is about 10 % of that of a traditional glass mirror.

The optical surface will be generated by replication from a concave master. The development of a replication process applicable to astronomical large and highly accurate mirrors has been carried out for several years at the Observatory of Côte D'Azur with the financial support of INSU and ESO. Excellent replicas of a 1-metre concave mirror have been recently achieved, which gives confidence that the M2 mirrors can be successfully replicated. In case of difficulties however, conventional polishing is foreseen as back-up. Replication is particularly suited for convex surfaces which, with conventional polishing, are much more difficult to produce and to test than concave surfaces. The mould to be used for replication is concave and can be tested quite easily. The mould can also be oversized which gives the possibility to attain an excellent optical quality up to the very edge of the mirror which is hardly possible with traditional polishing. The main advantages of replica are therefore a lower cost, a shorter lead time and a better optical quality.

With the scheme proposed by Matra, the first unit is expected to be delivered well in time for the integration on the first Unit Telescope.

Hunting the Bad Vibes at Paranal!

B. KOEHLER, ESO

1. Introduction

It is well known that interferometric devices are extremely sensitive to vibrations. The VLT, in its interferometric mode (VLTI), is not an exception to this rule. Indeed, vibrations which generate relative displacement of the optical element of the interferometer at sub-micron level may blur the fringe pattern and result in a significant decrease of the fringe contrast, that is one of the prime observables of a stellar interferometer. Among many other sources of fringe contrast decrease, the vibrations coming from the ground (referred to as microseismic noise) are especially critical and require particular attention during the design and development phase of the project. As a matter of fact, an important specificity of the VLTI with respect to laboratory interferometers is that the optical elements of the interferometer are firmly fixed to the ground and not isolated from the ground. This requires, therefore, a high dynamic stability of the ground itself. The reasons for which the optical elements cannot be isolated from the ground are: (i) the site extension does not allow to place the complete interferometer on a single bench, (ii) individual isolation systems, because of their intrinsic low stiffness, would be incompatible with other requirements such as high tracking accuracy of the telescope under wind load and could, in some cases, deteriorate even more the fringe contrast because of their free relative motion at the support resonance.

This article provides an overview of the approach followed by ESO to investigate the effect of microseismic noise on the VLTI and describes, more particularly, two measurement campaigns recently performed at Paranal to support this investigation. These activities are part of the more general system engineering effort undertaken to verify and regularly update the VLTI

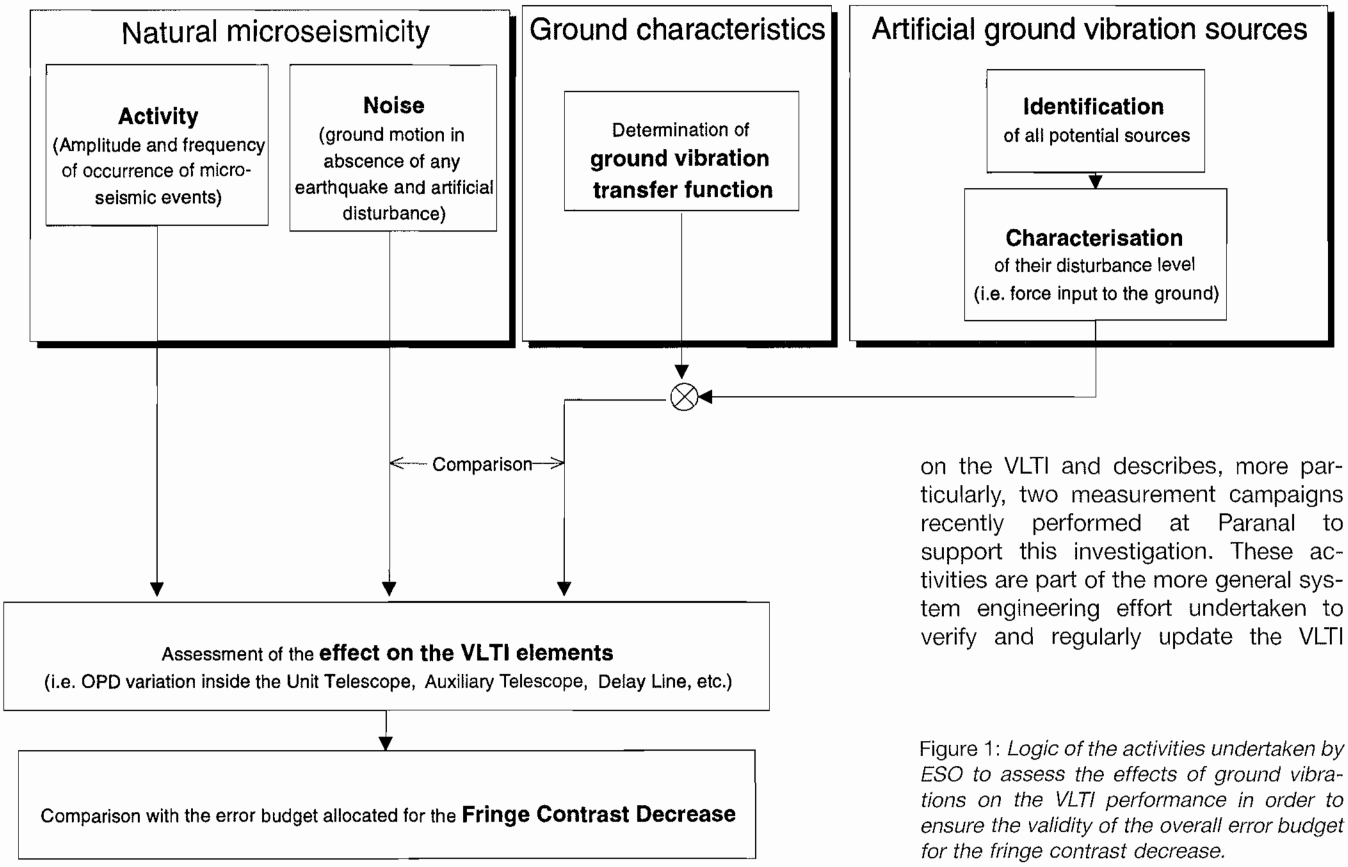

Figure 1: *Logic of the activities undertaken by ESO to assess the effects of ground vibrations on the VLTI performance in order to ensure the validity of the overall error budget for the fringe contrast decrease.*

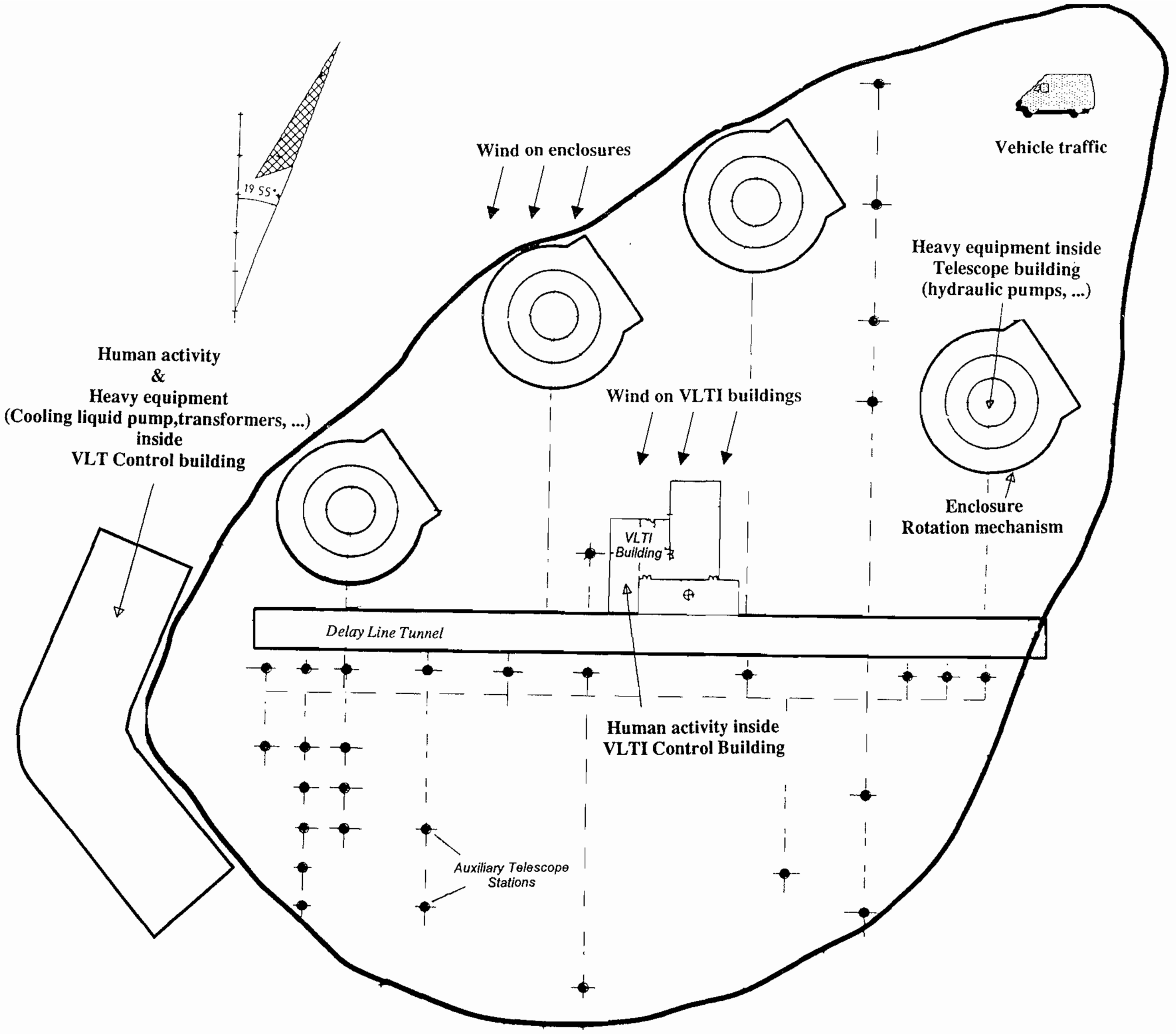

Figure 2: *Overview of the different artificial sources affecting potentially the VLTI. All these sources are subject to a characterization of their disturbance level and to an assessment of their influence on the VLTI performance.*

error budgets derived from the global VLTI performance requirements.

2. Overview

The logic of the investigation in the area of microseismic noise is schematically shown in Figure 1 and briefly described below.

Characterization of the natural microseismicity at Paranal: This consists in determining the natural ground motion at the site before any man-made disturbing sources are installed. Two types of seismicity are of interest: (i) the background noise which is the level of ground motion in the absence of any microseismic event, this level giving a reference for the “unpolluted” site, (ii) the microseismic activity characterized by the relation *intensity* versus *frequency of occurrence* of all micro-earthquakes. A specific campaign was dedicated to the measurement of these characteristics at Paranal (see section 4).

Determination of the Ground Vibration Transfer Function: Another important site characteristic related to the soil properties is the efficiency with which a disturbance at one location propagates through the ground to create a ground motion at a given distance where sensitive equipment is located. This characteristic is essential for the assessment of the effect of any artificial ground vibration source on a given VLTI element. It has been determined both theoretically and experimentally (see section 3).

Identification and characterization of all artificial ground vibration sources: An overview of the different artificial sources of microseismic noise potentially affecting the VLTI is shown in Figure 2. All these sources are subject to a characterization of their disturbance level and to an assessment of their influence on the VLTI performance. The results are used to specify or to check the design adequacy for various subsystems of the VLT Observatory such as the antivibration supports of the hydraulic pumps and of the liquid cooling pumps, as well as to derive operational constraints such as prohibiting the traffic on the platform during interferometric observations.

Assessment of the effects of ground vibrations on the VLTI: As soon as the level of ground motion at the location of the VLTI elements is determined, the effect on the VLTI performance can be assessed by computing the Optical Path Difference (OPD) variation generated by this motion. For very simple and small elements such as the folding mirrors at the output of the light ducts,

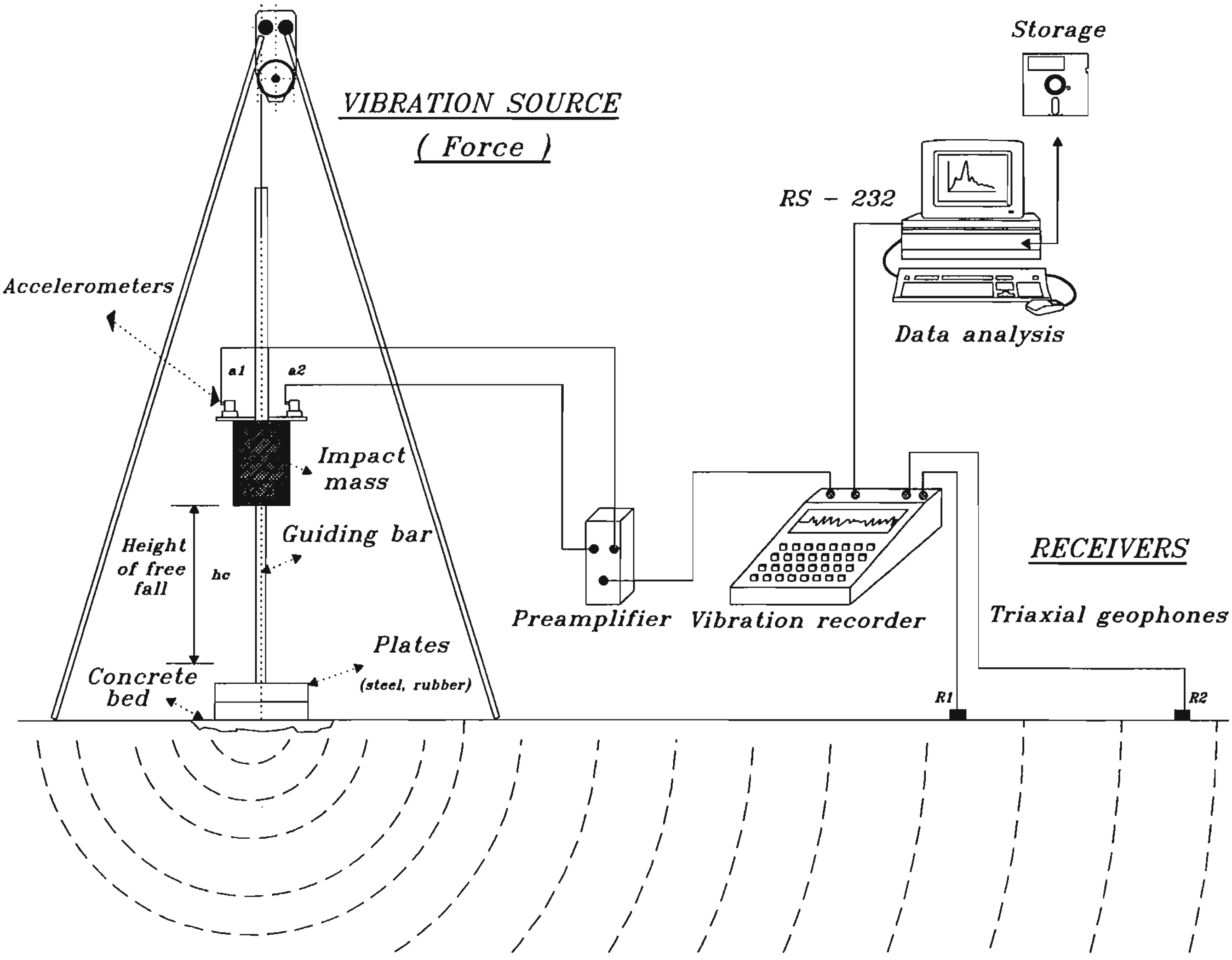

Figure 3: *Measurement set-up for the in-situ determination of the Ground Vibration Transfer Function (GVTF).*

the OPD variation can be directly derived assuming that the mirror follows exactly the ground motion. For complex elements such as the telescopes (or the delay lines), an accurate Finite Element Model is required. The ground motion is applied at the base of the telescope foundation and the OPD variation generated inside the telescope is computed from the displacements of the various mirrors. This computation is performed in the spectral domain.

The error budget for the OPD variation inside each telescope and each delay line is set to 14 nanometres RMS computed on any 10 millisecond time window corresponding to the detector integration time in the visible.

A level of 0.5 $\mu g/\sqrt{Hz}$ (above 10 Hz) for the Power Spectral Density (PSD) of the ground acceleration during VLT operation has been set as a design criterion for the VLTI. This level is used to easily compare the level of the various microseismic sources and to assess the generic influence of the ground motion on the different elements of the interferometer. When the PSD of the disturbance significantly differs from this design spectrum, a particular computation is required.

3. Ground Vibration Transfer Functions

In order to assess the influence of a ground vibration source on any of the VLTI elements (telescope, delay line, folding mirrors, beam combiner, instru-

Figure 4: *View of the geophone (foreground) and of the hammer-handling machine (background) used to measure the GVTF.*

Figure 5: *Overview of the Observatory site showing the telescope excavations and, in the centre of the "Platform" the equipment used to measure the GVTF. The view is taken from the north.*

ments, etc.), it is necessary to know how "well" the disturbance propagates through the ground between the source and the sensitive equipment. This ground characteristic, that we will call the Ground Vibration Transfer Function (GVTF), can be expressed in terms of the frequency-dependent amplitude (and phase) of the ratio: *[Displacement of the ground at the location of the sensitive equipment-called receiver-]/[Disturbance force input into the ground at the source location].*

3.1. Preliminary computer estimates

A preliminary estimate of GVTF was performed in November 1991 through computer simulation to allow early assessment of the effect of some major disturbance sources. The computer simulation, performed by the company Géodynamique et Structures (France), assumes a half-plan layered ground structure, horizontally isotropic, and makes use of the basic ground characteristics (mass density, compression and shear wave propagation velocities) previously measured on the site.

Results were obtained for different configurations of the source/receiver including different directions of the input force, different depths of the source and receiver, and different distances between the source and the receiver.

The results were used, in particular, to support the decision to install the main electrical transformers inside the Control Building located on the side of the Observatory Platform rather than inside the Interferometry Complex at the centre of the Platform.

3.2. In-situ measurements

In order to refine the above estimates it was decided to perform in-situ measurements of the GVTF at Paranal. This allows us to take into account the soil anisotropy and the particular geometry of the site not included in the above computer simulations. The one-week measurement campaign took place in September 1993 with the collaboration of the IDIEM company and Universidad de Chile (Chile).

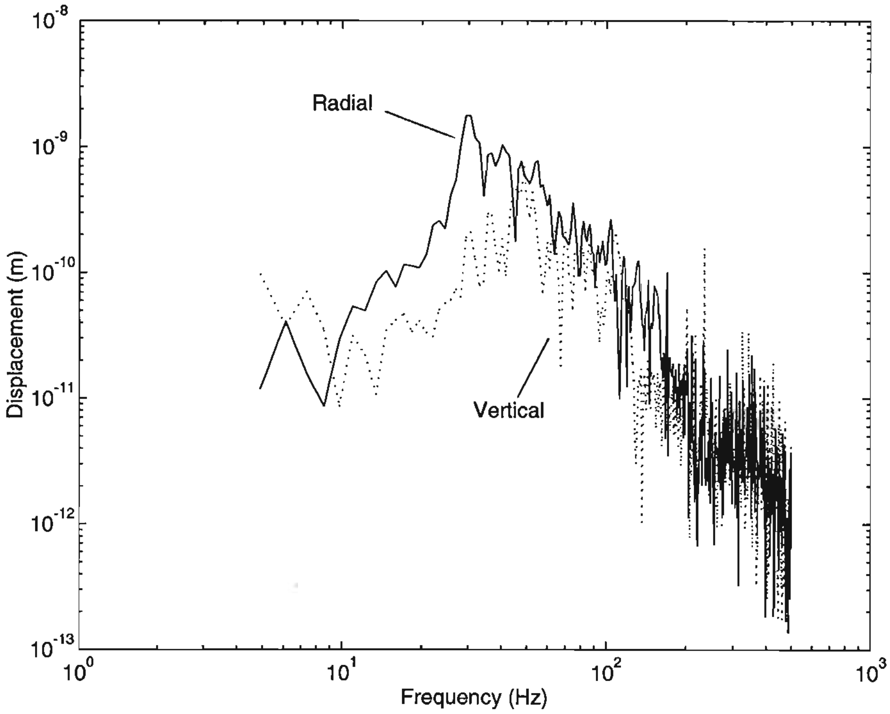

Figure 6: *Examples of Ground Vibration Transfer Functions obtained from in-situ measurement. The curves represent the amplitude of the ground displacement in radial and vertical directions in response to a 1000 N vertical disturbance force, as a function of its frequency. The source is at the Control Building location and the receiver is 50 m away, on the central platform (west part of the interferometric tunnel).*

Figure 7: *Obtaining accurate microseismic measurements free from external disturbance such as wind buffeting requires the seismometer to be buried on firm rock at least 40 cm below the surface, and requires a polyvalent seismologist! Here, Luis Rivera is at work in the excavation of telescope No. 4.*

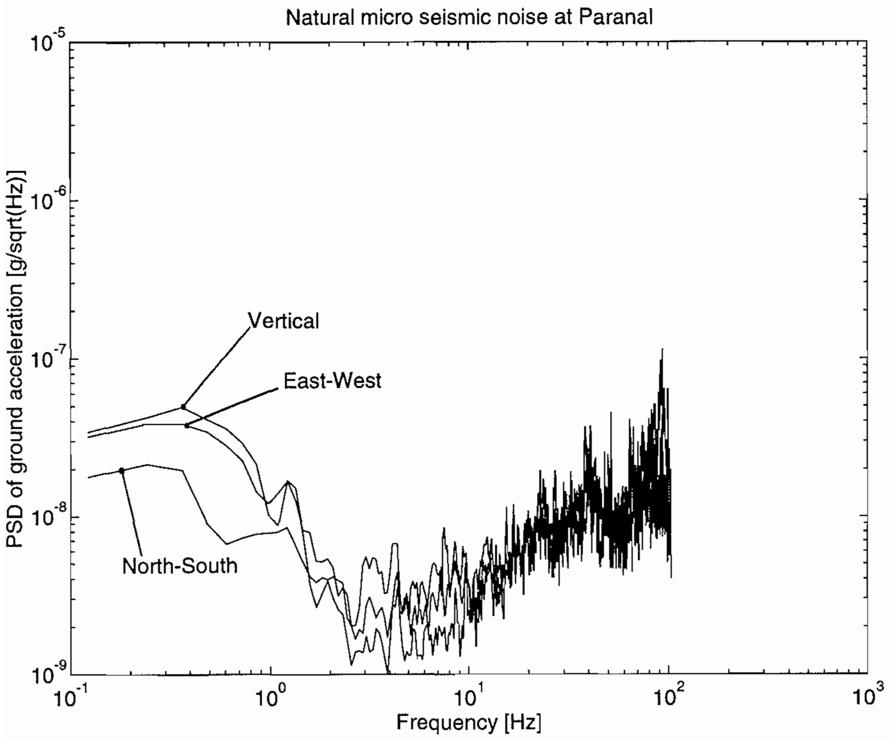

Figure 8: *Natural microseismic noise at Paranal in the absence of any seismic event and any artificial vibration source. The curves represent the PSD of the ground acceleration in the vertical, north-south, and east-west directions.*

3.2.1. Measurement set-up

The measurement set-up, shown in Figure 3, uses a force source consisting of a free falling hammer monitored by accelerometers and a set of triaxial geophones monitoring the ground velocity. The signals from the accelerometers and the geophones are fed to an acquisition electronics and saved on a PC for later processing. Figure 4 shows one of the geophones together with the drilling machine used to handle the hammer in the background. Figure 5 provides an overview of the Observatory Platform with the measuring set-up installed at the centre.

3.2.2. Results

Measurements were performed in a total of 19 different configurations in the excavation of the first telescope, on the central platform, in the excavation of the Control Building, and in between these locations.

Figure 6 displays an example of the results obtained for a source located at the Control Building and a receiver located on the central platform at the western extremity of the delay-line tunnel. This configuration is of particular importance since most of the vibration-generating equipment will be located in the basement of the Control Building and could, if no precaution were taken, disturb the folding mirrors and delay lines located inside the tunnel. For some configurations, the experimental results could be checked against those of the computer simulations. A good agreement of the average levels of the GVTF was generally found (e.g. ≈ $5 \cdot 10^{-12}$ m/N in the 10–100 Hz region at 10 m distance), but the in-situ measurements show important spectral features in the transfer function due to rock inhomogeneity.

These results are being used to update the assessment of the effect of the various artificial microseismic sources on the VLTI performance.

4. Natural Microseismicity

A second measurement campaign was undertaken at Paranal at the end of March 1994 to obtain a detailed characterization of the natural microseismicity. This campaign was performed in collaboration with the Ecole et Observatoire de Physique du Globe de Strasbourg (EOPGS) (France).

The measurement campaign had the following goals: (i) measure the *natural ground motion noise* at Paranal in the absence of any seismic event and any artificial vibration source, (ii) characterize the *microseismic activity* at Paranal (i.e. how often do microseismic events – earthquakes – happen and which intensity do they have?).

In addition, we seized the opportunity to characterize some artificial vibration sources which can only be assessed by in-situ measurements, such as car driving on the access road and people walking on the Observatory Platform.

The measurement set-up included high-sensitivity seismometers (Kinemetrics SS-1 and MarkProduct L4) associated with acquisition electronics (Reftek). The seismometers were installed on firm rock and buried at least 40 cm

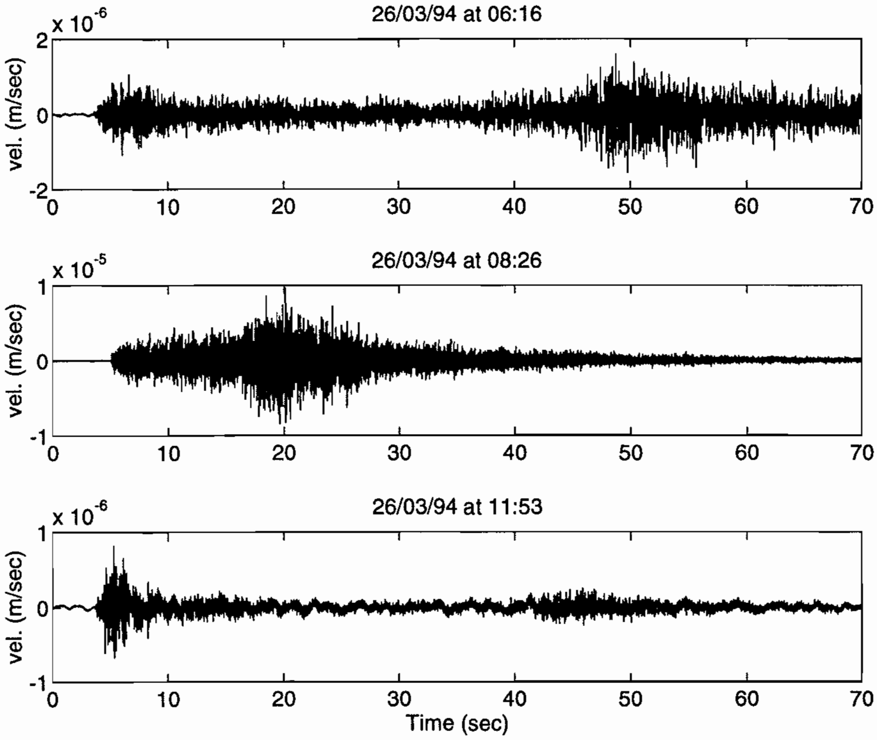

Figure 9: *Examples of micro-earthquakes recorded at Paranal during the night of March 25/26, 1994. The curves represent the chronogram of the ground velocity in the vertical direction.*

below the surface to avoid contamination by external disturbance such as wind buffeting (Fig. 7).

4.1. Natural background noise

Figure 8 shows the level of microseismic noise in the absence of any seismic event and any artificial vibration source for the vertical, north-south and east-west components of the ground motion. In the low-frequency part of the spectra, below 1 Hz, the effect of ocean waves is clearly visible, in particular on the vertical and east-west components, as expected from the Chilean coast geometry. This effect, which amounts to a few tenths of a micron, does not affect the VLTI because of its low frequency. In the medium (1–10 Hz) and high (10–100 Hz) frequency ranges, the level of ground motion ($<0.02\mu g/\sqrt{Hz}$) is extremely low, even when compared with that of very quiet sites available in the literature.

4.2. Microseismic activity

The microseismic activity was monitored during the ten-day campaign duration by placing the seismometers in trigger mode. The recording was triggered to any increase (by 30 % or more) of the signal RMS level. This allowed recording of very low-intensity earthquakes. These data will be complemented with the data obtained independently by the EOPGS with their permanent network installed 4 years ago in the Antofagasta area which monitors earthquakes of magnitude > 3.5. The statistical distribution of macro- and microseismic events at Paranal will be derived from these data.

A large number of events were recorded during the campaign (about one every 20 minutes). Figure 9 provides examples of such events showing the chronogram of the ground velocity while Figure 10 displays the corresponding acceleration spectra. The high frequency level of the acceleration PSD ranges from small values ($\approx 0.1\mu g/\sqrt{Hz}$) to larger values ($\approx 3\mu g/\sqrt{Hz}$) potentially affecting the desired ultimate performance of the VLTI in the visible. A detailed statistical analysis of the events' amplitude versus their frequency of occurrence is therefore required to assess their real influence on the VLTI operation. This analysis is in progress at the date of writing. However, a first conclusion is the confirmation of our plan to install a set of seismometers on the VLT site in order to monitor the microseismic activity during VLTI operation and to store, in a database, the information necessary to implement on-line and/or post-processing strategies taking into account the actual seismic activity experienced during the observations.

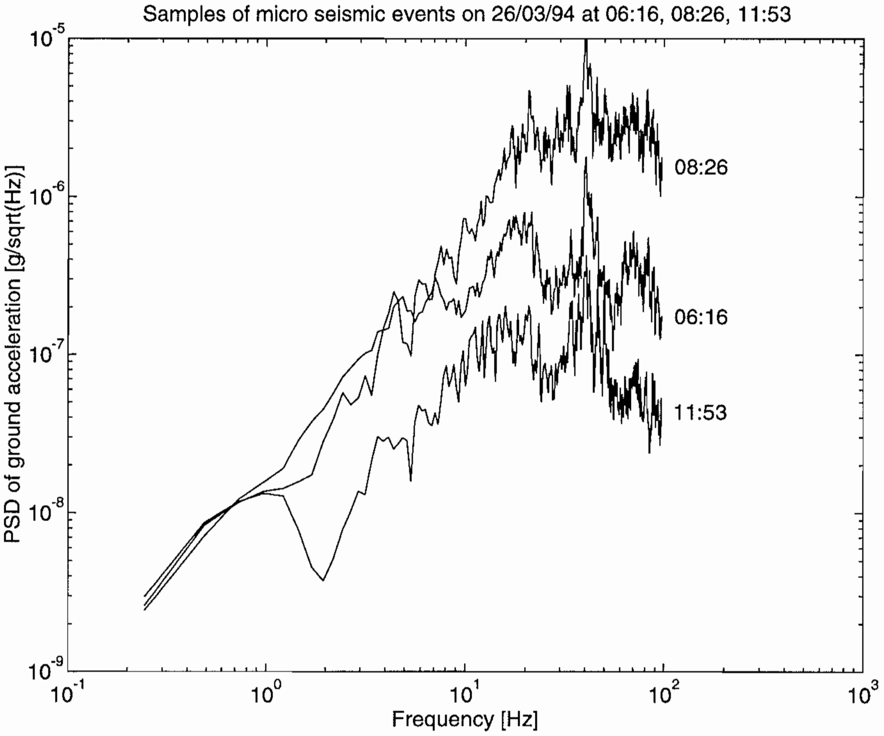

Figure 10: *PSD of the ground acceleration corresponding to the three micro-earthquakes shown in Figure 9.*

5. Conclusion

We have briefly described the activities undertaken by ESO to assess the effect of natural and man-made microseismic noise on the VLTI performance. First assessment of the ground vibration inside the VLTI facilities has been performed and is being updated as the detailed design of the VLT Observatory is progressing. The main conclusion is that the anticipated microseismic noise at the VLT site remains compatible with the error budgets derived from the required VLTI performance. A summary of the results obtained so far is given below.

(i) The natural microseismic activity at Paranal is not insignificant when compared with the ultimate performance of the VLTI in the visible. It may mean that a fraction of the time, probably still very small, will be "polluted" by micro-earthquakes. Final results are still expected in this area.

(ii) Vibration generating equipment inside the Control Building and inside the Telescope Building shall not transmit to the ground, at high frequency (> 10 Hz), a level of disturbance force higher than 1000 N and 100 N respectively. This constraint is taken into account, for example, by selecting screw-type pumps for the oil bearing and liquid cooling systems as well as by a proper design of their isolating supports and foundations.

(iii) People walking on the ground at 15 m distance, or less, start to contribute significantly to the level of microseismic noise. Control of the activity during interferometric observation as well as soft carpets in all service tunnels and in the VLTI Building are considered.

(iv) The wind acting on the telescope enclosure, despite the high load induced, has negligible impact thanks to the low-frequency characteristic of the wind energy and thanks to the filtering effect provided by the soft earthquake safety device located below the metallic structure of the enclosure.

(v) The enclosure bearing noise is not yet well known but does not appear very critical any more, thanks to the above-mentioned filtering effect.

(vi) Vehicle traffic on the platform during interferometric observation shall be strictly prohibited and traffic to and from the Control Building shall be carefully controlled.