Adaptive Vibration Cancellation on Large Telescopes for Stellar Interferometry

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ABSTRACT

In stellar interferometry fringe-tracking is a method of stabilizing the Optical Pathlength Difference (OPD) from the observed astronomical source to the instrument detector via different telescopes in an interferometric array.

At the ESO Very Large Telescope Interferometer, which includes four 8.2 m class Unit Telescopes (UTs), stabilization to better than a tenth of the observing wavelength is required in order to improve the quality and sensitivity of fringe measurements on the interferometer's scientific instruments.

Unfortunately, fast mechanical vibrations due to myriad sources in the observatory infrastructure propagate to various mirrors in the optical path and must be compensated for in real time. Due to its limited bandwidth the fringe tracking loop cannot be used for this purpose. Alternative approaches must therefore be adopted.

Vibrations imparted to the primary, secondary and tertiary mirrors of the UTs are currently measured by a grid of suitably placed accelerometers, converted to optical pathlengths and cancelled by a wideband feedforward compensation algorithm to a downstream optical delay line.

Although very effective, it is obvious that this system can not compensate for vibrations originating elsewhere on the optical path. We present here an adaptive narrow-band cancellation algorithm that can compensate remaining vibrations measured on the stellar signal on condition that they are sufficiently stable in amplitude and frequency.

Keywords: Vibration, Interferometry, Adaptive Control, ESO, VLTI

1. INTRODUCTION

The Very Large Telescope (VLT) at Cerro Paranal in Northern Chile is ESO's premier site for observations in the visible and infrared light. It consists of four 8.2-m Unit Telescopes (UTs), four re-locatable 1.8-m Auxiliary Telescopes (ATs), six 60-m optical delay lines and a beam combination laboratory.

Individual telescopes of the VLT observatory can currently work together, in groups of two or three, as the VLT Interferometer (VLTI)[1]. The light beams are then combined using a complex system of mirrors in underground tunnels. In this mode the angular resolution is improved many times compared to that of individual telescopes. The VLTI can reconstruct images with an angular resolution of milliarcseconds and will soon allow astrometry with microarcsecond precision. To achieve this, the difference in light paths must be kept to a fraction of the observing wavelength. A fringe sensor provides real time OPD measurements used by a feedback control system which actuates both the coarse (linear motor) and fine (piezoelectric actuators) stages of the optical delay lines and is optimized to achieve the lowest possible residual OPD in a Root Mean Square sense.

Despite the high construction standards and outstanding mechanical stability of the telescope support structure, micro vibrations of the order of one wavelength (1 to 2 μm) still propagate to the mirrors at frequencies beyond the bandwidth (circa 15 Hz) of the closed loop fringe tracking system. A recently commissioned accelerometer-based feed-forward vibration compensation system[2] proved very effective in counteracting the vibrations measured on the primary, secondary and tertiary UT mirrors by actuating the delay line piezoelectric actuators. Unfortunately vibrations originating elsewhere in the optical path and not measured by accelerometers still affect the quality of the stellar signal. We therefore implemented an adaptive narrow-band cancellation algorithm which we describe here.

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2. ADAPTIVE ALGORITHM

The digital closed-loop fringe tracking controller delivers real time OPD corrections to the tracking delay line at a sampling interval Δt = 500 µs. At every sample k, two quadrature sine waves S_k and C_k of frequency f_k are synthesized in real-time using the recursive formulation

$$\begin{aligned} S_k &= S_{k-1}\cos(2\pi\,\Delta t\ f_k) + C_{k-1}\sin(2\pi\,\Delta t\ f_k) \\ C_k &= C_{k-1}\cos(2\pi\,\Delta t\ f_k) - S_{k-1}\sin(2\pi\,\Delta t\ f_k) \\ S_0 &= 0 \\ C_0 &= 1 \end{aligned}$$

A linear combination of S_k and C_k with coefficients $\theta_{k,1}$ and $\theta_{k,2}$ is used to produce the adaptive compensation signal Ω_k which is then summed to the output of the fringe tracking controller:

$$\Omega_k = \theta_{k,1} S_k + \theta_{k,2} C_k$$

Ω_k is an amplified replica of S_k, phase shifted by $\varphi_{e,k} = \mathrm{atan2}(\theta_{k,2},\ \theta_{k,1})$. Since Ω_k is linear in θ_k, the latter can be estimated recursively in real time using the RLS (recursive least squares[5]) algorithm to minimize the control system error signal ε_k, as follows:

$$\psi_k = \begin{bmatrix} S_k \\ C_k \end{bmatrix}$$

$$\theta_k = \theta_{k-1} + \varepsilon_k \frac{P_{k-1}\psi_{k-D}}{\lambda + \psi_{k-D}^T P_{k-1}\psi_{k-D}}$$

$$P_k = \frac{1}{2\lambda}\left\{ \left(P_{k-1} - \frac{P_{k-1}\psi_{k-D}\psi_{k-D}^T P_{k-1}^T}{\lambda + \psi_{k-D}^T P_{k-1}\psi_{k-D}} \right) + \left(P_{k-1} - \frac{P_{k-1}\psi_{k-D}\psi_{k-D}^T P_{k-1}^T}{\lambda + \psi_{k-D}^T P_{k-1}\psi_{k-D}} \right)^T \right\}$$

$$P_0 = \begin{bmatrix} V_0^{-1} & 0 \\ 0 & V_0^{-1} \end{bmatrix}$$

$$\theta_0 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Where:

V_0	Initial parameter variance
λ	Forgetting factor
D	Plant pure delay (expressed in number of samples)

If f_k matched exactly the disturbance frequency the RLS estimator would converge towards a constant estimated phase shift φ^* dependent on the delay/lags in the system only.

Of course the disturbance frequency is never known accurately and it may also drift. In presence of a frequency mismatch df the optimum phase shift (in the least squares sense) varies in time, according to $\varphi = \varphi^* + 2\pi\ \mathrm{d}f\ t$. In this situation the RLS estimator produces a time varying φ_e and in absence of a frequency adaptation mechanism the disturbance cancellation performance deteriorates.

However note that φ is the integral of df. Provided df is slow enough compared to the RLS estimation dynamics φ_e closely tracks φ. Under these conditions the RLS estimator can be used as the phase detector in a Phase Locked Loop (PLL), i.e. it is possible to lock f_k onto the real disturbance frequency by applying a frequency correction depending on φ_e, as shown in the diagram in Fig. 1. As many instances as necessary can be instantiated and connected in parallel, taking of course care to remain within the available CPU capabilities. In our current implementation we allow up to ten concurrent instances.

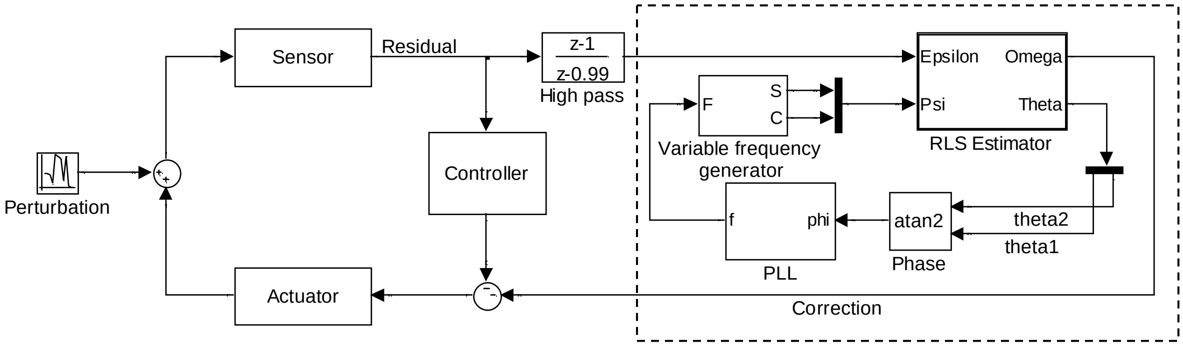

Fig. 1. Simplified diagram of the fringe tracking system, with adaptive vibration cancellation bounded by the dashed box.

The actual PLL implementation must also contain frequency limits and be protected against windup and phase wrap-around. This is achieved as follows:

$$\Phi_0 = 0$$

$$\Phi_k = \begin{cases} \mu_{k-1}\Phi_{k-1} & if\left|\varphi_{e,k} - \varphi_{e,k-1}\right| < \pi \\ \mu_{k-1}\left(\Phi_{k-1} - 2\pi\right) & if\ \varphi_{e,k} - \varphi_{e,k-1} \geq \pi \\ \mu_{k-1}\left(\Phi_{k-1} + 2\pi\right) & if\ \varphi_{e,k} - \varphi_{e,k-1} \leq -\pi \end{cases}$$

$$\mu_k = \begin{cases} 0.99 & if\ \tilde{f}_k \neq f_k \\ 1 & if\ \tilde{f}_k = f_k \end{cases}$$

$$\tilde{f}_k = K_p\left(\Phi_k + \varphi_{e,k}\right) + I_{k-1}$$

$$f_k = \begin{cases} f_{\min} & if\ \tilde{f}_k < f_{\min} \\ f_{\max} & if\ \tilde{f}_k > f_{\max} \\ \tilde{f}_k & otherwise \end{cases}$$

$$I_0 = 0$$

$$I_k = I_{k-1} + \Delta t K_i K_p\left(\Phi_k + \varphi_k\right) + \left(f_k - \tilde{f}_k\right)$$

where

Φ_k	Phase wrap accumulator
I_k	Integral accumulator
μ_k	Exponential smoothing coefficient
K_i	Integral gain
K_p	Proportional gain

3. SIMULATION

The algorithm was developed and tested in Simulink using a realistic model of the fringe tracking loop including sensor, actuators, processing and communication delays, noise, atmospheric OPD and five vibrations at 18, 24.2, 25.7, 47, 79 Hz with amplitudes between 50 and 1000 nm. In addition, the frequency and amplitude of the largest vibration at 18 Hz were slowly modulated between 17-19 Hz and 500-1000 nm in order to assess the robustness to drifting frequency and amplitude.

In Fig. 2 to Fig. 5 the adaptive algorithm is switched on at t = 20 s into the simulation. After a short transient the PLLs lock and a very significant attenuation of all vibrations follows. Power Spectral Density plots of the simulated OPD residuals, with and without the adaptive compensation, are shown in Fig. 6. Vibration amplitude attenuation ranges between 10 and 20 dB.

The ability of the PLLs to lock starting from an incorrect initial frequency guess is surprisingly good and results in a wide lock-in range, in excess of +/- 2 Hz. As an example Fig. 4 shows the initial transient of the compensator tracking the 24.2 Hz vibration starting from the initial 23 Hz guess.

The algorithm is insensitive to slow frequency and amplitude drift, as seen in Fig. 5, which shows the estimated frequency, amplitude and phase of the compensator tracking the amplitude and frequency modulated 18 Hz vibration mentioned above.

Importantly only the initial, minimum and maximum frequency parameters needed changing among compensator instances. It was found that a single combination of all other parameters, such as the forgetting factor and initial variance, is enough to track any vibration in the range of interest (10 to 100 Hz).

Crucially the algorithm was also found to be robust to slight variations of the fringe tracking loop sensitivity due to individual differences in actuator response. This is important because there are six optical delay lines that can be used depending on the telescope configuration and every single piezoelectric actuator has a slightly different frequency response when compared to the others.

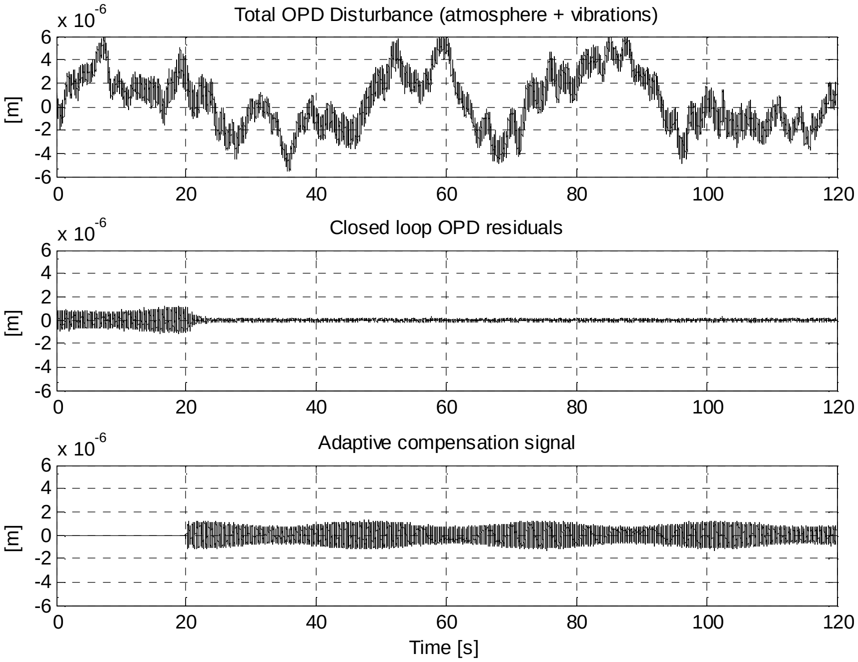

Fig. 2. Adaptive vibration cancellation algorithm simulation results. The total OPD disturbance which includes, among others, atmospheric OPD and vibrations is shown at the top. Note the reduction of closed loop residuals (middle) when the algorithm is enabled at T=20s. The adaptive compensation signal is shown at the bottom.

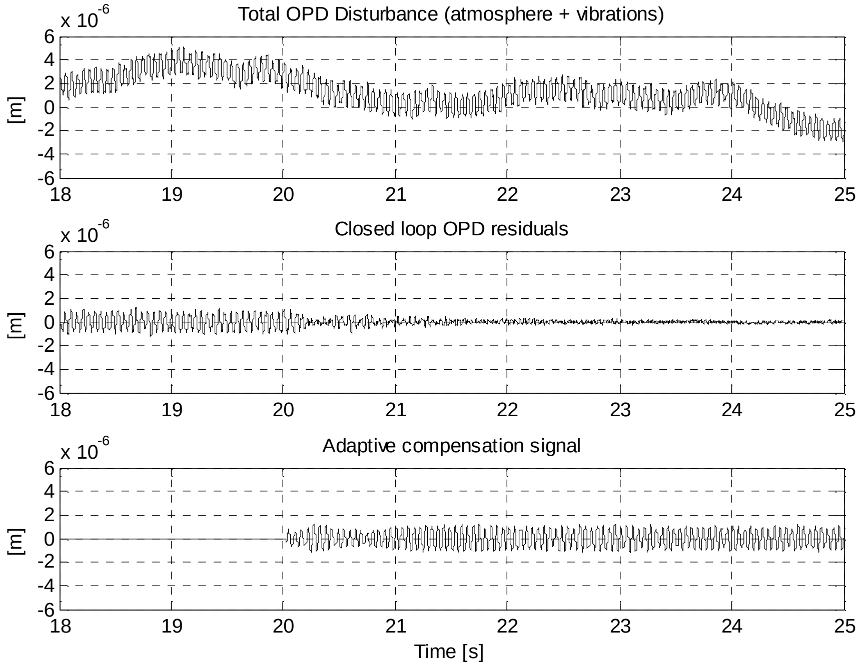

Fig. 3. Same as Fig. 2 but zoomed at around the algorithm switch-on time

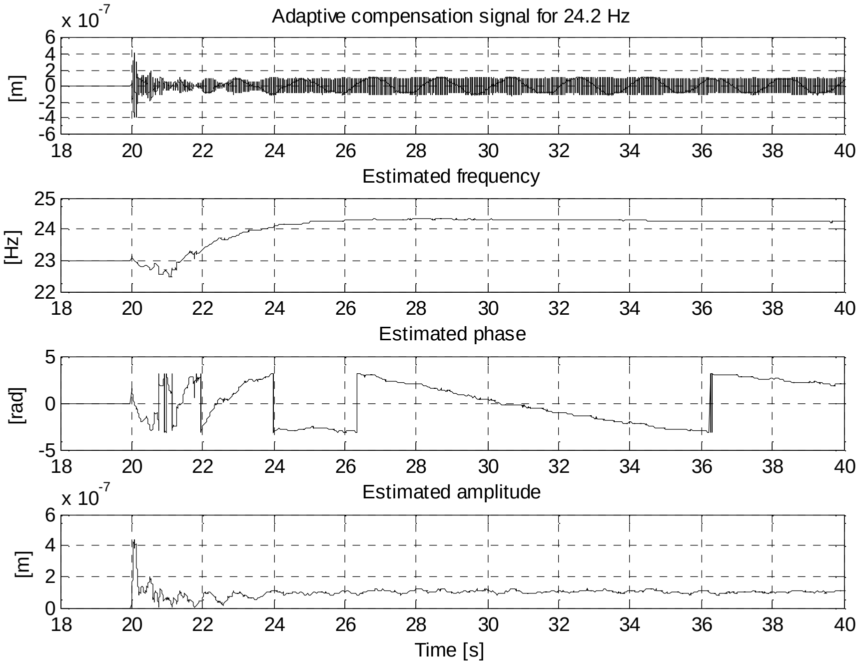

Fig. 4. Detail of the internal adaptive signals for the algorithm instance tracking the 24.2 Hz vibration

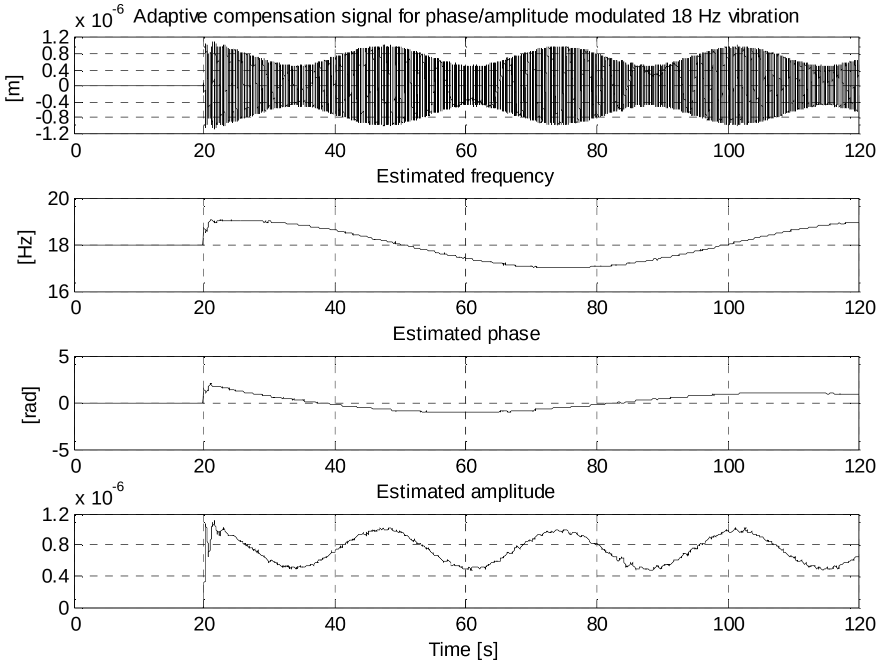

Fig. 5. Detail of the internal adaptive signals for the algorithm instance tracking the modulated 18 Hz vibration

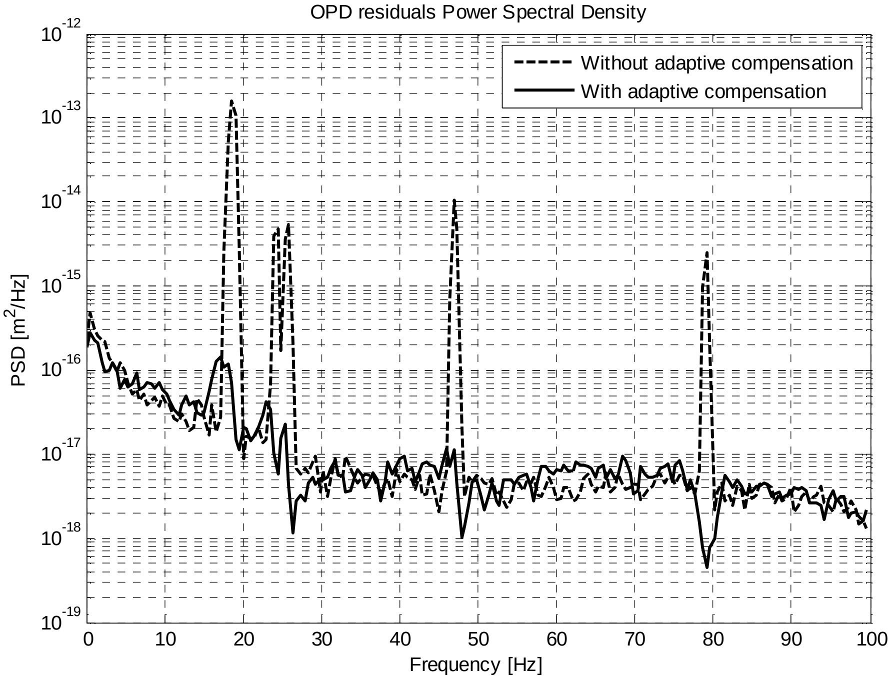

Fig. 6. Spectral analysis of the simulated OPD residual without/with adaptive compensation

4. IMPLEMENTATION AND RESULTS

The real-time implementation is based on VxWorks and is written in C code as a function block fitting in the ESO-developed framework TAC (Tools for Advanced Control[4]). Up to ten instances are allowed per interferometer channel. They run together with the closed loop OPD controller on a Motorola MVME2604 processor board. All the parameters described in the previous section are tunable on the system via the TAC infrastructure. Prior to tests at the observatory we successfully validated the real time implementation on the VLTI-PRIMA fringe tracking testbed[3].

The only enhancement made on the real system compared to the simulated algorithm is the ability to freeze the frequency/phase adaptation and slowly (seconds) smooth the amplitude down to zero in case of loss of fringe lock and therefore absence of error signal. This makes the adaptive algorithm robust to intermittent fringe lock conditions typically seen in less than ideal weather conditions, without affecting the performance in continuous fringe lock conditions.

The performance seen during the first night-time stellar interferometry tests is impressive. We initially attempted to attenuate the evident frequency peak at approximately 24 Hz. The algorithm was given a starting frequency of 24 Hz, with lower limit set at 23 Hz and upper at 25 Hz. Fig. 7 shows the internal adaptive signals. Fig. 8 and Fig. 9 show instead the spectral analysis of the closed loop OPD residuals, without and with adaptive compensation. The peak frequency without compensation is on average 24.17 Hz. Fig. 10 and Fig. 11 show the attenuation of multiple frequencies on a different telescope combination the following night, in a slightly more challenging weather environment which sometimes led to brief losses of fringe lock.

It is most important to note that, with the exclusion of the initial and boundary frequencies, all the instances of the algorithm are working with the same parameter values. The list of frequencies to be attenuated is manually input by the operator at the beginning of the night but this will be automated in the near future, as it can in principle be calculated by a computer script with no human intervention.

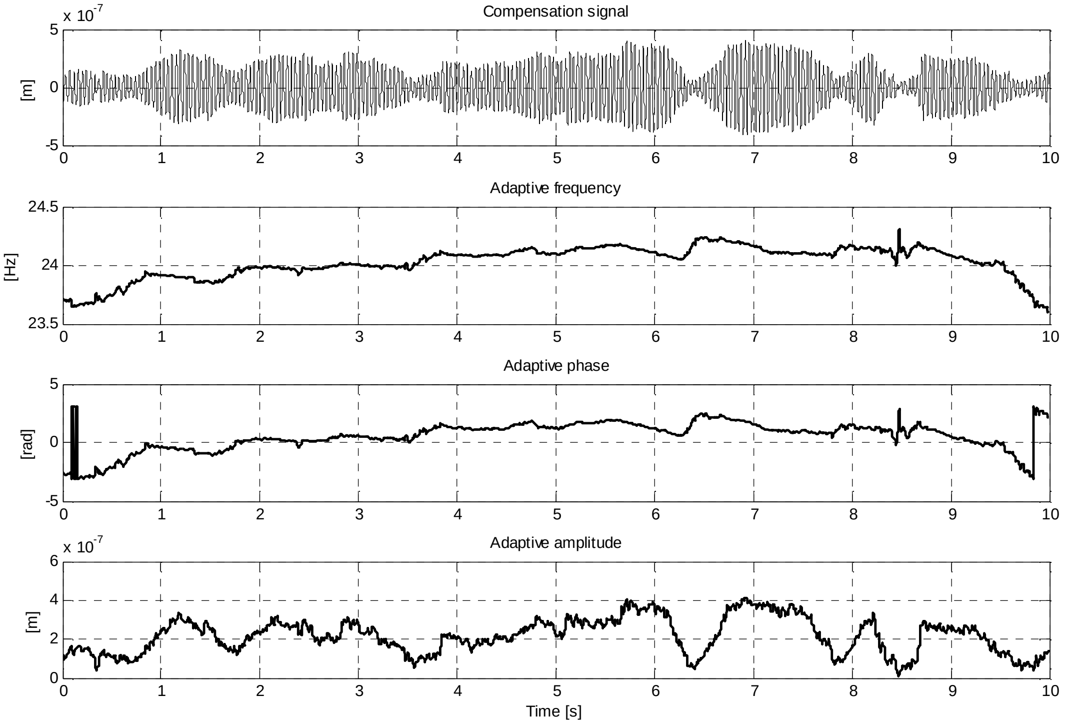

Fig. 7. Internal adaptive signals of the compensator tracking a 24 Hz vibration during interferometer operation on sky.

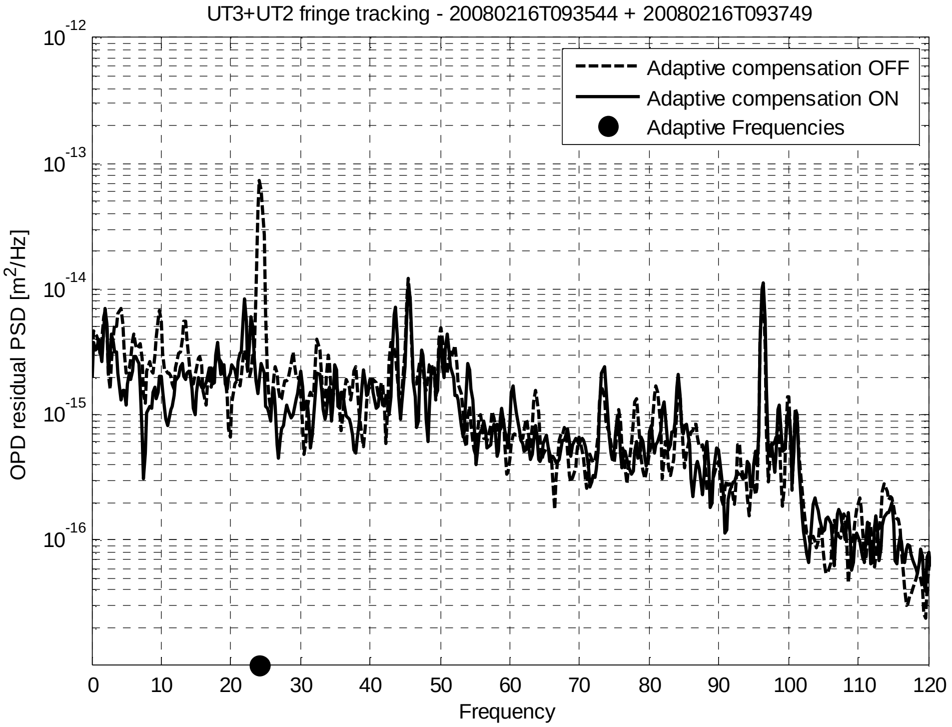

Fig. 8. Spectral analysis of measured OPD residuals without/with adaptive compensation.

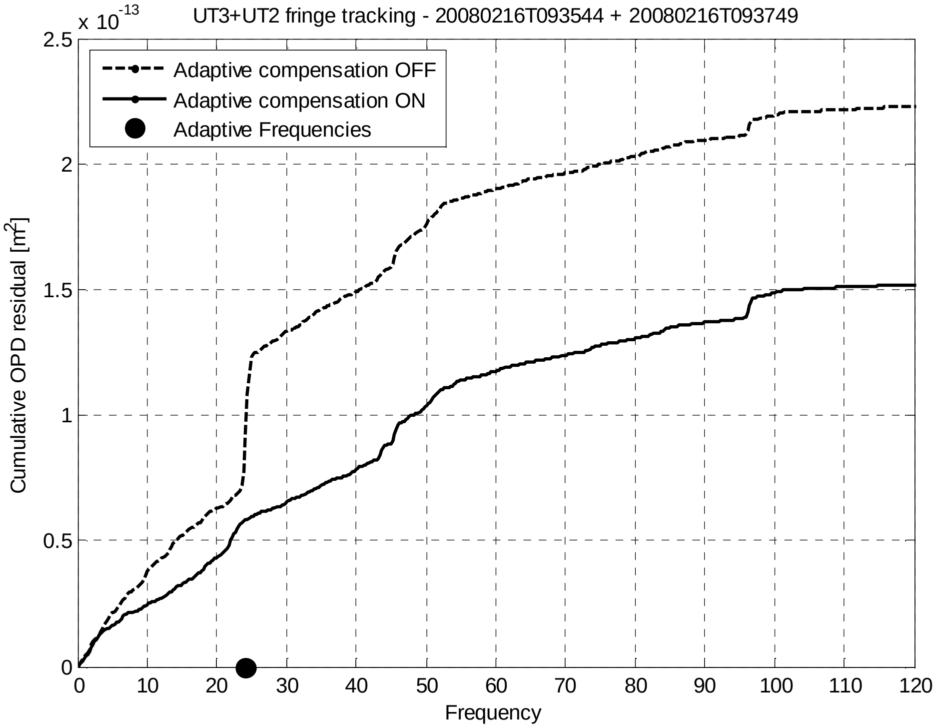

Fig. 9. Cumulative measured OPD residuals without/with adaptive compensation.

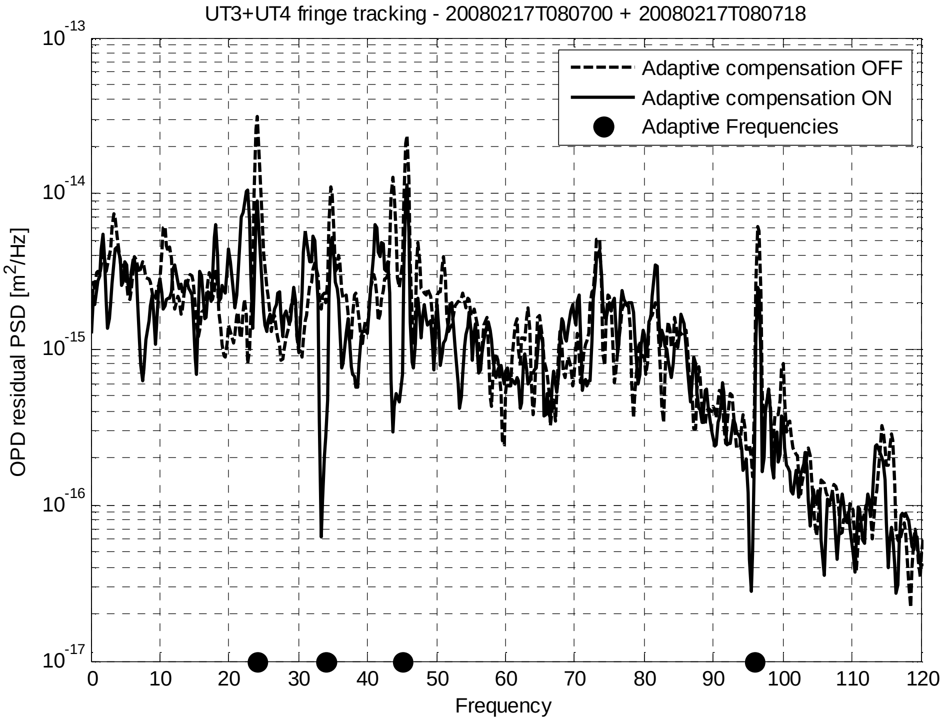

Fig. 10. Spectral analysis of measured OPD residuals without/with adaptive compensation.

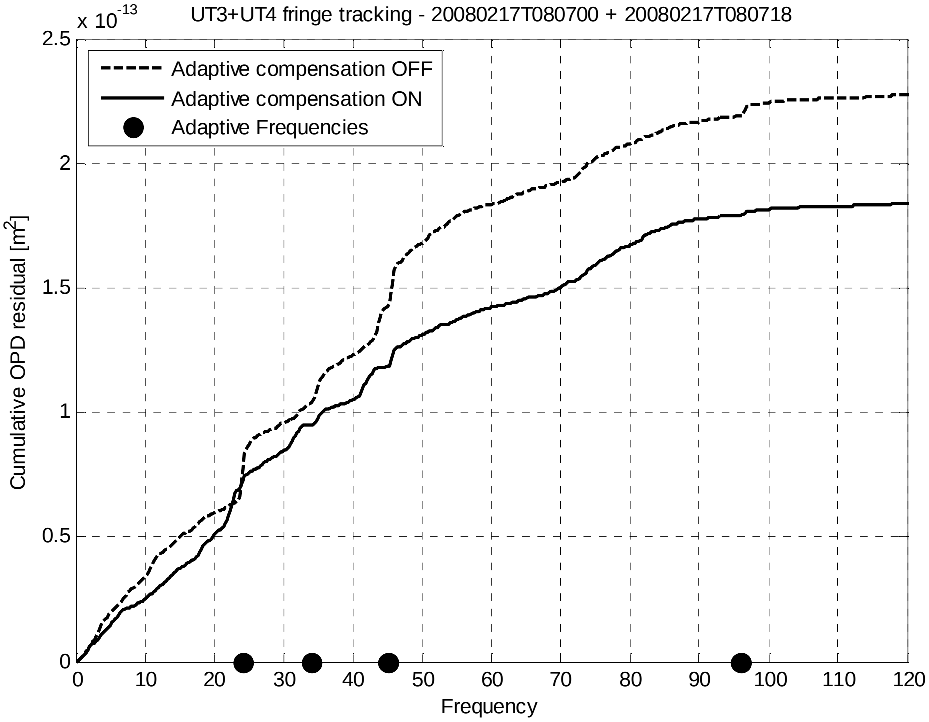

Fig. 11. Cumulative measured OPD residuals without/with adaptive compensation.

5. CONCLUSION

We successfully developed, implemented and tested a robust adaptive algorithm to attenuate near-harmonic, slowly drifting, relatively fast mechanical vibrations affecting the optical light path of the ESO Very Large Telescope Interferometer.

Night-time sky tests on our telescopes match well the simulated algorithm behavior and provide, as expected, several dB attenuation of vibrations at frequencies well above the closed-loop bandwidth of the fringe tracking loop.

Since the adaptive algorithm implementation is modular and re-usable, it is in principle applicable to any closed-loop control system affected by periodic vibrations.

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