Growing up - the completion of the VLTI

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Abstract. The completed VLTI with eight Delay Lines and eight ATs forms the basis for the second generation instrumentation. We describe the events up to first fringes with the test instrument VINCI using the siderostats, and the planning for the immediate future. Multi beam combination for 'smoother images' will be briefly discussed as well as artificial guide stars for fringe tracking. New technological developments like fiber optics amplifiers and integrated optics in combination with STJ open the door for a new type of interferometric arrays. Baselines as long as a a few kilometres come into reach. Examples of these second generation interferometers will be given.

1 Introduction

On March 17, 2001, at 10pm local time, the VLT Interferometer project reached a major milestone by observing the first interferometric fringes on a star, using two siderostats and the test camera VINCI. After almost 10 years of planning, analysing, simulating and testing this was a memorable moment especially because the quality of the first fringes was truly outstanding (see Fig.1). In the following commissioning phase several sources in the sky were observed to verify the performance of the VLTI. We found that all specifications were met or exceeded. However, numerous tasks are still ahead of us before science operations can start. We are now looking forward to the next major milestone combining the light from two Unit Telescopes in November this year.

The VLTI, its sub-systems and the first generation instrumentation are described in ample detail in [7].

2 The last two years

Early in 2000, the activities at Paranal started on a large scale. Containers arrived in front of the VLTI control building 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 the year, the first piece of high-tech equipment arrived when the installation of the Delay Lines started, ending five months later with

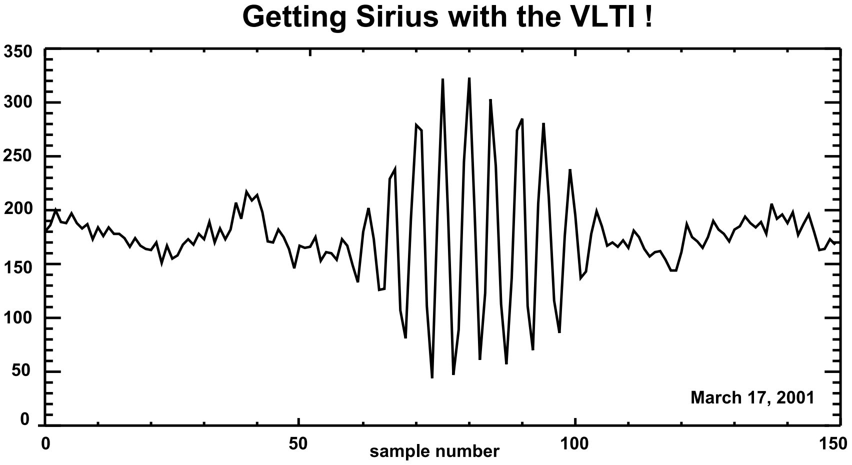

Fig. 1. The very first fringe pattern of the VLTI observing Sirius.

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, moving the 2m 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. In the meantime, three more Delay Line Systems were ordered.

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.

Meanwhile in Europe, the test camera VINCI was put together at the Observatory of Paris in Meudon, and the observing software was produced by the Observatory of Toulouse. 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. It proved extremely useful to have a three month test period in Garching, allowing us not only to put together the individual pieces of hard- and software under laboratory conditions, but also to rehearse the integration of the complete system after transporting it from Paris to Garching. With this experience, the integration, testing and commissioning of VINCI at Paranal was a swift and seamless exercise in the first two months of 2001, supported by the VINCI team from Meudon.

Finally, towards the end of February 2001, all mirrors, tables, benches, and detectors were installed and tested, and the tunnel and the laboratory were closed for normal access to ensure the clean room conditions and the stable thermal environment required for First 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.

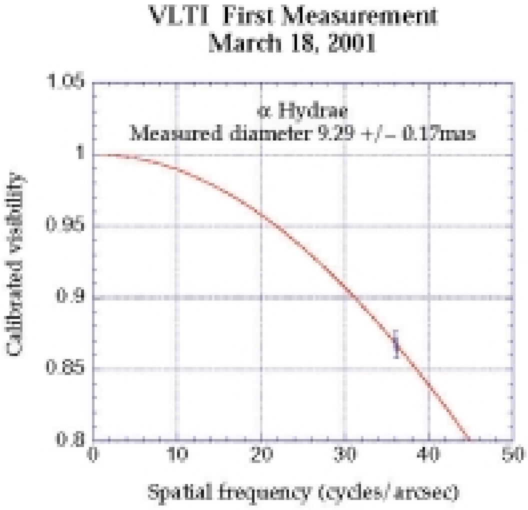

Fig. 2. Three individual measurements were taken to determine the first diameter of a star, α Hydrae. The best fit of the visibility curve and the three measured points, almost on top of each other, together with the error bar of 0.17 milli arcsec are displayed. The measured diameter of 9.29 milli arcsec is well within 15% of indirect (photometric) estimates of about 9 milli arcsec.

In the project schedule, the second half of March was available to fulfill the First Fringe criteria. We chose a baseline of 16m for the first attempt to see fringes. 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. And, after a few nights, the result was spectacular. The very first result, the fringe pattern of Sirius, is shown in Fig.1.

In the following nights, more stars were observed. We fulfilled all First Fringe criteria on March 18, 2001, by determining the diameter of α Hydrae to 9.29 ± 0.17 milli arcsec (see Fig.2). This measurement is within 15% of indirect (photometric) estimates of about 9 milli arcsec. After three nights, the criteria for stability were fulfilled in an impressive manner: 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 (see Table 1).

Parameter	Specification	Achieved
Transfer Function	0.25	0.87
Stability	± 5% over 5 hours	±1% over 3 days
measurement accuracy for a star diameter	±15%	±2%

Table 1. The criteria for First Fringes as specified and as achieved.

After the first period of commissioning the performance can be summarised as follows: Fringes were found on any bright star in the specified field of view (60 degrees of zenith) within 500μm of the nominal zero optical path difference position. In one case, Sirius was observed only 10 degrees above the horizon without difficulties. The smallest contrast that was measured was around 5%. No contribution from internal tunnel seeing could be detected. The limiting magnitude of VINCI, with the siderostats effectively stopped down to 100mm, is about K $\approx$ 1. It is possible to guide with the siderostats on stars down to V = 9, and to do blind acquisition in VINCI.

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 pattern and storing the data in the archive. A more sophisticated data analysis software package to determine stellar diameters was provided by the Jean-Marie-Mariotti Center in France. In the meantime, with the support of NEVEC[1] [1], most of this software is implemented in a second version of the ESO pipeline.

In the course of April, some interesting results were achieved, demonstrating the potential and the reliability of observations with the VLTI. Some more stellar diameters were determined (see Table 2), *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. Due to the sideral motion of R Leo, the effective baselines changed by

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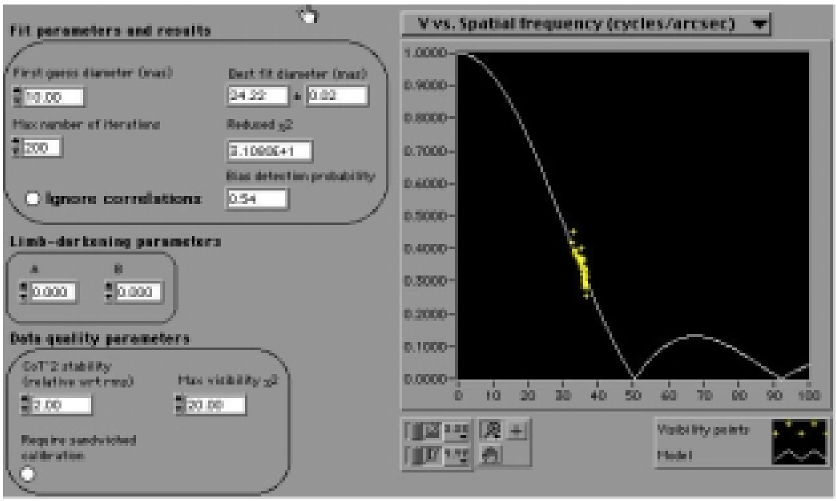
[1] NEVEC is the NOVA ESO VLTI Expertise Center at the Leiden Observatory



Fit parameters and results

First guess diameter (mas): 10.00

Max number of iterations: 200

Best fit diameter (mas): 24.22 ± 0.02

Reduced χ2: 3.1080E+1

Bias detection probability: 0.54

○ Ignore correlations

Limb-darkening parameters

A: 0.000

B: 0.000

Data quality parameters

CoT^2 stability (relative wrt rms): 2.00

Max visibility χ2: 20.00

Require sandwiched calibration ○

Fig. 3. 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 ≈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.

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.3 illustrates very nicely the effect of the change in baseline on the fringe contrast.

Star	Angular Diameter
γ Cru:	24.7±0.35 milli arcsec
α Cen:	9.6±0.5 milli arcsec
δ Vir:	10.4±0.6 milli arcsec
R Leo:	24.3±0.4 milli arcsec

Table 2. Star diameter measurements with the VLTI in April 2001.

4 The next two years

The next major milestone in 2001 will be First Fringes with UT1 and UT3 in November. The installation of the Coudé optical trains and of the relay optics in the Unit Telescopes is progressing - the Coudé focus of UT3 had its First Light in May - as well as of the beam compressors in the VLTI Beam Combination Laboratory. The beam compressors are required to convert the 80mm collimated beam from the UTs into a 18mm input beam for the instruments. In addition, tip-tilt sensor units (STRAP) will be installed in the Coudé foci of the UTs improving the beam feeding into the optical fibers of VINCI.

In 2002, the science instruments MIDI and AMBER and the fringe sensor unit FINITO will arrive, and the integration of the Auxiliary Telescopes will start. Once the ATs and the science instruments will be functional, regular science operations will start (see *e.g.* [6]).

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. As a detector for PRIMA either the two scientific instruments MIDI and AMBER can be used making use of the fringe stabilisation provided by PRIMA, or a dedicated PRIMA detector for high precision astrometry.

The objective of PRIMA is to enable 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. One object will then be used as a reference star for fringe tracking while the other object will be the science target. 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 (≈10 μarcsec over a 10 arcsec field).

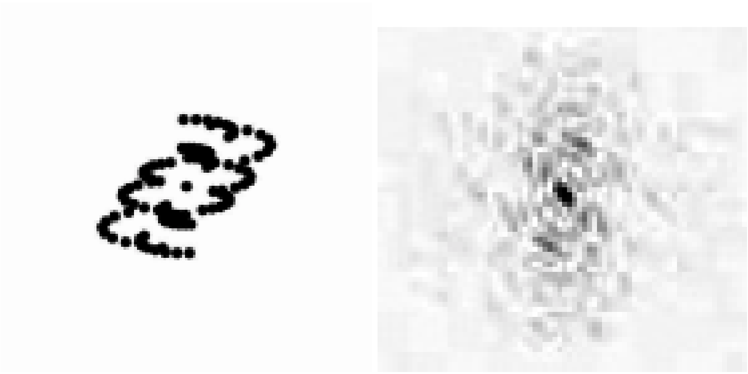


Fig. 4. The uv coverage on the left and the point spread function (PSF) on the right with a full width at half maximum of 4mas resp. 8mas in the narrow resp. wide direction of the PSF at 2.2μm. The uv coverage and the PSF are calculated for -15^o declination and 8 hours of observing with phase referenced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

GENIE is a joint project with ESA providing the ground demonstrator for DARWIN as a science instrument for the VLTI. The concept of GENIE is currently under discussion. It will be a nulling instrument, probably at a wavelength of 10μm. The goal is to use GENIE for planet detection with the VLTI.

5 Second Generation Instruments

The main limitations of the first generation instrumentation is 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 (see Fig. 4). 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 upto 8 beams (see Fig.5).

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 [2]. 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.

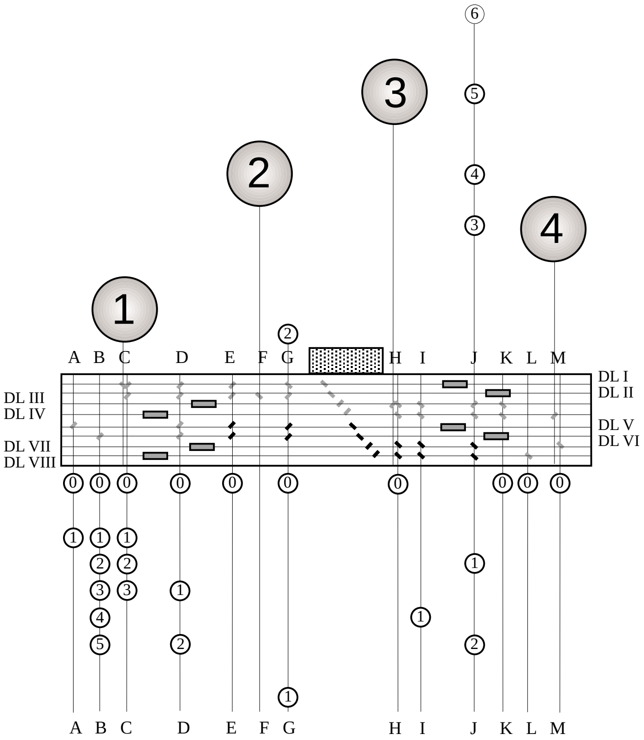


Fig. 5. The completed VLTI. The infrastructure of the VLTI has room for 8 Delay Lines. Thus, 8 Auxiliary Telescopes could be combined at the same time. The figures shows the planned distribution of the M12 mirrors (the mirrors in the tunnel reflecting the light from the telescopes towards the Delay Lines). With this distribution, all possible combinations of AT stations can be used except in case of a Delay Line failure.

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 [4], and, recently, integrated optics showed some very promising first scientific results [3]. These techniques would help to hugely 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.

6 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 [5]. In order to avoid any intensity loss at all one could use fibers with phase preserving amplification of light like 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.

7 Artificial Guide Star for Fringe Tracking

Due to atmospheric turbulence the sensitivity of interferometers is limited. While exposures on individual telescopes can last several hours producing seeing limited images, the interferometric fringes are whashed out if the integration time is much longer than the atmospheric coherence time of the order of 10msec. Depending on parameters like seeing, visibility measurement accuracy etc., the limiting magnitude on the Unit Telescopes is K = 12–15. In the vicinity of these stars, fainter objects down to K≈20 can be observed with systems like PRIMA.

However, one is confronted with the same problem as in natural guide star adaptive optics: one is limited to the vicinity of bright stars what reduces the sky coverage drastically. In adaptive optics, artificial laser guide stars (LGS) improve this situation substantially. This scheme cannot be applied to fringe tracking in interferometry. Fig.6 shows a concept to produce a LGS above each telescope and to observe both stars interferometrically. The difference in white light fringe

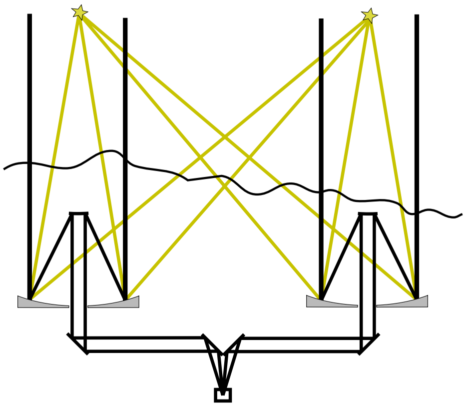


Fig. 6. Scheme for a twin guide star fringe tracker. Each telescope projects one guide star, and both stars are observed interferometrically. Keeping the difference of the white light fringe positions of the two stars stable by adjusting the OPD stabilises the fringes on the natural star under observation.

position of the two LGS provides the proper difference of the wavefront pistons for the two telescopes. However, since the size of the LGS is ultimately limited by the diffraction limit of the individual telescope, the contrast of the fringe pattern is close to zero because the LGS is resolved by the interferometer. Producing a LGS interferometrically through both telescopes one is confronted (amongst other problems like highly distorted fringe patterns) with the same problem as in adaptive optics: the fringe motion is cancelled because the light travels the same path up and down.

I would like to encourage the reader to spend some time thinking about this problem. Interferometry would benefit enormously from the availability of an artificial guide star drastically increasing the sky coverage.

Acknowledgments

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