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THE VLTI AND ITS SUBSYSTEMS

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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, so that any two UTs can be used for interferometry. In this article, we will describe the subsystems of the VLTI and the planning for the following years.

1 Introduction

On October 30, 2001 at about 1am, the two 8-m Unit Telescopes Antu and Melipal of the Paranal Observatory 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 commissioning phase between March and December 2001, 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.

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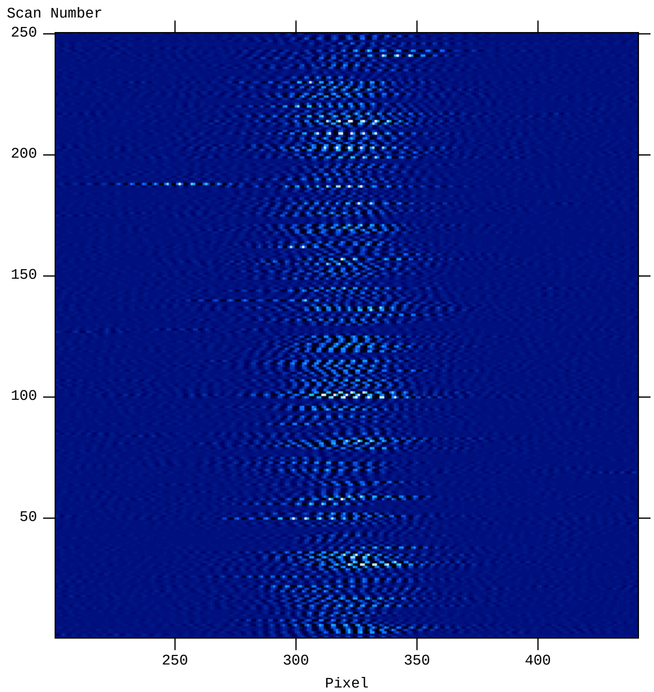

Fig. 1. First fringes of Achernar with VINCI and the two 8-m Unit Telescopes ANTU and MELIPAL on October 30, 2001. Each horizontal line represents the interferometric fringes in the K-band registered during a single scan with scan numbers increasing from bottom to top. Due to atmospheric turbulence,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

In 2002, there will be the first short period of shared risk science operations with the test instrument VINCI and the siderostats. At the end of the year, the first two science instruments MIDI and AMBER, and the fringe sensor unit FINITO will arrive at Paranal. 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 2004, the dual feed facility PRIMA will extend the capabilities of the VLTI to faint objects (K>12) and allow for high precision astrometry. Last but not least, a joint ESO/ESA project for GENIE, the DARWIN ground demonstrator planned for 2005, 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 an to combine a maximum of eight 1.8-m ATs if the Delay

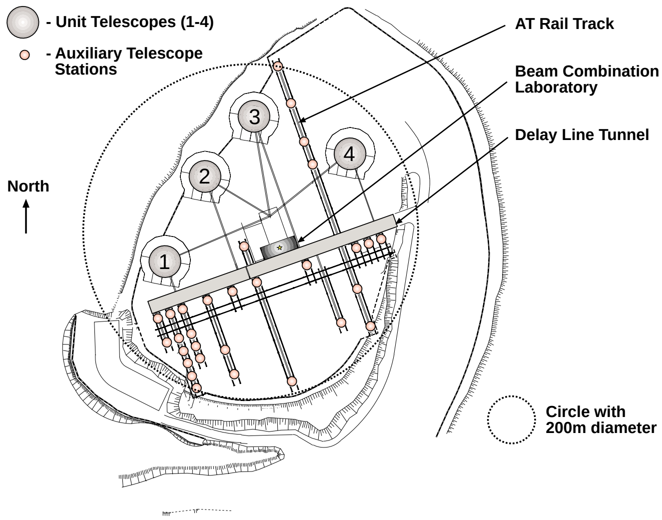

Fig. 2. The layout of the VLTI. The four 8-m Unit Telescopes (UT) and the stations for the 1.8-m Auxiliary Telescopes (AT) are displayed. The AT stations are connected by rail tracks on which the ATs can be relocated. Also shown are the Delay Line Tunnel and the beam combination laboratory. The Delay Line Tunnel has room for eight delay lines allowing the operation of eight ATs and a total of 28 baselines. The longest baseline with two ATs is 200m (indicated by the circle with 200m diameter). The longest baseline with two UTs is 130m.

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 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 cond. 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. 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 (Derie 2000), moving the 2.25m long carriages with the Cat's Eye reflector at speeds up to 0.5m/sec in the 130m

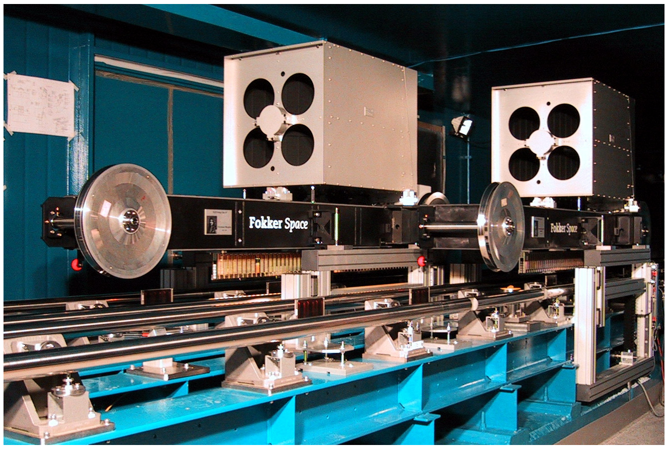

Fig. 3. Two carriages with cat's-eye systems in the Delay Line Tunnel at Paranal. The housing of the cat's-eye has four openings for two input and two output beams. Each carriage has three wheels running on 65m steel rails. The diameter of the wheels is about 40cm and the length of the carriage 2.25m.

long tunnel (see Fig. 3). 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.* 2002) 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.

At the same time, the 40cm siderostats were tested close to the Mirror Maintenance Building at Paranal. The VLTI control software was installed to make them "look" the same as the Unit Telescopes when using the VLTI Supervisor Software. They were moved up to the summit early in 2001. For first fringes they were placed on two AT stations with a baseline of 16m.

Meanwhile in Europe, 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.* 1996). 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 (see Fig. 4). By varying the optical path difference (OPD) between the beams with a mirror mounted on a piezoelectric actuator, a temporally modulated fringe pattern is produced on the detector. In addition to serving as the interferometric instrument VINCI provides alignment tools and reference sources for the VLTI and the scientific instruments. In September 2000, the instrument

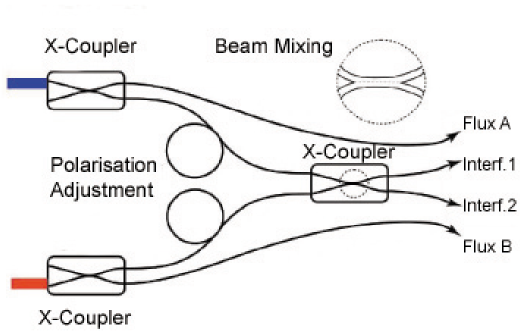

Fig. 4. The concept of VINCI's fiber beam combiner box MONA. The two X-couplers on the left provide a 2:1 split of the incoming light of which the larger fractions are then combined in the X-coupler on the right. Both outputs show a fringe pattern with a differential phase shift of 180 degrees, i.e. one output has a bright fringe while the other output displays a dark fringe. The photometric signals in Flux A and B are used to calibrate the fringe pattern.

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.* 2002).

The preparation for First Fringe with the siderostats was completed at the end of February 2001, when all mirrors, tables, benches, and detectors were installed and tested. The tunnel and the laboratory were closed for normal access to ensure the clean room conditions and the stable thermal environment required for interferometry. First Fringes with the siderostats were observed on March 17, 2001.

As a preparation for first fringes with the Unit Telescopes, the Coudé Optical Trains and the Relay Optics were integrated in the UTs. The optical layout of the VLTI with UTs and ATs is displayed in Fig. 5, 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 picking 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 third Delay Line System (required for using Melipal) had its final tests in July, and the beam compressors were assembled in the Beam Combination Laboratory of the VLTI. The concept driver for the optical layout of the VLTI Laboratory (see Fig. 6) was to provide the same beam diameter for the interfer-

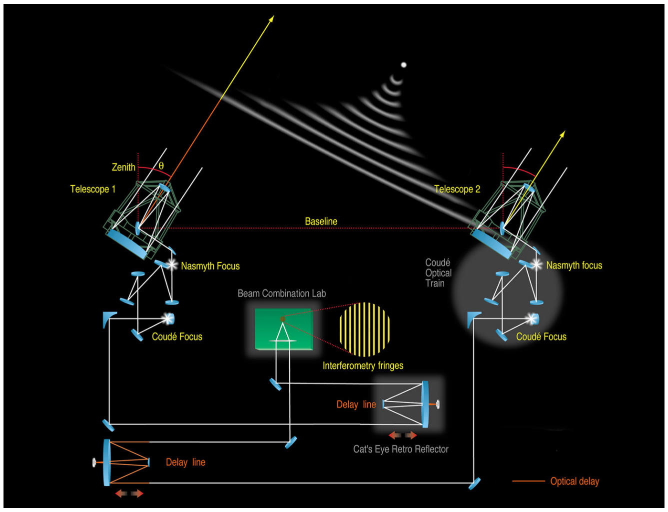

Fig. 5. The optical layout of the VLTI with two telescopes. The telescopes represent both UTs and ATs that have the same optical design. The Coudé Optical Trains are the mirrors after the tertiary mirror up to the Coudé Focus. The mirrors just before and just after the Delay Lines are called the transfer optics. Two Delay Lines are shown to demonstrate the principle of operation. The VLTI laboratory is represented by the beam combining lens forming fringes.

ometric instruments both when observing with UTs or ATs. Therefore, a beam compressor reduces the 80mm beam diameter from the UTs to 18mm matching the 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. 6) 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. 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.

It should be noted that the light path from each telescope is 250m long and that there are 28 reflections between the primary mirror and the IR detector. The image quality, however, is much better than the seeing limit. This was demonstrated with an image on the CCD in VINCI displaying an image quality of 0.45 arcsec diameter which was not different from the seeing measured by the seeing monitor of the observatory. This means that the deterioration due to all the reflections is very likely even below 0.1 arcsec.

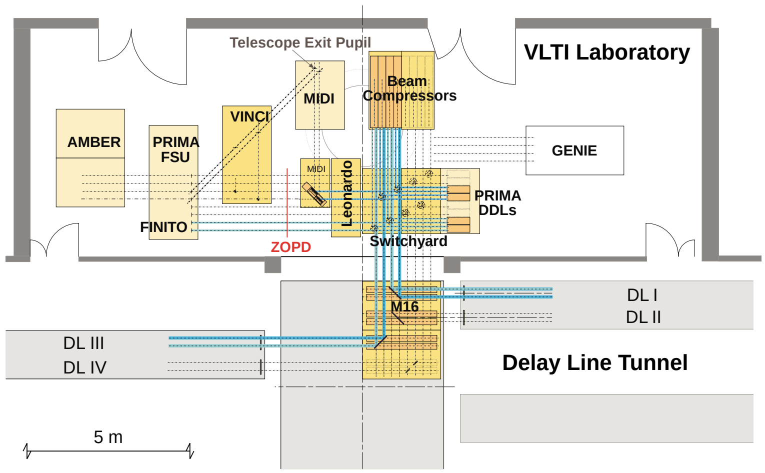

Fig. 6. The layout of the VLTI Laboratory. The switchyard can direct the beam into four directions: 1) to the interferometric instruments (on the left) without beam compression, 2) to the interferometric instruments after beam compression, 3) to the Differential Delay Lines after beam compression, and 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.

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.

In the project schedule, the second half of March was available to fulfill the First Fringe criteria. The tension was intense when star light was guided for the first time from the primary mirror of the siderostats, through the light ducts, the tunnel and the beam combination laboratory to the detector of VINCI. After a few nights only, the VLTI had first fringes observing Sirius (Fig. 7).

It is worthwhile noting that even in this early phase of commissioning the VLTI was run in complete remote control. Except for refilling the VINCI dewar and some other day time activities not a single visit of the tunnel or the beam combination laboratory was required during operation at night. For data reduction, a first version of the pipeline was in operation providing visibility values of the fringe

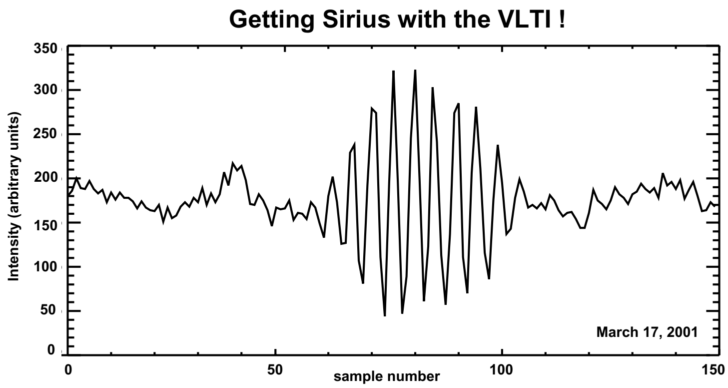

Fig. 7. The First Fringe pattern of the VLTI observing Sirius.

pattern and storing the data in the archive. A more sophisticated data analysis software package was provided by the Jean-Marie-Mariotti Center in France (Chelli *et al.* 2002). In the meantime, with the support of NEVEC[1] (LePoole *et al.* 2002), this software pachage was implemented in a second version of the ESO pipeline.

In the weeks following first fringes, more stellar diameters were determined *e.g.* of γ Cru (the star at the top of the ESO logo), of α Cen (our closest neighbor in the universe), of δ Vir and of R Leo. The typical intrinsic accuracy was 0.5 milli arcsec on diameters between 10 and 25 milli arcsec (Glindemann *et al.* 2001). Due to the sideral motion of R Leo, the effective baselines changed by about 10% over three hours. Observing R Leo over this period of time means that different points on the visibility curve can be measured. Fig. 8 illustrates very nicely the effect of the change in baseline on the fringe contrast.

Six months after first fringes with the siderostats, the two UTs Antu and Melipal were prepared to deliver the light into the Delay Line Tunnel. The night of October 29/30 started with tests of the Coudé Optical Trains and the Relay Optics. Around midnight, the UT team had finished the tests and the search for fringes started. Before actually seeing fringes with an interferometer for the first time, a number of assumptions has to be taken on the internal path lengths in each arm of the interferometer. When distances between individual mirrors can be measured with very high precision (some 10 microns), the distance between the telescopes, i.e. the baseline, is only known with a precision of some 10 millimeters. The latter is corrected after fringes are found on different stars and the so-called OPD model of the interferometer is refined. Depending on the discrepancy between the assumed baseline and the real baseline the first search for fringes can take several hours since the scan for OPD zero position where fringes can be found has to be done at speeds of about 1mm per minute.

However, only about one hour after we started the automatic fringe search

[1]NEVEC is the NOVA ESO VLTI Expertise Center at the Leiden Observatory

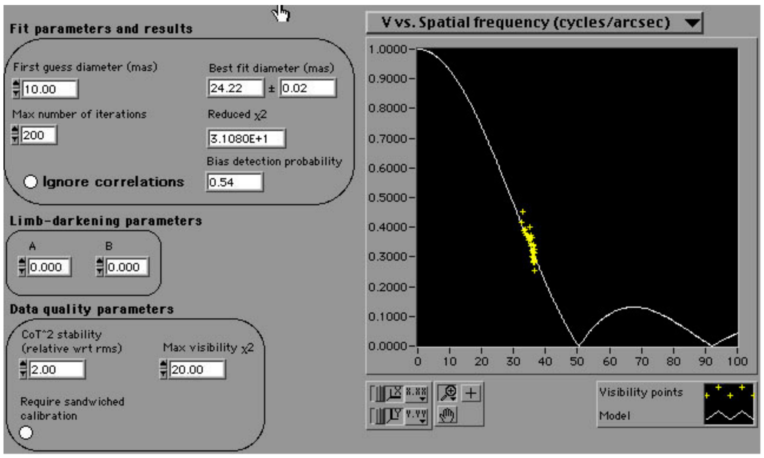

Fig. 8. The best fit of the visibility curve of R Leo and individual points on the curve measured over several hours. This result illustrates very nicely the change of effective baseline (from about 30 to 36 cycles per arcsec) with the sideral motion of the star. As expected, the measured contrast is going down for longer effective baselines. This computer display is part of the data analysis software provided by the Jean-Marie-Mariotti-Centre for Interferometry in France .

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: the first measurements of the diameter of red dwarfs (Kapteyns star, HD 217987 and HD36395), the precise determination of the diameter of Cepheids (Beta Dor and Zeta Gem), the light houses of the universe, and the first measurement of the core of Eta Carina.

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. 9. 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 in 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.

4 The performance after the first year

We fulfilled all First Fringe criteria on March 18, 2001, by determining the diameter of α Hydrae to 9.29$\pm$0.17 milli arcsec. This measurement is within 15% of indirect

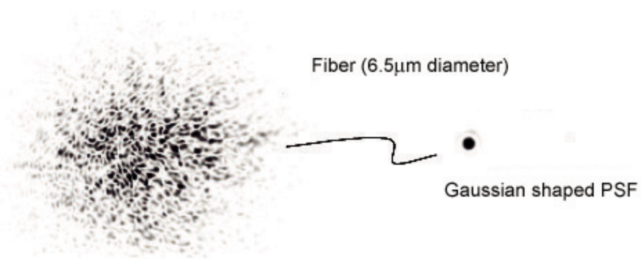

Fig. 9. The typical speckle pattern in the K-band in the focus of a 8-m UT. This speckle pattern is focused onto the optical fiber. Since the monomode fiber acts as a spatial filter the output beam has no aberrations.

(photometric) estimates of about 9 milli arcsec. After three nights, the criteria for stability were fulfilled as well: The equivalent point source contrast, i.e. 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.

After the first eight months of commissioning the performance can be summarised as follows (see Schöller *et al.* 2002): Fringes are found on any bright star in the specified field of view (60 degrees of zenith) within 300μm of the nominal zero optical path difference position. In one case, Sirius was observed only 10 degrees above the horizon without difficulties. Switching to other telescopes or baselines introduces an OPD error of 10mm that has to be corrected by an adjustement in the OPD model.

The transfer function decreased from 0.87 at First Fringes to about 0.7 because the MONA beam combiner box suffered from the drop in temperature in the Delay Line Tunnel. During the period of first fringes the temperature was considerably higher than the nominal 15.5^o Celsius since the activities in the tunnel and in the beam combination laboratory – the installations and tests of the Delay Lines and VINCI – had only stopped just before first fringes.

The smallest contrast that was measured was around 8%. No contribution from internal tunnel seeing could be detected. The faintest star that could be observed with the siderostats had a correlated K magnitude of 4.2. It is possible to guide with the siderostats on stars down to V = 9, and to do blind acquisition in VINCI. With the UTs the limiting magnitude is K = 7.7 in 0.6 arcsec seeing. Without adaptive optics correction this number is extremely seeing dependent.

The accurary of the visibility measurements as a function of correlated magnitude is displayed in Fig. 10. The results are based on the analysis of literally all the observations that were carried in the first eight months of commissioning. Therefore, the mean and median precisions are probably a bit pessimistic.

In February 2002, 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. About 150 hours were offered for these observations,

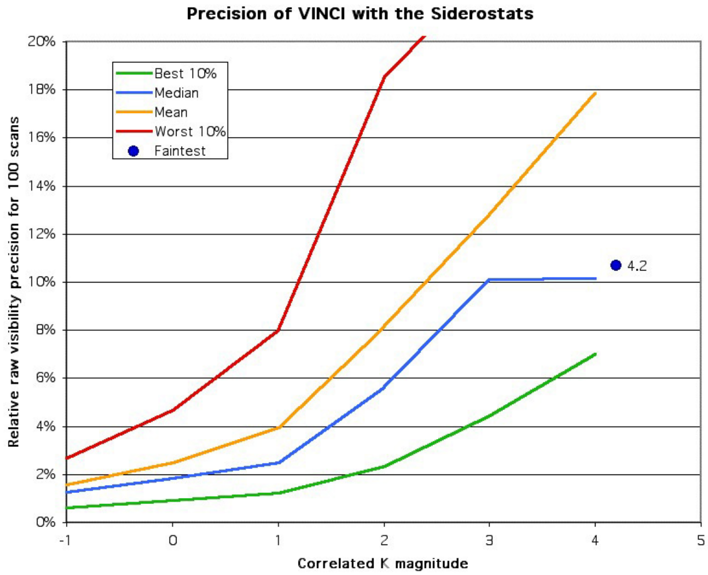

Fig. 10. Intrinsic accuracy for 100 scans in percent of the raw visibility. All available data between March and December 2001 were used to calculate these curves.

and 39 proposals were received. The following performance was offered: limiting correlated magnitude of K = 3 with an intrinsic accuracy between 1 and 5% for the squared visibility depending on magnitude and observing conditions. The offered baselines ranged from 8 to 200m. The result of the observations, i.e. the output of data pipeline (visibility and accuracy), as well as the raw data and the data reduction software were offered to the community.

5 The next two years

At the end of 2002, the science instruments MIDI and 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. Once the ATs and the science instruments will be functional, regular science operations will start (Paresce 2001).

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 design philosophy is to have a simple instrument concept combining two beams and providing a moderate spectral resolution ($\approx$200). The challenge lies in controlling the high thermal background. It is estimated that the individual beams will have an emissivity of about 50%, which corresponds to an equivalent photon noise on the sky of 53 mJy per Airy disk (with λ/D = 0.26” for an aperture of 8 m) for a broad band 10μm filter ($\Delta\lambda = 4\mu$m). Since the signal-to-noise-ratio scales as S/N$\propto$ D^2 the availability of the Unit Telescopes is a huge advantage over smaller apertures. The details of the instrument are described in these proceedings and in Leinert *et al.* 2002. MIDI will be delivered to Paranal in October 2002; first light with the Siderostats is planned for December 2002.

The near-infrared instrument of the VLTI, AMBER, will operate between 1 and 2.5 μm, at first with two telescopes with a spectral resolution up to 10000 (Petrov *et al.* 2002 and these proceedings, and Malbet *et al.* 2002). As noted above, for UT observations in the near-infrared adaptive optics is mandatory. The magnitude limit of AMBER on the UTs is expected to reach K = 20 when a bright reference star is available (i.e. with a dual feed facility) and K = 14 otherwise. The European consortium in charge of designing and manufacturing this instrument is led by the Universities of Nice and Grenoble. 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 February 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.* 2001). 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 January 2003.

The adaptive optics system MACAO will have a 60-actuator bimorph mirror and a curvature wavefront sensor in the visible. 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 a Fringe Tracker.

The first MACAO system will be installed on one of the Unit Telescopes early in 2003. It is planned to have MACAO ready for interferometric observations with two UTs in July 2003. MACAO is an in-house development (Arsenault *et al.* 2002).

The first two 1.8-m Auxiliary Telescopes will be ready for the VLTI in August 2003, the third in February 2004 (see Koehler *et al.* 2000 for details). Fig. 11 shows the erected mechanical structure of AT1 at AMOS in Liège, Belgium. The telescopes are relocatable on 30 stations of the VISA (VLT Interferometer Sub-Array)

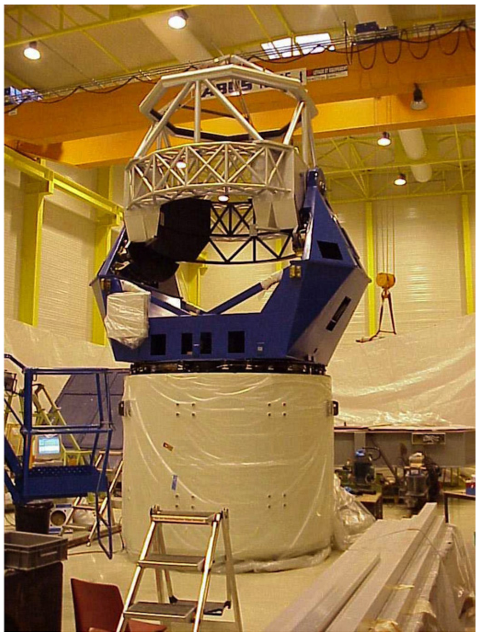

Fig. 11. The telescope structure of the first Auxiliary Telescope (AT) during final integration at AMOS in Belgium. The 1.8-m telescope with an Alt-Az mount like the Unit Telescopes provides a collimated beam 1.2m underground that is sent towards the Delay Line Tunnel through insulated light ducts. The ATs are relocatable on 30 stations using special transporters moving on rails. The transporter structure is not shown on the photograph.

providing baselines between 8 and 200m. Using three telescopes 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 Unit Telescopes.

6 PRIMA and GENIE - The next phase of the VLTI

Two more instruments will follow, completing the suite of first generation instruments: PRIMA in 2004 and GENIE in 2006. 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. 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. 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.

PRIMA is the key to access:
– higher sensitivity, the limiting magnitude will be about K = 20,
– 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 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 (Glindemann *et al.* 1999).

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. 12). 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 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.

PRIMA can be subdivided into 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) laser metrology system to measure $\mathrm{OPD_{int}}$, 3) 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 – and 4) fringe sensor unit to provide the signal for the fringe tracker.

Dual feed observations with PRIMA can start as soon as the star separator and the fringe sensor unit are installed. It is planned to use the main Delay Lines instead of differential delay lines in the first phase. Then, a reference star can be

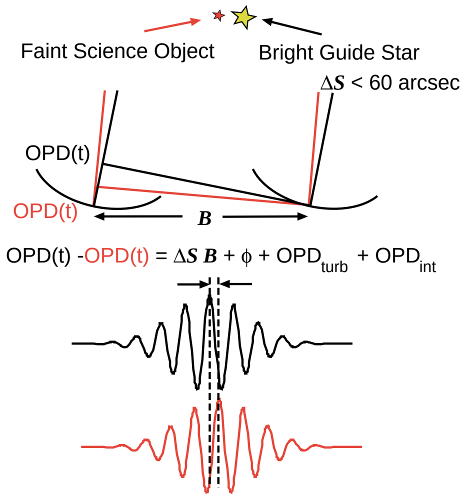

Fig. 12. Principle of phase referenced imaging and astrometry with an interferometer. The difference in the positions of the white light fringes of object and reference star are determined by the OPD given by the product of ΔS - the angular separation vector of the stars - and B - the baseline vector - by the phase ϕ of the visibility funtion of the science object, by the OPD caused by the turbulence, and by the internal OPD.

used for fringe tracking while integrating on the fainter science object as described above. If the fringe pattern can be stabilised over 10-100 sec the expected limiting magnitudes are about K $\approx$ 16 and N $\approx$ 8.

Phase information required for imaging and for astrometry becomes available if the laser metrology system is installed. An OPD measurement accuracy of 500nm rms over 10 min sets the limiting magnitudes to about K $\approx$ 20 and N $\approx$ 11. 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. Reaching the final goal of 5nm rms over 30min allows 10μarcsec astrometry and requires dedicated differential delay lines in order to reach the required dynamic performance. PRIMA shall be operational by 2004.

7 VLTI performance for science operations

The final goal of the VLTI is to produce images with a few milli arcseconds resolution. Fig. 13 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

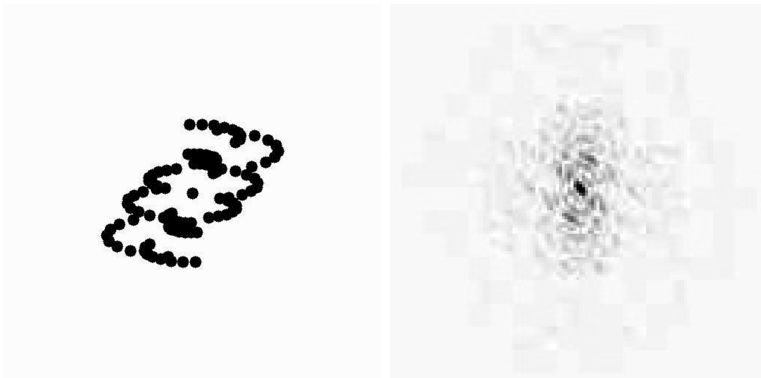

Fig. 13. The uv coverage on the left and the point spread function (PSF) on the right with a full width at half maximum of 4mas resp. 8mas in the narrow resp. wide direction of the PSF at 2.2μm. The uv coverage and the PSF are calculated for -15^o declination and 8 hours of observing with phase referenced 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.

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. 14. The limiting magnitude[2] depends – like for adaptive optics systems – on the required performance. For fringe tracking at the VLTI, the residual OPD is specified to be 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.

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

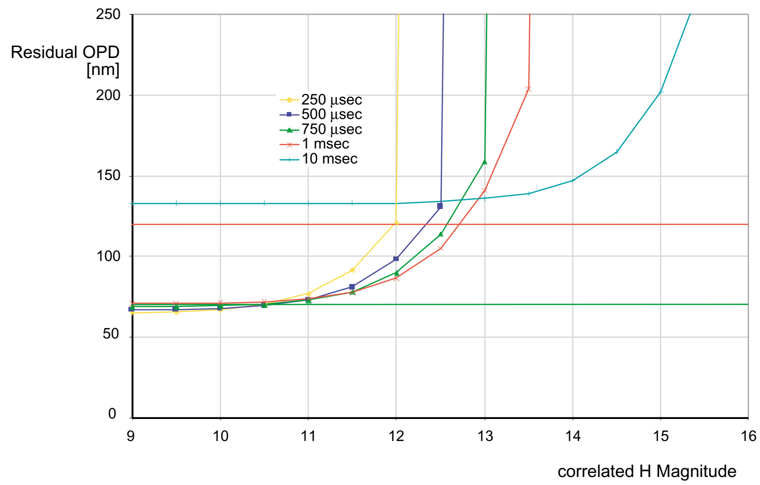

Fig. 14. Residual OPD for fringe tracking with FINITO as function of correlated H-magnitude with UTs. The curves represent the closed loop performance for different exposure times on the FINITO detector, taking into account the specified performance of the fringe sensor unit FINITO and of the piezoelectric 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

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.

The arrival of PRIMA at the end of 2004 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.

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.

However, the sky is full of scientific objects that can be observed and that will take advantage of an angular resolution which is 15 times higher than with individual telescopes (Paresce *et al.* 2001, 2002).

8 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 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$\times$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 1990). The OPD must not vary more than $\lambda/10$ over the field of view in order to always have the white light fringe on the individual stars. 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.* 1998), and, recently, integrated optics showed some very promising scientific results (Berger *et al.* 2001). 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.

Interferometric instruments will hugely benefit from technical progress in the areas fiber optics, integrated optics and STJ detectors, making the instruments both better performing and more compact.

9 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 about a factor of 10 higher. This means baselines of a few kilometers. The optical delays that have to be compensated are of the order of kilometers. 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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