Enabling Fringe Tracking at the VLTI

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Just as adaptive optics reduces the image blur induced by the atmosphere in conventional single telescope observations, Fringe Tracking, or co-phasing, reduces the blur in interferometric observations. We present the status of the VLTI after the deployment by the Interferometer Task Force of new beam quality control tools, which enabled the UTs and ATs to be co-phased, using FINITO as a fringe sensor.

Co-phasing the VLTI consists in canceling the Optical Path Length Difference (OPD) from the observed astronomical source to the instrument detector via the different telescopes of the array. The OPD depends on the geometry of the array and on the observation line of sight and changes with time at a typical rate of 1 cm/sec due the Earth's diurnal rotation. These changes are compensated internally by the Delay Lines, consisting of retro-reflectors mounted on carriages positioned along 60 m long rails and reflecting the collimated beam towards the re-combining laboratory.

In addition to the large and predictable geometric changes, the atmospheric turbulence introduces random OPD perturbations with amplitude of 10 µm, and the telescope infrastructures generate vibrations up to 100 Hz that propagate to the optics with an amplitude of one micron. Without Fringe Tracking, these perturbations limit the maximum integration time of scientific instruments to a few milliseconds. The purpose of Fringe Tracking is to stabilise the OPD within a fraction of the observing wavelength (goal 100 nm rms) in order to increase the scientific detector integration time and reach dimmer targets.

FINITO is an OPD sensor, operating in the *H*-band (1.65 µm). It generates fringes modulated in time by means of an internal OPD modulation. The synchronous detection of the phase shift between the observed fringe and the applied modulation provides an estimation of the OPD error. As any decent rejection of the atmospheric OPD requires a closed-loop control bandwidth of a few tens of Hz, a modulation frequency of a few hundreds Hz is needed with a typical detector sampling rate of 1 kHz.

FINITO was delivered in 2003 but Fringe Tracking could not be demonstrated at commissioning. In April 2005, an Interferometer Task Force (ITF) was set up at the Paranal Observatory to investigate the feasibility of Fringe Tracking with FINITO. Several failure causes were identified: Delay Line rail alignment errors, pointing errors induced by the internal turbulence downstream of the Adaptive Optics and intermittent explosions of the stellar images caused by saturations of the Adaptive Optics Deformable Mirror (DM). In addition, the impact of vibrations was beyond a mere degradation of the performance as it distorted the modulated fringe to a point that phase estimation was not possible.

ITF developed a beam quality control strategy based on the existing set of hardware, encompassing the pupil alignment and the control of piston, pointing and higher-order aberrations. Fringe tracking was demonstrated in March 2006 on the Auxiliary Telescopes (AT) in nominal atmospheric conditions with performance close to specification (100–150 nm rms). On Unit Telescopes (UT), the first stable closed-loop operations were demonstrated on sky in June 2006 albeit with a degraded performance limited by the telescope vibrations (460 nm rms). Vibration rejection methods were then developed by ITF and demonstrated their potential to reject 75 % of the residual energy and lower the residual OPD to 230 nm rms.

The next sections present the main features developed by ITF to achieve this performance:
– a Delay Line rail alignment tool making it possible to maintain the attitude error of the cat's eye within the tolerance,
– an Adaptive Optics Deformable Mirror Saturation Management Algorithm aiming at minimising the impact of saturations on the wavefront quality,
– a fast guiding mode based on IRIS, the VLTI laboratory Near Infrared Camera, rejecting the tip-tilt components of the tunnel turbulence,
– an acquisition procedure allowing to reduce the static pointing error to less than 5 mas,
– an open-loop vibration compensation method based on accelerometers mounted to the M1 cell.
– A closed-loop vibration tracking algorithm, rejecting harmonics in tip-tilt and piston beyond the control bandwidth of the Fringe Tracking controller.

Pupil control

A Variable Curvature Mirror (VCM) is mounted at the focal plane of the Delay Line cat's eye and can be adjusted in curvature to image the telescope pupil at the appropriate distance while the carriage moves along the rail. The curvature applied to the VCM increases the sensitivity of the exit pupil lateral displacement to cat's eye attitude errors induced by rail distortions. When ITF started, VCM operations were functionally not possible because the amplitude of the rail distortions were such that the DL laser metrology beam, also reflected by the VCM, would be lost while the DL twisted along the rail. ITF recycled the tools developed for the Delay Line installation and developed DELIRIUM, a rail observer based on capacitive sensors permanently installed on-board the DL carriage, monitoring the position and attitude of the carriage with respect to a mechanical reference. The profile of the guiding rail is then reconstructed and filtered with the calibrated influence functions of the rail supports to generate a vector of corrective com-

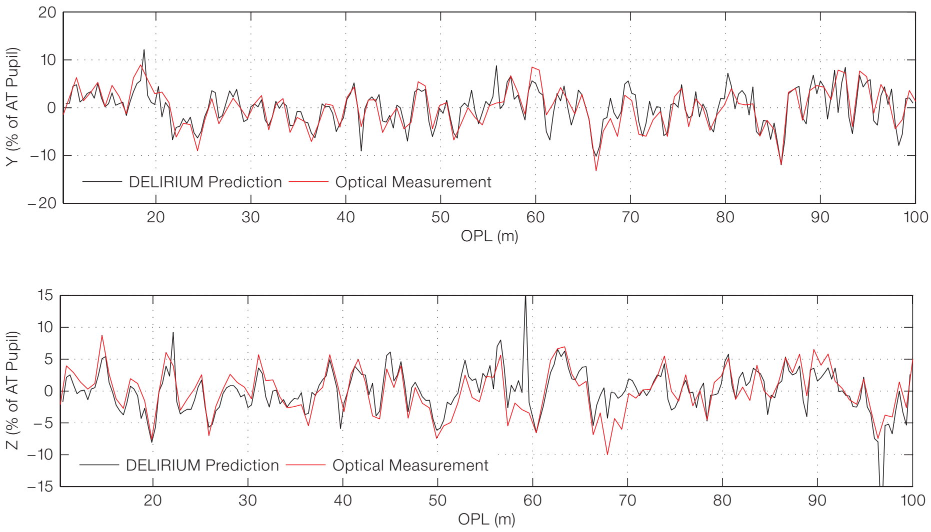


Figure 1: Lateral motion of the Pupil. Black = prediction based on DELIRIUM. Red: Actual Optical measurement. This performance is compatible with glitchless operations on the UTs and on the AT stations currently offered.

mands. After convergence of the rail alignment procedure, the residual carriage jitter is dominated by the contribution of the wobble of the wheels (Figure 1). The analysis of the DELIRIUM data accumulated over six months established that the evolution of the rail profile is driven by its response to temperature changes and that a regular maintenance will allow tracking the seasonal variations and guarantee a continuous operability of the VCM.

Rejection of atmospheric aberrations

The VLT Coudé Focus Adaptive Optics (AO) System, MACAO has been specified to deliver a mean Strehl ratio of 50 % in *K* in nominal atmospheric conditions, on axis with a bright reference star (R mag < 10), over long integration times (minutes). This requirement has been met and demonstrated at delivery but was unfortunately not sufficient for an application such as FINITO, running at 1 kHz with the task to deliver a reliable measurement of the phase at each cycle.

To maintain the best fringe contrast in the presence of optical aberrations, the beams are spatially filtered at the entrance of FINITO by means of monomode fibres, at the cost of a flux loss in proportion to the instantaneous Strehl ratio. Since fringes are sampled at high frequency, the critical performance parameters for MACAO is not the mean image quality, as in standard imaging AO applications, but the frequency and amplitude of intermittent image 'explosions' caused by uncontrolled Deformable Mirror (DM) saturations.

MACAO relies on a curvature mirror, very efficient at compensating low-order intra pupil aberrations, but quite inefficient at generating a higher-order wavefront with features at the spatial scale of the inter-electrode distances. The atmosphere does not generate a substantial energy in these so-called waffle modes, but the noise propagation in MACAO causes a substantial fraction of the DM stroke budget to be spent along them with hardly any impact on the wavefront quality. This causes the DM command to saturate frequently, even in good seeing conditions. A simple clipping of the command at saturations projects the energy propagated along the waffle modes on more efficient modes. This induces short PSF explosions that result in deep fibre injection dropouts. The Saturation Management Algorithm (SMA) developed by ITF implements a non-linear modal control along the waffle modes, triggered when saturations of the linear command are detected and aiming at minimising the impact of saturations on the wavefront. In addition, an Anti-Windup (AW) module freezes the projection of the controller integrator along the waffle modes during the saturation events, in order to prepare a faster recovery of the control after the event. SMA and AW have been demonstrated on Sky in engineering mode in February 2006 (Figure 2), and operated since then for all UT test sessions, although not yet offered to science operations.

Rejection of the tunnel seeing

Since the Adaptive Optics Wavefront Sensor is located in the Coudé Room, it does not correct aberrations developed downstream by the tunnel turbulence. The amplitude, projected on sky, of the pointing jitter caused by the tunnel turbulence is ~ 50 mas PV, distributed between 0 and ~ 5 Hz. As this amplitude compares to the *H*-band diffraction limit at the UT (45 mas), the impact of the tunnel tip-tilt turbulence on injection is potentially devastating. ITF has demonstrated on sky the capability of the IRIS Fast Guiding (IFG) mode to reject the tunnel tip-tilt and stabilise the pointing at the entrance of the VLTI instruments. This control tool relies on IRIS, the near infrared fast imager, originally designed to observe the slow drifts induced by the

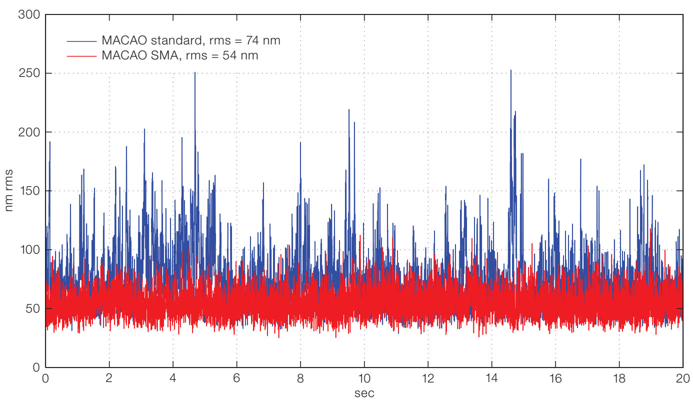
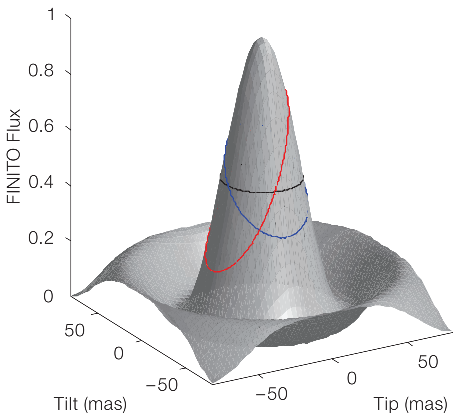


Figure 2: Residual Wavefront Error downstream M9 as reconstructed from MACAO Wavefront Sensor data. Standard MACAO algorithms (blue), Saturation Management Algorithm and Anti-Windup (red). Both sets of data were taken a few minutes apart in similar atmospheric conditions (0.9 arcsec).

thermal variations of the tunnel atmosphere. The controller operates in open loop, addressing the commands to a Tip-Tilt Platform located downstream the dichroic separating the beams fed to FINITO and IRIS. IFG has been demonstrated in K band only with an optical layout allowing FINITO and IRIS to be simultaneously operated but currently incompatible with AMBER operations. A re-organisation of the optical switches on the FINITO table is underway to allow simultaneous FINITO-IFG-AMBER operations.

Minimisation of static pointing error

The injection in the monomode fibre is degrading exponentially with the amplitude of the aberrations. Tip and Tilt are the most energetic atmospheric modes and remain the main residual aberrations downstream of MACAO and IFG, with typical residual amplitude of 10 mas rms per axis. 2σ deviations (~ 2 % of time) induce an injection loss of 60 % that increases dramatically in the presence of a small static pointing error. Minimising the static pointing error is essential to preserve the largest error allocation to the dynamic error. The early alignment strategy proposed for FINITO consisted in scanning the field along a regular grid pattern and recording at each position the mean injection over a user's defined integration time. Short integration times provided results contaminated by dynamic fluctuations and longer integration times led to prohibitive convergence times while results were still potentially biased by e.g. variations of the atmospheric transmission during the calibration. ITF developed an alternative unbiased approach, called Beam Tracking, consisting in minimising the flux fluctuations induced by the coupling between the static error and a circular tip-tilt modulation applied to the Tip-Tilt Platform of IFG (Figure 3). Modulating on a pure harmonic with a frequency selected in a vibration free region (20 Hz) allows extracting the static signal from the dynamic noise distributed over a broad spectrum. The procedure converges within a few tens of seconds to a static residual error estimated to be less than 5 mas.



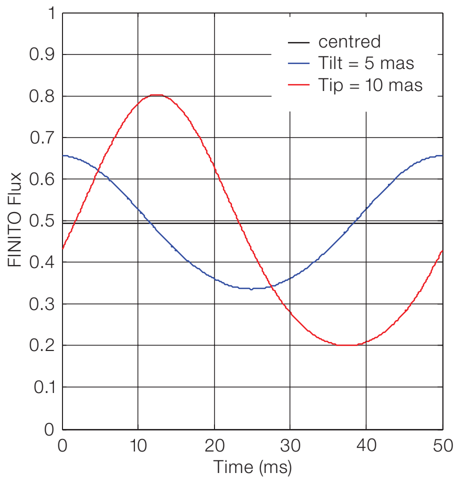


Figure 3: Beam Tracking principle: the circular modulation of the Tip-Tilt platform induces a periodic walk of the injection fibre around the mean PSF. The amplitude of the induced flux modulation is proportional to the static pointing error and its phase to the error direction.

Rejection of vibrations

The combination of the DM Saturation Management, the IRIS Fast Guiding and the Beam Tracking allows stabilising under typical atmosphere conditions (seeing = 1 arcsec, coherence time = 2.5 ms) the injection of bright stars (H magnitude ~ 5) from the UTs in the FINITO monomode fibres. This was first achieved in May 2006 but the first attempt to close the Fringe Tracking loop was not a success yet. The amplitude of the telescope vibrations not only degraded the performance but also prevented the phase to be correctly estimated due to large phase variations within the period of the FINITO internal modulation cycle.

A new phase reconstruction algorithm was designed to account for the fringe distortion caused by the OPD variations within the modulation cycle. Fringe Tracking was first enabled at 2 kHz with this new phase estimator. Stable but poor performance (~ 450 nm rms) was obtained in July with the UT1-3 baseline and early September with the UT3-4 baseline. The spectral distribution of the residual phase error was mainly found in sharp unresolved peaks distributed between 15 and 100 Hz. Most of the observed frequencies had already been identified by accelerometer measurements carried out at the telescopes and at the Coudé trains. The outstanding features were structural modes of the M1 cell and M3 towers (18 and 24 Hz) excited by the Cryo-Cycle-Coolers of the cold instruments, specially NACO on UT4, and forced vibrations propagated from the telescope basement equipment to the Coudé optics, e.g. the fans of the MACAO cabinets mounted to the structure of the Coudé room and shaking of M10 and M11 in the 45–50 Hz region.

ITF envisions a tri-therapy to bring the Fringe Tracking performance within the expectations of our future instruments. The first component should be a reduction of the environmental aggression by means of appropriate isolation or damping of vibration sources and propagation paths. The second component of the tri-therapy consists in pre-cleaning the beam delivered to the VLTI by means of accelerometer measurements filtered to estimate the induced OPD via a sensitivity model and fed forwards to the Delay Lines. A flotilla of accelerometers has already had First Vibration at the UT3 and UT4 M3 towers in September and provides a continuous monitoring of the vibration state, featuring a strong correlation with the optical phase seen by FINITO. The aptitude of accelerometers to compensate in open loop the main vibrations was demonstrated on sky in October (Figure 4, green curve and Figure 5). The third component of the tri-therapy, called Vibration Tracking (VTK) was also deployed in September. The idea is to model and compensate stable harmonics beyond the bandwidth of the Fringe Tracking controller by constraining in closed loop their frequency, amplitude and phase. VTK has been implemented in the FINITO controller and has demonstrated on sky its capability to reject about half of the Residual Phase energy

(Figure 4, red curve and Figure 5)[1]. This has not only reduced the residual phase to 260 nm rms but also allowed for the first time to close the Fringe Tracking loop at 1 kHz.

The tri-therapy test protocol was tested on 9 October and demonstrated the potential of combining these different approaches. While the vibration controllers were running, the fans of the MACAO electronic cabinets, known to excite the Coudé room optics via acoustic and structural propagations, were shut down. This reduced the amplitude of the dense forest of vibration peaks around 48 Hz that would not be efficiently rejected either by accelerometers feed forward (limited by communication delay at this frequency) or by VTK (limited by spectral resolution). The residual OPD went from 260 to 230 nm rms (Figure 4, cyan curve, Figure 5).

Possible improvements

Fringe Tracking has been demonstrated on bright stars in nominal seeing conditions. The limiting *H*-band magnitude has not been investigated but the experience accumulated in engineering mode indicates that AT operations will be limited by the stability of the photometric injection. The longer wavelength (*K*-band) selected for the PRIMA Fringe Sensor Unit is expected to attenuate the impact of the turbulence but the scientific potential of upgrading the ATs with a low-order Adaptive Optics system may need to be evaluated. On the UT side, the aptitude of the Vibration Tracking and Accelerometer approaches to partially reject the vibrations has been established. The progress demonstrated so far justifies that an intense parallel effort be initiated to improve the dynamical environment of the UTs.

[1] VTK was also successfully tested with MACAO to reject the 18 Hz Tip-Tilt Mode of the M1 cell.

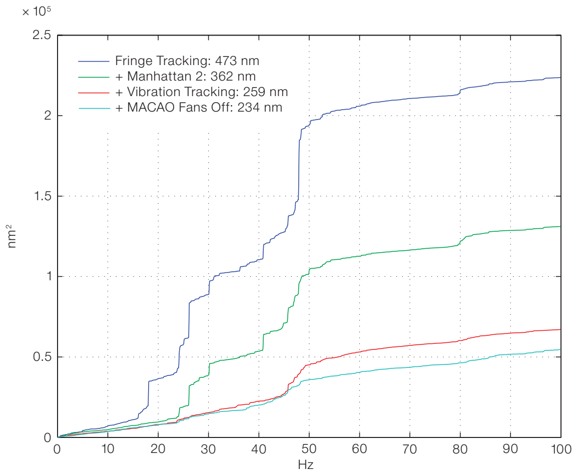


Figure 4: The blue curve shows the cumulative power of the phase (OPD) residual during 'naked' fringe tracking with a residual above 450 nm rms. Accelerometer feed forward to the delay lines is switched on (green) reducing the residual to 362 nm. Vibration tracking (VTK) is added (red) reducing the residual further to 259 nm. Finally MACAO cabinets cooling are switched off (cyan), bringing down the residual to 234 nm.

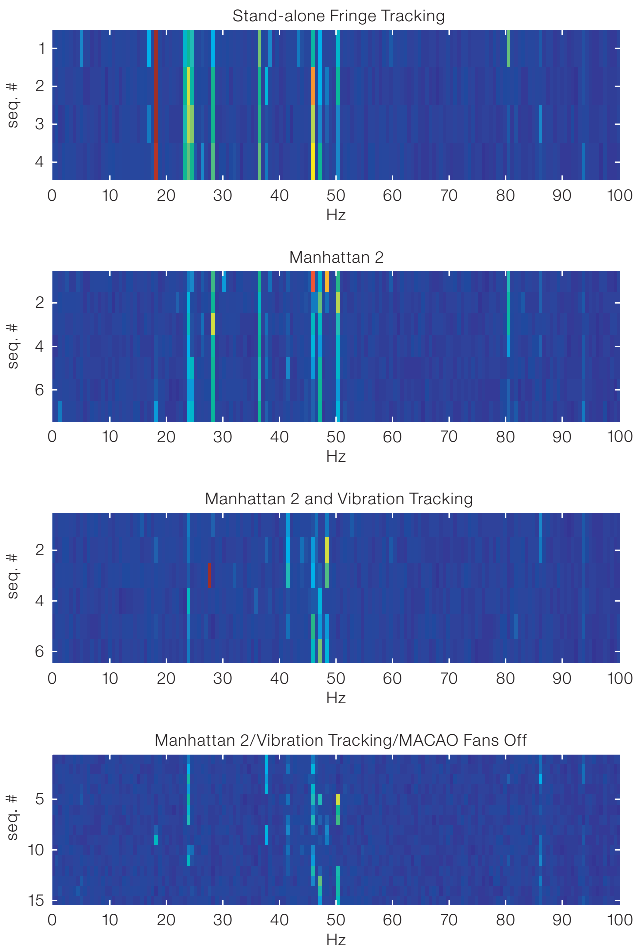


Figure 5: Tri-therapy experiment on the UT3-UT4 baseline. Each line of each plot is a PSD of residual OPD, seen by FINITO, in square root colour scale. The top sub-frame was obtained in stand-alone Fringe Tracking. The atmospheric Piston (< 5 Hz) is correctly rejected but the vibrations are amplified because their frequencies lie in the overshoot region of the controller. On the second frame, the accelerometers signal is fed to the Delay Lines. This permitted rejection of frequencies below ~ 30 Hz generated at M3. On the third frame, Vibration Tracking was started and rejected harmonics below 100 Hz. Switching off the fans of MACAO electronics cabinets reduced the residual amplitude in the 45 to 50 Hz region. All these data were acquired within a time window of two hours.