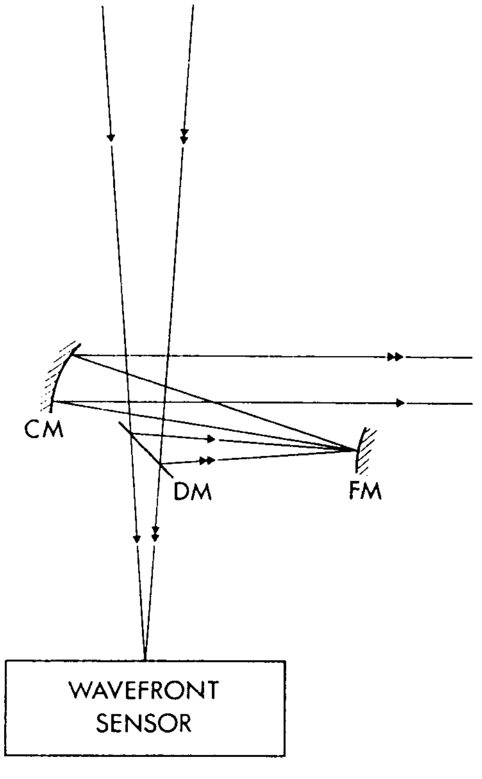

Figure 3.4-5 Coudé image relay optics

3.4.5 Configuration of the Auxiliary Telescopes

For the same reasons mentioned above, it is proposed to combine the beams of the auxiliary telescopes along the same rectangular grid using an equivalent type of relay optics (the field mirror in the coudé focus now may have to be of variable focal length, because of the varying distance to the delay line). From this evolved the concept of moving the auxiliary telescopes along the columns of the rectangular grid with the fixed stations located on the columns. For the Advanced Array we envisage one auxiliary telescope per column, and station separations as small as ≈ 8 meters. Column separations should range from 10 meters to ≈ 120 meters with probably about 6 columns. Figure 3.4-6 gives an example of such a configuration. Since all 8 meter telescopes and some VISA

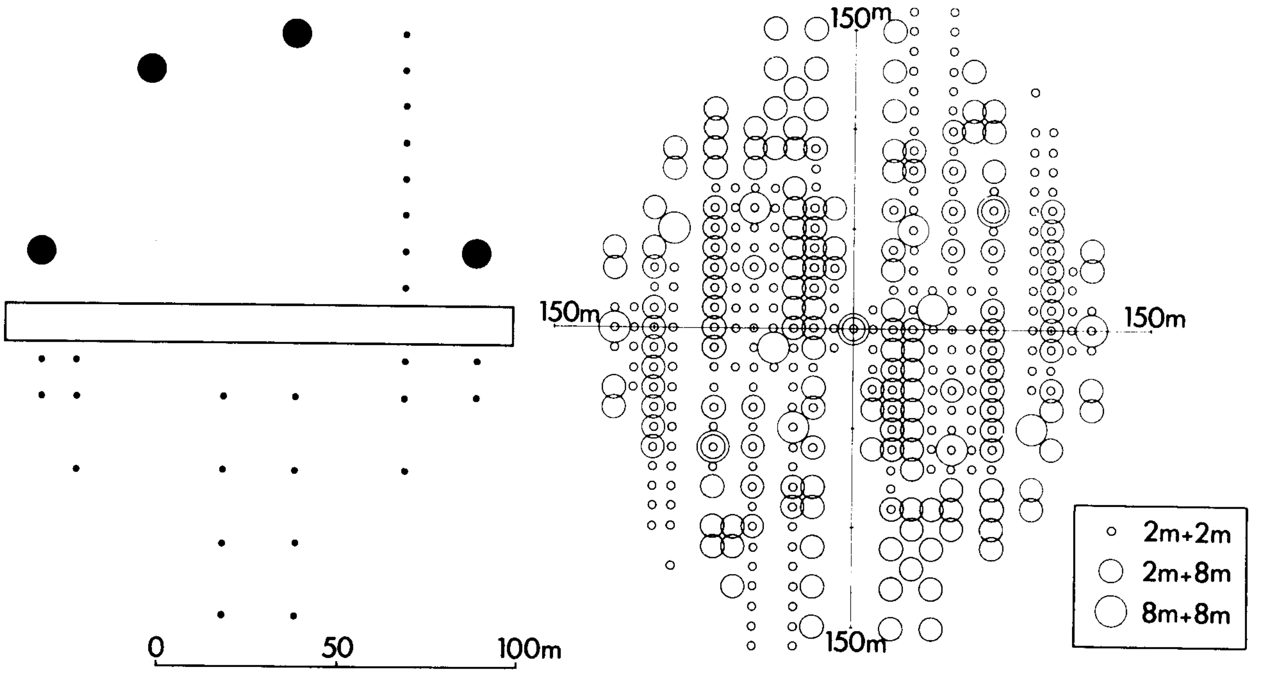

Figure 3.4-6 Possible VLTI configuration, and corresponding zenith (u,v) plane coverage, of 8 meter telescopes (TR type) and 26 auxiliary telescope stations.

stations are located on the same side of the beamcombining tunnel, it is easy to maintain their equal pupil/image orientation needed for wide FOV operation. The same is the case for a major subset of configurations of the VISA. The final configuration of the VISA, including the location of the beamcombining tunnel, depends on the site chosen and on other factors involving site development.

3.4.6 Beamcombination

The telescope pupil is relayed by the secondary mirror in the delay line to the beamcombining station. There the light from the different telescopes will be combined in a number of possible ways depending on the observations or experiment being carried out. These will include both *Image Plane* and *Pupil Plane* modes. Figure 3.4-7 shows the suggested image plane mode for a combination of four 8 meter telescopes and two auxiliary telescopes. Full definition of the beamcombining station, including fringe, image and pupil tracking, will be one of the next tasks of the panel.

3.4.7 Pathlength Control

A laser interferometer will monitor the distance between the beamcombiner and a retro reflector probably mounted in the center of the telescope secondary mirror (M_2). The resulting signal will measure variations in optical pathlength caused by vibrations, delay line motion, and relay optics drifts, and can hence be used to control these. Full vibration control will require, in addition, accelerometers mounted on M_1 and M_2.

3.4.8 Wavelength Coverage

Wavelength coverage depends very much on the properties of the available coatings. In the Advanced Array one simple silver coating can be used spanning the range from .6 to 25 µm with very good efficiency ($\leq$ 2 % loss per reflection or $\leq$ 25 % loss on the $\approx$ 14 surfaces between the telescope M_3 mirror and the beamcombiner). Aluminium coatings on M_1, M_2 and M_3 by themselves loose $\approx$ 10 % per reflection in this wavelength range ($\approx$ 27 % total) so that the total throughput to the beamcombiner is $\approx$ 55 %.

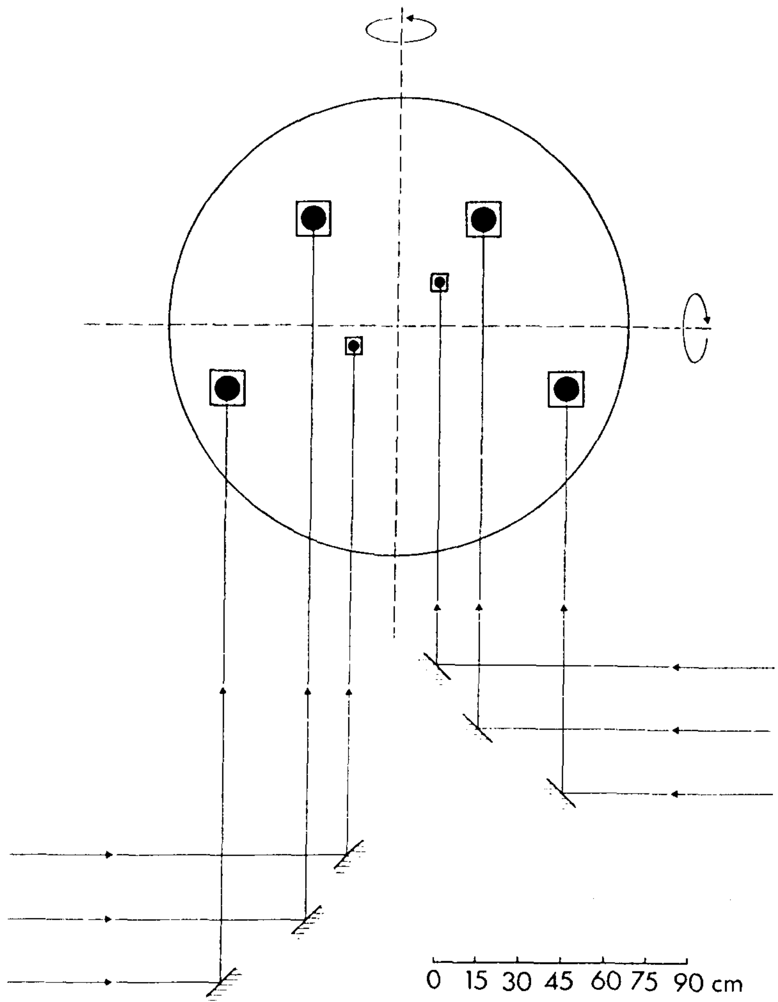

Figure 3.4-7 Image Plane beamcombination. Pupil images (large filled circles for 8 m telescopes, small for auxiliary telescopes) will be located on the movable and tiltable feed-mirrors M_f. The beamcombiner itself is a ≈ 150 cm diameter telescope which, in the wide FOV mode, may be mounted in a gimbal centered on a point central to the feed-mirrors.

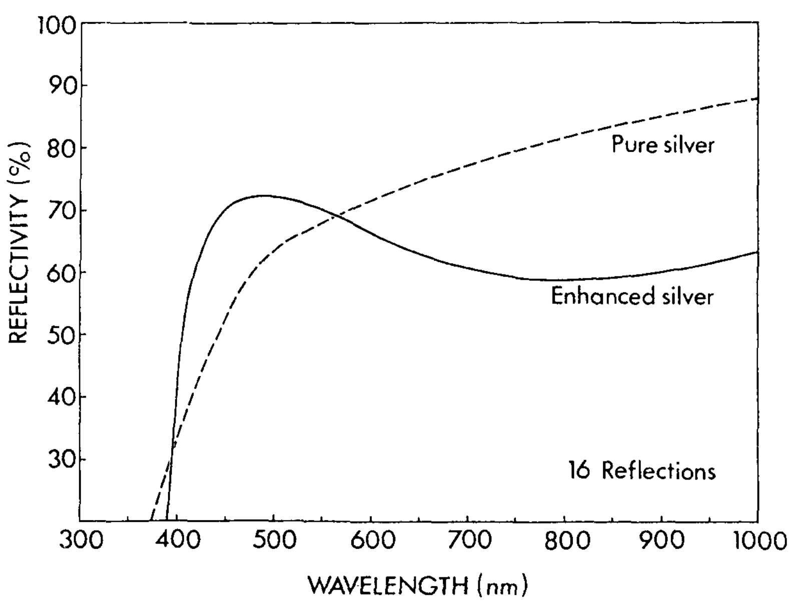

Figure 3.4-8 Reflectivity of unprotected and protected silver coatings.

Existing enhanced silver coatings (Figure 3.4-8) extend the usable wavelength range downward to 420 nm at the expense of the wavelength region between 600 nm and 1000 nm where reflective losses become as large as 4 % at 800 nm (corresponding to 44 % loss on 14 surfaces). It is expected that the properties of coatings will improve in the future so that full wavelength coverage between 400 nm and 25 μm with a single coating can be foreseen either already in the Advanced Array or otherwise in the Extended Array.

3.4.9 Telescope Transporters

Transporters will be needed to move the auxiliary telescopes between the different stations. Details of these depend very much on the design of the auxiliary telescopes which is in progress now. They may either be part of the telescopes themselves (wheels on rails) or be a separate item.

3.5 Instrumentation

In its simplest form the instrumentation will be cameras for the different wavelength regimes, with atmospheric dispersion compensators, recording the combined, fringed, images at the end of the beamcombiner simultaneously at a number of wavelengths. The initial complement of instruments should ideally include at least one such camera optimized for the R band (.6 to .8 μm), one optimized for the K band (2.2 μm), and one 10 to 25 μm camera. More complex instruments would include more extended spectroscopic and polarimetric capabilities, as well as the capability to do superresolution observations by differential interferometry techniques. Definition and acquisition of the general user instrumentation at the coherent combined focus will follow the path given in the VLT Instrumentation Plan.

3.6 Data Recording and Quick Look Analysis

Future activities of the panel will include the study of the data recording and quick look analysis needs. "Quick Look" analysis of the data implies the level of analysis needed to assess the quality of the observations at a level needed to evaluate the operationability of the VLTI and the quality of the observations.

3.7 Astronomical Weather Station

For flexible scheduling, observation planning, observation calibration, and remote observing it will be necessary to have an "Astronomical Weather Station" (AWS) at the VLT site for all uses of the VLT. For the VLTI the knowledge of image quality (r_o), coherence time (or fringe lifetime τ_o), the size of the isoplanatic patch ($\emptyset$), and, if measurable or inferable, the upper scale of turbulence is of prime importance.

3.8 Operation

We envisage the following phases in the operational implementation of the VLTI (see also schedules in section 6):

A. Assembly on site of individual components of Advanced Array

B. Commissioning of VLTI Advanced Array, leading to "first fringes"

C. Advanced Array operation and optimization

D. After achievement of Advanced Array performance specifications (TBD), start implementation of the Extended Array.

E. Remote Operation.

During phases B and C we foresee the need for a resident staff at the site working together with visiting scientists and engineers to implement and optimize the VLTI and its image acquisition systems. Remote observing will be very desirable because of the VLTI's remote location, but it is unlikely that it will be an option at an early stage.

4. Major Technical Issues

The following technical issues are highlighted as critical for the successful implementation of the VLTI.

4.1 Relating to Fringe Contrast

Maintaining fringe contrast is even more important than maintaining throughput in an interferometer. An examination of the factors contributing to fringe contrast decrease, and of their resulting tolerancing budget, identified the following as particularly critical:

- *VIBRATIONS*, pathlength changes at frequencies > 20 Hz have to be ≤ 50 nm RMS
- *COHERENCE TIME* or *FRINGE LIFETIME*, has to measured to better than 20 % at the time of the observations
- *OPTICAL QUALITY*, of the combined optics has to be better than .1 µm RMS
- *TRACKING ERRORS*, have to be less than .02 arcsec RMS
- *POLARIZATION*, has to be closely controlled

The numerical values above refer to the K band (2.2 µm), tolerancing becoming generally more tougher with decreasing wavelength. *PATHLENGTH EQUALITY CONTROL* becomes a critical item when broad spectrum bandwidths are needed and when fringe acquisition and tracking becomes impossible.

4.2 Relating to Reflective Coatings

Because of the large number of optical surfaces in the combination of the beams it is important to use coatings with the highest possible reflectivity (lowest emissivity), protected from environmental deterioration effects (eg dust collection). Retardation effects on coatings are a potential problem for fringe contrast and polarization control especially if spatially variable and non-repetitive from sample to sample. Research and development on optimizing coatings therefore has to be an ongoing effort not just for interferometric uses but also for other applications.

4.3 Relating to Field-of-View

To obtain any cophased/coherent FOV larger than the diffraction disk of the individual telescopes (eg ≈ 1 arcsec in the Advanced Array to increase to 8 arcsec in the Extended Array) it is necessary to make the combined exit pupil of an interferometer identical to the input pupil. This has to be done in detail: (i) the pupil configuration has to be maintained, (ii) the relative scales among the pupil diameters and relative to their configuration has to be maintained, and (iii) the handedness and orientation of the pupils with respect to the overall array configuration has to be maintained. Considering that almost all of these pupil reimaging parameters change while the array is tracking an object, meeting these conditions is a difficult task. The beamcombining system being developed will accomplish this, and a tolerance analysis has been made.

4.4 Relating to Beamcombination

The image plane beamcombination scheme described in section 3.4.6 is quite straightforward. It results in an image dissected by sets of interference fringes which will make it look like a speckled image, and which can be analyzed in the same ways using by now well established imaging algorithms. However, for many experiments pupil plane interferometry will be preferred, as perhaps will be the use of single mode fibers and their correlators. Those modes of beamcombination remain to be better defined.

4.5 Relating to Adaptive Optics

The use of adaptive optics in all telescopes is crucial when the high sensitivity promised by interferometry with large telescopes is to be achieved. ESO and its member countries should therefore continue to support the development of this technology. Its first step was the successful implementation of the 19 element VLT prototype system (also in France referred to as COME-ON project). It is to be followed by the development of systems (hardware and control software) using the many elements (≈ 250) needed at 2.2 µm wavelength for 8 meter telescopes. Other important components of a development program should include the development of IR (2.2 µm) wavefront sensors, modelling of the expected behavior of adaptive optics (including multi-conjugate adaptive optics), and the experimentation with artificial laser star generation.

4.6 Relating to Blind Fringe Acquisition

There will be many objects which are insufficiently bright or too resolved to allow fringe acquisition and guiding on their own images. For those it will be necessary to go to an offset bright, unresolved star to acquire fringes, and then to return while correcting for differential path differences and celestial rotation. This will require accurate metrology both astrometrically and geometrically (of the telescope positions). Accuracies in the 10 milliarcsec and 10 µm class are desirable, an order of magnitude less accuracy is acceptable.

4.7 Relating to Control and Systems Engineering

As already explained in section 1.4, high requirements have to be placed on the quality of the systems and control engineering of the VLTI if it is to be a functional facility. The requirements for this are unparalleled in optical astronomy.

5. MAJOR MANAGERIAL ISSUES

The following managerial issues occur when considering the implementation of the VLTI.

5.1 Relating to Manpower

ESO manpower requirements for the implementation of the VLTI depend very much on the model assumed for the realization of the VLTI. For the *preparatory phase*, as well as for the *final design/construction phase*, it was assumed that the lion share of the work would be done under contract with industry, engineering firms and other research institutes. Nevertheless the manpower requirements on ESO are still substantial, even under this model, since much of the definition, specification, tendering, monitoring, and acceptance testing of the project has to stay in hands of ESO. The skills involved are highly professional and at the level of engineers, scientists, contract monitors and administration.

5.2 Relating to Budget

The budget in the VLT proposal allowed for the VLTI implementation covers the construction of 2 auxiliary telescopes, 2 delay lines and 2 telescope tracks. The desire to increase this to 4 auxiliary telescopes and the additional delay lines in the Advanced Array, will therefore require the attraction of additional resources.

5.3 Relating to Commissioning and Operation

During the commissioning optimization phase of the VLTI there will be a need for an ongoing experimental effort on the VLT site to refine and develop the techniques which are part of interferometric imaging. It is also very likely that the full VLT interferometry facility will become the focus of interferometric developments within all ESO countries which will attract much of the very best talent available. This may be a unique aspect of the VLTI, one which ESO should take full advantage of. The implementation strategy during this evolutionary period of maybe 10 years therefore envisages an on-site R&D effort supported by a resident (in Chile) dedicated staff, operated in a manner very similar to an experimental physics facility.

6. IMPLEMENTATION SCHEDULE

Figure 6-1 gives the best current estimate for the proposed implementation schedule for the Advanced Array only. The main phases and milestones in this schedule are:

- 1989/1990 — Extended Phase A Studies
- Nov 1990 — Site Selection Followed by Final Definition of the VLTI Configuration
- Sep'90/Mar'91 — Full VLTI Systems Review and Definition
- Nov 1991 — Let Major Construction Contracts
- 1991/1994 — VLTI Final Design and Manufacturing; Site Development
- Mar 1995 — Start Assembly of the VLTI
- Nov 1995 — First Light UT1
- Jul 1996 — Start Commissioning of the VLTI
- Feb 1997 — First Light UT2
- Jul 1997 — Start Operation the VLTI
- 1997/1999 — Optimization of the VLTI, Planning for the Extended Array

7. MANPOWER ESTIMATES

Manpower estimates for the *design and construction phase* (now through 1995) are based on the model where the lion share of the work is done under contract. ESO's role is restricted to definition,specification, tendering, monitoring and acceptance testing. It is to be stressed that these estimates are very uncertain because of the limited experience at ESO in working in this mode.

During the pre-construction phase lasting 2 years (late 1989 to late 1991) ESO staffing requirement estimates are:

• Program Management/Monitoring	2.0 MY	or	1.0 MY/yr
• Optical Engineer	1.6 MY	or	0.8 MY/yr
• Mechanical Engineer	2.4 MY	or	1.2 MY/yr
• Electronics Engineer	2.0 MY	or	1.0 MY/yr
• Computer Analyst	0.4 MY	or	0.2 MY/yr

During the construction phase (1992 through 1995) very preliminary estimates are for:

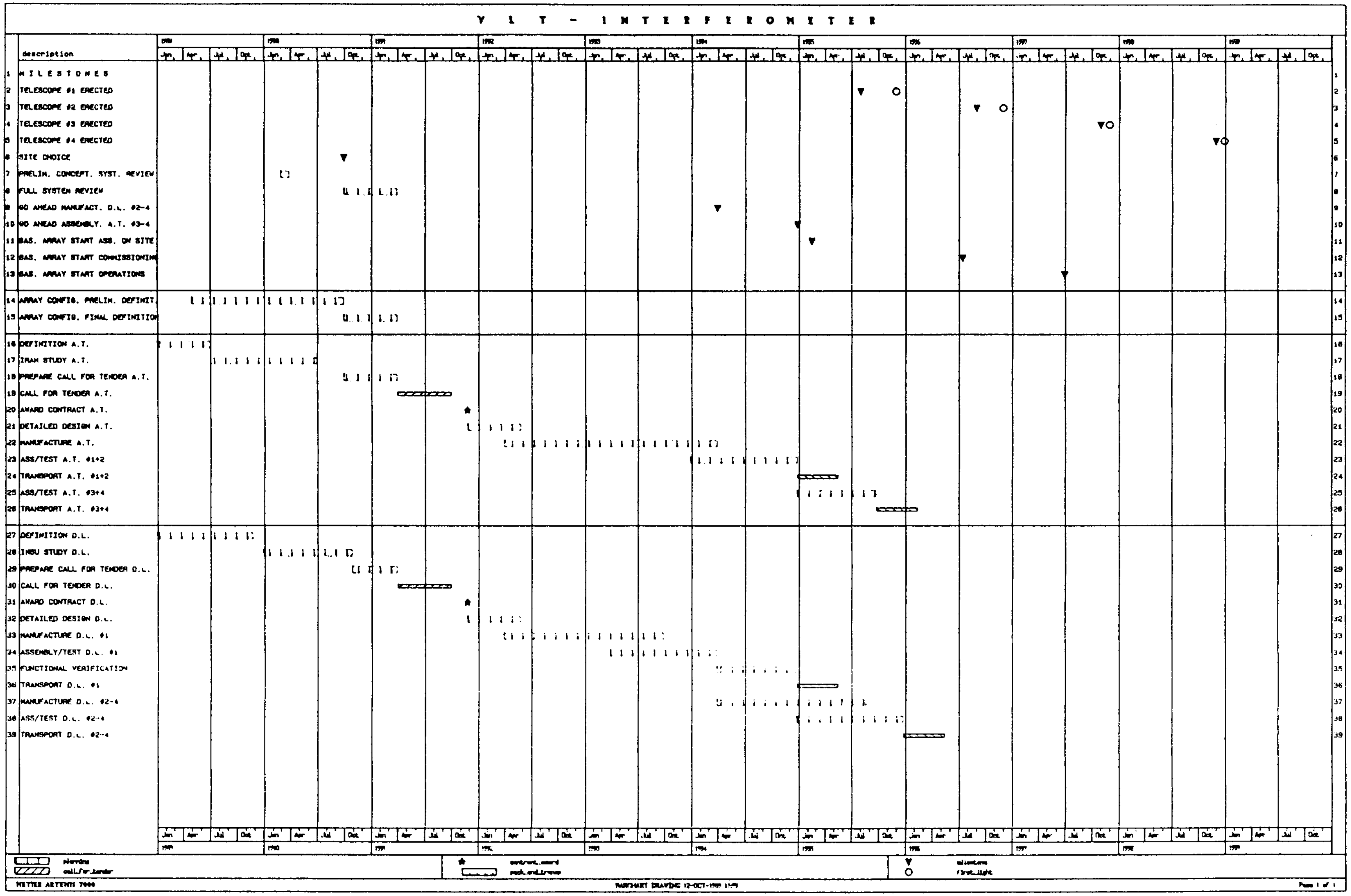
V L T - I N T E R F E R O M E T E R
description
1 M I L E S T O N E S
2 TELESCOPE #1 ERECTED
3 TELESCOPE #2 ERECTED
4 TELESCOPE #3 ERECTED
5 TELESCOPE #4 ERECTED
6 SITE CHOICE
7 PRELIM. CONCEPT. SYST. REVIEW
8 FULL SYSTEM REVIEW
9 GO AHEAD MANUFACT. D.L. #2-4
10 GO AHEAD ASSEMBLY. A.T. #3-4
11 BAS. ARRAY START ASS. ON SITE
12 BAS. ARRAY START COMMISSIONING
13 BAS. ARRAY START OPERATIONS
14 ARRAY CONFIG. PRELIM. DEFINIT.
15 ARRAY CONFIG. FINAL DEFINITION
16 DEFINITION A.T.
17 IRAM STUDY A.T.
18 PREPARE CALL FOR TENDER A.T.
19 CALL FOR TENDER A.T.
20 AWARD CONTRACT A.T.
21 DETAILED DESIGN A.T.
22 MANUFACTURE A.T.
23 ASS/TEST A.T. #1+2
24 TRANSPORT A.T. #1+2
25 ASS/TEST A.T. #3+4
26 TRANSPORT A.T. #3+4
27 DEFINITION D.L.
28 INSU STUDY D.L.
29 PREPARE CALL FOR TENDER D.L.
30 CALL FOR TENDER D.L.
31 AWARD CONTRACT D.L.
32 DETAILED DESIGN D.L.
33 MANUFACTURE D.L. #1
34 ASSEMBLY/TEST D.L. #1
35 FUNCTIONAL VERIFICATION
36 TRANSPORT D.L. #1
37 MANUFACTURE D.L. #2-4
38 ASS/TEST D.L. #2-4
39 TRANSPORT D.L. #2-4

Figure 6-1

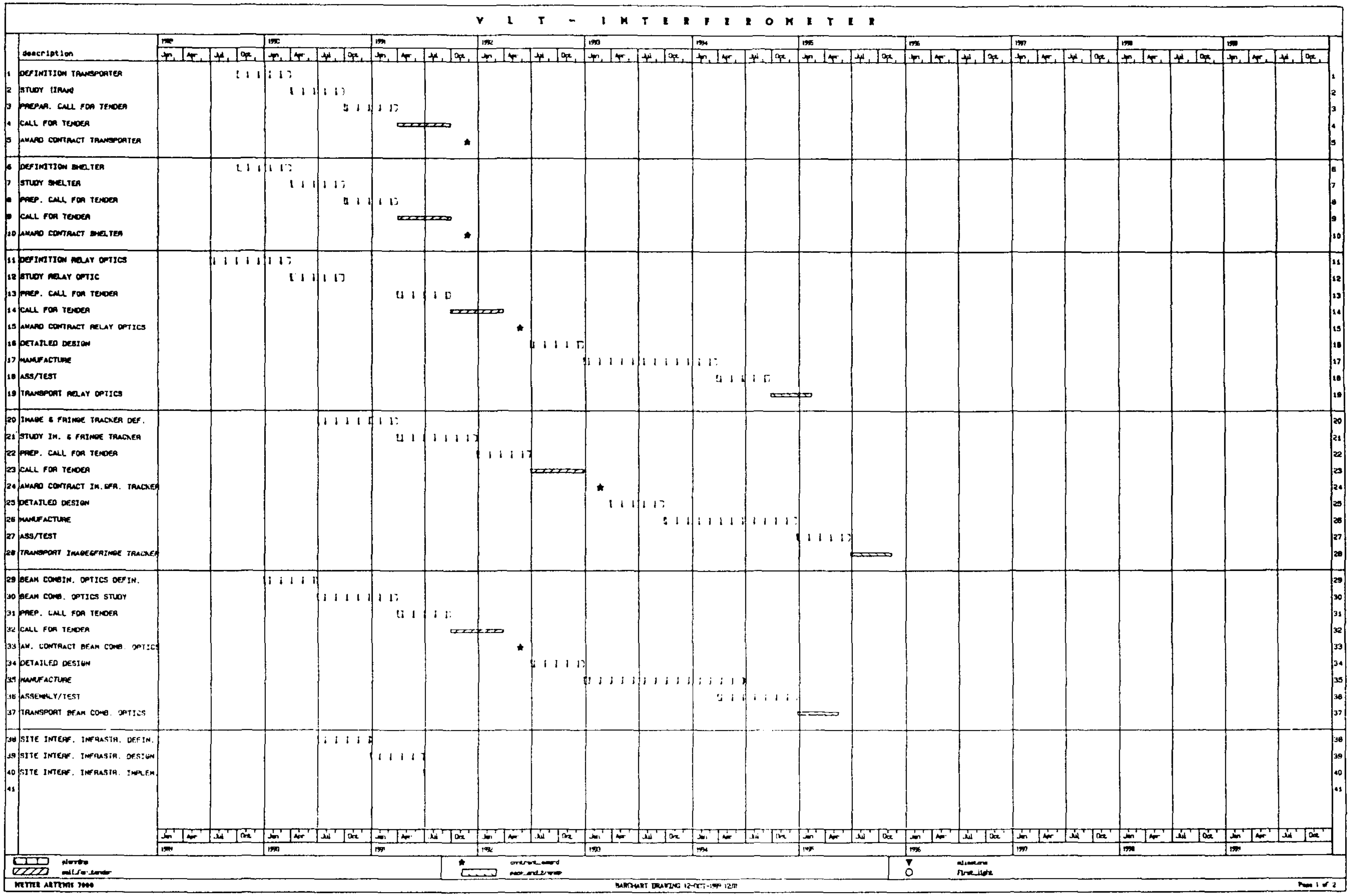

Figure 6-1 (continued)

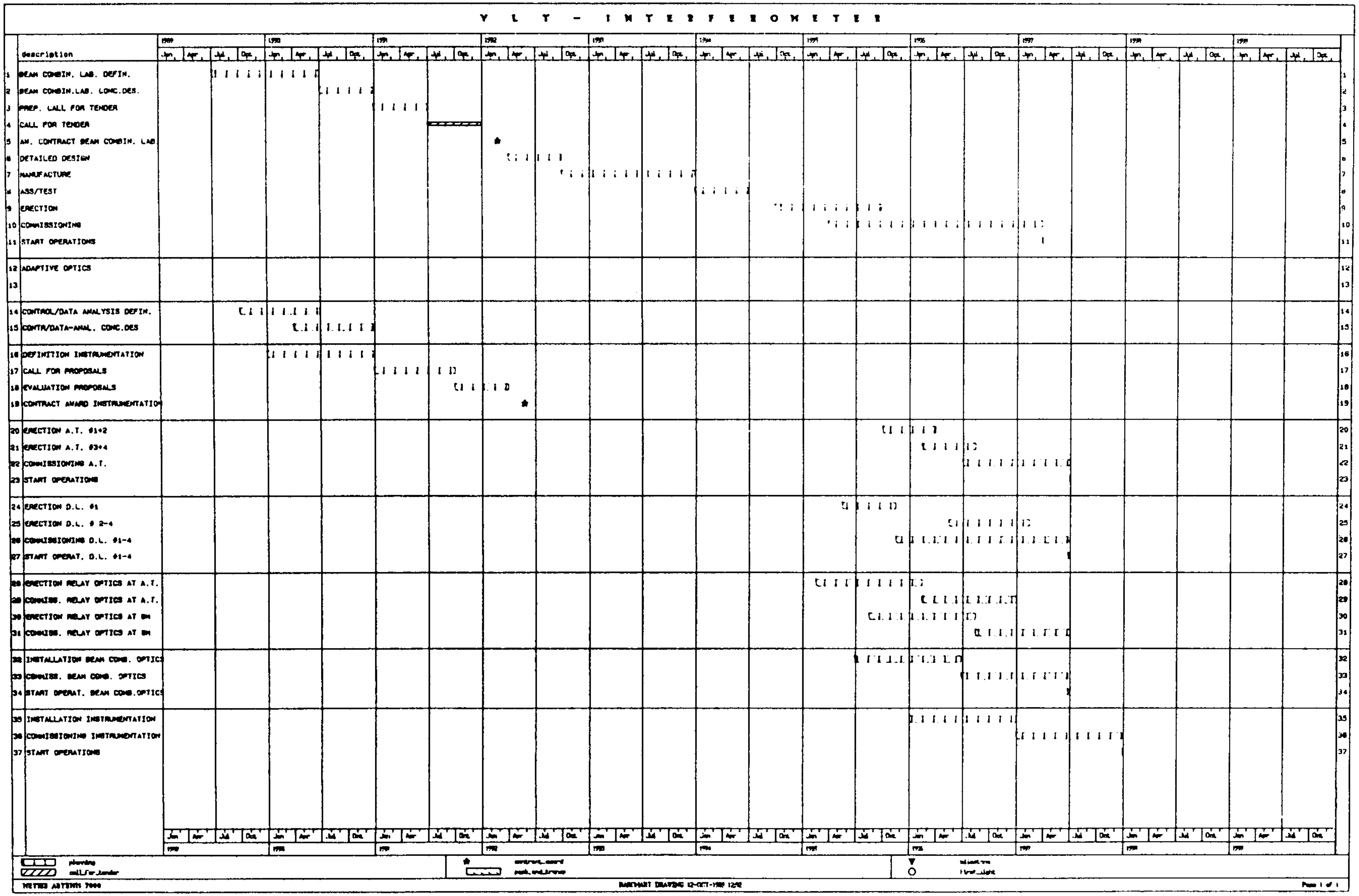

Figure 6-1 (continued)

• Program Management/Monitoring	4.0 MY	or	1.0 MY/yr
• Optical Engineer	2.0 MY	or	0.5 MY/yr
• Mechanical Engineer	2.4 MY	or	0.6 MY/yr
• Electronics Engineer	3.2 MY	or	0.8 MY/yr
• Computer Programmer	4.0 MY	or	1.0 MY/yr

Not included are time in the ESO project management and functions not included in the items not detailed in the implementation schedule (eg adaptive optics, site development).

In the *assembly/commissioning/operation/optimization phase*, starting in mid-1995, we envisage the need for a VLTI-dedicated on-site ESO staff consisting of:

- One Senior Scientist
- One Senior Engineer
- One Mechanics Engineer
- One Electronics Engineer
- Two Computer Programmers
- One Optics Technician
- One Mechanics Technician
- One Electronics Technician (digital)
- One Electronics Technician (analogue)
- Two Array Operators,

for a total of 12 staff members. In addition there will be a need to call regularly on the general VLT Observatory support staff even in the areas covered by this proposed staffing, because of additional support needs and because of only parttime presence of this staff on the VLT site. Contributing efforts by visiting scientists and engineers will also form an important part of this phase. It is premature now to anticipate staffing needs for the later, remote control phases.

8. BUDGET/BUDGET PROFILE ESTIMATES

Until the results of the Phase A/B studies of the VLTI components are in, the budget estimates have to be looked at as very tentative. The systems review in Sep'90/Mar'91 will take the results of these studies and define the VLTI construction program taking into account the funds available in the VLT Proposal and additional contributions by ESO member states. In the following the budget estimates for the Advanced Array and for the Interferometric Array as proposed in the VLT Proposal are given. The latter will be referred to as the "Basic Array". The cost differential is significant. A strategy is given to downscope the Advanced Array in case the additional contributions fall short of filling this budget gap,

8.1 Cost Estimate of Advanced Array

Figure 8.1-1 shows the budget profiles for the Advanced and Basic arrays. It includes the cost savings achieved by economy of scale. That implies that the additional contributions needed for the advanced array are guaranteed at the time of the awards for construction contracts (Nov. 1991). The total 51.8 MDM(1989) cost estimate for the Advanced Array includes : 4 Auxiliary Telescopes, 4 Delay Lines, 7 Telescope Tracks, 26 stations for the Auxiliary Telescopes and a beamcombiner allowing a small coherent FOV. This capability significantly exceeds the capability of the Basic Array which included only 2 Auxiliary Telescopes, 2 Delay Lines, 2 Tracks and fewer stations. With 10 stations and a minimal beamcombination capability we estimated the Basic array to cost 29.5 MDM, within the 26.5 MDM proposal budget estimate, given the uncertainty of the estimate and the 10 % budget contingency. The budget profile for the Basic array fits into the estimates of the total VLT program.

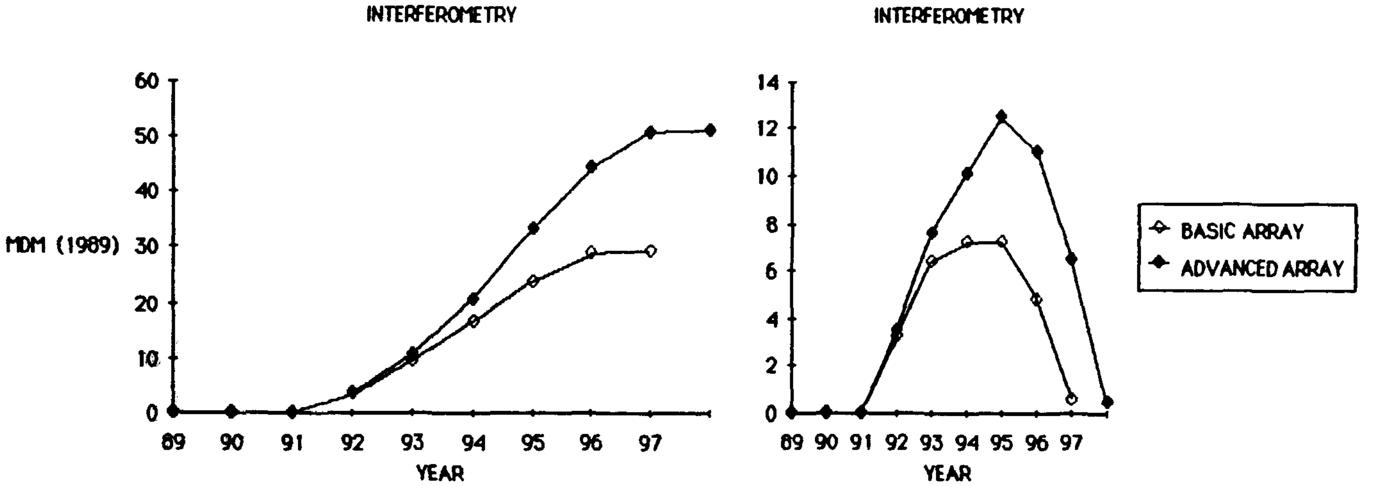

Fig.8.1-1 Budget profiles for the Advanced Array and Basic array following the implementation plan given in Figure 6-1. On the left is shown the cumulative expenditure, on the right the annual expenditure. The profiles for the Advanced Array assume that the additional contributions are guaranteed at the time the construction contracts are let. As the figure shows, most of the actual spending occurs later.

8.2 Program Adjustments to Meet the Available Budget

Considering the major enhancement in capability of the VLT Interferometric Mode, the 75% increase in the budget of the Advanced Array over the Basic array is economical. Notwithstanding that, the increased funding required (22.3 MDM) can at this moment not be guaranteed to materialize. The panel therefore identified the 4-step program given in Table 1 to meet the available budget at the time of the start of the VLTI construction. Each step down corresponds to an approximately equal decrease in the estimated budget. Each step also corresponds to a significant decrease in array capability. The Basic array will only work in the imaging mode with the frequent availability of at least one 8 meter telescope. That is not a realistic scenario because of the other major demands on the 8 meter telescopes. Step Basic +1, on the other hand, provides phase closure imaging capability without the need for a 8 meter telescopes. Step Basic +2, would allow the use of the entire array of 8 meter telescopes, and its 6 simultaneous baselines, when that is required for imaging of faint objects. Step Basic +3 doubles the number of baselines available to VISA only and the full Advanced Array provides for the simultaneous use of any 5 telescopes and 10 baselines, almost doubling the capabilities of the VLTI again.

TABLE 1

Stepwise Program Adjustments

Step Nr	Nr AT's	Nr DL's	Number of Baselines[a]	Can all 8^m Telescopes be used ?	Phase-Closure possible with VISA only ?	Cost Estimate MDM(1989)
Advanced Array	4	4	10 (6)	Y	Y	51.8
Basic +3	4	3	6 (6)	Y	Y	
Basic +2[b]	3	3	6 (3)	Y	Y	
Basic +1	3	2	3 (3)	N	Y	
Basic Array	2	2	3 (1)	N	N	29.5

[a] : assuming one fixed interferometer arm. In parenthesis is given the number of baselines with VISA only; [b] : referred to as "Basic-Plus Array"

9. CONCLUSION

This implementation plan is the result of a short, but intense study by the VLT Interferometry Panel. Although more remains to be done to define and design the VLT Interferometer in detail, before hardware implementation can be started, the time to move full throttle towards its implementation is now. The interferometry community is strongly motivated and driven both by the prospect of the breakthrough in astronomical knowledge, which will be achieved with the VLTI, and by the technological challenges posed by its implementation.

DEFINITION OF SYMBOLS AND ACRONYMS

CV	Coherence volume
FOV	Field of View
M	Beam diameter demagnification factor (M = 100 decrease pupil diameter from 800 cm to 8 cm)
Ω	Diameter of the cophased or coherent Field-of-View
ϕ	Diameter of the isoplanatic patch
r_0	Fried's parameter
τ_0	Wavefront coherence time
VLTI	VLT Interferometer (all telescopes)
VISA	VLT Interferometric Subarray (auxiliary telescopes only)