The VLTI – A Status Report

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Abstract. The Very Large Telescope (VLT) Observatory on Cerro Paranal (2635 m) in Northern Chile is approaching completion. After the four 8-m Unit Telescopes (UT) individually saw first light in the last years, two of them were combined for the first time on October 30, 2001 to form a stellar interferometer, the VLT Interferometer. The combination in pairs of all four UTs was completed in September 2002. In this article, we will describe the subsystems of the VLTI and the planning for the following years.

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

1. Introduction

On October 30, 2001 at about 1am, the two 8-m Unit Telescopes Antu and Melipal of the Paranal Observatory with a baseline of 102m were combined for the first time as a stellar interferometer observing fringes on the star Achernar (see Fig. 1), only six months and twelve days after the VLTI produced the first fringes with two siderostats. In the first year of commissioning, more than one hundred different objects were observed to verify the performance and the scientific potential of the VLTI. We found that all specifications were met or exceeded (Schöller *et al.* (2002) and Koehler *et al.* (2002)) .

Recently, on September 15/16 and 16/17, 2002, the combination in pairs of all four Unit Telescopes was completed using a total of five different baselines (see Fig. 2). Only the combination MELIPAL - YEPUN could not be provided due to the current configuration of delay lines in the interferometric tunnel.

The first period of a total of 150 hours shared risk science operations with the test instrument VINCI and the siderostats started in October 2002. 40 proposals from the community were received, representing

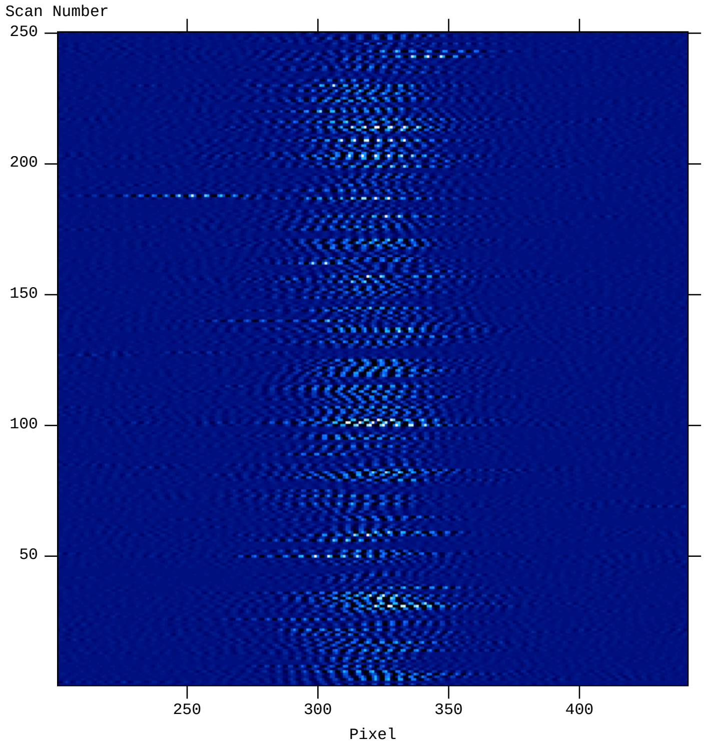

Figure 1. First fringes of Achernar with VINCI and the two 8-m Unit Telescopes ANTU and MELIPAL on October 30, 2001. Each horizontal line represents the interferometric fringes in the K-band registered during a single scan with scan numbers increasing from bottom to top. Due to atmospheric turbulence, the fringes are slightly shifted sideways between individual scans. The shift is typically less than one fringe (2.2 μm), illustrating the stability of the VLTI.

about 10% of all proposals submitted to ESO for the VLT observatory. During 2002, all science data between First Fringes in March 2001 and September 2002 have been released through the archive resulting in first scientific results which are described in Kervella *et al.* (2002), Wittkowski and Hummel (2002), Richichi and Wittkowski (2002), and Segransan *et al.* (2003). A summary of the scientific results of the first year can be found in Paresce *et al.* (2002).

The mid infrared instrument MIDI was delivered to Paranal in October 2002 and it is awaiting first fringes every minute. In the course of 2003, the fringe sensor unit FINITO and the near infrared instrument AMBER will arrive, the UTs will be equipped with the adaptive optics system MACAO, and four 1.8-m Auxiliary Telescopes (AT) will be integrated. Three more Delay Lines for a total of six will complete the first phase of the VLTI.

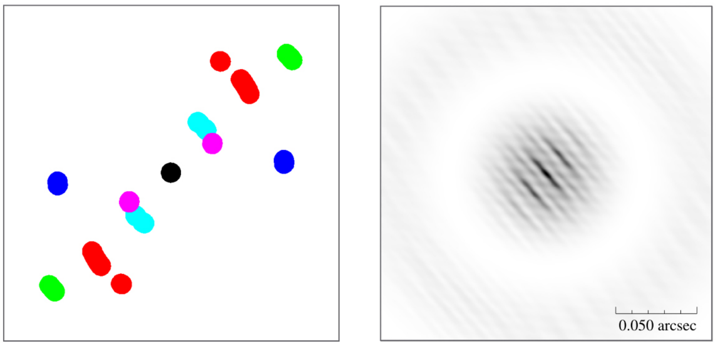

Figure 2. The result of observing Achernar in the K-band with all four Unit Telescopes on September 15/16 and 16/17, 2002. The uv coverage is shown on the left, and the point spread function (PSF) on the right. The width of the central fringe, *i.e.* the angular resolution limit, is about 3 by 15 milliarcsec due to the distribution of baselines used during these observations. On the largest scale, the image is enveloped by the Airy disk of a single 8-m Unit Telescope. Its first minimum at 57 milli arcsec off the center can be clearly seen.

In 2005, the dual feed facility PRIMA will extend the capabilities of the VLTI to faint objects (K = 16–19) and it will allow for high precision astrometry. Last but not least, a joint ESO/ESA project for GENIE, the DARWIN ground demonstrator planned for 2006, will open the door for planet hunts with the VLTI.

The interferometric array of the VLT observatory is displayed in Fig. 3. It 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.

2. VLTI instrumentation

MIDI was designed and built by a European consortium led by the Max-Planck-Institute for Astronomy in Heidelberg. It will operate in the N-band (8–12 μm). The details of the instrument are described in Leinert *et al.* (2002). MIDI was delivered to Paranal in October 2002; first light with the Unit Telescopes is scheduled for December 2002. Regular science operations are planned to start in October 2003.

The near-infrared science instrument, AMBER, will operate between 1 and 2.5 μm, at first with two telescopes, with a spectral resolution up to 10000. The European consortium in charge of designing and manufacturing this instrument is led by the Universities of Nice and Grenoble (Petrov *et al.* (2002) and Malbet *et al.* (2002)). AMBER was designed

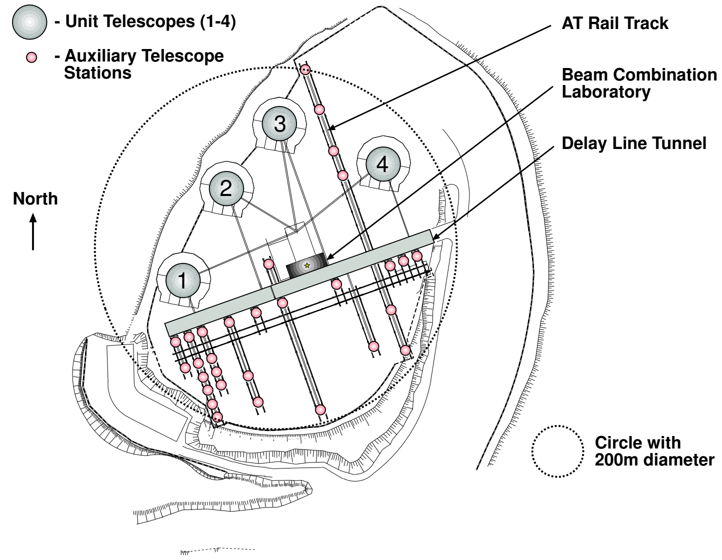

Figure 3. The layout of the VLTI. The four 8-m Unit Telescopes (UT) and the 30 stations for the 1.8-m Auxiliary Telescopes (AT) are displayed. The AT stations are connected by rail tracks on which the ATs can be relocated. Also shown are the Delay Line tunnel and the beam combination laboratory. The Delay Line tunnel has room for eight Delay Lines allowing the operation of eight ATs and a total of 28 baselines for each exposure. The longest baseline with two ATs is 200m (indicated by the circle with 200m diameter). The longest baseline with two UTs is 130m.

for three beams to enable imaging through phase closure techniques. It is planned to start commissioning AMBER with the Siderostats in the third quarter of 2003.

The VLTI fringe sensor unit FINITO is manufactured at the Observatory of Torino (OATo) (Gai *et al.* (2001)). FINITO operates in the H-band using fibers as spatial filters. The 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. FINITO can manage up to three beams, thus providing fringe tracking for AMBER in closure phase mode. The delivery to Paranal is planned for the first quarter of 2003.

The adaptive optics system MACAO will have a 60-actuator bimorph mirror and a curvature wavefront sensor in the visible. MACAO is an in-house development (Arsenault *et al.* (2002)). MACAO is essential for all near-infrared instrumentation including FINITO when observing with the Unit Telescopes. This means that also a mid-infrared instrument like MIDI needs adaptive optics in order to improve the limiting magnitude by using FINITO.

The first two 1.8-m Auxiliary Telescopes built by AMOS in Liège will be ready for the VLTI at the end of 2003, the third and fourth in 2004 (Flebus *et al.* (2002)). The telescopes are relocatable on 30 stations providing baselines between 8 and 200m. Using three telescopes with AMBER and, thus, three baselines at the same time will allow the application of closure phase techniques eliminating the influence of atmospheric turbulence on fringe position. Each AT will be equipped with a tip-tilt system correcting for the fast image motion induced by atmospheric turbulence. One should note that the ATs are available exclusively for the VLTI, forming an observatory that is operated independent of the UTs.

3. PRIMA and GENIE - The next phase of the VLTI

PRIMA and GENIE will complete the suite of first generation instruments around 2005. GENIE is a joint ESO/ESA project providing the ground demonstrator for DARWIN as a science instrument for the VLTI. The concept of GENIE is currently under discussion (Gondoin *et al.* (2002)). The goal is to use GENIE for planet detection with the VLTI.

The phase referenced imaging and micro-arcsec astrometry (PRIMA) facility is the third VLTI instrument. It is a dual feed system adding a faint object imaging and an astrometry mode to the VLTI (Quirrenbach *et al.* (1998) and Glindemann *et al.* (1999)). PRIMA is the key to access: 1) higher sensitivity, with a limiting magnitude of K = 19, 2) imaging of faint objects with high angular resolution (<10 milli arcsec), and 3) high precision astrometry (<10 μarcsec over a 10 arcsec field).

As a detector for PRIMA, either one of the two scientific instruments MIDI or AMBER can take advantage of the fringe stabilisation provided by PRIMA, or a dedicated PRIMA detector is used for high precision astrometry (Paresce *et al.* (2002)).

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 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.

PRIMA can be subdivided in four sub-systems: 1) star separator, an opto-mechanical system in the Coude focus of UTs and ATs to pick two objects within the 2 arcmin field of view and send the light to the

Delay Line tunnel, 2) fringe sensor unit to provide the signal for the fringe tracker, 3) laser metrology system to measure OPD_{int}, and 4) differential Delay Lines to correct the differential OPD for two objects that are separated up to 2 arcmin with a baseline up to 200m – then, the maximum differential OPD is 130mm.

In order to optimise the scientific output, a phased implementation plan was drafted. In the first phase, contracts for manufacturing the star separator systems for the ATs, and for two fringe sensor units will be placed. The second fringe sensor unit provides the high precision astrometry detector. Two main Delay Lines instead of differential Delay Lines will be used. The laser metrology system will be an in-house development with support from the Institute of Microtechnology in Neuchâtel, Switzerland (Lévêque *et al.* (2002)). This phase is dedicated to astrometry with the ATs.

Call for Tenders were issued for the star separators and the fringe sensor units, and the first kick-off meeting for the manufacturing of the fringe sensor unit took place in July 2002. Without a laser metrology system, the fringe pattern can be stabilised over 10–100 sec, and the expected limiting magnitudes on the ATs are about K=13 and N=5.

Phase information that is required for imaging and for astrometry becomes available as soon as the laser metrology system is installed. The limiting magnitudes with the ATs are K $\approx$ 16 and N $\approx$ 8. The Strehl ratio in the reconstructed image can be as good as 30% in the K-band and 80% in the N-band depending on the uv coverage. PRIMA shall be operational in 2005.

In the second phase, upgrades of the laser metrology allow for reaching the final goal of 5nm rms over 30min and, thus, 10μarcsec astrometric accuracy. Equipping also the UTs with star separators, increases the limiting magnitudes by 3 reaching K $\approx$ 19 and N $\approx$ 11. The second phase of PRIMA shall be operational by 2007.

4. VLTI operations and fringe tracking

The final goal of the VLTI is to produce images with a few milli arcseconds resolution. Fig. 2 shows the point spread function when observing Achernar with all four UTs in September 2002. The 'image' of Achernar is very similar to the theoretical point spread function since its diameter of 2 milli arcsec is smaller than the VLTI resolution limit fo 3 milliarcsec.

As a first step towards this goal, FINITO will provide fringe tracking in the H-band. Without a dual feed facility the reference star has to be found within the 2 arcsec field of view of the VLTI. Most likely, the

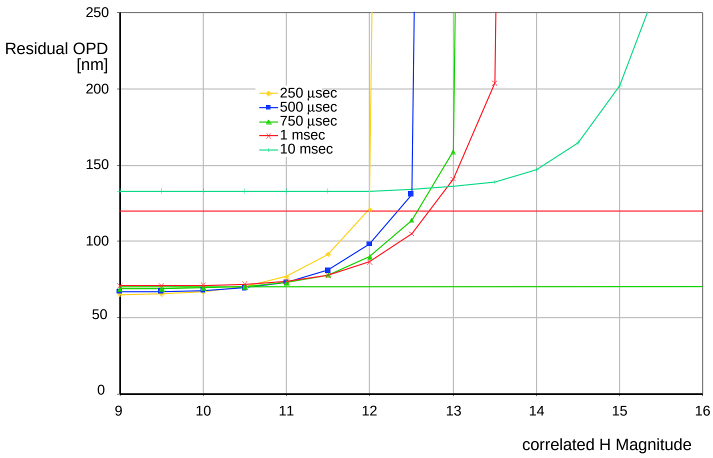

Figure 4. Residual OPD for fringe tracking with FINITO as function of correlated H-magnitude with UTs. The curves represent the closed loop performance for different exposure times on the FINITO detector, taking into account the specified performance of the fringe sensor unit FINITO and of the piezoelectric actuator in the Delay Lines, and the delays in signal transfer between these two elements. The performance of the adaptive optics system MACAO is also taken into account. The assumption for the atmospheric coherence time was 50msec in the K-band which is twice as long as the median coherence time at Paranal

science object itself has to be used as a reference star. This gives only a slight advantage for the accuracy of the visibility measurement, but it gives a considerable advantage for AMBER in spectroscopic mode if the light of e.g. the K-band is dispersed over many pixels.

The performance of FINITO is displayed in Fig. 4. The limiting magnitude[1] 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 loose less than 2% of contrast in the K-band. Then, the limiting correlated magnitude is H = 11. If the acceptable residual OPD is 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%. In the N-band at a wavelength of 10μm a residual OPD of 250nm means only a 2% loss in contrast. However, if the science object is very red the H-magnitude might become fainter than 16, although the N-magnitude is still manageable by MIDI.

The calculated performance of FINITO relies on MACAO, the adaptive optics system. MACAO is specified to deliver a Strehl ratio of 50% in the K-band for a guide star brighter than V = 13. The Strehl ratio is reduced to 25% with a V = 16 guide star. This on-axis performance

[1] All limiting magnitudes are given for the UTs.

has to be corrected for anisoplanacy: the K-band Strehl ratio is approximately reduced to 50% of its on-axis value if the guide star is 30 arcsec off-axis. Since the wavefront sensor is installed in the Coudé focus of the UTs, the guide star can be picked in a field of 2 arcmin. All these numbers were calculated for typical Paranal seeing conditions.

The arrival of PRIMA in 2005 will add one more parameter to the performance of the VLTI: the guide star for the fringe tracking can also be picked in the 2arcmin field of view of the Coudé focus. In addition, the PRIMA fringe sensor unit is specified to have a magnitude limit that is at least one magnitude fainter than FINITO.

The main difference compared to the former scenario is the consideration of the isoplanatic angle for fringe tracking introducing a random OPD of typically 400nm if the guide star is 25arcsec off axis. This means a loss in contrast of 50% in the K-band, and, thus, a loss of sensitivity since the correlated magnitude is reduced. The situation in the N-band is more relaxed; a residual OPD of 400nm reduces the contrast by only a few %. Now, one has to evaluate whether a fainter star closer to the science object introduces less residual OPD than a brighter star further away. The combination of a loss in Strehl due to a MACAO guide star far off-axis with a large residual OPD due to a fringe tracking guide star far off-axis can substantially reduce the performance.

5. Second generation instruments

The main limitations of the first generation instrumentation are the small field of view of one Airy disk (250 resp. 57milli arcsec in the K band for ATs resp. UTs), and the restriction to two (MIDI) resp. three (AMBER) beam combination. While phase referenced imaging – delivering contrast and phase for every baseline individually – as in PRIMA can cope with only two beams, the closure phase technique requires more than three beams to reconstruct unambigously contrast and phase of individual baselines. However, both techniques benefit from an instrument combining more beams (6 – 8) allowing for more efficient observing and producing instantly an excellent image quality (Glindemann *et al.* (2001)). The VLTI infrastructure can comfort instruments combining up to 8 beams.

Thus, there is a need for a second generation instrument with a multi way beam combiner. The question of how to combine the beams – with integrated optics or with bulk optics – is intimately related to the second important topic which is an enlarged field of view.

There are two different schemes to increase the field of view: mosaicing and homothetic mapping. Mosaicing an image means to scan the object in steps of one Airy disk and to put the individual images together to form the 'large' image, like in radio interferometry.

Homothetic mapping relies on reimaging the interferometric array into the entrance pupil of the instrument (Beckers (1990)), thus forming on the detector a regular image of the object displaying a superposed fringe pattern with a fringe spacing as small as 2 milliarcsec for a baseline of 200m at 2 μm. Taking images for many different array configurations one can then superpose the Fourier transforms of these images and reconstruct the complete image with a resolution down to 2 milliarcsec. One should note that the detector pixels should not be larger than 0.5 milliarcsec in order to scan the fringe at four points over one period. The required detector size is then 2000×2000 pixels for a 1 arcsec field of view.

Using mosaicing for enlarging the image makes fibers and integrated optics ideally suited for guiding and combining the beams. Optical fibers have proven their usefulness (Coudé du Foresto *et al.* (1998)), and, recently, integrated optics showed some very promising results (Kern *et al.* (2002)). These techniques would help to reduce the size of interferometric instruments.

The conclusion is that the most important feature of the second generation instrumentation is its ability to combine many beams, improving the image quality and the observing efficiency. Both closure phase and dual feed imaging would profit from using many beams at the same time. Large fields of view are very interesting but should be implemented through mosaicing rather than homothetic mapping.

6. The overwhelmingliy large array - La OLA

With extremely large telescopes like OWL lurking above the horizon interferometry only makes sense if it delivers an angular resolution that is at least a factor of 10 higher. This means baselines of a few kilometers. Then, the optical delays that have to be compensated are of the order of kilometers, too. However, rather than building Delay Line tunnels that are kilometers long one should combine moving cat's eyes like in the VLTI with static Delay Lines. Again, the technical progress in integrated optics would be extremely helpful when delivering fast optical switches. One could then continuously observe fringes while the static Delay Lines are being switched on with optical switches. The static Delay Lines and the beam transport could be built with bulk optics or with fibers. First experiments with a fiber interferometer with 500m long fibers were successful (Delage *et al.* (2001)). In order to avoid any intensity loss at all one could use fibers with phase preserving amplification of light as in fiber lasers. If the amplification could be triggered with only a few photons there would be virtually no limit for the length of the fibers.

The details of such an overwhelmingly large array such as number and size of the telescopes have to be discussed in more detail than can be done here. The possibilities range from a large number of 4m telescopes to a modest number of 8m telescopes. The boldest and most ambitious approach, however, is clearly to copy the VLTI concept by combining several OWL telescopes surrounded by an array of movable auxiliary telescopes with a diameter of *e.g.* 8m.

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