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 remaining two UTs will be integrated into the interferometric array later this year. 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. This was the first time that the VLTI was operated as a truely Very Large Telescope Interferometer. After almost 10 years of planning, analysing, simulating and testing this was a memorable moment especially because the quality of the first fringes was outstanding. 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.*[27] and Koehler *et al.*[18]) .

On June 19, 2002, fringes were also found with the Unit Telescopes Kueyen and Melipal with a baseline of 47m. Later in the year, there will be the first short period of shared risk science operations with the test instrument VINCI and the siderostats. At the end of 2002, the science instrument MIDI, and, in the first half of 2003, AMBER and the fringe sensor unit FINITO will arrive. In the course of 2003, the UTs will be equipped with the adaptive optics system MACAO, and three 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.

In 2005, the dual feed facility PRIMA will extend the capabilities of the VLTI to faint objects (K = 16–19) and 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. 2. 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.

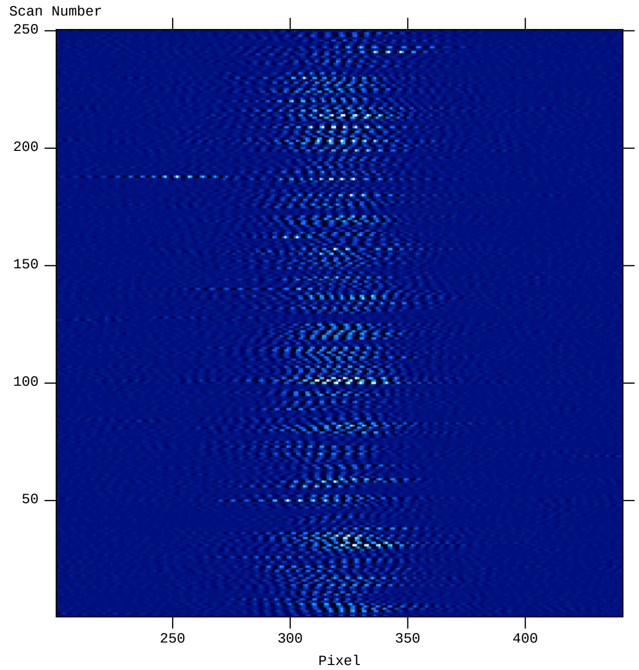

Figure 1. First fringes of Achernar with VINCI and the two 8-m Unit Telescopes ANTU and MELIPAL on October 30, 2001. Each horizontal line represents the interferometric fringes in the K-band registered during a single scan with scan numbers increasing from bottom to top. Due to atmospheric turbulence, 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.

2. THE LAST TWO YEARS

Early in 2000, the VLTI activities at Paranal started on a large scale. Containers arrived in front of the VLTI beam combination laboratory and equipment disappeared inside. Inside the tunnel, cables were installed and the computer network was configured. An ante room was built at the entrance of the VLTI beam combination laboratory to properly seal off the tunnel and the laboratory as clean rooms.

In the middle of 2000, the first piece of high-tech equipment arrived when the installation of the Delay Lines started, ending five months later with the commissioning of the third Delay Line. The Delay Lines were built by Fokker Space in Leiden (Hogenhuis *et al.*[14]). For the installation of the Delay Line rails a sophisticated measurement system with water level gauges was used providing a rail flatness of less than 25μm over the full length. The Delay Line System is one of the most spectacular subsystems of the VLTI, moving the 2.25m long carriages with the Cat's Eye reflector at speeds up to 0.5m/sec in the 130m long tunnel. While moving the carriage, the reflected beam is tilted less than 1.5 arcsec at all times, the absolute position accuracy is 30μm over the full range of travel of 65m and the position error is of the order of 20nm. One of the three mirrors of the cat's-eye is a variable curvature mirror (VCM, Ferrari *et al.*[10]) in order to reimage the telescope pupil into a fixed position in the VLTI laboratory while the Delay Line System is tracking. The cat's-eye can handle two input beams as required for a dual feed system.

The test camera VINCI was put together at the Observatory of Paris in Meudon, and the observing software was written by the Observatory of Toulouse. VINCI is a conceptual copy of FLUOR, the near-infrared interferometric instrument of the IOTA interferometer on Mount Hopkins in Arizona (US) (Coudé du Foresto *et al.*[6]). The main component of VINCI is the fiber beam combiner MONA built by Le Verre Fluoré using the light from two telescopes as input and producing four outputs: two photometric and two interferometric signals. By varying the optical path difference (OPD) between the beams with a mirror mounted on a piezo-electric actuator, a temporally modulated fringe pattern is produced on the detector. In addition to serving

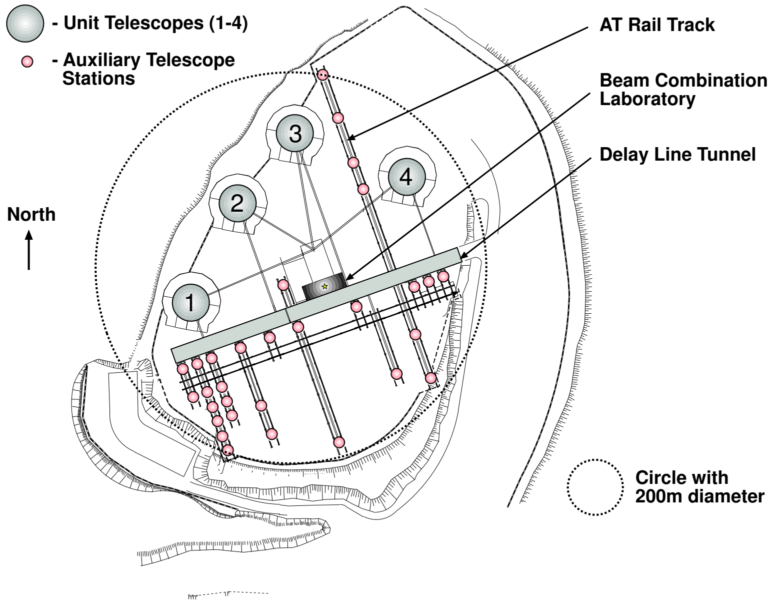

Figure 2. The layout of the VLTI. The four 8-m Unit Telescopes (UT) and the 30 stations for the 1.8-m Auxiliary Telescopes (AT) are displayed. The AT stations are connected by rail tracks on which the ATs can be relocated. Also shown are the Delay Line tunnel and the beam combination laboratory. The 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.

as an interferometric instrument, VINCI provides alignment tools and reference sources for the VLTI and the scientific instruments. In September 2000, the instrument was delivered to ESO Garching for integration with the infra-red camera LISA provided by the Max-Planck-Institute for Extraterrestrial Physics in Garching. The complete instrument was delivered to Paranal in January 2001. The integration, testing and commissioning took place in the following two months, supported by the VINCI team from Meudon (Kervella *et al.*[16]).

The optical layout of the VLTI with UTs and ATs is displayed in Fig. 3, for the sake of simplicity with only two telescopes. A star at infinity illuminates the apertures in the two telescopes with a plane wave that is guided through the Coudé Optical Trains into the Delay Line tunnel. The delay in arrival of the light at telescope 1 with respect to telescope 2 is compensated by the Delay Lines so that the beams have zero OPD when they interfere on the detector in the VLTI laboratory. The field of view of the VLTI is 2 arcsec. However, the dual-feed facility PRIMA will allow observing two stars at the Coudé focus of ATs or UTs each in a 2 arcsec field of view and separated by up to 1 arcmin.

The concept driver for the optical layout of the VLTI Laboratory (see Fig. 4) was to provide the same beam diameter for the interferometric instruments both when observing with UTs or ATs. Therefore, a beam compressor reduces the 80mm beam diameter from the UTs to 18mm matching the beam diameter of 18mm provided by the ATs. The nominal position of equal optical path length is set for all beams at the same distance after the switchyard (indicated by the line labelled 'ZOPD' in Fig. 4) to simplify the optical alignment of the interferometric instruments.

The VLTI philosophy is to avoid the need of human intervention in the Delay Line tunnel when switching between AT stations or UTs. The control software and all the hardware of the VLTI is designed to allow for remote operation (Wallander *et al.*[28]). Thus, the mirrors in the Delay Line tunnel reflecting the light into the Delay Lines and from the Delay Lines into the VLTI Laboratory will be controlled remotely.

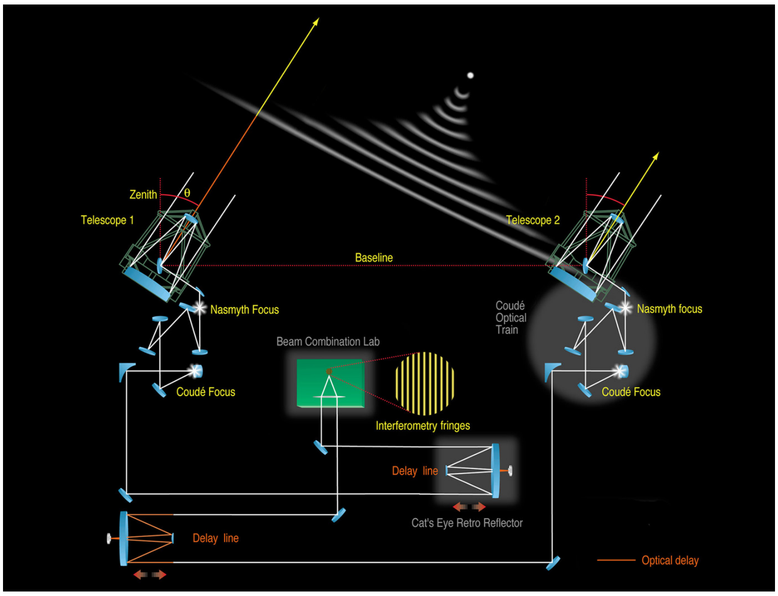

Figure 3. The optical layout of the VLTI with two telescopes. The telescopes represent both UTs and ATs that have the same optical design. The Coudé Optical Trains are the mirrors after the tertiary mirror up to the Coudé Focus. The mirrors just before and just after the Delay Lines are called the transfer optics. Two Delay Lines are shown to demonstrate the principle of operation. The VLTI laboratory is represented by the beam combining lens forming fringes.

3. FIRST FRINGES

Planning for First Fringes a few years ago, we decided to specify criteria asking for more than just catching fringes in passing for a lucky moment. We defined that the VLTI should reliably provide fringes with a transfer function of 0.25 (this is the contrast for a non-resolved star that is 1 in the perfect case) and with a contrast stability of 5% over 5 hours. In addition, a star diameter should be determined that is within 15% of a former measurement of the diameter. Choosing these numbers was somewhat arbitrary; it was a measure of our confidence in what could be achieved in reasonable time.

First Fringes with the siderostats on a baseline of 16m were achieved on March 17, 2001, observing Sirius (Fig. 5). One day later, we fulfilled our First Fringe criteria by determining the diameter of α Hydrae to 9.29 ± 0.17 milli arcsec which is within 15% of indirect (photometric) estimates of about 9 milli arcsec. After three nights, the criteria for stability were fulfilled as well: The interferometer transfer function, was measured to be 0.87 and to be stable to within 1% over three days what is far better than the required 5% over five hours.

It is worthwhile noting that even in the early phase of commissioning the VLTI was run in complete remote control. For data reduction, a first version of the pipeline was in operation providing visibility values of the fringe pattern and storing the data in the archive (Ballester *et al.*[2]). A more sophisticated data analysis software package was provided by the Jean-Marie-Mariotti Center in France (Chelli *et al.*[5]). In the meantime, with the support of NEVEC, the NOVA ESO VLTI Expertise Center at the Leiden Observatory (LePoole *et al.*[20]), this software package was implemented in a second version of the ESO pipeline.

Six months after first fringes with the siderostats, the two UTs Antu and Melipal were ready to deliver the light into the Delay Line tunnel. The night of October 29/30, 2001 started with tests of the Coudé Optical Trains and the Relay Optics. Soon after midnight, the automatic fringe search routine in VINCI reported interferometric fringes. The baseline of 102 m between Antu and Melipal differed by only 28 mm from their nominal length. With the experience from the previous six months of commissioning, 'routine operation' with the 8-m telescopes started almost immediately with a number of scientific observations,amongst them the first measurement of the core of Eta Carina resulting in the first scientific publication of the VLTI (Kervella *et al.*[17]).

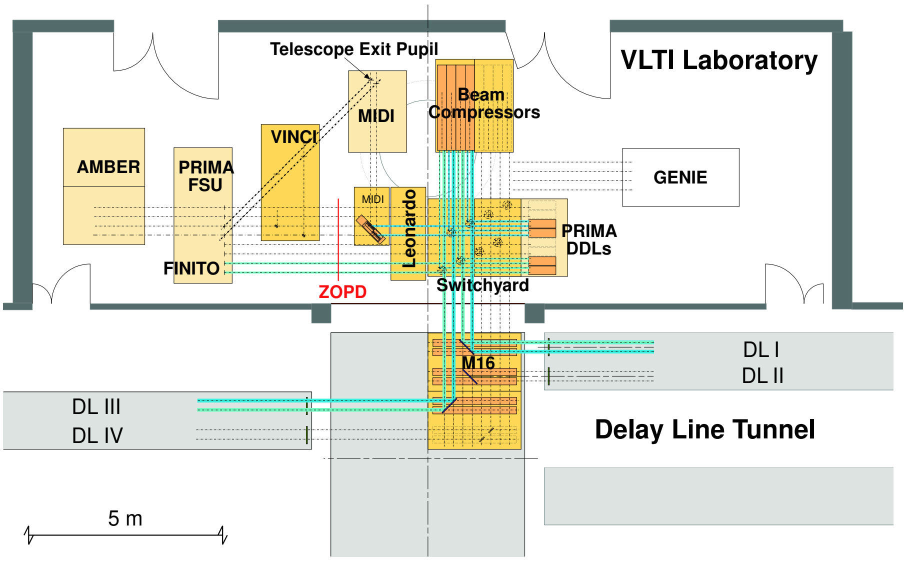

Figure 4. The layout of the VLTI Laboratory. The switchyard can direct the beam into four directions: 1) to the interferometric instruments (on the left) without beam compression, 2) to the interferometric instruments after beam compression, 3) to the Differential Delay Lines after beam compression, and 4) to the Differential Delay Lines without beam compression. The beam compressor reduces the beam diameter from 80mm to 18mm and it reimages the telescope pupil into the PRIMA FSU, MIDI and VINCI (the position of the pupil is indicated by a diagonal line). The location of GENIE is shown on the right.

It should be noted that the 8-m telescopes were used without any adaptive optics correction. The situation of feeding the speckle pattern into the fiber of VINCI is illustrated in Fig. 6. The fiber core with a diameter of 6.5μm matches the Airy disk of the 8-m telescopes with a diameter of 0.06 arcsec. It is readily apparent that the fiber is merely fishing for photons in the speckle cloud. On average, the intensity is about 100 times or 5 stellar magnitudes smaller than with adaptive optics. Even under these conditions, the limiting magnitude was pushed to K=7.7. Thus, without any other improvements but adaptive optics one can reach K=12.7.

In 2002, the siderostats were opto-mechanically upgraded improving the limiting magnitude by almost 2, and a new baseline of 66m was chosen in February. The integrated optics beam combiner IONIC, provided by the University of Grenoble, had first fringes in the H-band on July 18 (Kern *et al.*[15] and Kervella *et al.*[16]).

All data between First Fringes on March 17, 2001 and June 29, 2002 have been released successively. A summary of the scientific results of the first year can be found in Paresce *et al.*.[24] The VLTI was included for the first time in the ESO Call for Proposals for Period 70, starting in October 2002. Part of the VLTI commissioning time was opened for shared risk observing programmes in service mode with VINCI and the siderostats. 150 hours were offered and 39 proposals were received. The result of the observations, i.e. the output of the data pipeline (visibility and accuracy), as well as the raw data and the data reduction software will be offered to the community.

4. THE NEXT TWO YEARS

At the end of 2002, the science instrument MIDI, and, in the first half of 2003, AMBER and the fringe sensor unit FINITO will arrive. The integration of the first two MACAOs (the UT adaptive optics systems) and of the Auxiliary Telescopes will start early in 2003.

MIDI is being 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.*.[19] MIDI will be delivered to Paranal in October 2002; first light with the Siderostats is planned for December 2002. Regular science operations are planned to start in October 2003.

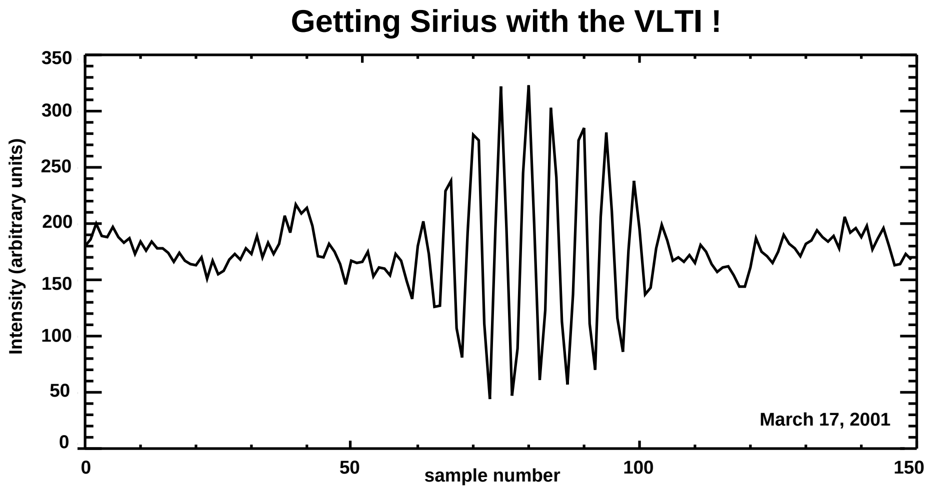

Figure 5. The First Fringe pattern of the VLTI observing Sirius.

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.*[25] and Malbet *et al.*[22]). AMBER has been designed for three beams to enable imaging through phase closure techniques. It is planned to start commissioning AMBER with the Siderostats in the second quarter of 2003.

The VLTI fringe sensor unit is called FINITO for 'Fringe sensing Instrument NIce TOrino', since the concept was developped and tested in a prototype at Nice Observatory (OCA). At the Observatory of Torino (OATo) the concept of the prototype is converted into a VLTI style instrument according to the VLT standards (Gai *et al.*[11]). FINITO operates in the H-band using fibers as spatial filters. The fibers are wound around piezoelectric elements providing the OPD modulation. At the exit of the fibers conventional beam splitters are used to perform the beam combination. The hysteresis in the OPD modulation is corrected in closed loop with a laser metrology system. 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. 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.*[1]). The deformable mirror will replace 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. This means that also a mid-infrared instrument like MIDI needs adaptive optics in order to improve the limiting magnitude by using FINITO. It is planned to have MACAO ready for interferometric observations with two UTs in July 2003.

The first two 1.8-m Auxiliary Telescopes built by AMOS in Liège will be ready for the VLTI in November 2003, the third in April 2004 (Flebus *et al.*[9]). 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. 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 independent of the UTs.

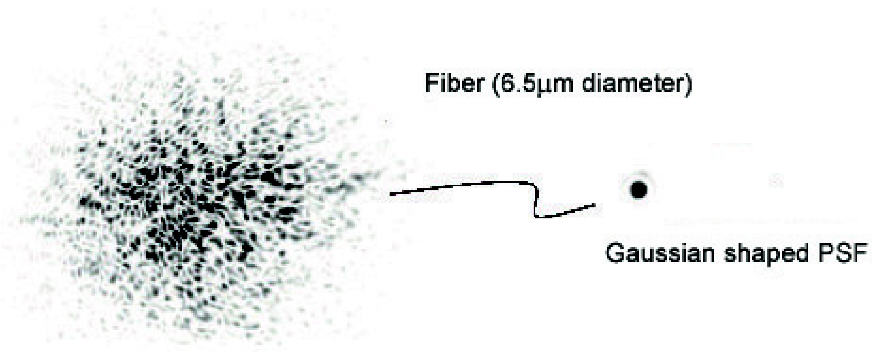

Figure 6. The typical speckle pattern in the K-band in the focus of a 8-m UT. This speckle pattern is focused onto the optical fiber. Since the monomode fiber acts as a spatial filter the output beam has no aberrations.

5. PRIMA AND GENIE - THE NEXT PHASE OF THE VLTI

Two more instruments will follow, completing the suite of first generation instruments: PRIMA in 2005 and GENIE in 2006. 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 being discussed (Gondoin *et al.*[13]). It will be a nulling instrument, probably in the N-band (8–12μm). 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.*[26] and Glindemann *et al.*[12]). PRIMA is the key to access:

– higher sensitivity, the limiting magnitude will be about K = 19,

– imaging of faint objects with high angular resolution (<10 milli arcsec), and

– high precision astrometry ($\approx$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.*[23]).

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.

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 (see Fig. 7). Controlling all optical path lengths of the reference star and of the science star inside the interferometer ($\mathrm{OPD_{int}}$) with a laser metrology system introduces the capability of imaging faint objects and of determining the precise angular separation between the two stars. The measurement has to be repeated for up to 30min in order to average out the variations of the differential OPD caused by atmospheric turbulence ($\mathrm{OPD_{turb}}$). With the two OPD terms being determined, the measurable is the sum $\Delta SB+\phi$. If both stars are point-like, the phase ϕ of the visibility function is zero, and if the baseline B is known with high precision, one obtains a high precision astrometric measurement of the angular separation ΔS. If only the reference star is point-like and the science object is an extended object with a non-symmetric structure the (non-zero) phase ϕ of the visibility function depends on the baseline vector B. Then, the measured sum $\Delta SB + \phi$ can be disentangled by repeating the measurement for several different baselines.

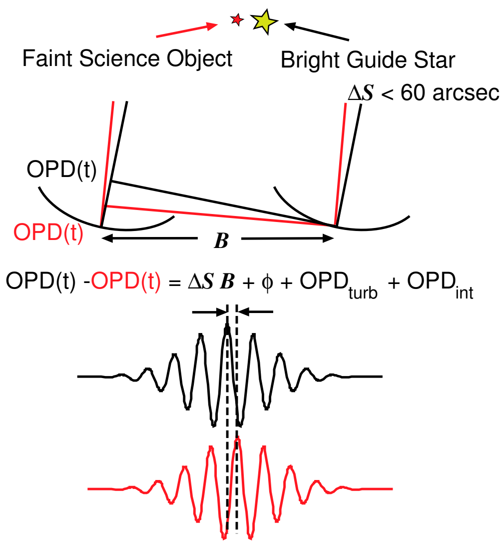

Figure 7. Principle of phase referenced imaging and astrometry with an interferometer. The difference in the positions of the white light fringes of object and reference star are determined by the OPD given by the product of ΔS - the angular separation vector of the stars - and B - the baseline vector - by the phase ϕ of the visibility funtion of the science object, by the OPD caused by the turbulence, and by the internal OPD.

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.*[21]). 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. An OPD measurement accuracy of 50nm rms over 10 min limits the astrometric accuracy to about 100μarcsec. 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.

In the last phase, star separator systems on all ATs and UTs, and differential Delay Lines will enable multi baseline operation with PRIMA for the second generation instrumentation.

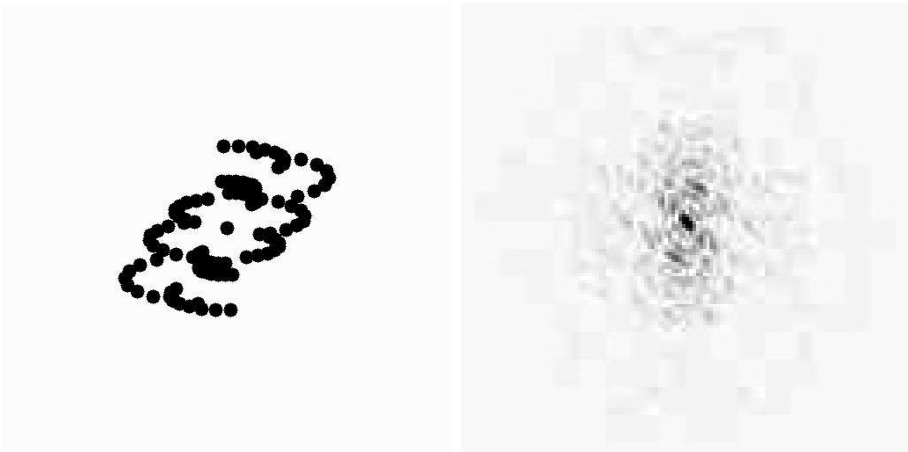

Figure 8. The uv coverage on the left and the point spread function (PSF) on the right with a full width at half maximum of 4mas resp. 8mas in the narrow resp. wide direction of the PSF at 2.2μm. The uv coverage and the PSF are calculated for -15^o declination and 8 hours of observing with phase referenced imaging (PRIMA) when combining all four UTs. Producing images with this quality at a magnitude of K$\approx$20 is the ultimate goal for the VLTI.

6. VLTI OPERATIONS AND FRINGE TRACKING

The final goal of the VLTI is to produce images with a few milli arcseconds resolution. Fig. 8 shows a simulated point spread function when observing for eight hours with all four UTs. The result shows an impressive allbeit elongated PSF with a full width at half maximum (FWHM) of about 4$\times$8 milli arcsec for a wavelength of 2.2μm.

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 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. 9. 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 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 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.

Thus, on-axis fringe tracking with FINITO and adaptive optics with MACAO requires carefully choosing the science object in order to take advantage of the improved performance with fringe tracking. One has to make sure that a visible guide star for MACAO is available within 1 arcmin of the science object. If the guide star is very faint or on the edge of the field the performance of FINITO has to be recalculated. The correlated magnitude will be lower, and the residual OPD will increase.

*All limiting magnitudes are given for the UTs.

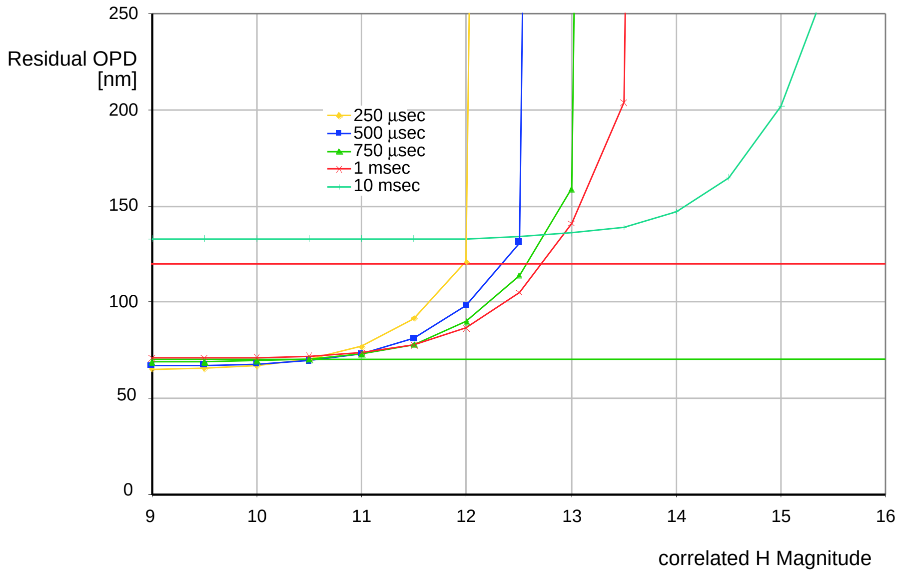

Figure 9. Residual OPD for fringe tracking with FINITO as function of correlated H-magnitude with UTs. The curves represent the closed loop performance for different exposure times on the FINITO detector, taking into account the specified performance of the fringe sensor unit FINITO and of the piezoelectric 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

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.

7. 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. The latter makes it a little bit cumbersome to obtain a smooth image quality that requires a good fill factor (i.e. many baselines) in the uv plane. While phase referenced imaging as in PRIMA – delivering contrast and phase for every baseline individually – 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. 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. This method is used in radio interferometry.

Homothetic mapping relies on reimaging the interferometric array into the entrance pupil of the instrument, 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. Although the thought of such an image quality is truely intriguing there are some stringent hardware requirements for the reimaging of the interferometric array and for the scale factors of the individual telescopes (Beckers[3]). The OPD must not vary more than $\lambda/10$ over the field of view in order to always have the white light fringe on each individual star. The accuracy requirements for the pupil reimaging (that has to be dynamic due to earth rotation) and for the scale factors scale accordingly. Fringe stabilisation is a must to increase the sensitivity but it is only useful if the conditions for homothetic mapping are met precisely. Considering all this, it seems that the next generation instrumentation should rather not rely on enlarging the field with homothetic mapping.

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.*[7]), and, recently, integrated optics showed some very promising scientific results (Berger *et al.*[4]). These techniques would help to reduce the size of interferometric instruments.

With integrated optics in combination with STJ (Superconducting Tunneling Junction) detectors one could build a very compact fringe sensor unit (FSU) with the capability not only to follow the white light fringe of very faint stars but also to find it. The peak-to-valley motion of the fringes due to atmospheric turbulence is about 60μm depending on atmospheric conditions. Then, a coherence length of 60μm would be required to always find the fringes in that region where they statistically have to be. Thus, with an FSU working at 1.6μm, a STJ detector with $\lambda/\Delta\lambda \approx 40$ is sufficient.

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.

8. THE OVERWHELMINGLY 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.*[8]). 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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A PERSONAL NOTE

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