

A decade of VLTI technical development

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ABSTRACT

Following the successful VLTI '*First Fringes*' obtained in 2001 with the siderostats and with the 8m telescopes and based on the results from the commissioning phase, it is now possible to review with a critical eye the development approach followed over the last ten years and to draw a few conclusions.

We first recall this approach that aimed at minimizing the risk of not meeting the stringent requirements imposed by interferometry. This approach is based on the elaboration of exhaustive error budgets, an extensive set of analyses and early tests with feedback on subsystem specs, the performance characterization at subsystem level with identification of improvements when needed; and finally the commissioning of the complete VLTI at system level.

To illustrate this process, we provide practical examples taken from the project's history. We focus on two areas that have been considered among the most critical ones over the entire project life, namely: the turbulence inside the interferometer arms ('internal seeing') and the mechanical vibrations ('OPD stability').

For these two areas, we will finally compare the performances predicted during the development phase with those obtained at Paranal and we will draw conclusions.

Keywords: Interferometry, Very Large Telescope, VLTI, thermal effects, internal seeing, commissioning

1 INTRODUCTION

The technical endeavor of building the VLTI¹ has reached today a crucial point. Following the '*First Fringes*' events of 2001 and the consecutive 'commissioning' phase, a precise assessment of the system performance of the interferometer can now be made. This is of course of fundamental interest for the future scientific exploitation of the VLTI, but is also an excellent opportunity to review the engineering approach followed over more than 10 years and to draw some first conclusions. In particular, it is now possible to compare the achieved performance with the original requirements and with the intermediate analysis results.

When the engineering phase of VLTI started in the early 90's, the feasibility of combining 8-m class telescopes in an interferometric mode at infrared and visible wavelengths was far from being demonstrated. The challenge of building the VLT 8-m Unit Telescopes (UT's) was already huge and adding stringent VLTI requirements on sub-systems such as stability at the nanometer level needed strong justifications. In addition, practical experience in stellar interferometry with >1-m class telescopes was very limited at that time.

In order to minimize the technical risk to an acceptable level, it was considered of utmost importance to adopt a proper system methodology usually applied on complex project but seldom in development for ground astronomy. The essence of this method is to validate, at each step of the project, the expected performance. The basic approach applied to the VLTI has been previously reported in several articles^{2, 3, 4} and is recalled in Figure 1. It involves, in a first phase, the splitting of the top-level performance into detailed error budgets that enable to define the requirements at sub-system level. The validation of each contribution is then started as early as possible in the life of the project through dedicated analysis³ and experimentation². In that framework, a so-called *end-to-end* or *integrated* model⁵ can provide a powerful tool for analyzing the combined system-level effects originating from the various sub-systems and disciplines including atmospheric physics, optics, mechanics and control. As soon as the hardware becomes available, validation by tests at sub-system level² can start in order to verify the compliance with the sub-system specifications. If needed,

improvement can be identified and initiated at that point. Finally, after system assembly and integration, the final validation of the global technical and scientific performance is performed during the so-called *commissioning*⁶ and *science verification* phases respectively. This represents the current status of the VLTI project when results of the main global performance have now been obtained.

The following sections will illustrate the successive steps with various practical examples taken from the VLTI project life.

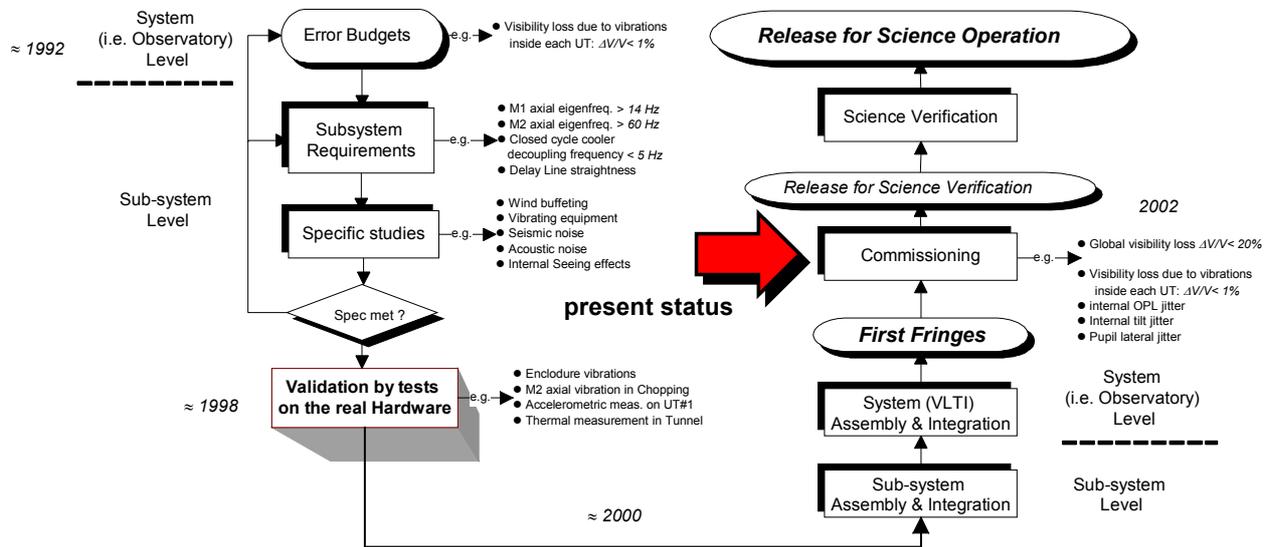


Figure 1: System approach followed for the VLTI technical development since the early 1990's.

2 THE FEASIBILITY STUDY AND SYSTEM SPECIFICATION PHASE

The VLTI entered its engineering phase in the early 1990's after its fundamental concept had been defined by the VLT interferometry panel^{7,8}. This concept included the following elements recalled for the historical perspective:

1. The VLTI is focused on the coherent combination of the VLT 8m telescopes
2. The four 8m telescope will be fixed in the location (!) implying development of delay lines. For cost and operational simplicity reasons, the internal VLTI optical path and the delay lines will be in air as opposed to vacuum.
3. An array of movable 2m-class auxiliary telescopes (maximum eight) shall complement the 8m-telescope array to enable full time use of the interferometer infrastructure. The extension of the array shall be comparable to maximum baseline between the 8m telescopes ($\approx 120\text{m}$).
4. An adaptive optics designed for near infrared ($2\ \mu\text{m}$) is essential for VLTI in both the 8m and the auxiliary telescope.
5. The infrared wavelength region originally identified in the VLT proposal (mainly driven by the issue of vibrations inside the 8m telescopes) shall be extended to include the visible.
6. The possibility of doing interferometry over a large Field-of-View (a few arcsec) shall be considered
7. The systems and control aspects associated with the VLTI are the prime hurdle in its implementation and requires a stepwise approach to achieve its ultimate capabilities thus minimizing risks.
8. The study has set as a goal the implementation of the initial VLTI configuration in the late 1990's

At that point, the two most critical technical areas of the VLTI were defined, namely: the '*internal seeing*' effects linked to the choice of an internal propagation in air (above item #2) and the *Optical Path Difference (OPD) stability* inside the 8m (and auxiliary) telescopes required for observation down to the visible (above item #5). A third critical area was the control aspect. The VLTI had specific real-time needs in particular for fringe tracking and adaptive optics. It had

also the challenge to control simultaneously many wide-spread, complex, high-precision subsystems such as telescopes, delay lines, adaptive optics, fringe tracker, instruments, etc. This VLTI control challenge benefited enormously from the important Hardware & Software standardization and development effort spent for the control system of the 8m telescope. This is reported elsewhere⁹. Finally, a number of specific technological challenges such as fringe sensing or polarization were identified.

In these very first years of VLTI development, a set of exhaustive error budgets were elaborated in order to split the top-level performance into individual contribution, as reported earlier¹⁰. One of the most important top-level performances for an interferometer is the maximum fringe contrast that can be obtained on an unresolved star (similar to the Strehl ratio for classical imaging). The so-called '*VLTI level 1 Requirements*' specified a contrast > 60% in K band with fringe tracking.

In parallel, the basic feasibility studies for the main VLTI elements, the delay lines¹¹ and the auxiliary telescopes¹², were conducted. These were used to confirm or update the sub-system requirements.

It is also during this period 1991-1992 that the VLT/VLTI infrastructure had to be defined in detail including: building layout, foundations for delay lines and auxiliary telescopes, electrical power and cooling needs, access, lifting devices, etc. At that stage, this could only be done based on global estimates in anticipation of future needs. However, whenever possible, simple analyses were conducted to support this work. An example of this found its origin in the animated discussion about the future location of the electrical transformers supplying the whole observatory. Their original location was in the center of the platform, next to the interferometry complex. They were finally moved away from the VLTI laboratory as a result of a quantitative assessment based on a typical vibration level of transformers (retrieved after a long search among specialized institutes!) that was input into a model of the Paranal ground vibration transfer function¹³ computed from measured rock properties.

In addition, that period saw the final layout of the UT array being nailed down based on a delicate compromise between scientific needs (the so-called '*UV coverage*') and practical site constraints such as wind shadowing and soil property.

3 THE SUBSYSTEM REQUIREMENT AND ANALYSIS PHASE

In the period 1992-1993, a set of detailed analyses, prototyping activities and measurement campaigns were initiated. The objective was to refine the sub-system requirements of the main VLTI elements including Unit Telescope (UT), Auxiliary Telescope (AT) and Delay Line (DL) as well as to verify the overall feasibility of the VLT/VLTI as an optical interferometer.

The development of prototypes was started for the Fringe Sensor Unit (FSU) and for the Variable Curvature Mirror (VCM).

In terms of analytical and experimental work, the two main critical areas mentioned above (§2) were given the priority.

As far as OPD stability is concerned, the scheme shown in Figure 2 was elaborated. A detailed description of the various activities and results has been given previously⁴ and will not be repeated here. The heart of the approach was a precise characterization of the various disturbance sources by analytical or experimental methods coupled to a very detailed FE model of the Unit Telescope used to compute the corresponding dynamic responses of each mirror. These latter were then combined with sensitivity matrices to assess the final tilt and Optical Path Length (OPL) fluctuation. An elasto-acoustic model of the UT inside its enclosure was also developed to assess the vibro-acoustic effect due to wind and local noise sources. Despite some 'ambient skepticism' concerning the ability of such complex models to accurately predict OPL fluctuation at the level of nanometer, these analyses proved to be of great value to refine subsystem requirements or design solutions just in time before industrial contracts were launched. Here are few examples:

- a) The first axial mode of the M2 unit, originally specified around 40 Hz, appeared to enter into resonance with the axial mode of the tube and M1 cell structure leading to an excessive sensitivity to micro-seismic noise. The specification was consecutively raised to >60 Hz for the M2 tendering. The value finally achieved is >100 Hz, avoiding this unlucky resonance situation.
- b) The response of the M1 & cell to dynamic wind load led to a requirement on the first axial eigen-frequency above 14 Hz.

- c) The cell stiffness for each mirror of the Coudé train could be specified to avoid common resonance.
- d) The diesel generators generating the electricity for the whole observatory were moved from a location close to the observatory platform to another one at the base-camp in view of the results of the acoustic analysis.

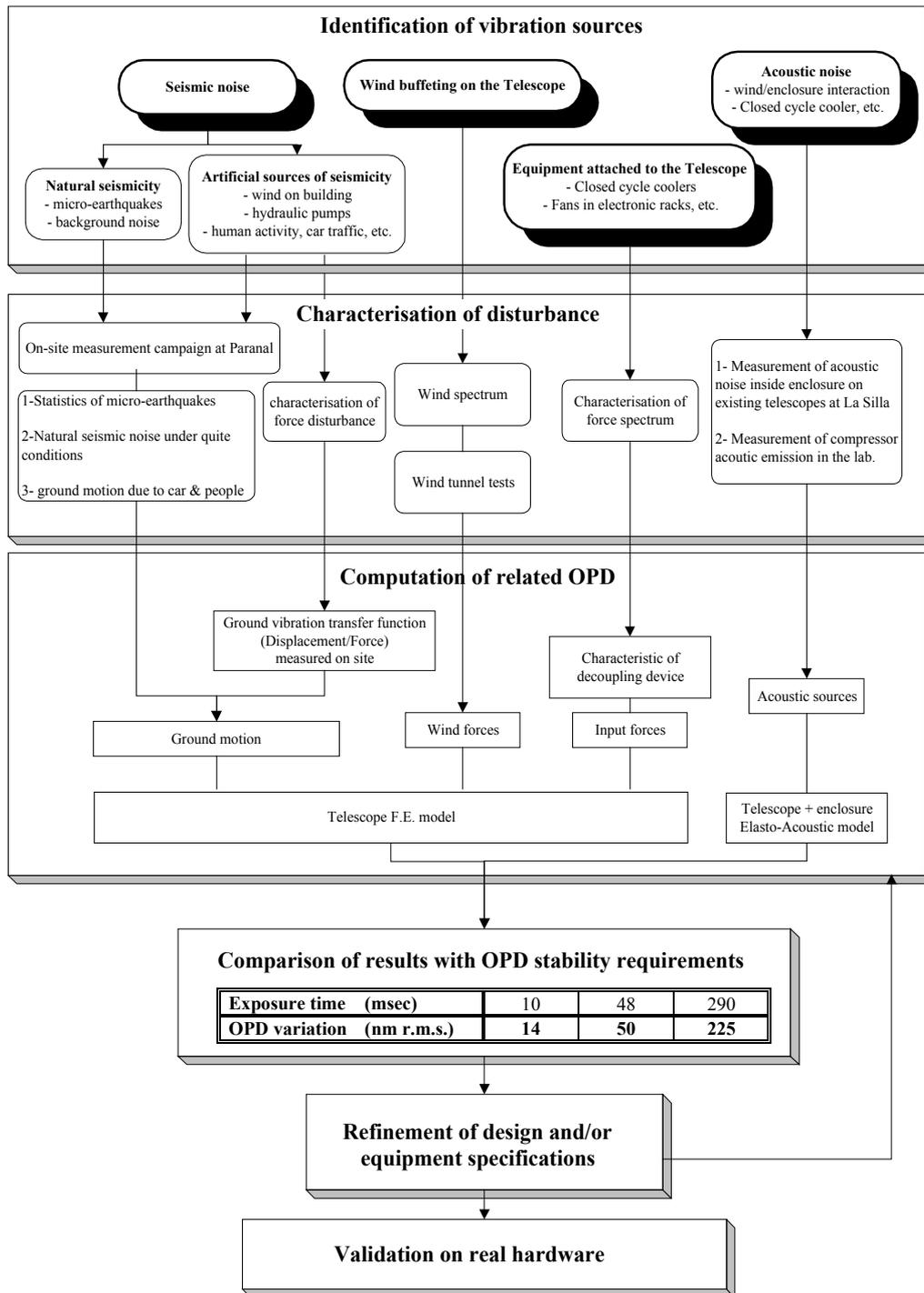


Figure 2: Overview of FEM analyses coupled to disturbance characterization & measurement to verify the OPD stability requirement during the VLTI design phase (1992-1996)

In the area of ‘internal seeing’, a similar approach combining experimental work and state-of-the-art computer modeling was selected as summarized on Figure 3. In a first stage, detailed thermal computer models of the VLTI infrastructure were used to estimate the temperature distribution, the airflow and finally the equivalent turbulence intensity (C_n^2) inside the tunnel in various operational conditions⁴. This enabled to optimize the thickness of the thermal insulation on top of the tunnel and around the AT station and to quantify sub-system requirements such as maximal allowable heat dissipation inside the Laboratory or Tunnel. Due to the uncertainty of this kind of modeling, a set of measurements was later done in an underground tunnel similar to that of Paranal¹⁴, confirming that the order of magnitude of required turbulence level appeared achievable.

The general outcome of these studies was the confirmation that the top-level VLTI performance was achievable, a quite useful argument at this crucial time when the VLT project was about to suffer severe budget constraints.

In parallel to the above activities, mainly dedicated to the UT and the VLTI infrastructure, the technical specifications were generated for the main VLTI elements, namely the AT and the DL. Unfortunately, the industry tendering process had to be stopped in December 1993 when the ESO council decided to postpone the actual procurements for VLTI, the UT Coudé trains and its adaptive optics!

This drastic decision had an obvious negative impact on the project schedule (and staff moral!). It had however some positive aspects. It gave the possibility to deepen the analysis/experimentation phase (e.g. micro-seismic measurement campaign¹³, precise acoustic noise characterization⁴, OPD characterization in underground tunnel¹⁴, End-to-End Model⁵, etc.), to further optimize the VLTI design and to secure performances. In addition, it enabled to extend the existing prototyping activities on the FSU and VCM but also to develop fall-back solutions such as an OPD monitoring system¹⁵. This latter was to be used for compensation with the DL in case the OPD fluctuation inside the UT would be too high. Fortunately, this system turned out not to be necessary but this prototyping activity was eventually a useful step for the future PRIMA metrology¹⁶.

The years 1994-1995 that followed the ‘black December 1993’ saw an intensive period of trade-off where a review of scientific objectives and the search for cost-effective solutions led to some major modifications in the project. One of them was the postponement -not cancellation!- of scientific instruments using the visible band with the consecutive postponement of VLTI devices such as atmospheric dispersion compensators and final tip-tilt correction in the laboratory. A second one was the reduction of the interferometer field of view from 8 arcsec to 2 arcsec together with the introduction of the dual-feed capability¹⁷ to become PRIMA.

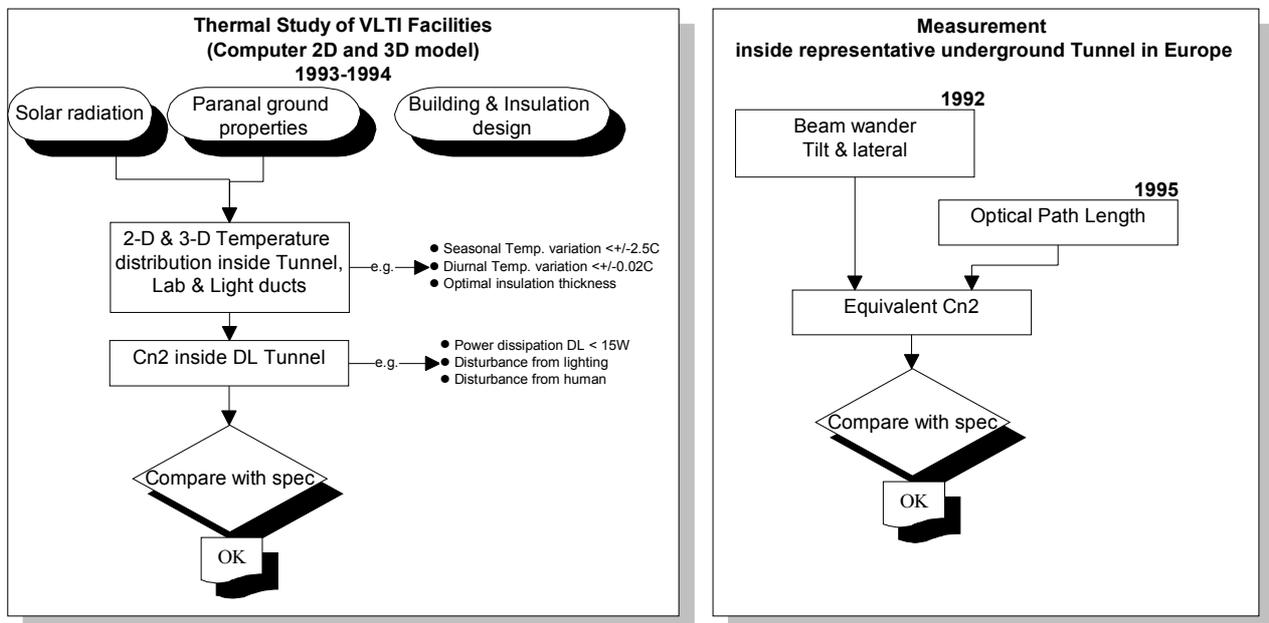


Figure 3: Overview of thermal activities related to internal seeing effects during the VLTI design phase

4 THE DESIGN & PROCUREMENT PHASE

The design and procurement of the proper VLTI components was finally resumed around 1996 with a mix of industrial contracts (DL, AT, UT Coudé trains, Transfer optics, etc.), internal development projects (adaptive optics, alignment units, etc.) and collaboration with scientific institutes (scientific instruments MIDI & AMBER, VINCI, FSU, VCM, etc.). During that phase, a standard engineering practice was applied with a strong component of systems engineering including, among others: strict control of sub-system performance, follow-up of error budgets, careful review procedures, maintenance of interface documents, etc.

To illustrate how the two major risk areas identified above were constantly taken into account in the design phase, we will give here the example of the support for the various optical tables used in the VLTI laboratory. These tables host either optical elements of the VLTI train (e.g. beam compressors, switchyard, etc.) or a scientific instrument. Their supports may appear a rather trivial component. However a poor design could easily destroy the OPD stability of the interferometer. Indeed, the concept of the whole VLTI observatory is that of creating a huge stable optical bench (the observatory platform itself) to which the various elements (telescope, delay lines, folding optics, instruments, etc) have to be connected as rigidly as possible. It was soon recognized that the commercial optical table legs would not provide the required stiffness. A specific design was therefore developed at ESO to be used as a standard for all VLTI optical tables. The design process can be summarized as follows:

- Computation of the minimum required eigen-frequency of the support to ensure that, under the typical expected Paranal micro-seismic noise of $500\text{ng}/\sqrt{\text{Hz}}$, the stability of a mirror rigidly placed on it would be $\leq 3\text{ nm}$. This led to a first eigen-frequency requirement of $\geq 80\text{ Hz}$ and damping ratio to be maximized.
- Design elaboration and optimization through FE modeling (see Figure 4) complying with the above requirement while taking care of differential thermal expansion between the floor concrete and the support steel to avoid stress on the optical table. This led to a ‘shoe box’ design that uses the high shear stiffness of steel plates to which L-shape ribs are attached to avoid local resonance modes of the plates. A large number of screws are present in order to maximize the internal damping characteristic of the support.
- Accelerometer measurement in the ESO lab in Europe to check achieved eigen-frequency. This showed that the grouting below the support feet had to be selected with care. A specific grout material (Sikadur 31) appeared necessary for this application to ensure high stiffness and good damping characteristics.
- Measurement at Paranal of the overall OPD stability of the optical elements placed on these tables supports.

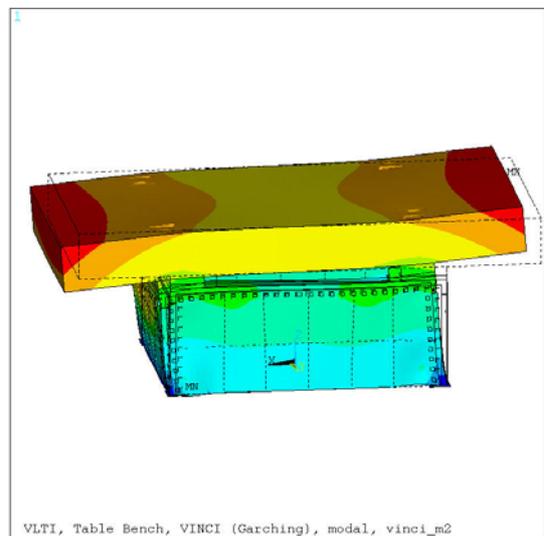


Figure 4: Support for optical tables specifically designed at ESO for VLTI needs (e.g. first resonance $> 80\text{ Hz}$).

The design of the supports for the various pumps spread over the observatory (see Figure 5) is another example of how the VLTI needs have been taken into account, as much as possible, during the development of the VLT Observatory.

5 SUB-SYSTEM TESTS

As a part of the risk mitigation strategy, specific and partial tests were undertaken on the subsystems (or even components thereof) as soon as practically possible. This enabled in many instances to identify potential non-compliance and take appropriate corrective actions. Table 1 summarizes the various tests done concerning OPD stability using a set of high-sensitivity, low-noise accelerometers. The main results of these tests as well as those related to internal seeing have been presented in the past^{2, 3, 18}.

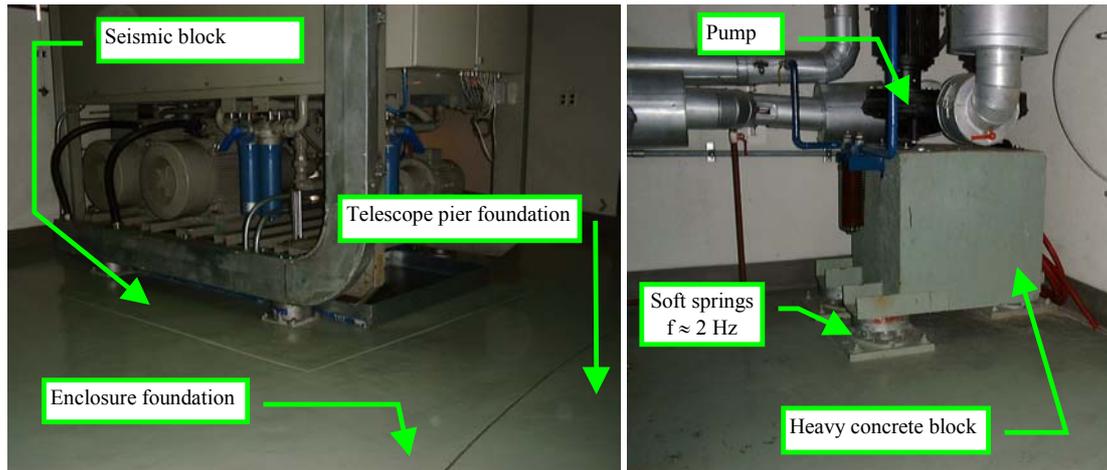


Figure 5: Example of proper pump designs to eliminate their impact on OPD stability. Left: main hydraulic bearing system in the basement of each UT. Right: liquid cooling secondary pump close to the VLTI laboratory.

Year	Sub-system	Where	Main outcome
1996	<i>UT1 Top Ring</i>	Europe	<ul style="list-style-type: none"> • Good fit with FEM and qualification of FE analysis for VLTI
1997	<i>UT1 Enclosure</i> (before telescope installation)	Paranal	<ul style="list-style-type: none"> • Seismic disturbance from mechanisms: louvers, vent. Doors, etc. = OK • Seismic disturbance from dome rotation = critical • Wind buffeting on Enclosure = OK
1997	<i>M2 Unit</i>	Europe	<ul style="list-style-type: none"> • OPD jitter after focus step = OK • OPD jitter during fast tip-tilt compensation = OK • OPD jitter during chopping (for MIDI) = OK
1998	<i>UT1 Telescope</i> (partially integrated)	Paranal	<ul style="list-style-type: none"> • Very first check of structural stability: OK / to be improved • Identification of main vibration modes.
1998	<i>UT1 Telescope</i> (complete structure except M3, no mirrors)	Paranal	<ul style="list-style-type: none"> • Overall good OPD stability (typically 30 to max.150 nm RMS) • Hydrostatic Bearing System (HBS) = fully OK • Cooling pump = to be improved • M4 arm stiffness = to be improved • Dome rotation = critical • Complete modal survey. Good fit with FEM.
1999	<i>Tunnel & Light ducts</i>	Paranal	<ul style="list-style-type: none"> • OPD due to internal seeing = OK
2000	<i>UT3</i> (with mirrors, no instrument)	Paranal	<ul style="list-style-type: none"> • As above • M3 Tower = to be improved
2000	<i>Optical Table Support</i>	Europe	<ul style="list-style-type: none"> • First eigen-frequency = OK
2000	<i>M16 translation stage</i>	Europe	<ul style="list-style-type: none"> • First eigen-frequency of translation stage = OK
2001	<i>UT1</i> (with ISAAC)	Paranal	<ul style="list-style-type: none"> • Closed Cycle Cooler = to be improved • Damping pads below Coudé electronics = to be improved
2001	<i>UT3</i> (with FORS)	Paranal	<ul style="list-style-type: none"> • OK
2002	<i>UT4</i> (with NACO)	Paranal	<ul style="list-style-type: none"> • Closed Cycle Cooler = to be improved

Table 1: Overview of sub-system tests related to OPD

To illustrate the advantage of this early testing approach, we describe below a few improvements that resulted from such tests.

Support arm of the Nasmyth folding mirror (M4)

Following the UT#1 commissioning in July 1998, the first eigen-frequency of the M4 Arm attached to the Nasmyth Adapter-Rotator appeared relatively low. This turned out to have a significant impact on the global OPD stability. After a detail FE analysis, it was decided to increase this frequency by adding a second beam connecting the M4 Arm to the Adapter-Rotator structure (see Figure 6-left). The improvement on the resonance frequency was confirmed by accelerometer measurement in the ESO laboratory in Europe (Figure 6-right) before the modification was finally

installed on all UT's at Paranal. The subsequent OPD measurement campaigns (2000-2002) proved that the M4 arm resonance is not anymore a significant contributor to the overall OPD stability.

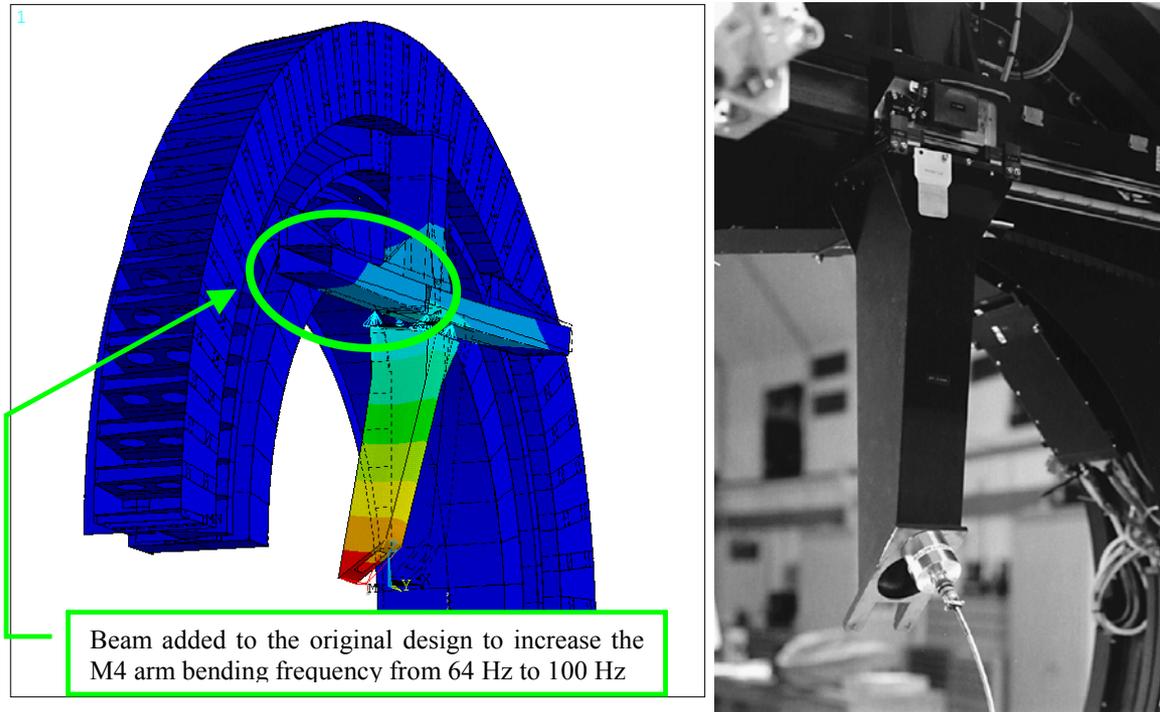


Figure 6: Example of an improvement decided after early OPD stability tests on UT1 in 1998: reinforcement of the M4 arm attached to the Nasmyth Adaptor-Rotator. Left: FEM analysis. Right: accelerometer measurement.

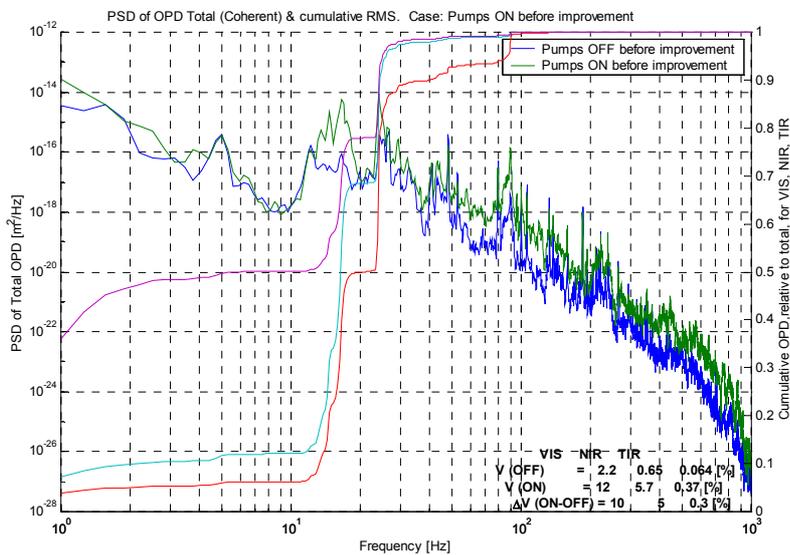


Figure 7 : Example of improvement started after testing on UT3 in 2000: isolation of the Pumps of the liquid cooling system in the basement of each UT. Left: Spectrum of OPL fluctuation with pumps ON & OFF. Right: the pumps with the two main vibration propagation paths. Current OPD jitter: 110nm RMS (5% contrast loss in K) goal after improvement: <50nm RMS (<1% loss).

UT liquid cooling pumps

The preliminary OPD test campaign on UT1 in 1998 and the detailed characterization on UT3 in 2000 showed that the pumps of the liquid cooling system located in the basement of the UT's were responsible for an OPD jitter exceeding the requirement. It was therefore decided to proceed with an improvement. Figure 7 shows the spectrum of the global OPL fluctuation inside the UT deduced from the acceleration measured on/near each mirror¹⁸. An OPD jitter of about 110 nm RMS over 50 msec exposure time is generated by the pumps. This corresponds to a 5% visibility loss for K band observation (for a specification of 1%). Local accelerometer measurements on the pumps enabled to identify three main disturbances associated with vibrations propagating either through the distribution pipes (the 12-14 Hz peaks) or through the ground (the 24 Hz and 96 Hz). The first improvement consisted in changing the vibration insulation pads below the pumps. Even though first fringes were obtained in this configuration, it proved to be insufficient to bring the OPD stability inside the ultimate VLTI performance goal of 1% visibility loss for each UT. The second, more difficult, improvement related to the propagation through the pipes is now being investigated.

6 SYSTEM VERIFICATION AT PARANAL

The system verification activities started immediately after '*first fringes*' with the siderostats in March 2001. This so-called *commissioning* phase is the subject of another paper in these proceedings⁶. We give here a few examples of the system performances to compare them with the specified values and the results from the analysis phase.

6.1 Temperature

In April 2001, a network of 17 temperature sensors was permanently installed at the outlet of each light duct along the delay line tunnel, and inside the interferometric laboratory. Since then, the temperatures have been recorded 24 hours a day with a 5 min sampling time, a resolution of 0.01°C and an accuracy of 0.05°C. During commissioning of the VLTI, these data have been compared to the expected internal thermal conditions. In addition, they were used to possibly identify the impact of temperature fluctuations on the quality of the recorded interferometric data.

Figure 8 shows the mean night temperatures recorded inside the tunnel (i.e. averaged between 23h00 and 9h00 UT). This figure also includes the temperature recorded 10 cm below the ground and similarly averaged between 23h00 and 9h00 UT. The temperatures inside both the delay line and the interferometric laboratory are well correlated with the ground temperature. The average annual value is 15.7°C inside the laboratory and 16.5°C in the tunnel, not far from the predicted 15.5°C. The Peak-to-Valley temperature variation over one year is about 4°C inside the laboratory and 6°C inside the DL tunnel. The two highest temperature variations correspond to T8 and T6, i.e. the sensors which were the most sensitive to the opening of the siderostats during VLTI observation. This temperature evolution still slightly exceeds the sub-system specification (2.5°C PTV in Lab and 5°C PTV in tunnel). Some elements may contribute to the observed excess of average temperature and fluctuation: i) the human presence in laboratory and tunnel -still rather frequent during that period-, ii) the heat dissipation from the DL laser metrology -currently under improvement-, iii) the absence of air conditioning inside the siderostats -as opposed to AT- that allows warm air to flow into the duct and tunnel during the day. These contributions should eventually

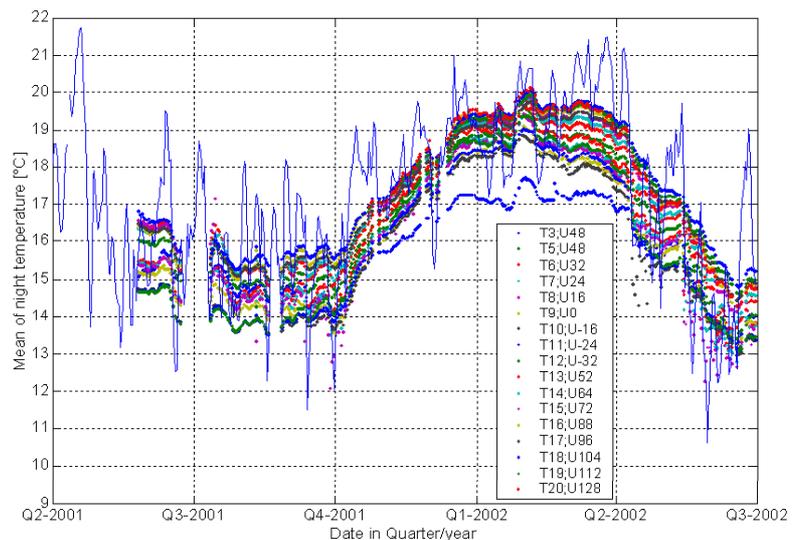


Figure 8: Mean temperatures inside the tunnel (averaged during the night between 23h00 to 9h00 UT). Each sensor is labeled with its U_coordinate inside the delay line tunnel. Only Sensor T3 is not located inside the delay line tunnel. It is located inside the interferometric laboratory. The continuous line corresponds to the temperature recorded 10cm below the ground.

disappear. The ultimate ‘success criterion’ remains, in any case, the stability of the optical beams reported in the following sections.

6.2 Internal OPD stability

Figure 9 shows a spectrum of the OPD fluctuation measured in auto-collimation up to the Nasmyth focus of on UT1-UT3 with DL positioned at 100m of OPL. The contribution of internal seeing to the OPD stability is well below that of the atmosphere but is still above the value specified in the VLTI error budgets. The detailed understanding (e.g of the 1Hz disturbance on Figure 9) and the full characterization of the OPD fluctuations is still part of the commissioning activities and improvement can be expected in the future.

6.3 Internal Tip-Tilt stability

The tip-tilt jitter generated inside the DL tunnel is shown in Figure 10 for the furthest position of the DL. When dividing the 0.8 arcsec RMS (X+Y) observed in the tunnel by the telescope magnification factor of 100 (valid for UT & AT), the resulting 8mas/sky slightly oversteps the 5 mas/sky predicted from the thermal study (equivalent $C_n^2 \approx 10^{-15}$). Figure 11 presents the record of the internal tip-tilt error obtained by re-imaging an artificial source located at the UT Nasmyth focus onto the CCD camera of VINCI. It includes therefore turbulence in the UT Coudé tubes. The standard deviation amounts to about 20 mas RMS (X+Y) equivalent on the sky. This value clearly exceeds the 8 mas/sky generated inside the tunnel. It shall be noted that a fraction (still unknown) of this jitter will be corrected by the MACAO-VLTI adaptive optics located at the Coudé focus. Whatever the final result will be, the above values remain lower than the global anticipated tip-tilt errors (including residual atmospheric tilt) of 25 mas RMS (Airy disk/10 in K band).

The current plan to re-introduce an additional fast tip-tilt compensation inside the laboratory (postponed in 1993) will enable to reduce this tilt-jitter, particularly for the shortest wavelength bands of AMBER (J and H). In the meantime, a proper temperature control inside the Coude room (not yet in use) is likely to improve this value.

6.4 Lateral beam (pupil) stability

Figure 12 shows the lateral beam jitter measured by re-imaging an artificial source located at the entrance of a light duct onto the VINCI CCD. With a jitter of about 160 μm RMS (X+Y) over a few minutes, the result is well within the specified value of 300 μm RMS. These values are given *before* the Beam Compressor (i.e. represent the case of observation with AT). They are divided by 4.4 when the Beam Compressors are used (UT and siderostat cases).

6.5 Global visibility performance

The global validation of the VLTI performance can be summarized by the visibility obtained on an unresolved star. This provides the so-called ‘*instrumental visibility*’ or interferometer ‘*transfer function*’.

At the day of ‘*first fringes*’ with the siderostats in March 2001, the instrumental visibility measured with VINCI was already in excess of $V_{VLTI/SID+VINCI}=85\%$ with a stability of about 1-2%. The same parameter measured during *first*

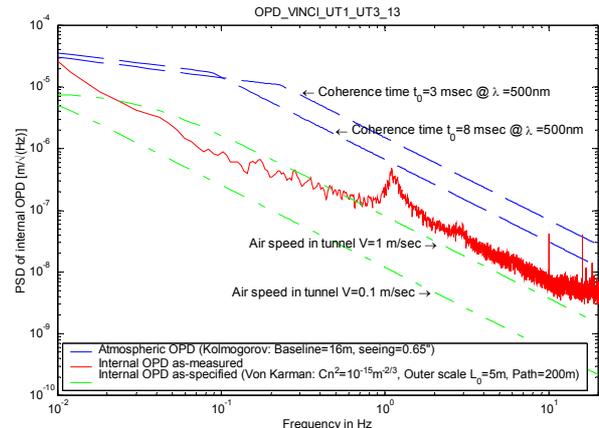


Figure 9: Spectrum of internal OPD due to internal seeing measured in autocollimation (converted to single path)

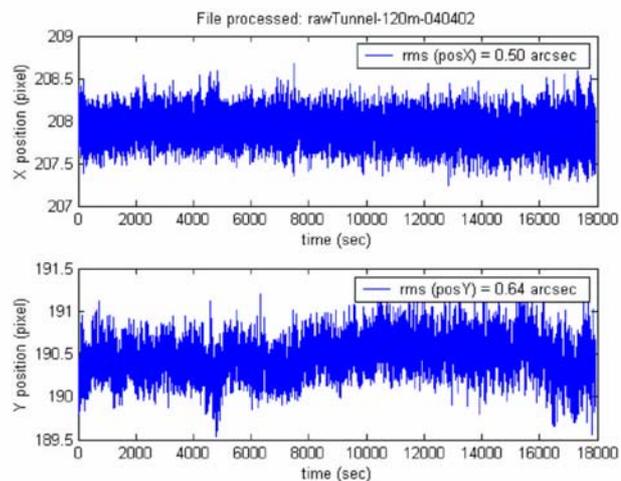


Figure 10: Internal Tip-tilt errors due to 'internal seeing' inside the tunnel. Artificial source located in the center of the tunnel send through the DL (at OPL=120m) and re-imaged on VINCI CCD.

fringes with the UT was $V_{V_{\text{VLT/UT+VINCI}}}=61\%$, most probably affected by the non-optimal polarization adjustment inside VINCI¹⁹. More recently, the IONIC integrated-optics beam combiner plugged into VINCI¹⁹ provided a contrast of $V_{\text{VLT/SID+IONIC}} > 80\%$ in the H band.

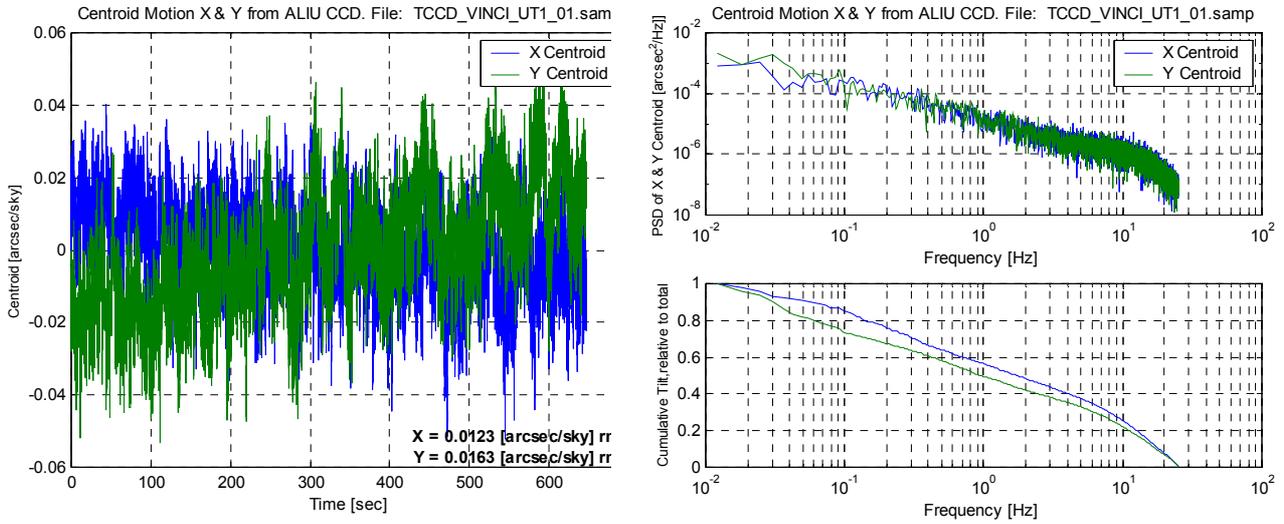


Figure 11: Internal Tip-tilt errors due to ‘internal seeing’. Laser source at UT1 Nasmyth re-imaged on VINCI CCD (31/10/01). Includes turbulence effects inside telescope, in particular ‘chimney’ effect inside Coude tubes.

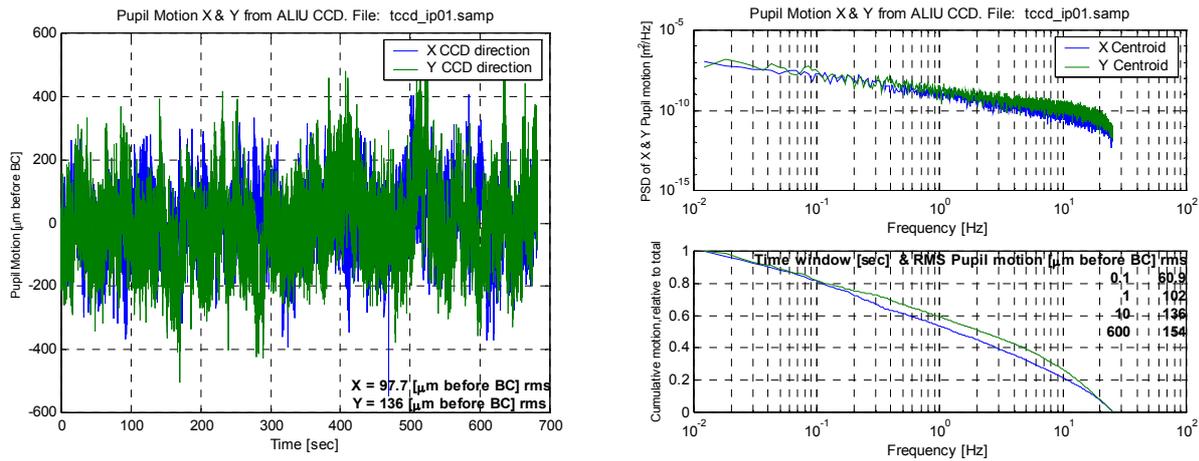


Figure 12: Lateral Pupil jitter [μm inside tunnel -i.e. before BC-] as measured during VLTI commissioning.

The above can be considered excellent parameters for the VLTI ‘birth certificate’. Yet, it should not hide the fact that more engineering work lies ahead of us. This includes: i) further characterization and potential improvement of error budget contributions, in particular those to which VINCI is less sensitive than other future instrumental modes, ii) maintaining these good performance in time with proper performance monitoring and maintenance scheme, iii) successful integration of future sub-systems in particular the MACAO-VLTI adaptive optics and the FINITO fringe tracking loop.

7 CONCLUSION

We have tried to give an historical overview (albeit necessarily incomplete) of the technical development of the VLTI.

A fundamental element of the selected approach has been a combination of extensive analyses and experimental characterization -performed as early as possible in the project life- followed by very early testing at partial/component level. This has permitted to immediately track down the potential showstoppers or performance limitations and to take

corrective actions while still possible. Although such an approach may appear expensive in terms of effort in the early phase of a project, we believe that it had its reward in the excellent performance obtained from the day of *first fringes* (>85% instrumental visibility in K with 1-2% stability).

This will allow spending now a minimum of time and effort to gain the last bit of performances needed for a forefront scientific exploitation. It will also help concentrating on the remaining challenges: integrating the MACAO-VLTI adaptive optics system into the interferometer and implementing the dual-feed PRIMA facility.

ACKNOWLEDGEMENT

The technical achievement of VLTI is obviously the result of the hard work of a very large number of people inside and outside ESO including institutes and industries. In line with the 'historical' flair of this paper, we would like to specifically mention here those ESO staff members who worked with full time assignment on the VLTI but who, at some point, left the project and ESO. These are former VLTI group heads: J. M. Beckers, F. Merkle, O von der Lüche, and the late J.M. Mariotti, as well as engineers: M. Faucherre, D. Ferrand, N. Wolff, F. Carbognani, M. Verola and A. Gennai. We have not forgotten the many moments spent together; the pleasant, less pleasant, and the dramatic ones. We hope ESO will have the chance, one day, to welcome as many of them as possible at Paranal for a tour in the VLTI facility!

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