# Observing with the ESO VLT Interferometer

*The ESO VLT Interferometer (VLTI) has been in operation since achieving First Fringes in March 2001. A broad spectrum of activities has been covered ranging from commissioning, shared-risk science observations, science demonstration and guaranteed time observations, to regular observation programmes in service and visitor mode. The VLTI operations scheme is fully integrated into the well established regular operations scheme of all VLT instruments. In particular, the same kind and level of service and support is offered to users of VLTI instruments as to users of any instrument at the single UTs on Paranal. Thereby, the VLTI has become worldwide the first general-user optical/infrared interferometric facility offered with this kind of service to the astronomical community.*

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The ESO VLT scheme allows astronomers to submit visitor mode or service mode observation programmes. In visitor mode, the astronomer is present at the telescope and can adapt the programme to specific requirements at the time of observation. In service mode, the observation details and constraints are submitted to ESO beforehand, and the observations are scheduled and carried out by ESO staff.

Service mode observing was conceived by ESO in the early days of the planning of VLT operations as a key component in optimizing the scientific return and the operational efficiency (cf. Comerón et al. 2003). The VLTI science operations scheme profits enormously from the experience gained during service mode observations at the single UTs since April 1999 and the implemented infrastructure. It follows and is fully integrated into the regular VLT operations scheme from the initial preparation of the proposal to the delivery of the data.

Table 1 shows the numbers of scheduled programmes using VLTI instruments (so far MIDI only) for the ESO observing periods P73 (observations from April to September 2004), P74 (October 2004 to March 2005), and P75 (April to September 2005). The first regular VLTI observing period (P73) has been concluded with a completion rate of 80 % of the scheduled service mode observing blocks (OBs). These regular VLTI observing periods were preceded by commissioning and shared-risk science observations using the *K*-band commissioning instrument VINCI, as well as by observations within MIDI and AMBER science demonstration and guaranteed time programmes. These observations greatly helped to establish the VLTI-specific aspects of the regular operations scheme as well as to test the overall data flow system for the VLTI instruments (cf. Ballester et al. 2004).

Also shown in Table 1 are the distributions of the regular VLTI programmes scheduled so far among programme types, observing modes, as well as scientific categories (B: Galaxies and galactic nuclei; C: Interstellar medium, star and planet formation; D: Stellar evolution). Evidently, by far most of these programmes are normal programmes. A clear majority of programmes are executed in service mode, which is partly caused by the need to combine different baseline configurations (see below). There is an increasing number of scheduled programmes within the scientific category B, while the majority of the VLTI programmes are so far about equally distributed among scientific categories C and D. On the subject of this article, see also the proceedings of the 2002 Les Houches EuroWinter School “Observing with the Very Large Telescope Interferometer”, edited by G. Perrin and F. Malbet. A recent description of the technical status of the VLTI can be found in Glindemann et al. (2004) and references therein. In the following, we discuss specific aspects regarding VLTI observations as currently offered to the community.

## Why use the VLTI for astrophysics?

Modern astronomical observatories have succeeded in measuring the flux density across the electromagnetic spectrum for many cosmic objects, at least for the brightest objects in each important class. While one further desires to obtain the flux densities of fainter and more distant targets, another obvious goal is to map out each object’s intensity structure, as a function of wavelength, in as much detail as possible (cf. Rees 2000).

For optical and infrared wavelengths, several interferometric facilities have been operated for this purpose[1]. These facilities, however, have so far often been limited to the brightest stars owing to their small collecting areas, and have often not been very easy to use for any astronomer. With the construction of the Keck and VLT Interferometers including 8–10 m class telescopes, optical/infrared interferometry is now also feasible for relatively faint sources. This, for instance, promptly enabled the first near- and mid-infrared long-baseline interferometric measurements of active galactic nuclei. In addition, the VLTI instruments provide unprecedented spectro-interferometric capabilities. Finally, as the science operations of the VLT Interferometer were integrated into the regular science operations scheme of the instruments at the single 8 m telescopes, VLTI observations can now be relatively easily performed by any astronomer.

The range of astrophysical topics that can be addressed by the VLTI can be seen by looking at the science that has already been achieved using optical/infrared interferometers. General results were reviewed by, for instance, Quirrenbach (2001), Baldwin & Haniff (2002), and Monnier (2003). First scientific results that emerged from the VLTI

[1] See the overview provided by Peter Lawson at *http://olbin.jpl.nasa.gov*

| Period | Total | Type | | | Mode | | Category | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Normal | GTO | DDT | s | v | B | C | D |
| 73 | 23 | 18 | 4 | 1 | 15 | 8 | 1 | 12 | 10 |
| 74 | 19 | 14 | 4 | 1 | 13 | 6 | 2 | 8 | 9 |
| 75 | 24 | 20 | 4 | – | 18 | 6 | 3 | 12 | 9 |
| Total | 66 | 52 | 12 | 2 | 46 | 20 | 6 | 32 | 28 |

Table 1: Scheduled VLTI (MIDI) programmes in ESO observing periods P73–75. Listed are the total numbers of scheduled runs, as well as the distribution of programme types (normal, guaranteed time observations (GTO), director discretionary time (DDT) programmes), of programme modes (service mode 's' or visitor mode 'v'), and of scientific category ('B': Galaxies and galactic nuclei; 'C': Interstellar medium, star and planet formation; 'D': Stellar evolution).

were reviewed by Richichi & Paresce (2003), and more recent astrophysical results from the VLTI are summarized by Wittkowski et al. (this issue, page 36).

## Terminology related to interferometric observations

The principle of an observation of a celestial light source with an interferometer corresponds to the classical experiment by Thomas Young in 1803 that first showed the wave nature of light. Details on the principles of optical interferometry in astronomy can be found as well in the articles mentioned above (Quirrenbach 2001; Baldwin & Haniff 2002: Monnier 2003). Also, the textbook-style proceedings "Principles of Long Baseline Stellar Interferometry" of the 1999 Michelson Summer School in Pasadena, edited by Peter R. Lawson, provide an excellent introductory overview of the technique and application of optical interferometry (available at *http://olbin.jpl.nasa.gov/iss1999/coursenote.html*).

The primary observables of an interferometer are the amplitude and phase of the observed interference pattern, also called "fringe pattern" or just "fringes". These quantities, when normalized, are also referred to as amplitude and phase of the complex "visibility". The object intensity distribution and the complex visibility are related by a Fourier transform. The spatial frequencies are often denoted $u$ and $v$, and the Fourier plane is also called the "$uv$-plane". The total flux of the source within the field of view multiplied with the visibility amplitude for a given experiment is called the "correlated flux", corresponding to the "correlated magnitude".

The theoretical visibility amplitude of a point source is unity for any wavelength and baseline. A source is called "unresolved" (with a given instrumental setup) if its angular diameter is so small that the visibility amplitude with the given instrumental setup is consistent with unity within the precision of the measurement.

In practice, the measured visibility amplitude of a point source would be less than unity due to losses caused by atmospheric and instrumental perturbations. The real visibility amplitude of a point source as it would be obtained in an observation is called the "transfer function". To measure the transfer function, stars of known, and ideally as small as possible angular diameter are observed, and the ratio of theoretically expected and measured visibility amplitude is derived. This experimental transfer function will change due to changes of atmospheric and instrumental conditions on time scales of minutes to years.

The phase of the observed fringe pattern is disturbed by unknown atmospheric perturbations of the refractive index above each telescope on different time scales down to typically a few milliseconds at optical wavelengths, the "coherence time" of the atmosphere. This means that the observed fringe pattern constantly moves and that the integration time that is used to record the interferometric fringes can not be much longer than this time scale. To overcome this limitation, a fringe-tracking instrument, or "fringe tracker", can be used that monitors and corrects at high frequency the phase variations of the observed fringe pattern in order to stabilize it. Then, a scientific instrument can record the stabilized fringe pattern with a much longer integration time in order to improve the precision and to observe fainter targets.

Despite the use of a fringe tracker, the unknown differences of the atmospheric perturbations above each telescope cause the measured visibility phase not to correspond to the object phase of the scientific target. There are two ways to overcome this limitation. (1) The phase of the complex triple product (also called the "closure phase"), formed by multiplication of three complex visibilities corresponding to three baselines forming a triangle, is not corrupted by the phase noise caused by atmospheric turbulence, and thus gives directly the object closure phase of the scientific target. (2) If two close targets are observed through the same atmospheric pattern at the same time, and the object phase of one of the targets is known, the object phase of the unknown target can be derived relative to that of the known target. This information also includes the angular distance between the (photocentres of the) two targets, and can be used for astrometry. Also, if one target is simultaneously observed at two sufficiently close wavelength bands, the difference of the object phase at these bandpasses (of the same target) can be derived.

## Overview of the VLTI

The VLTI comprises four fixed 8 m Unit Telescopes (UTs) and four movable 1.8 m Auxiliary Telescopes (ATs), two of which already arrived on Paranal. The ATs can be positioned on thirty different stations. Figures 1–3 show views of the VLTI platform. Two science instruments, a near-infrared (AMBER) and a mid-infrared (MIDI) beam-combination instrument, are in operation.

For period 75, the VLTI was offered with all four UTs, equipped with the MACAO Coudé adaptive optics systems, and the mid-infrared interferometric instrument MIDI. During the year 2005 this configuration will be extended significantly. First fringes between the first two ATs were achieved on 3 February 2005. This makes it possible to use the VLTI from now on nearly every night with competitive telescopes for further commissioning and technical tasks, as well as for science operations. It is foreseen to start the science operations with ATs using a small subset of AT configurations, and to expand the number of offered configurations as our experience is growing. For period 76, i.e. observations from October 2005, the MIDI instrument is offered with all UTs, as well as with several AT baselines. The near-infrared closure-phase instrument AMBER is being commissioned, has already obtained its first

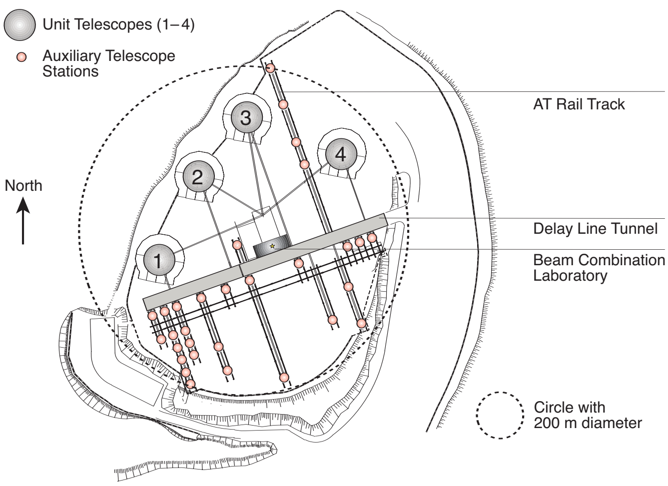


Figure 1: View of the Paranal platform with the position of the four fixed 8 m VLT Unit Telescopes (UTs) and the 30 positions for the movable 1.8 m Auxiliary Telescopes (ATs). Compare with the aerial view in Figure 2 and the recent photograph in Figure 3.

Figure 2: An aerial view of the Paranal platform as of December 1999, still in construction, with the four 8 m UTs and several foundations of the 30 stations for the 1.8 m ATs.

scientific data during the last quarter of 2004 within science demonstration and guaranteed time programmes, and is offered for regular observations with the UTs from period 76 (observations from October 2005).

Additional improvements will arise from the infrared imaging sensor (IRIS), installed in the VLTI laboratory in early January, which will stabilize the image of the observed objects in the focus of the instruments. The fringe tracker FINITO will hold the interferometric fringes in such a way that the science instruments can integrate them for much longer times than otherwise prescribed by atmospheric turbulence. Finally, the phase reference and micro arcsecond astrometry facility (PRIMA) will allow astrometric measurements with high accuracy and to directly retrieve spatial phase information of scientific targets.

## The MIDI instrument

MIDI is the mid-infrared instrument of the VLTI. It combines two beams (either from two UTs or from two ATs) to provide visibility amplitudes. The light is dispersed after beam combination with a spectral resolution of either R ~ 30 (prism mode) or R ~ 230 (grism mode). The limiting magnitude for unresolved sources, i.e. the limiting correlated magnitude, is currently $N$ = 3.25 (2 Jy) for service mode observations using the UTs and the prism mode. For visitor mode observations, when the investigator is present at the telescope and can decide whether the acquisition image and achieved beam overlap fulfills expectations, ESO accepts expected correlated magnitudes down to $N$ = 4 (1 Jy). More technical information regarding the MIDI instrument can be found at *http://www.eso.org/instruments/midi/*.

## The AMBER instrument

AMBER is the near-infrared phase-closure instrument for the VLTI. The instrument has been designed to combine simultaneously three beams, coming from a triangle of telescope stations, in order to obtain closure phases. The combined beams are spectrally dispersed with resolutions of R ~ 30 (low resolution, LR), R ~ 1500 (medium resolution, MR), or R ~ 10 000 (high resolution, HR). This means that each instantaneous AMBER measurement provides three sets (a set includes a number of spectral channels) of visibility amplitudes, for the three baselines comprising the triangle, as well as one set of triple products (including triple amplitude and closure phase). More technical information regarding the AMBER instrument is available at *http://www.eso.org/instruments/amber/*.

## User support and preparation tools for the VLTI

In the same way as for other VLT instruments, all relevant information for the use of VLTI instruments is provided by ESO through different standard documents and via the standard ESO webpages, including the call for proposals, the instrument and template manuals, as well as the webpages with general and instrument-specific proposal and observation preparation instructions.

In order to assess the feasibility of a planned observation with MIDI or AMBER, it is mandatory to estimate the visibility values for the expected intensity distribution of the science target and chosen VLTI configuration. The interactive tool provided and developed by ESO to obtain such visibility estimates is *VisCalc* (Visibility Calculator). A more detailed description of this tool including examples can be found in the recent article by Ballester et al. (2004).

The second tool provided and developed by ESO to support VLTI observation preparation is *CalVin*, which may be used to select, for each science target, a calibration star (cf. Ballester et al. 2004). Based on different user-defined criteria, *CalVin* selects suitable calibrators from an underlying list of calibrators. The strategy to preferably select calibration stars from the limited underlying lists of calibration stars preserves objects which have already been studied. Hence, more and more detailed knowledge of these calibration sources will be rapidly acquired (cf. Ballester et al. 2004). For work related to diameter estimates of calibration stars, see also the last section in Wittkowski et al. (this issue) and references given there.

Proposals for observations using VLTI instruments are prepared and submitted using the standard ESO tool as for any VLT observation (see *http://www.eso.org/observing/proposals/*). For VLTI observations, the proposal includes an additional interferometric table that lists the expected angular sizes of the proposed targets and their expected visibility values and correlated magnitudes (as for instance obtained with *VisCalc*).

The actual observations are prepared with the standard phase 2 proposal preparation (*P2PP*) tool. A detailed description of observation preparation, observation tools, phase 2 and OB preparation can be obtained from the pages of the ESO User Support Department (USD) at *http://www.eso.org/org/dmd/usg/*. Just as with service mode support for any other VLT instrument, VLTI observers can obtain assistance from astronomers at the USD specialized in interferometry.

## Sequences of observations

In order to obtain sufficient accuracy and precision of the object visibility values, observing sequences with alternating observations of scientific targets and interferometric calibration stars are performed. The data taken on all calibration stars are public once they arrive in the ESO archive. Hence, each investigator can make use of the information based on all measured calibration stars.

The scientific goal of an interferometric observation campaign can often only be reached if visibility measurements at a range of different points of the *uv*-plane are combined. This can be achieved by combining different ground baselines and by making use of Earth's rotation.

The sky-projected baseline length and angle, as well as the zenith distance, are uniquely defined for a given target and ground baseline configuration by the hour angle, or the local sidereal time, at which the observation is executed. The local sidereal time (LST) at which the observation shall be executed can be inserted into each observation block (OB). By this, observations at different sky-projected baseline lengths and angles can be planned, while the individual OBs are executed as stand-alone entities without the need of linked observations. However, priority is given to completing all observations on a scientific target once they have started. The preparation and planning of such observation sequences is supported by the visibility calculator *VisCalc* (see above).

## The constraint sets and scheduling of VLTI observations

The required ground baseline configuration, as well as the local sidereal time at time of execution (see above) are constraints that are specific to VLTI observations and do not exist for observations with instruments at the single UTs. Moreover, the performance of VLTI-specific subsystems such as the adaptive optics systems (MACAO) for VLTI, or the fringe tracker have to be monitored in addition.

On the other hand, other constraints, as for example the requirements for the regular seeing condition or for the lunar illumination may be less important for VLTI observations than for classical VLT instruments such as ISAAC or the FORSes. In general, the scheduling of VLTI observations is complicated by the additional constraints on baseline configuration and LST. As a result, one tries to avoid additional stringent constraints in order to enable a smooth and efficient science operation of the VLTI.

## Quality control of VLTI data

Since P73, the MIDI data pass through the entire data flow operations systems in the same way as the data of any other VLT instrument (cf. Ballester et al. 2004). The raw files obtained during service mode observations are processed for quality control purposes using the data reduction system developed by ESO, the algorithms of which have been provided by the MIDI consortium. Each processed OB is associated with a FITS file product containing quality control parameters and results, such as the visibility value and the instrumental transfer function for data of known calibration stars, or a calibrated visibility value for a scientific target. For P73, 80% of the OBs received by the pipeline resulted in data products. For the start of the AMBER science operations, a similar data flow operations system will be available for AMBER data.

## Reduction of VLTI data

The ESO pipeline data reduction as described above was developed for quality control purposes and optimized to process most of the data obtained (with a large variety of flux levels, visibility amplitudes, etc.) in an automatic way with acceptable accuracy and precision. A more detailed reduction of data from a specific programme may be necessary for scientific purposes which usually have more stringent requirements for precision and accuracy.

Two data reduction packages are currently available for the scientific reduction of MIDI data, available from MIDI consortium members of the University of Leiden and the Max-Planck-Institute for Astronomy in Heidelberg (a merged version can be found at *http://www.strw.leidenuniv.nl/~nevec/MIDI/index.html*; also see *http://www.mpia-hd.mpg.de/MIDISOFT/*). A third one from the Observatory of Meudon is about to be released to the astronomical community. These packages have some technical differences, the details of which can be found in their documentation. For a given specific purpose, one of these packages may be more suitable than another. Detailed technical information on MIDI data reduction is also being collected and compiled by Christian Hummel, and provided to the user community on an "as is" basis at *http://www.sc.eso.org/~chummel/midi/midi.html*.

So far, one package exists for the reduction of AMBER data, available from consortium member Astrophysical Lab of the Observatory of Grenoble. The AMBER package has not yet been released to the public.

MIDI data reduction will usually result in one calibrated visibility amplitude for each spectral channel and observation. For AMBER, the resulting processed and calibrated data will usually include three calibrated visibility amplitudes, corresponding to the three baselines of the triangle, and one calibrated triple product (triple amplitude and closure phase) for each spectral channel and observation.

If such interferometric data, obtained with a three station array such as the VLTI with the AMBER instrument and taken in several spectral channels and (projected) baseline configurations, are combined, it may already be possible to directly reconstruct the image of a simple object intensity distribution, for example of a binary star. The first optical images reconstructed from such sparsely sampled visibilities and closure phases, obtained with the "Cambridge Optical Aperture Synthesis Telescope (COAST)" and the "Navy Prototype Optical Interferometer (NPOI)", were presented by Baldwin et al. (1996) and Benson et al. (1997), respectively. However, in the majority of cases so far, and probably as well in the near future, the interpretation of optical/infrared calibrated visibility values and closure phases from long-baseline interferometry is accomplished by comparison to models. A model-predicted object intensity distribution is used to compute the corresponding synthetic visibility values and closure phases for the employed baseline configurations and spectral channels, and these values are compared to the measured ones in order to find agreement or disagreement. Usually, model parameters are adjusted in order to find the best possible agreement with the measured data.


## Acknowledgements

The integration of VLTI observations into the regular ESO science operations scheme has involved a lot of people inside and outside ESO, too many to name here. We warmly acknowledge this collective effort.


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Figure 3: A recent photograph taken on the VLTI platform in January 2005 by Bertrand Koehler. The first two ATs, located at station E0 and beside G0, are shown in the foreground, as well as UTs 3 and 4 (MELIPAL and YEPUN) in the background. The building that can be seen in between the ATs is located on top of the interferometric lab, where the beams coming from the UTs or ATs are combined. The beams are sent through an underground light-duct system to the interferometric lab. Courtesy B. Koehler.