VLTI technical advances – present and future

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ABSTRACT

The Very Large Telescope Interferometer (VLTI) on Cerro Paranal (2635 m) in Northern Chile reached a major milestone in September 2003 when the mid infrared instrument MIDI was offered for scientific observations to the community. This was only nine months after MIDI had recorded first fringes. In the meantime, the near infrared instrument AMBER saw first fringes in March 2004, and it is planned to offer AMBER in September 2004.

The large number of subsystems that have been installed in the last two years – amongst them adaptive optics for the 8-m Unit Telescopes (UT), the first 1.8-m Auxiliary Telescope (AT), the fringe tracker FINITO and three more Delay Lines for a total of six, only to name the major ones – will be described in this article. We will also discuss the next steps of the VLTI mainly concerned with the dual feed system PRIMA and we will give an outlook to possible future extensions.

Keywords: Interferometry, Very Large Telescopes, Interferometric Instrumentation, Very High Angular Resolution, Adaptive Optics, Astrometry, Phase Referenced Imaging, VLTI

1. INTRODUCTION

Over the last three years, since the first fringes were recorded in March 2001, the VLTI has constantly expanded from a single instrument (VINCI) to three, from a pair of siderostats to four 8-m telescopes, from three Delay Lines to six, from no corrections of atmospheric turbulence, to fringe tracking (FINITO) and adaptive optics (MACAO), or, to put it in the language of software engineers, from 100,000 lines of code to 750,000 lines of code in the control software.[23]

Yet, the difficult bit is still to come. The difficult bit is establishing stellar interferometry as a standard, i.e. efficient and reliable, observational technique that produces major scientific results. This requires not only a superb technical machinery but also efforts in promoting interferometry and in providing support to the community for observing preparation and for data reduction.

At ESO, we have integrated the VLTI in the observatory structure, both at Paranal where the VLTI is treated like a fifth UT[19] and in Garching where the User Support Group[21] and the Data Flow Operations Group[16] expanded their services to interferometry and where the Observing Programme Committee (OPC) that so far has been responsible for distributing time on individual telescopes now also evaluates the scientific proposals for observations with the VLTI being, thus, in direct competition with those of individual telescopes. The first round of VLTI proposals for MIDI that were submitted by scientists in the community in September 2004 were evaluated very positively by the OPC. 23 out of 30 proposals received observing time with MIDI. This is a very encouraging sign since it reflects the very high quality of the science programmes at a very early stage of this observing technique.

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The European scientific community was also active when founding three expertise centres (NEVEC, JMMC and FRINGE) supporting astronomers throughout the community in observing with the VLTI. Also, a European Interferometry Initiative was formed in the context of Opticon with goals like providing support for instrument developments and organising interferometry schools.

All of this is very positive. And it is a huge obligation. If under these circumstances the VLTI fails either technically or scientifically then it is difficult to imagine any organisation spending any sizeable amount of money on interferometry in the foreseeable future.

In this article, we will briefly describe the individual subsystems and we will give an outlook on instruments and interferometers to come.

2. STATUS

The most visible sign of progress with the VLTI is the severe crowding in the beam combination laboratory at Paranal (see Fig. 1). At the beginning, there was only a switchyard table, two beam compressors, a simple reference source and the test instrument VINCI. Now, the spacious 20m by 7m laboratory is very densely filled with large optical tables carrying a two beam, mid infrared science instrument (MIDI), a three beam, three band near infrared science instrument (AMBER), a three beam fringe tracker (FINITO) and a four-beam reference source (ARAL[15]). This year will see the replacement of the VINCI fiber beam combiner by an integrated optics beam combiner (IONIC) and the installation of the infrared tip-tilt tracker (IRIS). In 2005, the subsystems of PRIMA for dual feed operation will arrive.

In the Delay Line tunnel, six of the eight tracks are now furnished with Delay Line Systems forming the back bone of the VLTI. They are equipped with Variable Curvature Mirrors (VCM) ensuring reimaging of the telescope exit pupil on the instrument entrance pupil even while the Delay Lines are moving.[3]

In the next paragraphs, the VLTI subsystems will be discussed in their order of appearance at Paranal.

2.1. MIDI, the mid infrared science instrument

MIDI was designed and built by a European consortium led by the Max-Planck-Institute for Astronomy in Heidelberg. It is a two beam instrument operating in the N-band (8-12 μm). The details and the scientific goals are described in Leinert *et al.*.[11] MIDI was delivered to Paranal in October 2002; first light with the 8-m Unit Telescopes was achieved in December 2002.

In June 2003, the very first observation of an extra-galactic source (NGC1068) in the mid infrared was achieved. The scientific results were discussed by Jaffe *et al.*[8] and by Rottgering *et al.*.[20] Near infrared observations of NGC1068 with VINCI in the K-band were summarised by Wittkowski *et al.*.[22]

The instrument was offered to the community in September 2003, and regular science operations started in April 2004. The efficiency during the first observing run in April was very satisfying achieving slightly less than 30 min per visibility point. In the meantime, investigations are underway to observe deeply embedded sources.[17]

The extension of the wavelength range to the Q-band (17-25 μm) is under discussion as well as an upgrade to a four beam combiner, APresMIDI.[12]

2.2. MACAO, adaptive optics for the Unit Telescopes

The adaptive optics system MACAO has a 60-actuator bimorph mirror and a curvature wavefront sensor in the visible. MACAO is a development of ESO's adaptive optics group (Arsenault *et al.*[1]). It is specified to deliver a Strehl ratio of 50% in the K-band for a guide star brighter than V = 13. The Strehl ratio reduces to 25% with a V = 16 guide star. The deformable mirror replaced one of the mirrors (M8) of the Coudé optical train of the UTs, thus requiring no additional optical elements. The curvature wavefront sensor is placed in the Coudé focus of the UTs picking the reference star in a field of 2 arcmin. MACAO is essential for all near-infrared instrumentation including FINITO, when observing with the Unit Telescopes.

After the first two MACAOs were operational, First Fringes with two UTs and VINCI were achieved in August 2003. MACAO works extremely well.

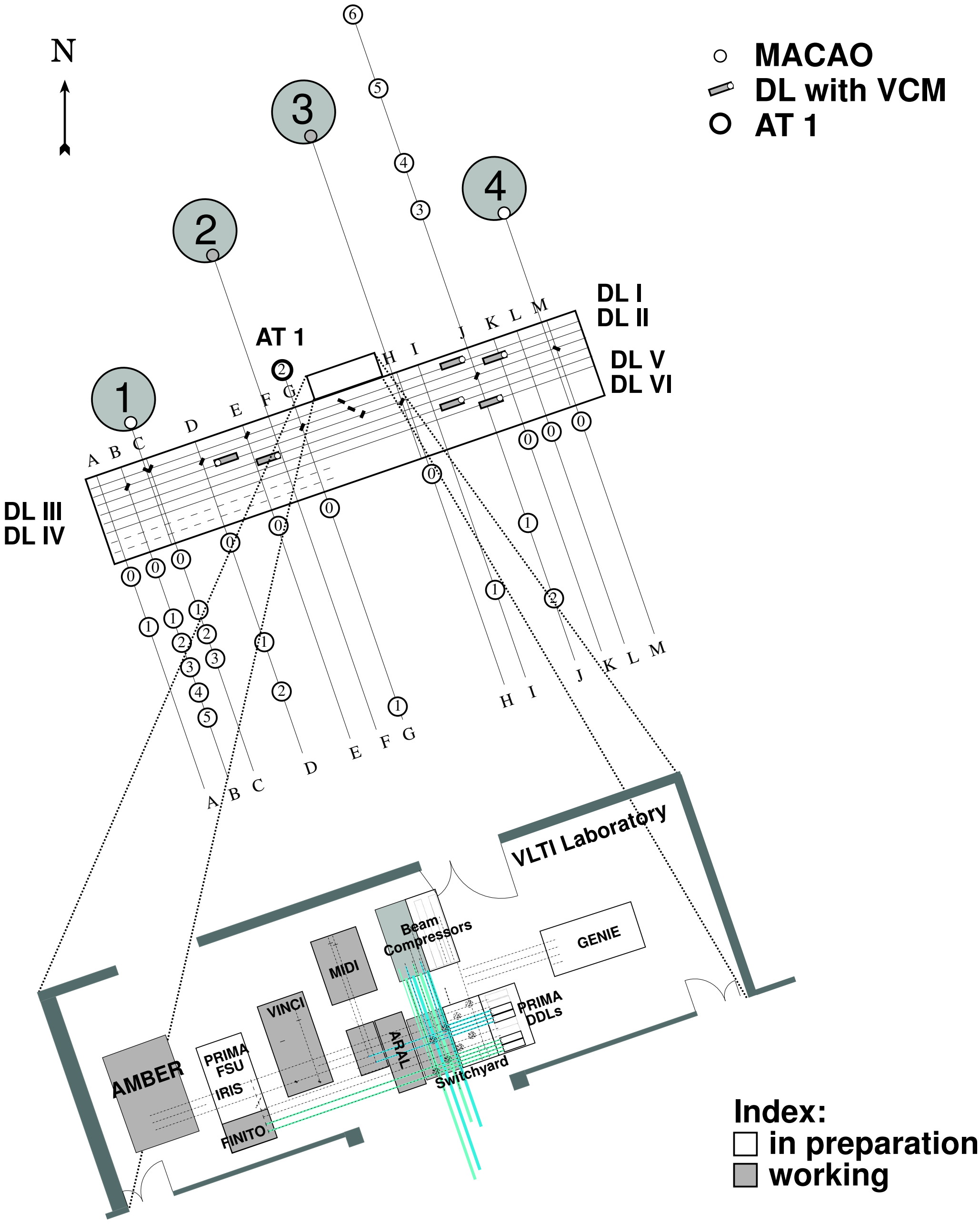

Figure 1. The interferometric array of the VLT observatory and the beam combination laboratory. The VLTI is unique in offering the possibility to combine four 8-m UTs with a maximum baseline of 130m, and to combine a maximum of eight 1.8-m ATs if the Delay Line tunnel is equipped with eight Delay Lines. The ATs can be moved to 30 different stations with a maximum baseline of 200m providing an excellent uv-coverage. The beam combination laboratory is displayed zoomed out of the array in order to present all instruments. The color index indicates the systems that are under development or working.

2.3. FINITO, the three beam fringe tracker

The on-axis fringe sensor unit is called FINITO for 'Fringe sensing Instrument NIce TOrino', since a prototype was developed and tested at Nice Observatory (OCA). At the Observatory of Torino (OATo) the concept of the prototype was converted into a VLTI style instrument (Gai *et al.*[4]). FINITO operates in the H-band using fibres as spatial filters. It can manage up to three beams, thus providing fringe tracking for AMBER in closure phase mode. The overall closed loop system of the fringe tracker consists of FINITO as fringe sensor unit and of a piezoelectric element in the Cat's-eye of the Delay Line as actuator.

The limiting magnitude depends – like for adaptive optics systems – on the required performance. For fringe tracking with the VLTI, the specifications for the residual OPD is 70nm in order to lose less than 2% of contrast in the K-band. Then, the limiting correlated magnitude is H = 11 on UTs. For residual OPD of 150nm (corresponding to a contrast loss of 8%) the limiting magnitude is H = 14. Even with a reference star of H = 16 the residual OPD of 250nm still reduces the contrast by less than 25%.

The system was delivered to Paranal in July 2003. A number of problems occured during the first test phase, from alignement problems over bad coatings to software bugs when controlling the piezo elements. The worst problem, however, was the permanent interruption of flux in the fibres due to turbulence in the tunnel (mostly tip-tilt) and due to bad tracking of the siderostats. Another way of putting it is to say that our control software was (or we were) not sufficiently smart to handle this problem. By March 2004, the problems had been resolved and the software was much more sophisticated inhandling flux interruptions by stopping tracking and resuming it as soon as the signal was of sufficient quality. The best performance was at about 100nm rms of residual OPD and 30min of 'interrupted' tracking, 'interrupted' in the sense of properly handling loss of flux and resuming operation.

2.4. The first 1.8-m Auxiliary Telescope

The first of the 1.8-m Auxiliary Telescopes built by AMOS in Liège had First Light in January 2004,[10] the second one will follow in December 2004, with First Fringes expected in January 2005.

AT1 works very well and the performance is within specifictions with the exception of an astigmatic aberration (twice as large as specified) when observing close to the horizon. This is caused by the mount of the primary mirror.

The telescopes are relocatable on 30 stations providing baselines between 8 and 200m. Each AT is equipped with a tip-tilt system correcting for the fast image motion induced by atmospheric turbulence. Under the seeing conditions at Paranal, tip-tilt correction on a 1.8-m telescope in the near infrared means almost diffraction limited image quality. One should note that the ATs are available exclusively for the VLTI, forming an observatory that is operated independently of the UTs.

2.5. AMBER, the near infrared science instrument

The near-infrared science instrument, AMBER, operates with three beams in the J, H and K-band with a spectral resolution up to 10000. The European consortium in charge of designing and manufacturing this instrument was led by the Universities of Nice and Grenoble. The details and the scientific goals are discussed in Malbet *et al.*.[13] AMBER has been designed for three beams to enable imaging by applying phase closure techniques.

AMBER saw First Fringes with two siderostats on March 21 of this year. All measured performance parameters were within specifications. It is planned to start science operations with AMBER in April 2005.

2.6. IRIS, the infrared tip-tilt tracker

Although the Delay Line tunnel is specified to have little turbulence by permitting e.g. only very small heat dissipation of all equipment in it, the requirement to keep a diffraction limited image of an 8-m telescope rockstable is extremely high. It means allowing for less than 1 arcsec beam wander over an optical path length of 100-200m. (Due to stopping down the 8-m UT to a beam diameter of 8cm, 1 arcsec in the tunnel corresponds to 10milli arcsec in the sky).

Therefore an infrared tip-tilt sensor, IRIS, will be installed in the beam combination laboratory by the end of 2004.[5] Later, IRIS could be replaced by a higher order wavefront sensor in order to provide correction signals for MACAO in the infrared that is measured in the beam combination laboratory where the optimum correction is required. And this will allow the observation of embedded sources that are now too faint in the optical for guiding.

2.7. PRIMA, the dual feed facility

In 2005, the dual feed facility PRIMA will extend the capabilities of the VLTI to faint objects (K = 16–19) and will permit high precision astrometry with the goal of 10 μarcsec over a 10 arcsec field. As a detector for PRIMA either one of the two scientific instruments MIDI or AMBER will be available for imaging, or a twin Fringe Sensor Unit for astrometry.

PRIMA enables simultaneous interferometric observations of two objects - each with a maximum size of 2 arcsec - that are separated by up to 1 arcmin, without requiring a large continuous field of view. Then, the sensitivity of the VLTI is improved by using a bright guide star for fringe tracking – similar to the guide star in adaptive optics for wavefront sensing – in one of the two feeds, allowing one to increase the exposure time on the science object in the other feed up to 10-30 minutes depending on the position in the sky.

The principle of operation relies on finding within the isoplanatic angle ($\approx$1 arcmin) of the science target a sufficiently bright star (H $\approx$ 12) that can be used as a reference star for the stabilisation of the fringe motion induced by atmospheric turbulence. All optical path lengths of the reference star and of the science star inside the interferometer have to be monitored with a laser metrology system. The measurement has to be maintained for up to 30min in order to average out the variations of the differential OPD caused by atmospheric turbulence.

PRIMA as a concept can be subdivided in four pieces of hardware each of them deeply embedded in the VLTI:

– **Star separator system**
This is an opto-mechanical system in the Coude focus of the UTs and ATs picking two objects within the 2 arcmin field of view and sending the light to the Delay Line tunnel.[2] Two star separator systems for ATs are being manufactured by TNO/TPD in the Netherlands. The Final Design Review was passed successfully in April 2004 and the delivery is planned for March 2005. The purchase of two star separator systems for the UTs is currently under discussion. Equipping the UTs with star separators increases the limiting magnitudes by 3 reaching K $\approx$ 19 and N $\approx$ 11.

– **Fringe sensor unit**
There will be two fringe sensor units located in the beam combination laboratory. One unit will be used to provide a signal for the fringe tracker by observing a bright guide star.[14] The stabilised fringe pattern then helps MIDI and AMBER to increase the exposure time on the second, fainter science object. The second fringe sensor unit can be used instead of MIDI or AMBER for performing high precision measurements of the fringe position of a second star and, thus, enabling high precision astrometry.

The fringe sensor units are being manufactured by Alenia Spazio in Italy. The Final Design Review was passed successfully in September 2003 and the delivery is planned for April (first unit) and June (second unit) 2005.

– **Laser metrology system**
The laser metrology system is an in-house development with support from the Institute of Microtechnology in Neuchâtel, Switzerland. The challenge is to provide an accuracy of 5nm rms for the OPD measurement over 30 minutes. The Final Design Review will be held in at the end of 2004, and the installation is planned for the second half of 2005.

– **Differential Delay Lines**
Observing two stars that are separated up to 2 arcmin with a baseline up to 200m causes a differential OPD up to 130mm. This needs to be corrected if both stars shall display fringes. The differential Delay Line (DDL) and dedicated software for astrometry will be provided by a consortium from Geneva, Leiden and Heidelberg[18] with a scheduled delivery date of April 2007. Until 2007, PRIMA will use two main Delay Lines instead of differential Delay Lines to correct for the differential delay. This mode of operation reduces the accuracy due to the lower correction bandwidth of the main Delay Lines, and it allows only three telescopes to be combined at the same time with PRIMA, since three telescopes require all six main Delay Lines to be used.

The differential Delay Lines will then permit reaching the final goal of 5nm rms over 30min and, thus, 10μarcsec astrometric accuracy.

2.8. GENIE, the ESA/ESO Nulling instrument

GENIE, the first joint ESA/ESO project, is the ground demonstrator for DARWIN as a science instrument for the VLTI. It will be a nulling instrument in the L'-band. Currently, two feasibility studies are being prepared by Alcatel and Astrium.[7] The goal is to use GENIE for measurement of exo-zodiacal light with the VLTI.

3. SECOND GENERATION INSTRUMENTS - THE 4×4 VLTI

The main limitation of the first generation instrumentation is the restriction to two (MIDI) resp. three (AMBER) beam combination. MIDI in combination with the dual feed system PRIMA could in principle fill the uv-plane of faint objects very slowly by collecting visibility and phase information baseline by baseline. AMBER however, by reconstructing the phase through its closure phase by switching between different triple combinations of four ATs or UTs, would be limited to rather bright objects.

Thus, both techniques benefit from an instrument combining more beams (4-6) in combination with a dual feed system for 4-6 beams.[6] This would combine the faint object mode of PRIMA with improved and much more efficient filling of the uv-plane. This would also permit switching between the closure phases of any three of the 4-6 beams, and phase referenced imaging on the 6-15 individual base lines. This concept of a four telescope VLTI with instrumentation combining at least four beams and a four-beam PRIMA is named the 4×4 VLTI.

The proper number of telescopes to be combined is always subject to debate. People who are used to combine two telescopes think that four telescopes is what is needed. If you are accustomed to four telescopes you are longing for eight. And if you talk to radio astronomers anything below 12 telescopes is close to completely useless. The fact is that the number of baselines increases quadratically as N(N-1)/2 with N the number of telescopes.

The proper number completely depends on the scientific goal of your observation: If you are looking for planets or circumstellar disks a small number of telescopes would be fine, and if you are looking for large scale structure with fine detail and very many resolution elements you want a large number of telescopes. It is however safe to say that anything but model fitting will be very time consuming with two telescopes and a single baseline. A logical and reasonable intermediate goal would be to expand the VLTI to the 4×4 VLTI with four telescopes and six baselines keeping in mind that the infrastructure at Paranal is ready to host eight Delay Lines combining up to eight telescopes.

There will be a workshop at ESO in April 2005 where concepts of second generation VLTI instruments will be presented and discussed. Based on this workshop the decision on the next generation instruments will be taken.

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