The Very Large Telescope Interferometer: an update

Pierre Haguenauer*[a], Roberto Abuter[b], Jaime Alonso[a], Javier Argomedo[a], Bertrand Bauvir[b], Guillaume Blanchard[a], Henri Bonnet[b], Stéphane Brillant[a]. Michael Cantzler[a], Frédéric Derie[b], Françoise Delplancke[b], Nicola Di Lieto[b], Christophe Dupuy[b], Yves Durand[a], Philippe Gitton[a], Bruno Gilli[a], Andreas Glindemann[b], Serge Guniat[a], Stéphane Guisard[a], Nicolas Haddad[a], Gerhard Hudepohl[a], Christian Hummel[b], Nathaniel Jesuran[a], Andreas Kaufer[a], Bertrand Koehler[b], Jean-Baptiste Le Bouquin[a], Samuel Lévêque[b], Christopher Lidman[a], Pedro Mardones[a], Serge Ménardi[b], Sébastien Morel[a], Isabelle Percheron[b], Monika Petr-Gotzens[b], Than Phan Duc[b], Florence Puech[b], Andres Ramirez[a], Fredrik Rantakyrö[a], Andrea Richichi[b], Thomas Rivinius[a], Johannes Sahlmann[b], Stefan Sandrock[a], Markus Schöller[b], Nicolas Schuhler[a], Fabio Somboli[a], Stanislav Stefl[a], Mario Tapia[a], Gerard Van Belle[b], Anders Wallander[b], Stefan Wehner[a], Markus Wittkowski[b]
[a]European Southern Observatory, Casilla 19001, Santiago, Chile;
[b]European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

ABSTRACT

The ESO Very Large Telescope Interferometer (VLTI) offers access to the four 8 m Unit Telescopes (UT) and the four 1.8 m Auxiliary Telescopes (AT) of the Paranal Observatory located in the Atacama Desert in northern Chile. The fourth AT has been delivered to operation in December 2006, increasing the flexibility and simultaneous baselines access of the VLTI. Regular science operations are now carried on with the two VLTI instruments, AMBER and MIDI. The FINITO fringe tracker is now used for both visitor and service observations with ATs and will be offered on UTs in October 2008, bringing thus the fringe tracking facility to VLTI instruments. In parallel to science observations, technical periods are also dedicated to the characterization of the VLTI environment, upgrades of the existing systems, and development of new facilities. We will describe the current status of the VLTI and prospects on future evolution.

Keywords: Optical long baseline interferometry, Very Large Telescope Interferometer

1. INTRODUCTION

The Paranal Observatory is located on the top of Cerro Paranal in the Atacama Desert in the northern part of Chile and what is believed to be the driest area on Earth. Cerro Paranal is a 2,635-m high mountain, about 120 km south of the town of Antofagasta and 12 km inland from the Pacific Coast, a situation ensuring excellent observing conditions.

The Very Large Telescope Interferometer (VLTI) is one of the largest optical interferometer in the world with its four fixed 8.2-m Unit Telescopes (UTs) and four 1.8-m Auxiliary Telescopes (ATs) that can be relocated on any of the 30 available stations (see Fig. 1). This unique array allows access to baselines between 47-m and 130-m with the UTs, and between 8-m and 202-m with the ATs. From the telescopes, the light is sent to the underground interferometric facility, which comprises the delay lines tunnel and the VLTI coherent laboratory where the instruments are located. The delay lines (DL) equalize the optical path length (OPL; distance traveled by light from the target to the instrument) while tracking on the astronomical object. Six delay lines are currently available in the 140-m long tunnel. A system of movable mirrors allows sending the light from each DL to any of the sixteen input channels of the VLTI laboratory, providing a very versatile facility. The wavefront distortions induced by the atmosphere are corrected in real time by adaptive optics systems: the MACAO curvature wavefront sensors on the UTs, and the STRAP tipt-tilt sensors on the ATs. Two instruments are currently offered for science: the MIDI N-band two-beam combiner, and AMBER combining three-beams in J, H, and K bands. The IRIS guiding camera delivers a stable focal point for the instrument. The FINITO fringe tracker is now offered on ATs and will be on UTs in October 2008, and allows for real time correction of the optical path difference (OPD) between three telescope beams. The PRIMA instrument shall be installed at Paranal during the second half of 2008, and will thus complete the first development phase of the VLTI.

* phaguena@eso.org; phone: +56 55 43 5239.

Since April 2007 (Period 79), MIDI (MID-infrared Instrument) is offered on ten different baselines with the ATs, ranging from 16-m to 128-m, and on all six UTs baselines. For the same periods, AMBER (Astronomical Multi-BEam combiner) has been offered with all four UTs triplets and four ATs triplets. Both instruments are operated in visitor and service mode, following the established general operations schemes of all VLT instruments. The available nighttime at the VLTI is currently used at the 60% level for science operations, the rest of the time being used for monitoring and characterization of the system, improvements and installation of new elements.

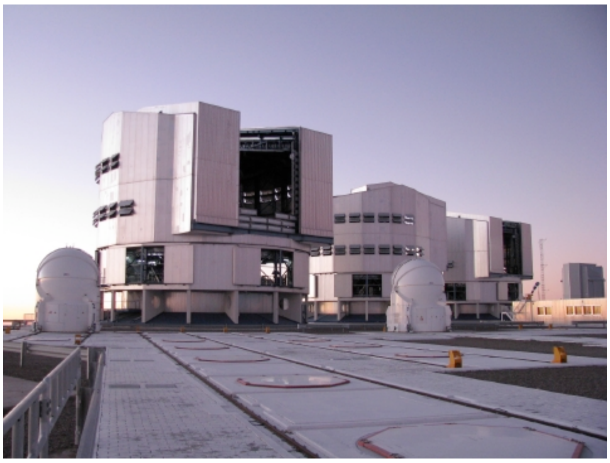

Fig. 1. The VLT Interferometer at Paranal in 2008. On the left picture, one can see the four ATs spread out on the summit, offering a variety of size and orientation of baselines. On the right picture, one can see two of the ATs in front of the UTs. In the foreground, some of the ATs stations are visible with their covers.

2. SUBSYSTEMS PROGRESSES

This section presents the newly delivered and updated systems during the last two years at the VLTI. Earlier descriptions of the VLTI can be found in the proceedings of previous SPIE conferences[1,2].

2.1 Auxiliary Telescopes

Since January 2007, the fourth AT has been delivered to operation. None of the current instruments can yet make use of the four ATs at the same time (but it will in the future, see 5.2), but the flexibility of the array is improved: six baselines can be accessed simultaneously per configuration of the telescopes. Solutions to get full advantage of this array configuration flexibility (baseline length and orientation, sky coverage, improved configuration change) are currently under study, taking into account the different requirements of the instruments and their scientific objectives.

An upgrade of the STRAP (System for Tip-tilt Removal with Avalanche Photodiodes) tip-tilt sensor is currently developed to improve the maintainability and the performances of the system. Delivery is expected by the end of 2008.

The new STS[3] (STar Separator) relay optics structures (ROS) for the PRIMA dual feed operation have been aligned on AT3 and AT4 and are under commissioning. They will allow selecting two different stars in the field of view of the telescopes and send their light simultaneously to the VLTI instruments.

2.2 IRIS Fast Guiding

Instrument using single-mode fibers are very sensitive to tip-tilt for the injection of the telescope flux. The adaptive optics systems, the MACAOs (Multi-Application Curvature Adaptive Optics) wavefront sensors on the UTs and the STRAP tip-tilt sensors on the ATs, allow correcting for the tip-tilt originating from the atmosphere. But these systems are located in the telescopes themselves and the light still has to propagate from there to the VLTI instruments, i.e. over a few hundreds of meters. Any new perturbation is then neither seen nor corrected by the AO (Adaptive Optics) systems. The IRIS[4] (InfraRed Image Sensor) camera placed in the VLTI laboratory close to the instruments is thus used to keep the infrared images of the science beams on reference pixels and maintain thus the alignment. IRIS performs this guiding by actuating the XY table (XYT) of the telescopes AOs systems, but due to the dynamics of the XYT, a good rejection of the tip-tilt can only be obtained at very low frequencies (< 1 Hz), sufficient only to maintain the overall alignment.

But for the fibered instruments, it was clearly seen that this correction was not fast enough and that their performances were reduced by tip-tilt at higher frequencies, due to propagation in the light-ducts and tunnel and to residuals from the AO. The IRIS Fast Guiding (IFG) has thus been implemented for FINITO (Fringe-tracking Instrument of NIce and Torino) and AMBER (the same solution has been implemented in the design of the PRIMA Fringe Sensor Units). Their feeding optics (flat mirrors sending the light from the VLTI to the instruments) are composed of mirrors mounted on piezo tip-tilt actuators (called ACU) and provide correction of the tip-tilt at higher frequencies. The XYT table guiding is maintained for low frequencies and the faster residual tip-tilt signal from IRIS is applied to the ACUs in real-time. The system is operated in open loop (IRIS not seeing the correction that is applied), and allows compensation of tip-tilt up to 10Hz (limited by the delay in the communication between IRIS and the ACUs). In addition to the real-time tip-tilt correction, static offsets to the ACUs are used to match the input fibers positions with the optical axis of the VLTI.

The IFG is now operational on both FINITO and AMBER, improving the mean flux injected in the fibers and also reducing the flux dropouts.

2.3 Delay Lines

Variable Curvature Mirror

The variable curvature mirrors[5] (VCM) are now implemented on all six delay lines (DL). The VCM is placed at the focus of the DL's cat's eye, and its curvature is adjusted by changing the pressure in the chamber behind the mirror. The pupil longitudinal position can thus be maintained at its nominal value in the VLTI laboratory, with a precision of about 1m, while the distance to the input telescope pupil changes with the DL position. Without the VCM, the field of view (FOV) on the ATs can be reduced to a size smaller than the observed star in the case of the farther stations and thus long optical path length (OPL). With the VCM, the FOV can be maintained to a usable size, allowing operations with long baselines and distant AT stations. The use of the VCM is particularly critical with the ATs, as the telescope output pupil is located close to the telescope. The system has thus been installed first on DL5 and DL6 at the end of 2005 for technical validation and verification of the performances, and in August 2006 on DL4, as these three DLs are the ones currently devoted to AT operation. The full deployment of the system, including thus now all the six DLs, was achieved in 2007, making it also available for UT operation.

By maintaining the pupil longitudinal position and the FOV size, the VCMs allow reducing the thermal background seen by the instrument and improve the flux for the instruments.

Rail shape control

The installation of the VCM was clearly demonstrated to improve the performances of the VLTI, but it also made the requirements on the alignment of the DLs optics and trails more stringent. The laser metrology used for fine positioning of the DL follows a path similar to the stellar light and thus goes through the cat's eye and the VCM.. The higher curvature of the VCM when inflated to adjust the pupil position increases the requirements on the alignment of the vertex of the VCM on the exact focal point of the DL cat's eye, and on the alignment of the rails themselves as a non linearity will induce a differential movement of the carriage compared to the metrology. A non-flat rail will produce pupil lateral movements and a decrease of the detected flux in return from the DL for the metrology that can lead to a loss of the DL fine position control.

Thus to be able to reliably operate the DLs with their VCMs, the DELIRIUM[6] system was implemented as a rail shape monitoring facility: The system is composed of::

- A wire running along the DL guiding rail, supported in two points located at the extremities of the rail. It provides a reference for the rail measurement.
- Two 2-axis capacitive sensors, mounted on both ends of the chassis of the carriage. They measure their distance to the wire (4 degrees of freedom).
- An inclinometer located on the top of the carriage chassis measures the roll axis of the carriage (rotation around the rail direction, 1 degree of freedom).
- The DL metrology (coarse or laser) measures the longitudinal position of the carriage along the rail (1 degree of freedom).

This set of sensors provides a complete knowledge of the carriage trajectory (3 translations + 3 rotations) with respect to the reference wire.

The rails of each DL are thus scanned over their full length and the results of the measurement used to determine the correction to apply to the rails supports. An automatic procedure is used for the daily monitoring of the shape of the rails of all six DLs, and corrections are applied manually when necessary. Fig. 2 presents an example of the output of the DELIRIUM measurement, for a routinely maintained rail. The rail shape is given for the horizontal and vertical directions. One can see that the rail is kept flat with an accuracy of ± 10 µm in both directions over its full physical length of 60m (120m OPL). The periodic structure seen on the vertical direction corresponds to the wobbling of the carriage due to the non-perfect phasing of the two guiding wheels.

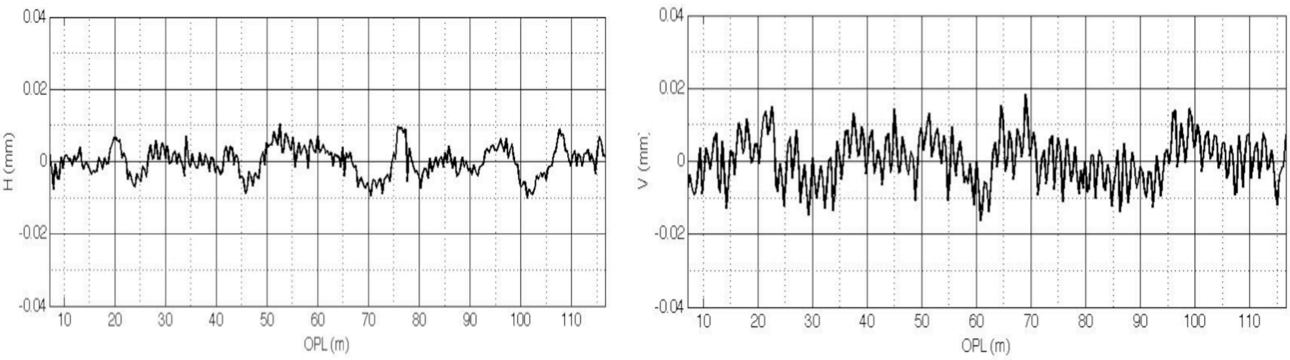

Fig. 2. Shape of the rail of one DL, in horizontal (left) and vertical (right) directions.

With the DELIRIUM system, a routine monitoring of all DLs alignment is performed and the accurate control of the rails flatness is there ensured.

2.4 Fringe tracking

The VLTI fringe tracker FINITO[7] (Fringe-tracking Instrument of NIce and TOrino) is a three telescopes facility for the VLTI instruments. A pair-wise combination is performed in H band, with one telescope beam common to the two channels, used as a reference. One polarization on each beam is used for photometric calibration. A Michelson-like beam combination is performed on both channels, and the two interferometric outputs of each of the two channels are used for the phase measurement. A temporal scan of 5 fringes is performed by a fiber modulator, the optical path difference (OPD) being created by the expansion of the fibers thanks to a piezo-electric. An internal metrology is used to control the linearity of the modulation. The 5-fringes scan allows ensuring that the phase is always locked on the center fringe, by measuring the coherence on the packet. The measurement of the phase shift of the fringes on the two channels gives the OPD between the beams and a real-time correction is sent to a piezo-actuated mirror on the corresponding DL.

A strong effort led by ESO[6] started in April 2005 allowed offering FINITO for astronomical observation with both MIDI and AMBER. The fringe tracking was offered in visitor mode on the ATs in April 2007, and then in both service and visitor mode in September 2007. The fringe tracking facility will be offered for operation with the UTs in October 2008, the delay compared to the ATs coming from the more challenging environment of the UTs (mainly vibrations, see section 4). The first few months of VLTI operation with FINITO allow already extracting some interesting information and statistical analysis of the performances[8]: with coherence time higher than 3ms, one can expect OPD rms values to be between 70nm and 140nm in a quite wide range of atmospheric conditions. Fig. 3 shows an example of the performances obtained on sky with FINITO. The rms of the OPD is 128 nm on channel1 and 132 nm on channel 2, under average atmospheric conditions. The frequency peaks seen (50 and 63 Hz) in the power spectral density might be an internal effect of FINITO but their origin is not yet fully known.

FINITO is thus now routinely offered with the ATs, improving the performances of the VLTI instruments (longer integration times accessible, better precision on interferometric observables), and first results are very promising[9]. Even further gain in data quality could be obtained with FINITO operation[8] with already identified solutions.

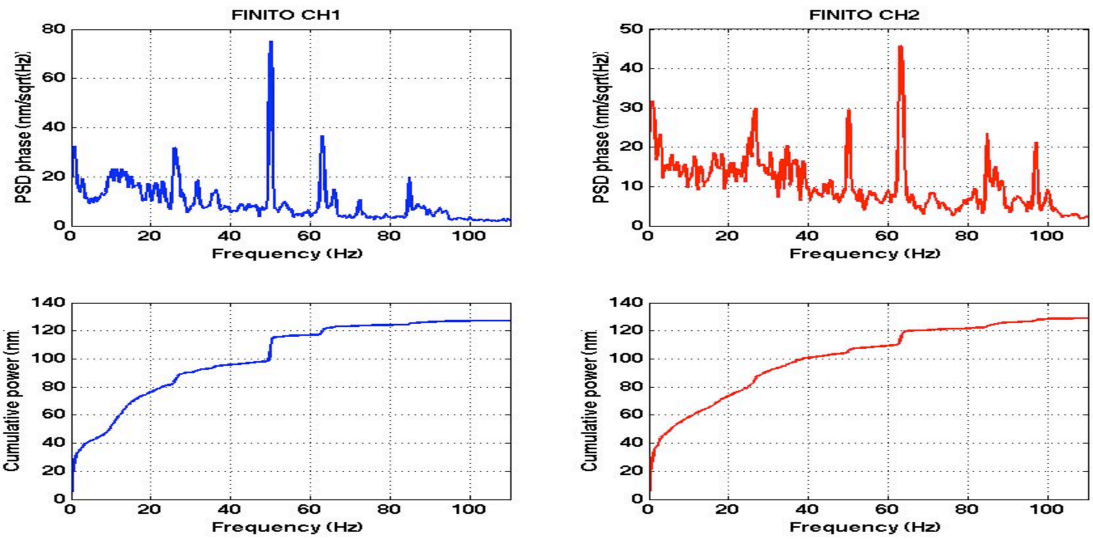

Fig. 3. Power spectral density (top) and cumulative power (bottom) of the phase measured on the two FINITO channels. The phase was locked during the full 10s recording. The atmospheric conditions were: coherence time equal to 2.2ms, seeing of 0.99 arcsec.

3. VLTI CHARACTERIZATION

The hardest points of VLTI operations have been now overcame and the global system has now reached a level where most of the infrastructure and subsystems can be considered in a sufficiently stable state. It was thus a good time to conduct a complementary effort to deepen the characterization of the VLTI in a number of areas where the current performances of the facility are either partially on even not quantified. With this characterization campaign, the performances of the new instruments will be better assessed and their design realized on a more solid basis. The status of the VLTI characterization is reported in these proceedings (see [10]), and we will just recall here the parameters that are planned to be quantified:

- Residual tip-tilt in the VLTI laboratory (UT and AT cases),
- High order aberrations introduced in the light-ducts and tunnel,
- Pupil longitudinal and lateral stability,
- Focus quality,
- Transmission,
- Dual-feed operation,
- Instruments non-common OPD stability,
- Polarization,
- Field of view size and position stability,
- OPD models precision,
- Background level,
- Straylight.

4. VIBRATIONS BATTLE

4.1 Manhattan2

The Manhattan2[11] systems uses accelerometers placed on the structure of the UTs to measure vibrations, which are responsible for OPD perturbations. The mirrors M1, M2 and M3 on all four UTs have now been equipped with this system. The accelerometers signals are acquired and processed by a dedicated local control unit (LCU), and made available through the reflective memory network (RMN) to the fringe tracking loop algorithms. Using the delay lines as actuators, the system can then attenuate the OPD residuals seen by the interferometric instruments.

In the baseline scenario the system is used for feed forward control. All optical surfaces OPDs of one telescope are added together to generate one telescope OPD signal written on the RMN at the location corresponding to the associated delay line. The delay line reads the OPD correction signal from the associated telescope and adds it to its setpoint. The sampling rate of the system is 2 kHz. Taking into account the system delays, in particular the delay line actuation, it is possible to achieve a good attenuation of the vibrations effect in the frequency range of interest (~10-30 Hz).

Fig. 4 presents some results of the vibrations attenuation using the Manhattan2 system. UT3 and UT4 were combined here on FINITO channel 1. The atmospheric conditions where: seeing of 0.6 arcsec, and coherence time of 4 ms. The power spectral density of two FINITO phase measurements are shown: with the feed-forward of the OPD measured by Manhattan2 enabled (ON), and with the feed-forward disabled (OFF). The two records of 10s where taken consecutively, with one minute of separation, in order to ensure as much as possible the same conditions of atmospheric perturbation and of vibrations in the telescopes. In the operating frequency range of the system (10-30 Hz), the attenuation of the impact of vibrations can clearly be seen on the figure: the peak at 18 Hz has disappeared and the one at 24 Hz is strongly attenuated. The peaks at 35 Hz and 46 Hz are present in both cases as they are either to high in frequency to be corrected by the accelerometer systems, or have their origin on another mirror than M1, M2 or M3. Using the OPD correction computed from the accelerometers signals allowed here to reduce the rms on the OPD from 573 nm to 414 nm, i.e. about 400 nm rms of OPD have been compensated by the system (sqrt (573^2-414^2)).

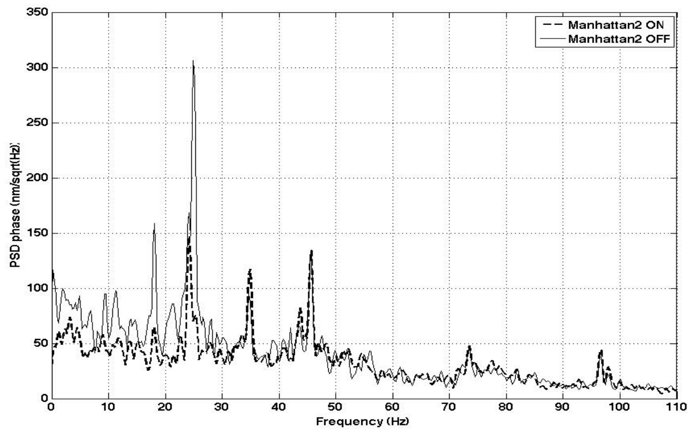

Fig. 4. Power spectral density of the OPD measured on one FINITO channel combining the beams from UT3 and UT4, with the Manhattan2 system off (solid curve) and on (dashed curve).

The Manhattan2 vibrations compensation reduces their impact on the instrument, and is now used during all UT science runs, in all instruments configurations.

4.2 Vibration Tracking

The accelerometer system described above is monitoring only the vibrations on M1 to M3. But, when operating with the UTs, the telescope light has to go through twenty mirrors before reaching the instruments. All of these mirrors can also be excited by vibrations sources and thus degrade the interferometric signal quality. The frequencies of the vibrations introduced at these levels are usually to high and out of the range of correction by the fringe trackers.

An adaptive narrow-band cancellation algorithm (described in details in [12]), called VTK (Vibration TracKing) has thus been implemented on the VLTI system to fight those vibrations. The starting point for the development of VTK was that the vibrations create sharp and quite stable frequency peaks in the spectrum of the OPD measured by the fringe tracker. This assumption was confirmed on FINITO data recorded with the UTs. From there, if the vibrations are stable enough, one can try to counteract them by injecting in the path the same signal but in phase opposition. With the implemented VTK algorithm, one just has to enter the targeted frequencies (up to 25 in the current version), and the system will use the OPD measured in FINITO and lock on these frequencies. The system continuously and automatically adapts the frequency, phase and amplitude of the counteracting signals to follow the evolution of the vibrations. Vibrations could be followed by the VTK on a range of ±2 Hz around the initial target.

Fig. 5 presents results obtained with the VTK correction used with the interferometric combination on both channels of FINITO, with UT1, UT3 and UT4. The spectral analysis of the measured OPD and the cumulative power are presented for both channels. The frequencies tracked by VTK were:

- Channel 1: 24 Hz, 34 Hz, 44 Hz, 96 Hz.
- Channel 2: 10 Hz, 24 Hz, 45 Hz, 96 Hz.

The atmospheric conditions were average ones during this test: seeing of 0.8 arcsec and coherence time of 4 ms. The attenuation of the tracked vibrations effect can be seen on the spectrum of the OPD. The rms of the OPD was lowered from 429 nm to 382 nm on channel 1 (195 nm rms compensated), and from 607 nm to 555 nm on channel 2 (246 nm rms compensated).

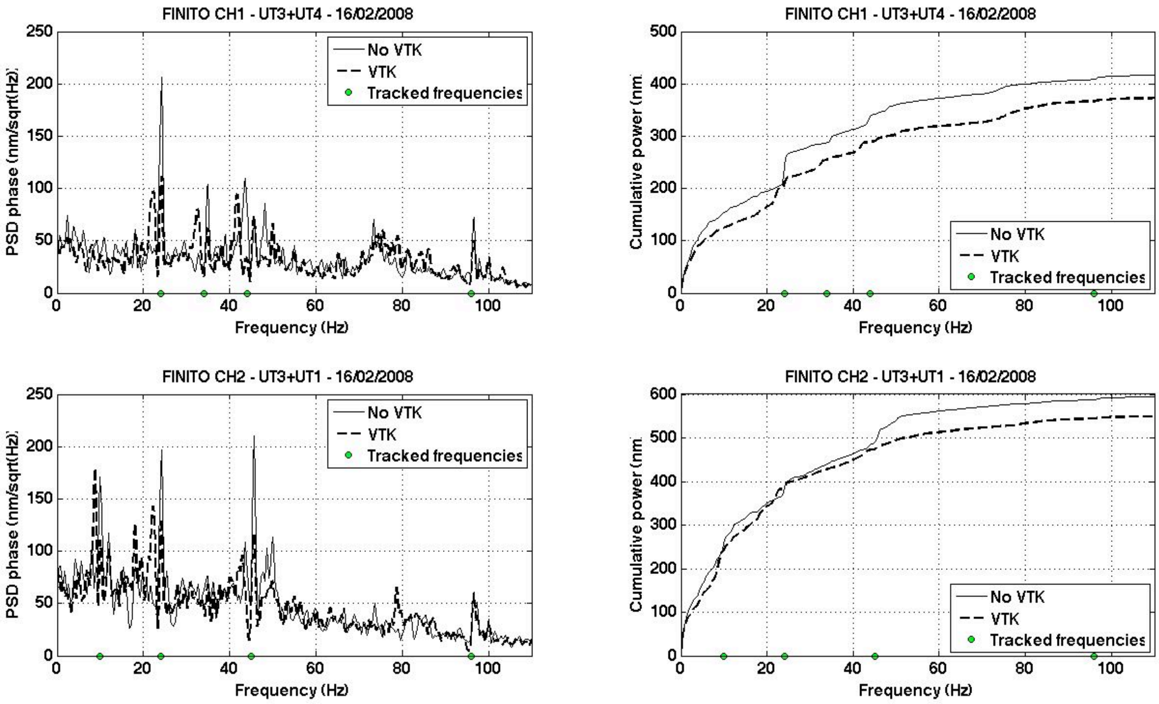

Fig. 5. Results of VTK measured on FINITO with UTs. Power spectral density (left) and cumulative power (right) of the OPD measured on both FINITO channels, with VTK disabled (solid curve) and enabled (dashed curve).

The rms of the OPD with fringe tracking on the UTs could not be lowered up to now to the level of the ATs (see Fig. 3) due to the vibration environment. One has to note here also that on UT1 the instruments configuration during the test was not in the best configuration in terms of vibration level. Lower level is expected during scientific runs when the telescope and instruments are put in the optimal configuration. The effort to lower the vibrations and reduce the OPD disturbances on the UTs will be pursued.

4.3 Vibrations sources

In addition to the work conducted to actively attenuate the UT vibrations, some effort is being made on identifying the sources of these vibrations and implementing solutions when possible. The electronic cabinets of the MACAO systems for example were proven to be sources of acoustic and mechanic vibrations on the mirrors in the UT's Coudé rooms, and their location has therefore been changed. The pumps for the cooling system of the UTs have also been investigated and new solution tested. A complete characterization campaign has been performed on UT4 to determine the level and frequencies of vibrations on all the mirrors in a Coudé train used by the VLTI beams, in order to determine where the efforts have first to be directed to damp the vibrations and identify their sources. The level of vibrations of all the Nasmyth and Cassegrain instruments of all UTs has also been measured in the scope of identifying possible perturbations sources.

Some progresses have already been made on reducing the vibration level for the VLTI instruments. The work currently made on this matter will also benefit the other VLT instruments, especially high resolution ones, and the effort will be carried on.

5. FUTUR PROJECTS

5.1 Near future

The AIV (Assembly, Integration, Verification) of PRIMA (Phase Referencing Imaging and Microarcsecond Astrometry) is currently envisioned to take place at Paranal during July and August 2008. The tests of some of the subsystems composing the instrument (star separators, metrology) have already started on the VLTI. The first tests of the full system are planned at the end of the AIV, and the commissioning should be done at the end of 2008 and beginning of 2009. Laboratory results of the FSU of Prima can be found in [13].

5.2 A little further

The phase A studies of three instruments for the VLTI second generation: GRAVITY[14], MATISSE[15], and VSI[16], have been completed and reviewed in September 2007. All three instruments have now entered the next design phase, and the current development phase is aimed at bringing these instruments at the VLTI in the period 2012-2015.

ACKNOWLEDGMENTS

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