AN APPROACH TO STABILIZING 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 VLT 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 couple to UT support structure and propagate to the large telescope mirrors. The mirror motions are fast and large (typically about a wavelength) and must be compensated for in real time. We have implemented a scheme to measure the accelerations imparted to the primary, secondary, and tertiary mirrors of the UTs via a grid of suitably placed accelerometers. The measured accelerations, coupled with a simple geometric model, are converted to optical pathlengths and cancelled by wideband feed-forward compensation to a downstream optical delay line.

THE ESO VERY LARGE TELESCOPE INTERFEROMETER

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 (Figure 1).

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 up to 20 times compared to that of individual telescopes. The VLTI can reconstruct images with an angular resolution of milliarcseconds and will soon allow astrometry at 10 microarcsecond precision.

In order to achieve the above, the light paths must be kept equal to less than a tenth of the observing wavelength. A fringe sensor provides real time OPD measurements used by a feedback control system. This fringe tracking system 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 support structure, we found that 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 control system. In order to attenuate these to an acceptable level, we engineered an accelerometer based feed-forward vibration cancellation system, which counteracts the vibrations measured on the mirrors by actuating the delay line piezoelectric actuators. A similar system to estimate the coherent motion of individual mirror segments is in use for interferometry with the segmented Keck telescopes [2].

Figure 1: The VLT Array on the Paranal Mountain, Chile

SYSTEM OVERVIEW

The system consists of piezoelectric accelerometers located on the telescope mirrors, a signal processing unit at the telescope and the piezo actuator of the optical delay line associated with the telescope.

We placed accelerometers at the 8.2-m primary mirror (M1), at the secondary mirror (M2) and at the tertiary mirror (M3) of the telescope (Figure 2). The accelerometer signals are amplified and then processed by a real time computer. The computed corrections are forwarded to the delay line via a fast optical fiber network, inherent to the interferometer control system.

The system operation scenario is as follows: two (or more) Unit Telescopes with associated delay lines observe the same star. The collected light beams are

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routed through the delay lines towards the fringe sensor, where they are coherently combined. The fringe tracking loop is closed with the delay line actuator. Our stabilization system senses the mirror vibrations, estimates their effect in terms of optical path length variation and sends this as error signal to the delay line, which compensates for the mirror displacement.

After the accelerometer signals are amplified and converted into displacement, a simple geometrical model of the telescope (M1 and M2 facing each other and M3 at 45° inclination) is used to correctly add the individual mirror contribution. The result is forwarded to the delay line using a commercial fibre reflective memory network operating at 2 kHz sampling rate. For optimum cancellation, the phase between disturbance and correction has to be 180°, which limits the applicable bandpass of the system (see signal processing section).

Following ESO guidelines, the system is operated remotely and can be used by non-specialised personnel. Graphical user interfaces allow to program the amplifiers and to enable the feed forward to the delay lines.

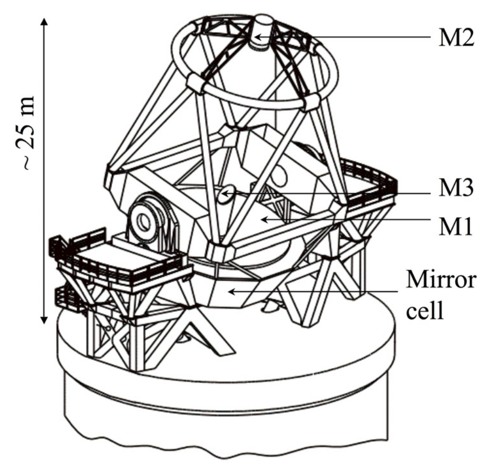

Figure 2: Sketch of a VLT Unit Telescope. The three principal mirrors are indicated.

MECHANICAL INSTALLATION

We decided to employ the Brüel & Kjær single-axis piezoelectric accelerometer model 4370, since it combines low noise and high sensitivity at reasonable cost. All accelerometers are oriented perpendicular to the optical surfaces. They are either bolted or attached with magnets, while kept electrically isolated from the telescope structure. Four accelerometers are mounted on supports clamping the outer edge of the primary mirror M1. Using results from finite element modelling we concluded that a square configuration, with two accelerometers being aligned with the telescope altitude axis, is suitable to sense the main vibration modes of M1. Secondary and tertiary mirror are assumed to exhibit predominantly rigid body motion, therefore one accelerometer is attached to the M2 support structure and two accelerometers are mounted on the back of M3.

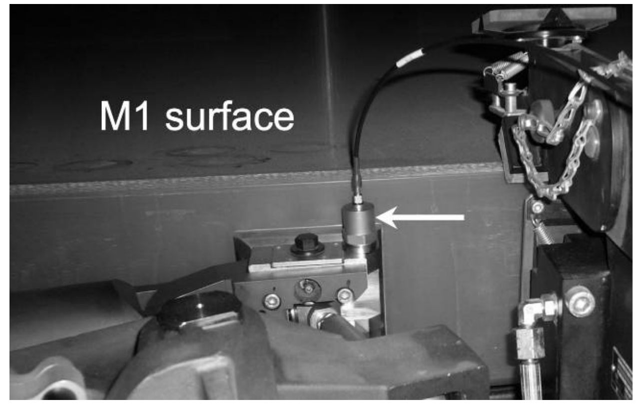

Figure 3: Accelerometer (indicated by the arrow) mounted on a M1 support.

The accelerometer signals are routed through double-shielded cables with up to 40 m length towards the signal processing unit, which is located inside the mirror cell below the main mirror.

The signal processing unit consists of two amplifiers (Brüel & Kjær model Nexus 2692) with four channels each, an analog-to-digital converter, a timing module, a CPU and a fiber communication module. All these components are installed in a standard VME crate and housed by a cooled cabinet. This is to avoid thermal dissipation into the ambient air, which degrades the performance of the telescope. Remote configuration of the amplifiers can be performed through a serial link.

Figure 4: Installation of the accelerometers on the telescope.

SIGNAL PROCESSING

Since acceleration is the second derivative of position, it may seem logical to simply double integrate the accelerometer signals to obtain position. This approach would not work for two reasons: first, the doubly integrated low frequency noise would swamp the output signal; second, the pure delay in the system (which we measured to be in the range of 1.75 to 2 ms), manifesting itself as a phase shift, would affect the quality of the cancellation above a few Hertz.

For these reasons we implemented a digital filter that is very close in magnitude to a double integrator between 10-50 Hz but has less phase than 180 degree in the same range, so as to compensate the system pure delay. In addition, a Butterworth high pass filter attenuates low frequencies to bring the noise at the low end of the spectrum within acceptable limits (Figure 5).

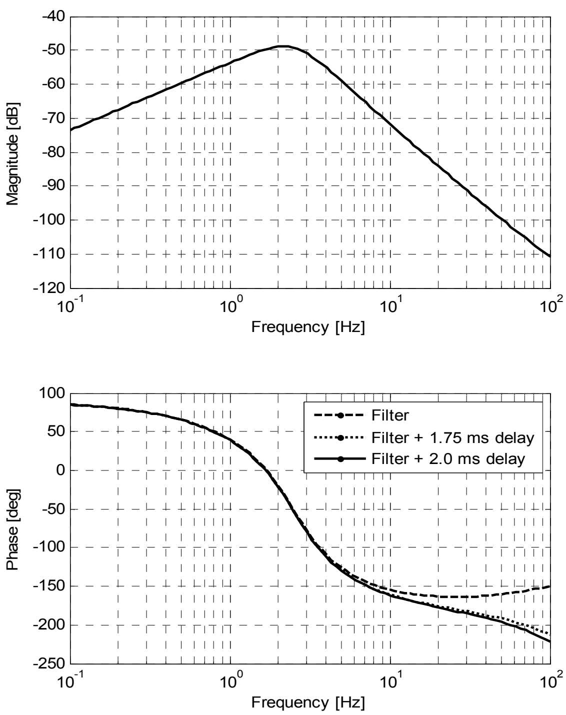

Figure 5: Digital filter frequency response.

The real-time software is based on VxWorks and is implemented using the ESO-developed framework TAC (tools for advanced control) [3]. In addition to digital filtering, it also performs the following functions:

- acquisition of the raw accelerometer signals, including validation and flagging of inconsistencies
- linear combination, based on geometry, of the filtered position signals from M1, M2 and M3
- publication of the combined position signal on the Reflective Memory Network (based on GE Fanuc VME-5565 boards) for use by the delay line as a compensation signal.

RESULTS

The vibration cancellation system was commissioned successfully in the period from August 2006 to June 2007 and is now in operation on three out of four Unit Telescopes. Once fine tuned, the system did not require any further calibration or modification. The only operator user interface consists of the on/off switch and accelerometer fault indicators, all implemented graphically on the controlling workstation.

We achieved reliable attenuation of mirror vibrations in the 15-35 Hz range (Figures 6, 7) along with a noticeable but slight increase of the very low frequency residuals. This is due to integrated accelerometer noise, which we can not suppress further without compromising the desired phase in the frequency range of interest.

Of course, not all parasitic vibrations occur on M1, M2, or M3, where accelerometers are currently placed. In particular, we have not yet tracked down the optical surface responsible for the large vibration at 47 Hz. This can therefore not be attenuated by the feed forward system in its present configuration.

We are currently planning to identify which mirror is responsible for it and add one or more additional accelerometers to the system. By so doing, we hope to be able to further improve on the results shown below.

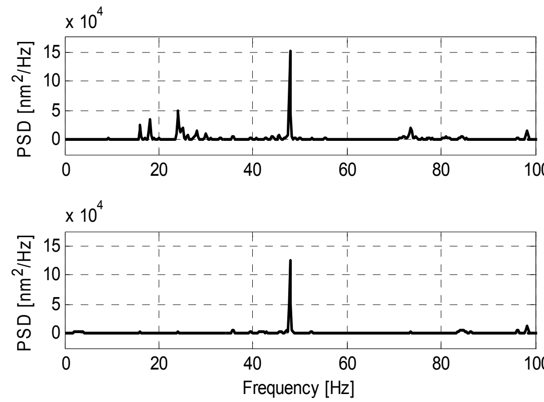

Figure 6: Power Spectral Density of the OPD residual during fringe tracking, without (top) and with accelerometer feed-forward (bottom).

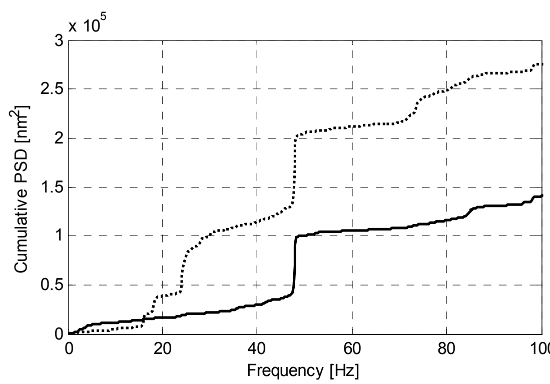

Figure 7: Cumulative PSD of the OPD residual during fringe tracking, without (dotted) and with accelerometer feed-forward (solid). The total residual is reduced from 530 to 382 nm RMS.

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