The Very Large Telescope Interferometer: current facility and prospects

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1 A brief history

Right from the start of the Very Large Telescope project in the late 1970s, interferometry was seen as an integral part. The early move from a linear array for the 8.2 m Unit Telescopes (UTs) to a trapezium structure was a sign of this. During the early 1990s, the European Southern Observatory (ESO) designed the general optical layout of the interferometer. After an ESO council decision in 1993, the deployment of the VLTI was halted and only concrete was cast: the tunnel, laboratory and light ducts were built.

The VLT Interferometer (VLTI) gained momentum, when the Max-Planck-Gesellschaft (MPG) in Germany, the Centre National de la Recherche Scientifique (CNRS) in France, and ESO signed a three-partite-agreement to finance a third Auxiliary Telescope (AT) in 1996, and the first two science instruments, MIDI and AMBER, were proposed by the community in 1997.

In 1998, contracts for ATs and Delay Lines were placed with European industry and the development of AMBER and MIDI started. The installation of test siderostats and Delay Lines started on Paranal in 2000, followed by the test instrument VINCI in 2001. This phase was finished when first fringes with VINCI on the siderostats was achieved on March 18, 2001.

Regular VLTI observations with the first scientific instrument,

Fig. 1. The summit of Paranal in early 2005. The picture is dominated by the enclosures of UT1 to UT4 from left to right. In the background between UT3 and UT4 one can see the enclosure of the VLT Survey Telescope (VST). Flanking the VST in the foreground, the first two ATs can be seen. To the left of the ATs and at the far right of the picture, the small enclosures of the two test siderostats are visible, which have been removed in the meantime. The white lids in the front to the left are covering some of the 30 station pits to which the ATs can be moved.

the mid-infrared instrument MIDI, on the 8.2 m UTs started in April 2004. Since October 2005, MIDI is also offered on the movable 1.8 m ATs on three different baselines. At the same time the near-infrared instrument AMBER started its observations on three UTs simultaneously. AMBER is offered for first science on three ATs from April 2007.

2 Status

Today, the Very Large Telescope Interferometer (VLTI) on Cerro Paranal (see Fig. 1), about 80 km south of the city of Antofagasta in Northern Chile is without doubt the largest optical interferometer in the world. It comprises a total of eight telescopes, four fixed 8.2 m Unit Telescopes (UTs) and four movable 1.8 m Auxiliary Telescopes (ATs), which can be located on 30 stations.

The four large telescopes are all equipped with the adaptive optics

Fig. 2. One of the Unit Telescopes can be seen on the left and one Auxiliary Telescope (in the Paranal AT integration hall) on the right.

Fig. 3. One of the Delay Lines (with an optical alignment tool inserted in one of the optical paths).

system MACAO, which is located in the Coudé rooms. The six baselines spanned by the UTs are between 47 m and 130 m, while the ATs cover a range between 8 m and 202 m. While all UT baselines have been realized for science, seven of the 30 stations to which the ATs can be relocated have been used so far and three baselines (16 m, 32 m, and 64 m) are regularly used for science operations. The ATs are moved between stations in daytime.

The light collected by the telescopes is sent through light ducts to the underground Delay Line tunnel. This tunnel has a length of 140 m and is the home of the six Delay Lines. The Delay Lines are used to ensure that the optical path length (the path traveled by the light from the star through each telescope to the beam combination instrument) is equalized for all beams, while tracking the object. The beams are combined in the interferometric laboratory in the two science instruments, MIDI and AMBER. During the commissioning phase, the test instrument VINCI was used. The near-infrared tip/tilt tracker IRIS allows to hold the beams at a given focal point and the fringe tracker FINITO stabilizes the optical path difference (OPD) between up to three beams. The PRIMA dual feed facility (Delplancke et al., 2006) will complete the first phase of the VLTI. At the end of 2006, nearly all hardware is installed. Missing is PRIMA, which is scheduled to arrive at the end of 2007. Pictures of the telescopes and Delay Lines can be found in Figs. 2 and 3.

3 What does the VLTI infrastructure do and how does it do it?

The VLTI infrastructure is supposed to put the light "into the one place at the one time". It injects the image plane into the VLTI laboratory at a given point, makes the interferometer output pupils coincide with the input pupils of the various instruments and ensures that OPD variations are only atmospheric or even residuals of the atmosphere. A schematic overview about the VLTI infrastructure is given in Fig. 4.

To achieve this goal, each UT is equipped with a MACAO adaptive optics system, that concentrates the bulk of photons within the Airy ring. This beam is propagated via the relay optics to the delay lines.

The delay lines follow the geometric OPD as prescribed by the locations of the telescopes and the observed source, accurately determined by an OPD model. The variable curvature mirror

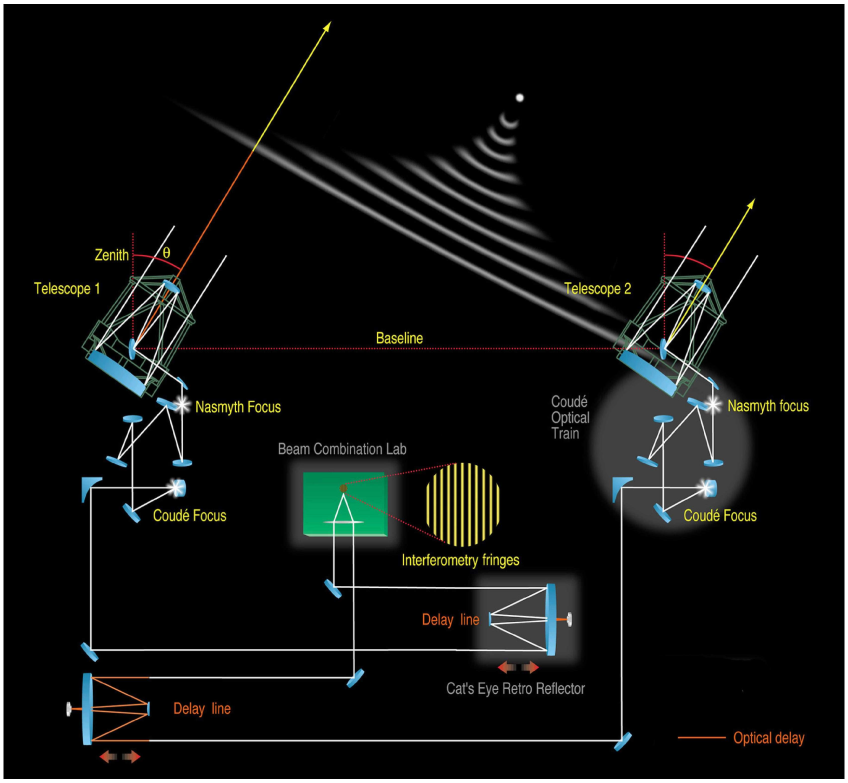

Fig. 4. Schematic overview about the VLTI infrastructure.

(VCM), sitting in the image plane of the Delay Line's cat's eye, moves the pupil in axial direction to the desired output pupil position. The availability of the VCM is crucial for operations of the ATs, since otherwise the AT field of view is completely vignetted and limited to less than 1″.

IRIS (Gitton et al., 2004) is the laboratory tip/tilt tracker in the VLTI. It operates in the near infrared (H or K band) and can track up to four beams in parallel (two beams for MIDI operations, three beams for AMBER operations, or two dual beams for PRIMA operations). IRIS serves two purposes. After an object has been acquired in the Coudé focus of either the UT MACAO system or the AT STRAP in the visible, it allows to acquire the source in the laboratory. Additionally, it allows to correct for drifts between the telescope and lab foci, which are introduced by turbulence and thermal drifts.

FINITO (Gai et al., 2004) is a three beam fringe tracker that operates in the H band. FINITO corrects for atmospheric and

Table 1
Overview about the VLTI science instrumentation modes. The limiting magnitudes are given for the most sensitive mode for P79 (starting April 2007). AMBER J band operations are not offered yet, neither are some other AMBER modes.

	Band	Number of beams	Spectral resolution	Limiting magnitude	
				UTs	ATs
AMBER	K	3	35	7	5.1
	H	3	35	–	5.5
	K	3	1500	4	1.6
	K	3	10,000	1.5	–
MIDI	N	2	30	4	0.7
	N	2	230	2.8	0.3

instrument OPD variations by controlling the Delay Lines with high bandwidth. After an extensive debugging time, which mainly addressed the VLTI infrastructure, FINITO is able to track fringes for both the ATs and UTs. AMBER and MIDI science observations will both benefit from FINITO fringe tracking very soon.

4 Instrumentation and Operations

The characteristics of the two science instruments, MIDI (Leinert et al., 2003) and AMBER (Richichi and Petrov, 2004), including their spectral coverage, number of beams combined, spectral resolution and currently offered limiting magnitudes, are recalled in Table 1. Figure 5 shows both instruments in the VLTI laboratory.

The VLTI is fully integrated in the VLT data flow system. MIDI and AMBER follow the established general operations scheme of the other VLT instruments, including the proposal form, OB preparation and execution, FITS data format, and science data archive. Observations are performed both in Visitor Mode and in Service Mode. The progress over the last five years is best illustrated by the different instrumental modes which were offered

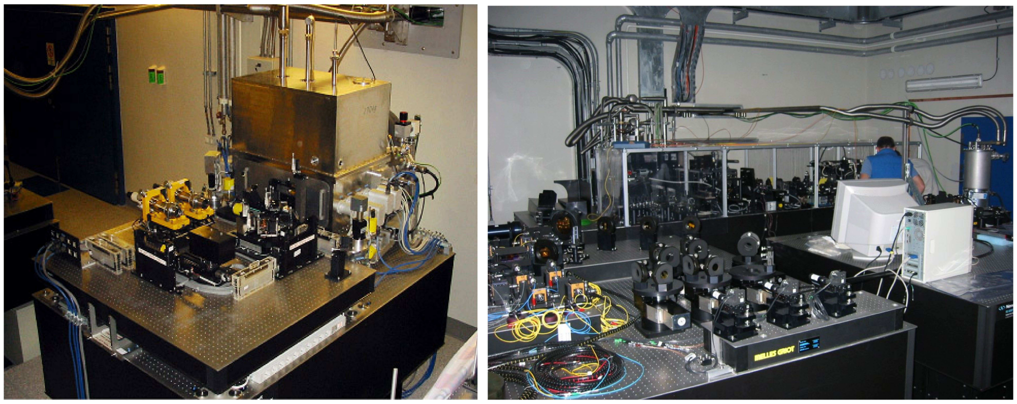

Fig. 5. MIDI (left) and AMBER (right) in the VLTI laboratory.

Table 2
Modes offered to the interferometric community over ten periods.

P70	Oct 2002	VINCI on siderostats
P71	Apr 2003	as P70
P72	Oct 2003	no modes offered to allow further integration
P73	Apr 2004	MIDI on two UT baselines, prism only, 5 Jy
P74	Oct 2004	MIDI on three UT baselines, also grism, 1 Jy
P75	Apr 2005	MIDI on all UT baselines
P76	Oct 2005	also MIDI on three AT baselines, science photometry mode, slightly better limiting fluxes; AMBER offered on all four UT triples, LR-HK, MR-K (low/medium resolution)
P77	Apr 2006	as P76
P78	Oct 2006	AMBER also offered in HR-K, reduced overheads on AMBER
P79	Apr 2007	AMBER on AT baselines

(see Table 2). VLTI science operations is using more than 40% of the nights in a given period, until now nearly equally split between the UTs and the ATs. The remaining nights are used for further integration, commissioning, and technical tests.

During science nights, the observing team consists of one night astronomer, who runs the instrument, and a telescope instrument operator (TIO), who runs the interferometer. When using the ATs, the same TIO is also running the telescopes. In case of UTs, each telescope additionally has its own TIO, to take care of the much complexer control (e.g., the MACAO systems) and

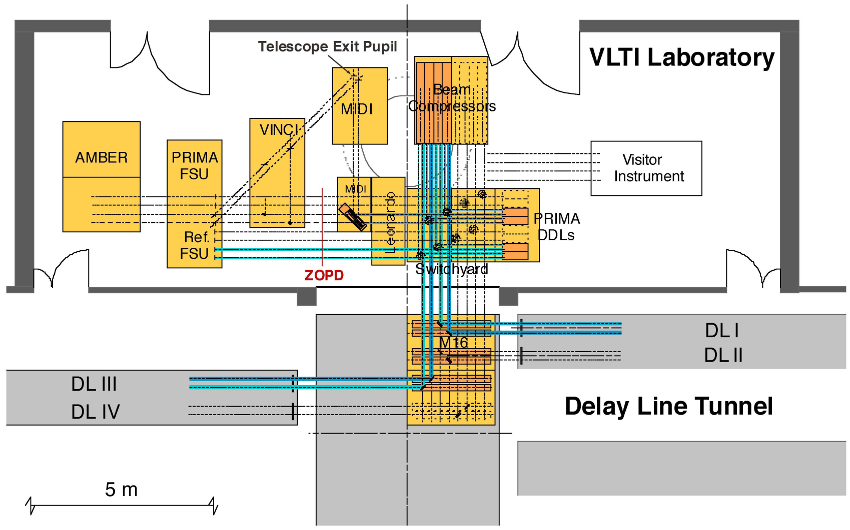

Fig. 6. The VLTI laboratory layout.

to ensure the safety of each telescope. The VLTI team has six operations staff astronomers and three fellows. In the near future we will start qualifying other operations astronomers for VLTI, to spread knowledge and to become more flexible. More than half of the TIOs are able to run the VLTI.

In a regular period (i.e., no integration or commissioning), daytime operations consist of maintenance activities. An engineer fills the function of VLTI manager, controls all access to the interferometer during daytime and coordinates all required interventions. Our experience has shown that we do not need to realign the interferometer on a regular basis. The main task which we have to repeat at the start of each night is viewing the telescope pupil. The pupil is moved via the motorized M10 mirror, which sits in the folded Coudé focus.

5 Image and pupil planes

The VLTI has a myriad of image and pupil planes, which all have to be aligned with respect to each other.

There are four image planes before the laboratory: the folded Nasmyth focus (in air), the Coudé focus (on MACAO), the folded

Coudé focus (on M10), and the focus on the Delay Line's VCM. In the laboratory (see Fig. 6), there is a focus on the Beam Compressor secondary, in the Differential Delay Lines, and in all instruments (MIDI, VINCI, PRIMA FSU, IRIS, FINITO, and AMBER).

Pupil planes can be found at M2, M8 (MACAO deformable mirror) and in the center of the Delay Line tunnel. The Delay Line VCM images the last pupil onto the primary of the beam compressors. The beam compressors image the pupil onto a diagonal line in the VLTI laboratory, which goes roughly through the MIDI cold stop, the VINCI injection parabolae and the PRIMA FSU feeding optics.

6 Functionality

To illustrate the complex and nested control structure of the VLTI, we will give two examples of VLTI functionality: the fringe acquisition and offsetting the image.

To acquire a fringe, the telescopes and Delay Lines are preset to the positions given by the object coordinates and telescope locations, taking the pointing models of the telescopes and the interferometer OPD model into account. On the UTs, a Nasmyth focus guide star is acquired within a $30'$ field of view. This guide star is also used for the active optics. Then, a Coudé guide star is acquired within $2'$, on MACAO (UTs) or STRAP (ATs). Next, the science object is acquired on IRIS and put on the reference pixel defined for each beam. Afterwards, the science object is centered on the AMBER fibers or the MIDI reference pixel. Acquisition on MIDI will require chopping of the telescopes to remove the thermal background. Once the objects are acquired, the fringes are searched by modulating the OPD in small steps around the zero OPD (ZOPD).

If AMBER wants to offset the image in front of its fibers, it sends

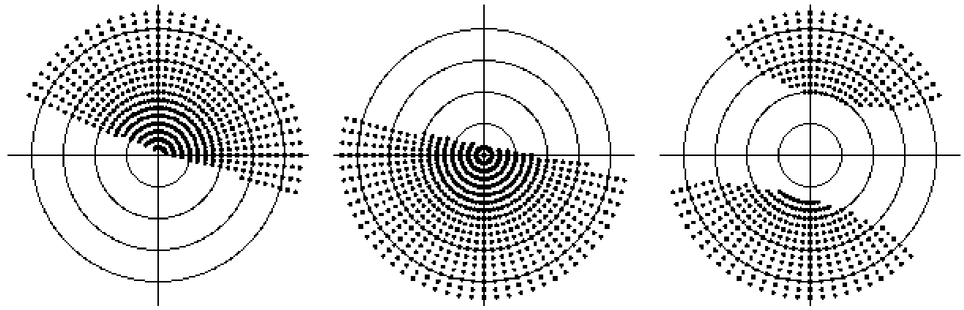

Fig. 7. Delay Line restrictions for the B5-G2-J6 AT configuration: B5-G2, G2-J6, and B5-J6 (from left to right). North is to the top and east to the right. Rings are 20° apart in zenith distance and the outermost ring starts at 80° zenith distance, or 10° elevation. The dots indicate the regions of the sky which are not accessible for the VLTI. While each baseline alone has already severe limitations, the three baselines together leave no sky accessible.

an OFFSGUV command (offset guide probe in UV, i.e. ground coordinates) to the interferometer supervisor software (ISS). ISS forwards this command to IRIS and IRIS modifies its reference pixel. IRIS sees that its guide star is not at the (new) reference pixel and sends an offset to the telescope main guider, e.g., on a UT to the MACAO system. This offset is applied to the xy-table which holds on top the MACAO curvature sensor. The MACAO sensor sees that the star is moving away from its central reference point and will counteract by sending a command to the M8 tip/tilt stage. If the M8 tip/tilt stage is getting close to its operational limit, it will offload the tip/tilt to the M2 mirror, and the M2 mirror maybe on the telescope itself.

7 Operational constraints

There are several factors limiting the operations of the VLTI: availability of Delay Lines (e.g., one can not use three ATs on the eastern half of the mountain), design of tracks (one can not use two telescopes on the same northern or southern track), the horizon (some AT stations are shaded by the larger UTs), and the limited stroke length of the Delay Lines. To illustrate the latter problem, Fig. 7 shows the sky accessibility for the configuration B5-G2-J6, which is nearly zero.

8 Improvements

In December 2004 ESO held an internal review of the existing VLTI infrastructure to establish its performance, operability, maintainability, and capability to host PRIMA. Although scientifically successful, the VLTI infrastructure required certain subsystems to be brought to robust operation and some others to be fully commissioned to streamline the operations and allow further deployments. In particular, before PRIMA deployment and second generation instrumentation we would need to know that we can fringe track. The Paranal Observatory accepted the infrastructure and launched the Interferometry Task Force (ITF) in April 2005 to seek the understanding necessary to make improvements to the system. A major fraction of the time not used for science was set aside for the ITF. The work was focusing on the BFQ – the Big FINITO Question, i.e. fringe tracking on the UTs. Towards the main goal, also the SFQ (the Small FINITO Question, fringe tracking on the ATs) was addressed.

After thorough system tests, it was shown that there were only two things preventing fringe tracking: the instability of light injection into the fibers and vibrations on the UTs. The results of the ITF effort are described in detail by Bonnet et al. (2006).

8.1 Injection stabilization (1) — the Variable Curvature Mirror and the Delay Line rail shape

The variable curvature mirror (VCM) (Ferrari et al., 2003) sits in the image plane of the Delay Line's cat's eye and allows to manipulate the longitudinal pupil position with an accuracy of about 1 m. Thus it is possible to image the telescope pupil onto e.g. the cold stop of MIDI, reducing the thermal background being diffracted in from surfaces at ambient temperatures. The VCM is needed since the optical distance from the telescope to the instruments is changing when the Delay Line moves. The VCM is

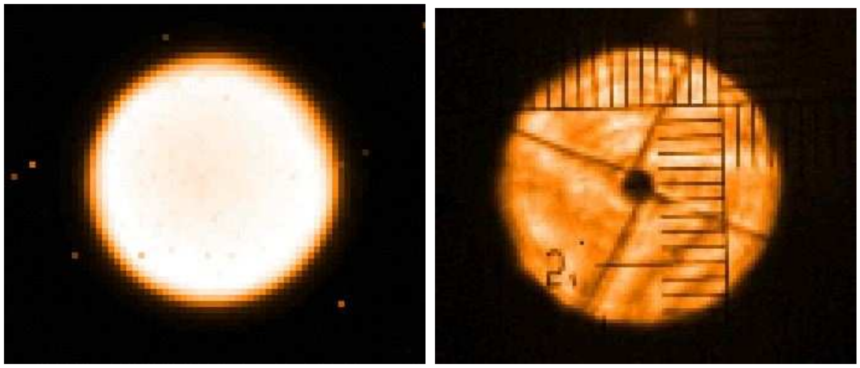

Fig. 8. Field-of-view and pupil of one AT, as seen on the ARAL TCCD, when inflating the VCM to the correct position.

mandatory to have an unvignetted field of view when using the ATs. Note that the M10/M11 assembly in the UTs is imaging the telescope pupil to the center of the Delay Line tunnel, while the output pupil of the ATs is located close to the telescope itself, i.e. a varying distance from the tunnel center, depending on the AT location.

Unfortunately, having a higher curvature in the focal plane of the Delay Line leads to more stringent requirements for the optical alignment of the mirror itself and finally to more stringent requirements for the alignment of the rails on which the Delay Line moves. The highest curvature of the VCM is needed when an AT is very far away from the tunnel center and the Delay Line at the end of the rail. If the rails are not well aligned, the metrology laser light might even not leave the carriage. Thus, to ensure a functioning VCM, it was mandatory to align the Delay Line rails with a precision better than $20\,\mu$m.

On each Delay Line the ITF installed two capacity sensors (each giving positions in x and y relative to a metal wire; see Fig. 9) and one roll sensor. The last degree of freedom is determined by the laser metrology. After being able to reconstruct the actual shape of the rail from the measurements, it was possible to calculate an error vector through an interaction matrix. Each value in the error vector corresponds to a manipulation of a screw in the rail supports. Corrections under a certain threshold (e.g., $7\,\mu$m) are not applied. More than one iteration is necessary if the rails were

Fig. 9. One capacity sensor and the reference metal wire below a Delay Line.

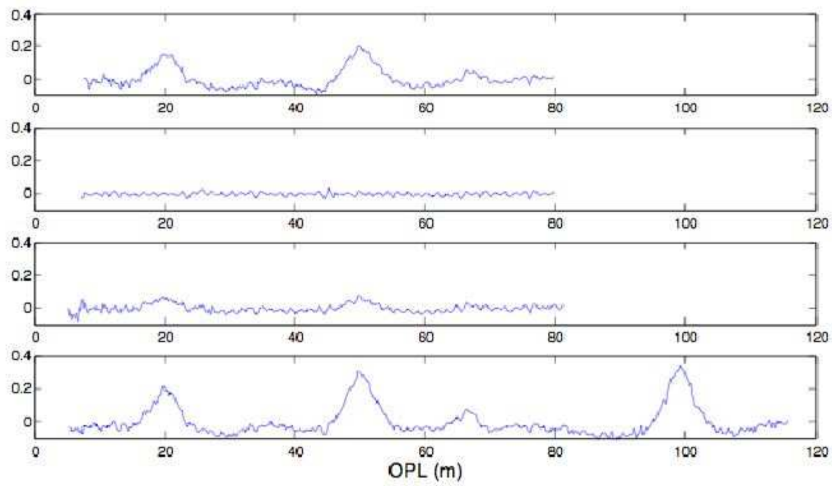

Fig. 10. Shape of Delay Line rails in vertical direction. On the x-axis the optical path length of the Delay Line position is given in m (twice the mechanical stroke). The y-axis gives the deviation from straightness in mm. The upper three curves show from the top DL6 on June 10, June 17, and August 2 in 2005. The curve at the bottom shows DL5 on August 5, 2005. The top and bottom curves were taken months after the last realignment, the second from the top directly after a realignment and the third from the top six weeks and a temperature drop of 2°C later. The spikes at 20 m, 50 m and 100 m correspond to junctions in the concrete. On DL6 there are no data after OPL 80 m due to limits on the maximum stroke in 2005 for DL6.

not aligned for a longer period of time.

Additionally to being able to realign the Delay Line rails, it was important to understand what triggers the deformation of the rails. The two main suspects were temperature drifts and seismic activities. Looking at the measured rail shapes (Fig. 10) one

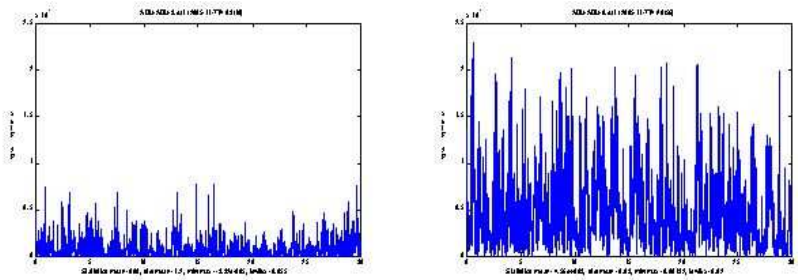

Fig. 11. Injection into FINITO from the ATs without a VCM (left) and with a VCM (right). While the gain in average flux is about a factor of 5 in this case, the number of flux dropouts was not reduced.

can see that the main deformation mode of the rails has spikes exactly at the position of the tunnel concrete junctions. With data over a large range in both time and temperature, it was possible to show that about 90% of the deformation projects into this mode and correlates with the temperature. Seismic activities could widely be ruled out after Paranal was hit by a heavy earthquake on June 13, 2005 at 22:44 UT, during a Delay Line rail alignment campaign. The corresponding earthquake was about 500 km north of Paranal (i.e., the seismic wavefront was parallel to the rails), close to the city of Iquique, with a strength of 7.9 on the Richter scale. Measurements of the DL6 rail shape were performed at 08:38 UT and 23:23 UT that day. No difference of the shape could be made outside of the measurement errors.

Having a VCM operational in the Delay Lines and thus increasing the field of view for the ATs to its nominal value gives an increase in flux into the FINITO fibers, as can be seen from Fig. 11. While this improves the overall situation, flux dropouts are still present.

8.2 Injection stabilization (2) — tip/tilt tracking

For a next step in improving the injection stability into the fiber, the tip/tilt signal of the infrared tip/tilt tracker in the interferometric laboratory (IRIS) was used to keep the stellar image centered on the FINITO fiber.

The scope of IRIS was originally based on slow (<10 Hz) compensations of drifts between the image position in the telescopes and the image position in the laboratory, mainly introduced by "tunnel seeing". The actuators are the xy-tables which hold the head of the MACAO (UTs) or STRAP (ATs) sensor.

The ACU actuators directly in front of the FINITO fibers, normally used only to align the fiber, were tuned from a few Hz bandwidth to a few 100 Hz bandwidth and IRIS now drives them in open loop (the signal from IRIS feeds the ACU but there is no feedback to IRIS).

8.3 Injection stabilization (3) — MACAO systems

Although the MACAO adaptive optics systems on the UTs are meeting the specifications for long term (i.e., 5 s) Strehl performance, they did suffer from saturation of the mirror, creating point spread function explosions and flux dropouts. Saturation does occur when the voltage of any individual electrode exceeds 400 V. Saturations do occur even in good seeing conditions because of the noise propagation along the waffle modes: those modes are poorly propagated by the system and therefore the noise propagation along these modes absorbs a large fraction of the voltage budget at almost zero wavefront improvement. Clipping the command at saturations triggers a non-linear response of the system that projects the energy propagated along these inefficient modes on more efficient ones, causing a chaotic wavefront distortion. The saturation management algorithm (SMA) is an attempt to minimize the wavefront error cost of the saturation. Anti-windup (AW) is an additional feature consisting in opening the loop on the uncontrolled mode during saturation events to avoid divergence of the integrator and therefore prepare a faster recovery at the end of the saturation event. These algorithms led to a drastic improvement of the minimum Strehl at any given time and atmospheric condition.

Unlike the ATs, which do not show significant vibrations, we have seen for some time vibration induced contrast losses on the UTs. Vibrations were the main reason why fringe tracking on the UTs did not succeed after all other problems were fixed. They are still today the major source limiting the performance of FINITO fringe tracking.

The main vibration contributors identified so far are:

- MACAO electronics cabinet fans in the Coudé rooms, mechanical and acoustic coupling to the Coudé room mirrors (M9, M10, and M11)
- pump in the auxiliary cooling circuit, introducing acoustic waves in the cooling liquid, which excite M5
- M3 tower eigenmode
- M1 cell eigenmode

Possible ways to cope with these vibrations are:

- damping and/or removal of the exciting sources
- feed forward piston errors from accelerometer measurements
- feed forward other measurements of the piston (e.g. derived from tip/tilt on MACAO or from FINITO data beyond the control bandwidth)

All three strategies are followed at the same time.

8.5 FINITO fringe tracking

On March 24 2006, FINITO was able to fringe track on the ATs over time periods of tens of minutes. There were glitches, but FINITO was able to recover. The atmospheric conditions were good, but not exceptional. Fringe tracking has successfully been repeated since then. The piston rms seen was on the order of

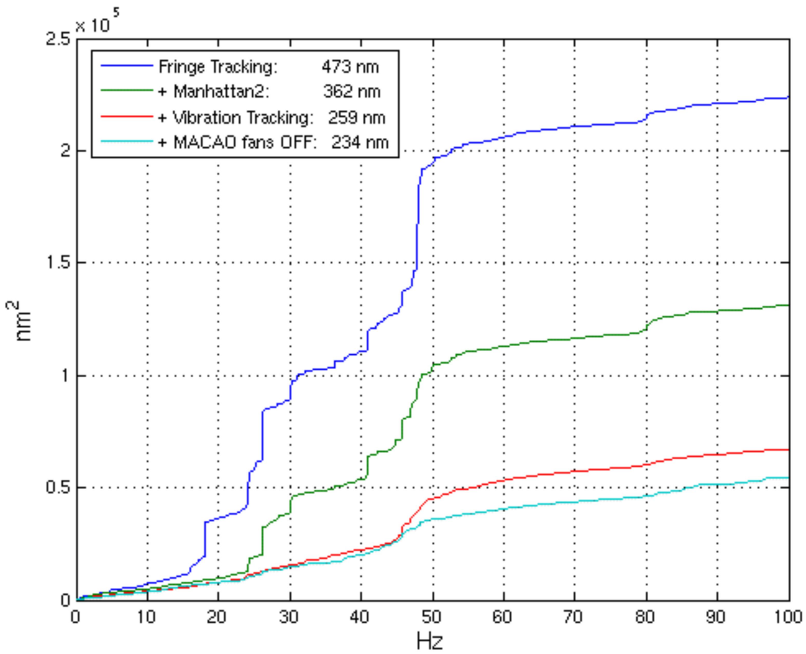

Fig. 12. UT fringe tracking improvements. The upper curve shows the cumulative power of the phase (OPD) residual during “naked” fringe tracking with a residual above 450 nm rms. Accelerometer feed forward to the delay lines is switched on (next curve from top) reducing the residual to 362 nm. Vibration tracking (VTK) is added (third curve) reducing the residual further to 259 nm. Finally, MACAO cabinet cooling fans are switched off (bottom curve), bringing down the residual to 234 nm.

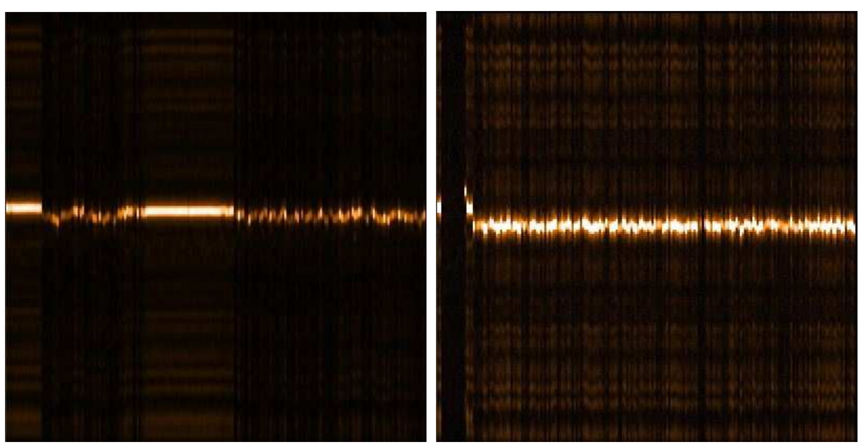

Fig. 13. Display of the first MIDI data with a working fringe tracker in the night of March 29, 2006 (left). The horizontal lines denote the periods where FINITO was keeping the fringes stable. In the periods with the fuzzy signal in between, FINITO is trying to find the fringes again, successfully after it has lost them for the first time. Compare this with the data acquired when MIDI tracks its own fringes (right).

100 nm.

By the middle of May, fringes could also be tracked over long time periods on the UTs, but with a piston rms of about 450 nm, in good weather conditions and with a reduced telescope diameter (5.3 m).

Since then, a lot of progress has been made, which led to a performance below 250 nm (see Fig. 12). An example of how MIDI benefits from FINITO can be seen in Fig. 13.

9 Future

9.1 Immediate future

The main task of the ITF has been fulfilled, namely proving that fringe tracking on the UTs is possible. The ITF focus has shifted towards eliminating the vibration problem. At the same time, the solutions found for the various injection problems have been or will be implemented in an industrial way: all six Delay Lines will be equipped with VCMs, the new algorithms have to be implemented in the standard software version of the MACAOs, FINITO accepts now three beams and tracks on two baselines, and at least AMBER will also need a fast tip/tilt actuator to stabilize the flux injection. Furthermore, beam splitting dichroics were installed in the laboratory to allow sharing of H and K band flux between AMBER, IRIS, and FINITO. AT4 will be integrated in VLTI operations in early 2007.

9.2 Longer term future

The Phase Reference Imaging and Microarcsecond Astrometry (PRIMA) system is schedule for installation by the end of 2007 (Delplancke et al., 2006).

ESO has awarded phase A studies for three potential second generation VLTI instruments: GRAVITY (Gillessen et al., 2006), MATISSE (Lopez et al., 2006), and VSI (Malbet et al., 2006). The results of these studies are due in 2007 and installation is targeted for 2011.

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