Light at the End of the Tunnel – First Fringes with the VLTI

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1. Introduction

On March 17, 2001, at 10 p.m. 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 (Table 1). 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.

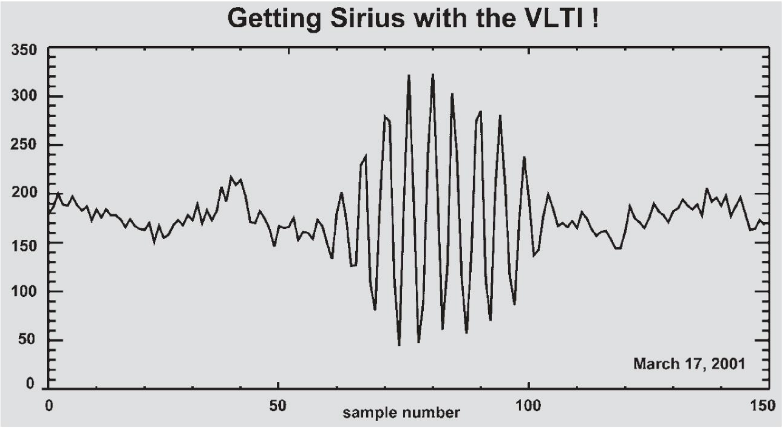

Figure 1: The very first fringe pattern of the VLTI observing Sirius.

2. The Last Two Years

At the time when the last *Messenger* article on the VLTI [1] was written, only 18 months ago, the Delay Line Tunnel was a rather deserted place. It was empty and clean but there was not a single one of those dozen mirrors that are now in place, aligned with sub-millimetre precision. And there was no Delay Line System moving a Cat's Eye reflector system with micrometre precision.

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

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

Figure 2: The Delay Line Integration Team with staff from ESO, Fokker, TPD/TNO and S&B after integrating the second Delay Line on November 22, 2000.

Early in 2000, activities started on a large scale. Containers arrived in front of the VLTI control building and equipment disappeared inside, like in the hold of a cargo ship. Inside the tunnel, hundreds of holes were drilled, 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. With the installation of computers and telephones the VLTI control building looked more and more like a real control centre.

In the middle of the year, the first piece of high-tech equipment arrived when the installation of the Delay Lines started. After the Delay Line Integration Team had spent the better part of last year in the tunnel, the first three Delay Line Systems were commissioned (see Fig. 2). For the installation of the rails of

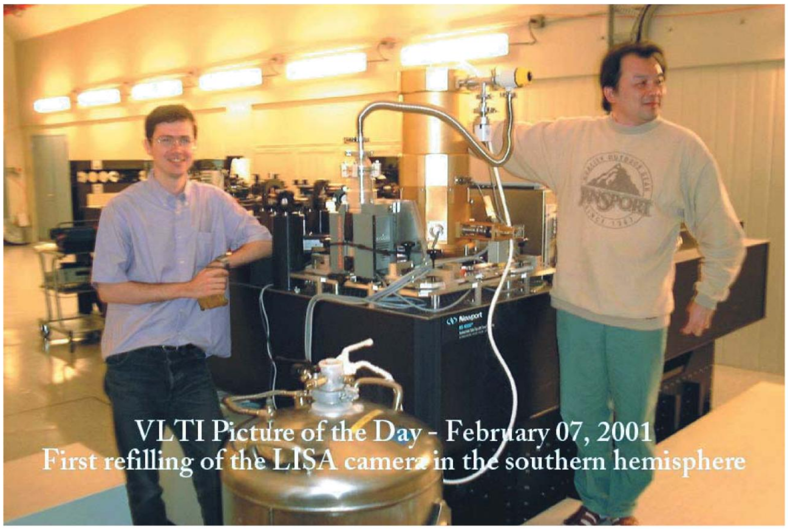

Figure 3: VINCI in the VLTI beam combination laboratory. On February 7, 2001, the opto-mechanical alignment was finished and the LISA camera was cooled down for the first time at Paranal.

the Delay Lines, a sophisticated measurement system with water level gauges was used providing a flatness of less than 25 μm over the full length. The Delay Line System is one of the most spectacular subsystems of the VLTI, moving the 2-m-long carriages with the Cat's Eye reflector at speeds up to 0.5 m/sec in the 130-m-long tunnel. While moving the carriage, the reflected beam is tilted less than 1.5 arcsec at all times, the absolute position accuracy is 30 μm over the full range of travel of 65 m and the position error is of the order of 20 nm. Fulfilling the specifications, the contract with Fokker was closed a few weeks ago.

At the same time, the 40-cm siderostats were tested close to the Mirror Maintenance Building. 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 and tested successfully shortly thereafter.

Meanwhile in Europe, the test camera VINCI was put together at Paris Observatory in Meudon, and the observing software was produced by the Observatory of Toulouse. Only one year after the signature of the contract, the instrument was delivered to ESO Garching for integration with the infrared 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 (see Fig. 3), supported by the VINCI team from Meudon.

At the beginning of 2001, the Delay Line Tunnel and the beam combination laboratory at Paranal saw some heavy pieces of equipment arriving: five optical tables each weighing around a ton. Solid optical alignment units were also installed providing a reference mark at every turn of the beam.

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.

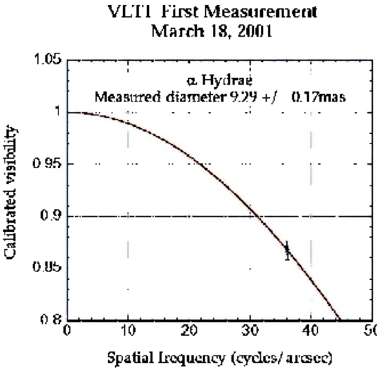

Figure 4: Three individual measurements were taken to determine the first diameter of a star, α Hydrae. The best fit of the visibility curve and the three measured points, almost on top of each other, together with the error bar of 0.17 milliarcsec are displayed. The measured diameter of 9.29 milliarcsec is well within 15 % of indirect (photometric) estimates of about 9 milliarcsec.

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 contrast of 0.25 for a non-resolved star (when it is 1 in the perfect case) and with a contrast stability of 5% over 5 hours. In addition, a star diameter should be determined 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 fulfil the First Fringe criteria. We chose a baseline of 16 metres for the first attempt to

γ Cru:	24.7 ± 0.35 milliarcsec
α Cen:	9.6 ± 0.5 milliarcsec
δ Vir:	10.4 ± 0.6 milliarcsec
R Leo:	24.3 ± 0.4 milliarcsec

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

Figure 5: The First Fringe Team after having measured the first star diameter.

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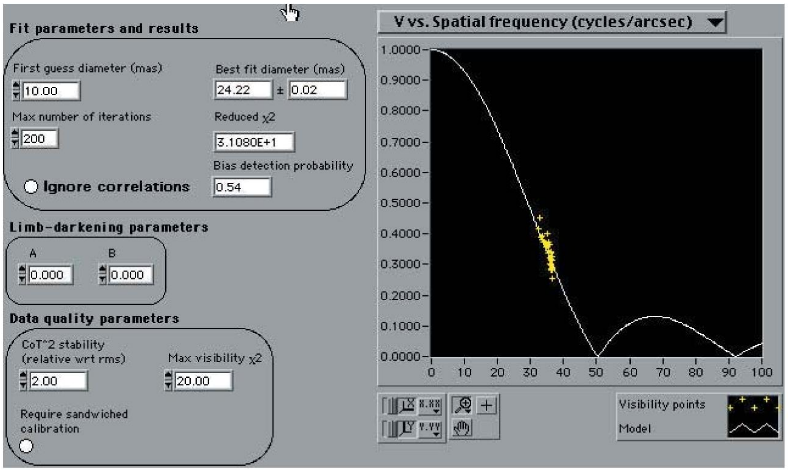

Fit parameters and results

First guess diameter (mas): 10.00

Best fit diameter (mas): 24.22 ± 0.02

Max number of iterations: 200

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 ○

Figure 6: 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 13.7 m to 16 m, i.e. 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.

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 Figure 1.

This was a joyful moment and the champagne corks were popping. But it was also a touching moment when we kept a minute of silence remembering Jean-Marie Mariotti who was one of the fathers of the VLTI and who died much too early three years ago.

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 milliarcsec (see Fig. 4). This measurement is within 15% of indirect (photometric) estimates of about 9 milliarcsec. The next day saw a very happy and exhausted First Fringe Team (Fig. 5). 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).

After the first week 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 500 μm of the nominal zero optical path difference position. In one case, Sirius was observed only 10 degrees above the horizon without difficulties. The smallest visibility 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 100 mm, is about K ≈ 1. It is possible to guide with the siderostats on stars down to V = 9, and to do blind acquisition in VINCI.

During the first few nights we had the benefit of a benign atmosphere providing rather slow seeing and, thus, slow fringe motion. The mean value of the Paranal atmosphere is a factor of two faster, either reducing the sensitivity about one magnitude due to shorter integration times for the same signal-to-noise ratio (SNR) of the measured visibility, or reducing the SNR for the same sensitivity. The latter requires averaging over more observations in order to improve the SNR.

Figure 7: 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 1.2 m 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.

It is also 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 Centre in France. In the meantime, 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 on the right of the ESO logo), of α Cen (our closest neighbour in the universe), of δ Vir and of R Leo. 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. Figure 6 illustrates very nicely the effect of the change in baseline on the fringe contrast.

It is planned to have a few periods of about 8 days of science observations later this year. All scientific results will become public in the ESO archive as it was done with the UT science data during UT commissioning.

4. The Next Steps

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 80 mm collimated beam from the UTs into a 18-mm input beam for the instruments and to improve the sensitivity when observing with the siderostats. In addition, tip-tilt sensor units (STRAP) will be installed in the coudé foci of the UTs improving the beam feeding into the optical fibres of VINCI.

This wraps up the VLTI activities for this year. A complete summary of the subsystems and of the instruments of the VLTI can be found in the proceedings of the SPIE conference on Interferometry in Optical Astronomy [3].

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. Figure 7 shows the erected mechanical structure of AT1 at AMOS in Liège, Belgium. Once the ATs and the science instruments are functional, regular science operations can start. The following article by Francesco Paresce [2] gives a taste of the science programmes that are planned with the VLTI.

5. Acknowledgements

In addition to the authors of this article, about twice as many ESO staff have contributed to the VLTI. Unfortunately, there is not enough room to name them all. Fortunately, we did have the support of such a large and experienced team, and we would like to thank all of them for their enthusiasm and their hard work.

The results presented in this article were produced with the software provided by the Observatoire de Paris for the Jean-Marie-Mariotti Centre for Interferometry in Grenoble.

References

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[2] Paresce, F., et al. 2001, *The Messenger* – This volume.
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Scientific Objectives of the VLT Interferometer

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Astronomers have long sought to improve the sensitivity and spatial resolution of their observations in order to see as far back in time and as sharply as possible. As the photon-collecting power scales as the telescope diameter D^2 and spatial resolution as D^{-1}, the solution of the problem has always been in the form of ever larger collecting-aperture telescopes. Unfortunately, although this solution did indeed increase dramatically the sensitivity of astronomical observations, it still was far from ideal in terms of spatial resolution owing to the negative effects of the earth's atmosphere. On the ground, the improvements were mainly due to finding the proper location where the seeing was best (California, Hawaii and Chile) and, more recently, to the technique of adaptive optics as shown schematically in Figure 1.

Apart from the development of a ~100-m-diameter telescope, the foreseeable breakthroughs in optical/IR resolution in the near future are essentially only two: operating in space (HST and, in the future, NGST) and aperture synthesis interferometry. In essence, even going to space with a simple filled aperture telescope of 6 m diameter (NGST) still does not approach the potential of the latter technique even on the ground. This is especially true in the infrared at 2.2 μ where very high sensitivity can be coupled to very high angular resolution of ~1 milliarcseconds (mas).

Because of these considerations, interferometry has begun to play a central role in ground-based high-resolution astronomy, and numerous instruments have been completed or are in the process of construction (see Table 1 for a summary of the present situation in this regard). Several large-aperture interferometers will come on-line in the next few years. The impending presence of these new instruments represents an important incentive both for clarifying the scientific cases for various VLTI implementation plans and for ensuring VLTI's competitiveness in the international context over the next 10–20 years.

It has always been ESO's aim to operate the VLT in an interferometric mode which allows the coherent combination of stellar light beams collected by the four 8-m-diameter telescopes (UT) and by several smaller 1.8-m-diameter auxiliary telescopes (AT). Thus, the VLTI has the unique advantage of being the only large telescope facility together with the LBT designed from the very start as an interferometer. This means that it will have three main characteristics that are unprecedented for this type of array:

- very high precision visibilities (up to $\Delta V/V=10^{-4}$) for moderately bright sources,

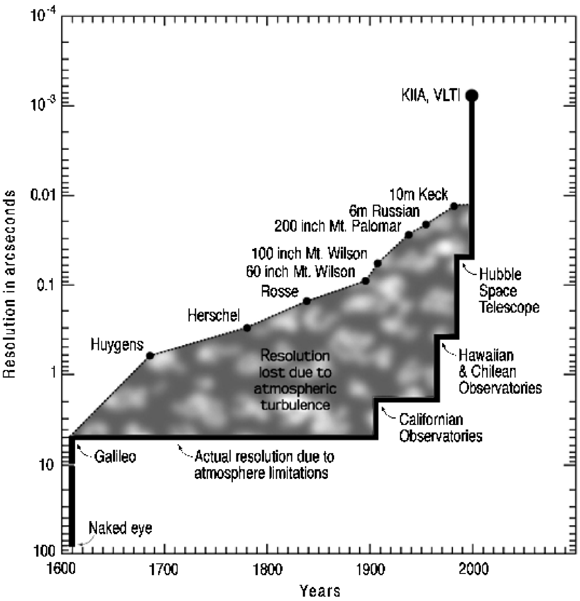

Figure 1. Spatial resolution as a function of historical time since Galileo. Adapted from P. Bely (ESA SCI(96)7, 1996).