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INVESTIGATIONS OF POWER AND SPATIAL CORRELATION CHARACTERISTICS OF SEISMIC VIBRATIONS IN THE CERN LEP TUNNEL FOR LINEAR COLLIDER STUDIES.

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and CLIC-Note 217

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ABSTRACT

Results of seismic vibration measurements made in the LEP tunnel in March 1993 are presented. It is shown that the LEP site is one of the quietest accelerator sites in the world with rms amplitudes for frequencies greater than 10 Hz not exceeding 0.1nm. The results show that spatial correlation disappears at high frequencies (10-100 Hz) for distances of more than a few tens of meters. At low frequencies the amplitudes are greater, at about 0.1 Hz the amplitude of vibration is almost 1 micron but the correlation at this frequency is very good up to a distance of 3km. Good correlation over long distances will certainly simplify the linear collider alignment problem and can only be achieved if the tunnel is built on a site which has a continuous and solid rock structure. It has been shown that essential systems such as water cooling plant and ventilation systems can significantly increase the level of vibrations.

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INTRODUCTION

The feasibility of building a high energy (500 - 2000 GeV) electron - positron linear collider is being studied at CERN, DESY, Branch INP (Protvino), KEK and SLAC [1]. To be able to transport low emittance beams to the interaction point and to make head-on collisions with vertical beam sizes of a few nanometres in such a collider can only be achieved using beam-based active alignment systems [3,4] and requires in addition a thorough understanding of the characteristics of seismic vibrations.

A collaboration between CERN and INP (Protvino) to measure seismic vibration levels on the CERN site began in 1992. The first series of measurements were made in the TT2A tunnel (an old beam transfer tunnel) and have been reported earlier [2]. This report gives the results of a second series of measurements which were made in the LEP tunnel and are probably representative of the conditions that will exist in the tunnel of a future linear collider. The main emphasis in this work has been placed on the spatial correlation of vibrations over long distances.

LOCATION AND CONDITIONS OF MEASUREMENTS

The measurements were carried out in the CERN LEP tunnel in the arc between points 4 and 5 (see Fig.1a) during the shutdown at the end of March 1993. Points 4 and 5 are the furthest away from both Geneva and CERN. They are situated about 7 km to the North of the CERN main site and 11 km to the North-West of the centre of Geneva. They are the deepest points of the LEP tunnel (about 120 m and 80 m underground respectively) - this is where the tunnel goes under the Jura mountains (see Fig.1b). This part of the tunnel was bored out of the "molasse" rock and from test borings made many years ago is known to be compact, homogeneous, hard and dry. The location of the TT2A tunnel is shown in Fig.1c.

EQUIPMENT AND METHODS

All results were obtained with the Russian-made SM-3KV single-axis seismic probes which are described in detail in [2]. The probes are essentially pendula carrying small coils. The voltages induced in these coils are proportional to the speed with which they oscillate in a known magnetic field. These probes measure vibrations in the 0.1-100 Hz band .

The data acquisition system for the probes consists of a CAMAC-crate containing CAMAC modules specially built for this application by INP and INP Branch staff (ADC, preamplifier, multiplexor, crate-controller), an IBM PC AT computer and special software. The system is described in detail in [2]. For the spatial correlation measurements we used two identical data acquisition systems placed up to 3km apart. A timer connected to both systems via two 1.5km long cables was used to synchronise the start and stop of data taking to the required few milliseconds accuracy. Since there was no data communication link between the two systems correlation calculations could only be made after having manually transported diskettes from one computer to the other.

Data treatment methods are described in detail in [2]. For completeness the main expressions and relationships are given again in the Appendix.

RESULTS OF MEASUREMENTS

a) Power spectra.

Power spectra of seismic vibrations were measured in the LEP tunnel for quiet conditions. "Quiet " in this case means during the night at the weekend with all accelerator systems and devices turned off and no humane activity in the tunnel. The results obtained for the vertical vibrations are compared in Fig.2 with results obtained in the TT2A and UNK tunnels.

The figure shows that whereas in the 0.3-100 Hz band the spectra of vibrations in the LEP and UNK tunnels are approximately the same, in the 2-10 Hz band the LEP tunnel is quieter - this is because the LEP tunnel is deeper underground (the measurements in the UNK tunnel were made at a depth of about 25m). In the frequency band where the so called "cultural" noise usually manifests itself, i.e. at f > 1Hz, the vibration level in the TT2A tunnel which is on the main CERN (Meyrin) site is much higher than in LEP and UNK. From the integrated spectrum shown in Fig.2 we see that the rms amplitude of vibrations with frequencies greater than 10 Hz does not exceed 0.1 nm for both the LEP and UNK tunnels.

The peak in the 0.07-0.2 Hz band (the "micro-seismic peak") is attributed to the action of the waves of nearby oceans on the land. The amplitude of the peak depends on the distance from the ocean and on the prevailing weather above the ocean. The difference in amplitudes of the peak measured in the LEP and TT2A tunnels is probably due to seasonal variations of ocean activity around Europe. In Protvino the peak amplitude is usually 2-3 times lower than in CERN because CERN is closer to the ocean than Moscow. It is interesting to note that the frequency of the peak is usually greater for Protvino than for CERN. Comparing the data with results of seismic measurements made in Novosibirsk [6] and Japan [7] we see that the frequency of the micro-seismic peak is approximately the same in Protvino and in Novosibirsk but the amplitude in Novosibirsk is almost one order of magnitude lower (Novosibirsk is far from the ocean in the centre of the Asian continent). The amplitude in Japan is approximately the same as in Protvino but the frequency is about twice as high (about 0.35 Hz) - this is probably explained by the fact that in one case the perturbation comes from the Atlantic and in the other case the Pacific.

Comparison of power spectra measured in the LEP and TT2A tunnels for all three axis (see Fig.3) show that the vibrations in quiet conditions are almost isotropic.

When making seismic measurements in very quiet conditions as found in the LEP tunnel it is very important to know the dynamic range of the measuring probes. The ratio of the maximum seismic signal to the noise in the electronics of the probes can be evaluated from Fig.4 where both the spectra of vertical vibrations in quiet and noisy conditions and the spectrum of "the noise of the electronics" are shown. The "noise of the electronics" was obtained by preventing the probe's pendulum from moving with special blocking screws. In our working region 0.07-100 Hz the signal-to-noise ratio is large enough for noisy conditions but is insufficient for very quiet conditions above 70 Hz. The amplitudes of vibrations at these frequencies however are small enough (about 0.01 nm) in our case to be neglected. The "noise of the electronics" was usually greater during day time than night time because of the increased level of external electromagnetic noise produced during the normal working day. For some measurements however the probe electronics were modified to give an output response (see upper curve in Fig.5) with an improved signal-to-noise ratio. The lower curve gives the velocity-meter like response of the un-modified probe. The symbols in Fig.5 are measured calibration points.

b) Correlation measurements.

One of the most important characteristics of seismic vibrations for a linear collider is the correlation of vibrations of two points at a given distance apart. Good correlation will certainly simplify the dynamic alignment of the various linear collider elements which is essential in preventing emittance growth [1,3,4]. The results of the correlation measurements are mainly presented in the form of correlation spectra (see definition for example in [2] or [5]).

Typical data for probes placed at 0m and 3000m apart are shown in Fig.6. One can see that when the probes are side by side (top picture in Fig.6) their responses are almost identical. When the probes are 3000m apart (middle picture in Fig.6) some differences in amplitude and phase become apparent.

The dominant signal that we see in Fig.6 is the so called "micro-seismic signal" or "7-second hum". It has a large amplitude and therefore other frequencies are almost not seen. The high frequency contributions and the differences in the responses at higher frequencies become more visible if we show velocity rather than displacement (bottom picture in Fig.6). There is clearly an advantage in presenting seismic data in a spectral form as opposed to a direct presentation of displacements.

In the middle figure we see that the vertical amplitude of the micro-seismic signal at "point 4" is bigger than at "point 5". For the horizontal signals the opposite was true, the amplitude of the micro-seismic signal at "point 4" was smaller than at "point 5". The micro-seismic amplitudes obviously have a spatial variation which depends on the local surface structure as well as the properties of the surroundings.

Correlation spectra (the real part of the correlation function in the frequency domain to be exact) for distances between probes of 0 to 3000 m are shown in Figs.7-12. The solid lines correspond to night time measurements and the dashed lines to day time measurements. The correlation spectra of the probes placed together confirm that in the 0.07-70 Hz band the signal-noise ratio is large enough. At high frequencies however (70-100 Hz), LEP being so quiet, the noise of the electronics becomes comparable with the very low level seismic signal and makes accurate correlation measurements difficult. At some frequencies the correlation measured during night time is better than that measured during day time, this is because there is an increased level of external electromagnetic noise during the day.

The correlation spectra in these figures show a smooth decrease in correlation of the high frequency part of the spectrum as the distance between probes increases. Even at a distance of 3000m the micro-seismic signal is still well correlated. This indicates that at least in this region of the LEP tunnel there are no serious breaks in the Earth's surface structure. A poor correlation of the micro-seismic signal would certainly complicate the alignment of a linear collider. Such a machine should preferably be built on a large geological plate composed of solid rock such as granite.

Information about local sources of vibrations can be obtained from the correlation spectra. For example in Fig.8 (correlation of two horizontal probes oriented transversely to the LEP tunnel) there is an "anti-correlation" peak rising above the noise at 1.05 Hz for a distance of 1000m between probes, and a correlation peak at 1.05 Hz at a distance of 2000m. This suggests that there is some device producing vibrations above the seismic background at this frequency and that the waves propagate with a phase shift between π and $\pi/2$ over 1000 m. If we assume that the waves propagate only along the tunnel we can estimate the velocity with which the waves propagate to be 2000-4000 m/sec. This source can be identified in the power spectrum (see for example the peak near 1 Hz in Fig.4 or Fig.19).

The correlation spectra can be used to estimate how the velocity changes with frequency. The result however depends on which wave propagation model (one or two dimensional) is used. If we assume that there are no sources between the points of measurement and we neglect dissipation, then using a one dimensional or plane wave model the real part of the correlation is equal to $\cos(\omega*z/v)$. If we use a two dimensional or cylindrical wave model we get $J_0(\omega*z/v)$ or $<\cos(\omega*z/v*\cos(\theta))>$ where <> means averaging over the angle "θ" in the interval $0 < \theta < 2\pi$. The imaginary part of the correlation is exactly zero for both these models. The analysis is done in the following way. The real part of the correlation factor is re-plotted as a function of distance for a fixed frequency using all the different correlation spectra. The best fit to this new data using either the cosine or Bessel function determines the velocity. Repeating this for various frequencies and plotting velocity as a function of frequency enables any noticeable trend or functional relationship to be established. The analysis was limited to those frequencies where the correlation function was varying and reasonably well behaved. This excludes very low frequencies where the correlation value was constant (= 1.0) and the higher frequencies where there was no or erratic correlation. The analysis of our data gave velocities $v \pm \sigma$ of (4400±900) m/sec for the one-dimensional model and (6600 ±1300) m/sec for the two dimensional model. Within the precision of our measurements these velocities therefore do not depend on frequency. This value for the propagation velocity is more than twice that measured in the TT2A tunnel and is almost certainly due to the stiffer rock structure surrounding the LEP tunnel. The higher the velocity, the longer the wavelength in the medium and the closer the linac movement is to that of a rigid body - the linear collider should therefore be build in a place that has a stiff rock structure.

The imaginary (sinus-like) parts of the correlation spectra are shown in Figs.13-18. The non-zero correlation near 0.5 Hz is probably due to small differences in the phase characteristics of the different probes. The contributions of local noise sources (for example the 5 Hz peak from the monorail) can be seen in these figures.

c) "Cultural" (or man-made) noise.

Although we have seen that the LEP tunnel is basically a very quiet place auxiliary accelerator systems and devices will create additional noise. Some examples are shown in Figs.19-23.

In Fig.19 we compare power spectra measured during quiet and noisy conditions. "Noisy " in this case means the day-time activity during a shutdown with many people working in the tunnel and with additional systems and devices switched on. For example in Fig.19 a peak at 5 Hz appeared whenever the monorail was operated. The human activity increases the rms amplitude of vibrations in the region of frequencies above 1 Hz by an order of magnitude. This man-made activity disappeared during the night - this is shown in the 3-dimensional plot in Fig.20 (the spectra in this plot have been slightly smoothed by a spline fit). Note also in this figure the small variations in the amplitude of the "micro-seismic signal" with time. In Fig.21 we see the vibrations produced by the monorail far away (about 1 km) from the measurement point. The upper and lower traces show data with monorail off and on. This source of noise is of course absent when the accelerator is being operated.

Some systems are required to run during the normal operation of an accelerator. Fig.22 shows the effect of the water cooling station for the magnets. This station is situated in an annex of the tunnel and was about 200 m from one of the probes and 800 m from the other. At some frequencies the level of vibrations increases by factors of three or four. The influence of the ventilation system (measured near point 4 of the LEP tunnel) is shown in Fig.23. The data in these two figures covers a frequency band which is outside the normal working region of the probes but since only the ratio of two spectra from the same probe is used (without moving or even touching them) the data obtained is probably correct. The ventilation system has a strong influence on the vibration level - at some frequencies the level is increased by a factor of one hundred. For a linear collider such systems would have to be designed and situated more carefully to reduce vibrations to acceptable levels.

CONCLUSIONS

Measurements made in the LEP tunnel show the level of seismic vibrations in "quiet" conditions to be very low - the root mean square amplitude of vibrations with frequencies greater than 10 Hz for example does not exceed 0.1nm. It has been shown however that essential systems such as water cooling plant and ventilation systems can significantly increase the level of vibrations. A careful design and location of such systems is clearly necessary for any future linear collider.

This study has shown that the correlation disappears at high frequencies (10-100 Hz) for distances between probes of more than a few tens of meters. The vibration level at these frequencies is however small. At low frequencies the amplitudes are greater, at about 0.1 Hz for example the amplitude of vibration is almost 1 micron but the correlation at this frequency is very good up to 3km.

Good correlation over long distances will certainly simplify the linear collider alignment problem but can only be achieved if the tunnel is built on a site which has a continuous and solid rock structure.

As a general comment the best conditions for a linear collider from the point of view of seismic vibrations are (1) that the linac be as short as possible (2) that the motion be correlated over as large a frequency range and distance as possible (3) that the velocity of propagation in the surrounding rock be as high as possible so that the linac moves as much as possible like a rigid body.

ACKNOWLEDGEMENTS

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APPENDIX

Power spectral density is defined as follows:

$$P(f) = 2 \lim_{T \to \infty} \frac{1}{T} \left| q(f) \right|^2$$

where

$$q(f) = \int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)\, e^{-i\omega t}\, dt$$

Since the power spectrum of a real signal is a symmetric function we limit ourselves to positive frequencies in our definition of power spectrum density and therefore multiply by a factor 2.

The autocorrelation function (non-normalised) of a random process :

$$a(\tau) = 2 \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} x^*(t)\, x(t+\tau)\, dt$$

is connected to the power spectrum via the Fourier transformations:

$$P(f) = \int_{-\infty}^{+\infty} a(\tau)\, e^{-i\omega\tau} d\tau$$

$$a(\tau) = \int_{-\infty}^{+\infty} P(f)\, e^{i\omega\tau} df$$

The dispersion or variance σ^2 (the most important characteristic of a random signal) can be obtained from the power spectrum by integrating over the frequency range

$$\sigma^2 = \frac{1}{T} \int_{-\frac{T}{2}}^{+\frac{T}{2}} |x(t)|^2\, dt = \int_0^{\infty} P(f)\, df \quad \text{for } \langle x \rangle = 0$$

Inspection of the power spectrum readily indicates which frequencies make the major contributions to the overall amplitudes.

In practise however the time of measurement T is limited. So in order to find the power spectrum with some precision many measurements are averaged.

$$P(f) = 2\left\langle \frac{1}{T} |q(f)|^2 \right\rangle$$

The normalised cross-correlation function in the frequency domain is given as follows

$$N_{12}(f) = \frac{\langle p_{12} \rangle}{\sqrt{\langle p_1 \rangle \langle p_2 \rangle}}$$

where $p_{12}(f)$ is the mutual power spectrum

$$p_{12}(f) = \lim_{T \to \infty} \left\langle \frac{1}{T} q_1(f)\, q_2^*(f) \right\rangle$$

where ' and < > means complex conjugation and averaging on different measurements respectively. The real part of $N_{12}(f)$ we called "correlation", and the modulus of $N_{12}(f)$ "coherence".

The measured variable x(t) in this work is velocity and P(f) as defined above is the velocity power spectral density (PSD_v) and has units of $(\mu m/s)^2/Hz$. The associated "displacement" power spectral density PSD_d has units of $\mu m^2/Hz$ and is defined as PSD_v / w^2 where w is the local circular frequency. A presentation of results in the form of a PSD_d is particularly useful since the total rms displacement Z_{rms} is given by

$$Z_{rms} = \sqrt{\int_0^{+\infty} PSD_d(f)df}$$

and the contributions of the various frequencies to the total rms displacement can be determined by integrating the spectrum from $-\infty$ or f_{max} to the frequency of interest.

$$I(f) = \sqrt{\int_f^{f_{max}} PSD_d(f)df}$$

If the power spectrum is defined in [micron^2/Hz] then the integrated spectrum has the dimension [micron].

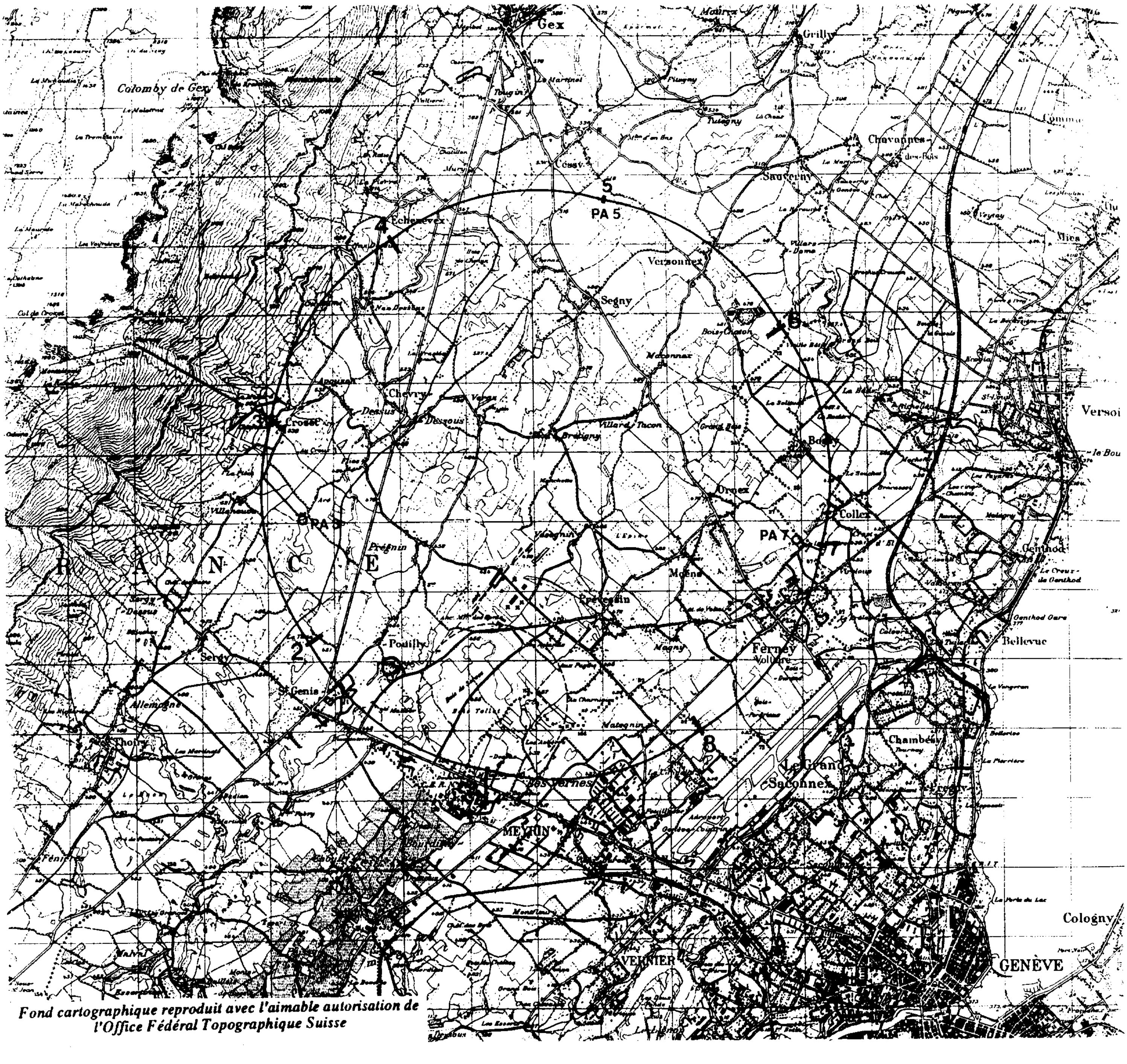

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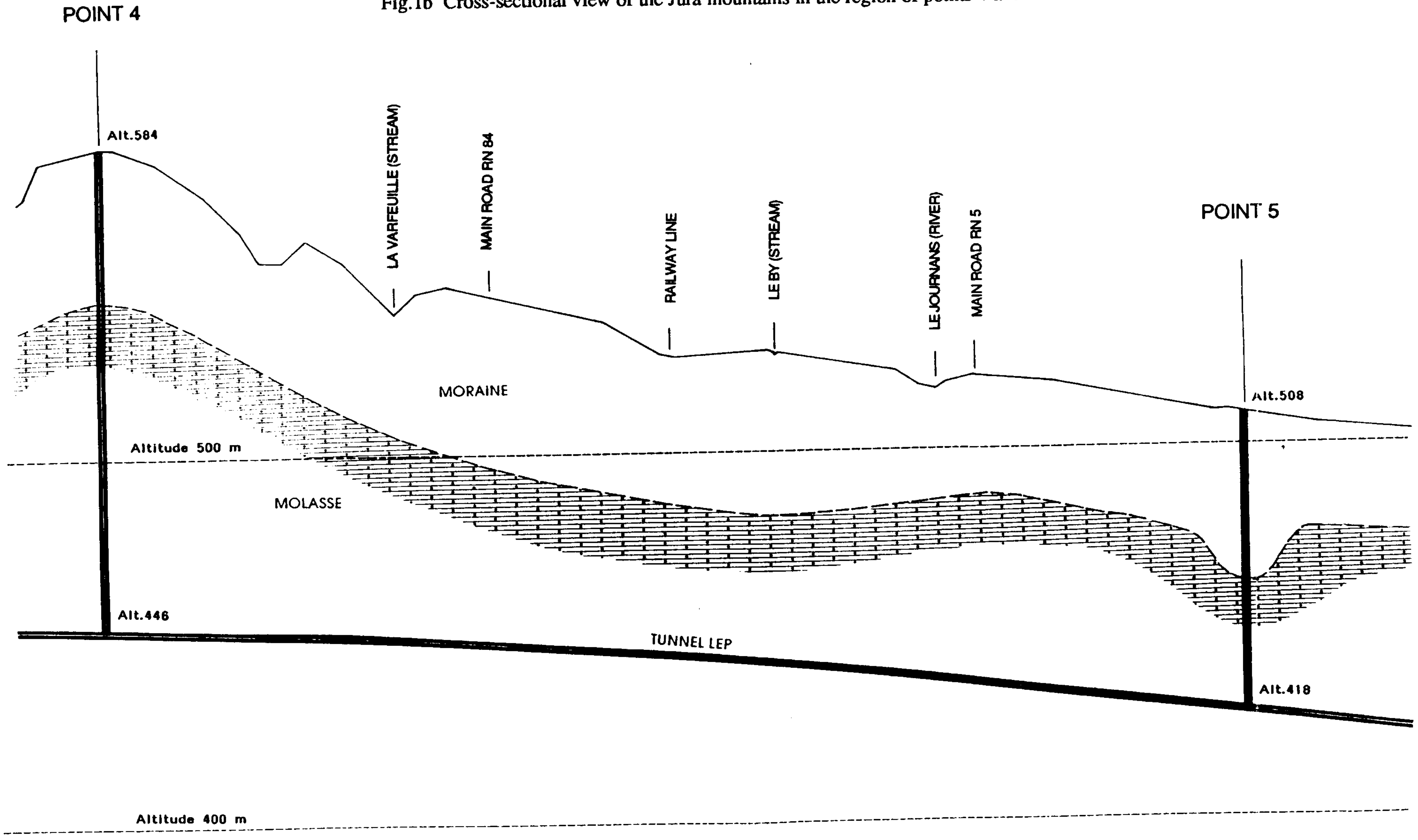
Fig.1a Plan view of the LEP tunnel showing the location of points 4 and 5.

Fig.1b Cross-sectional view of the Jura mountains in the region of points 4 and 5.



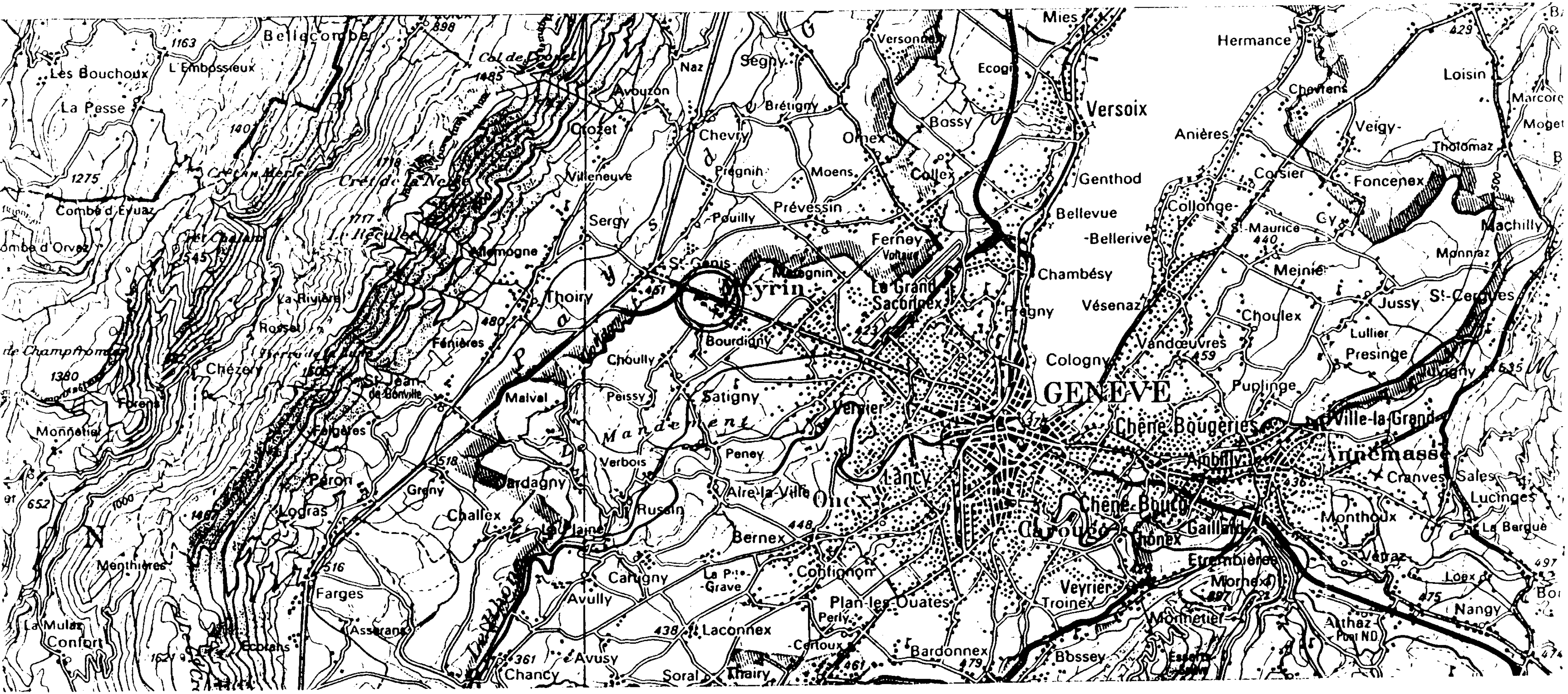
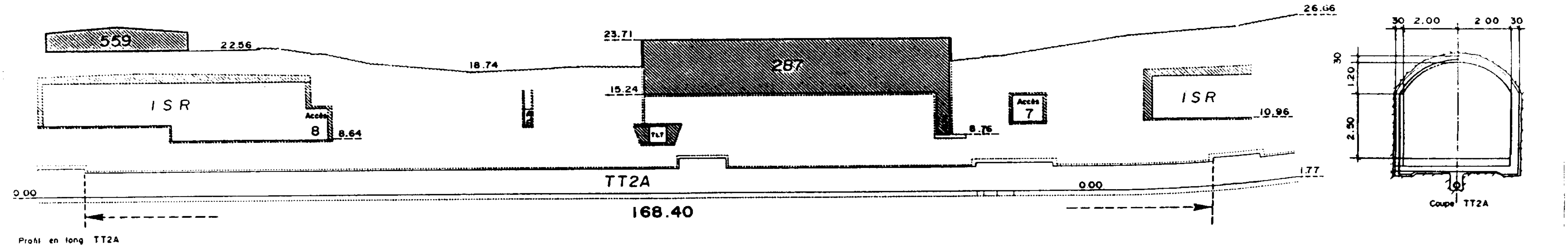


Fig.1c Situation of the tunnel TT2A on the main CERN site.



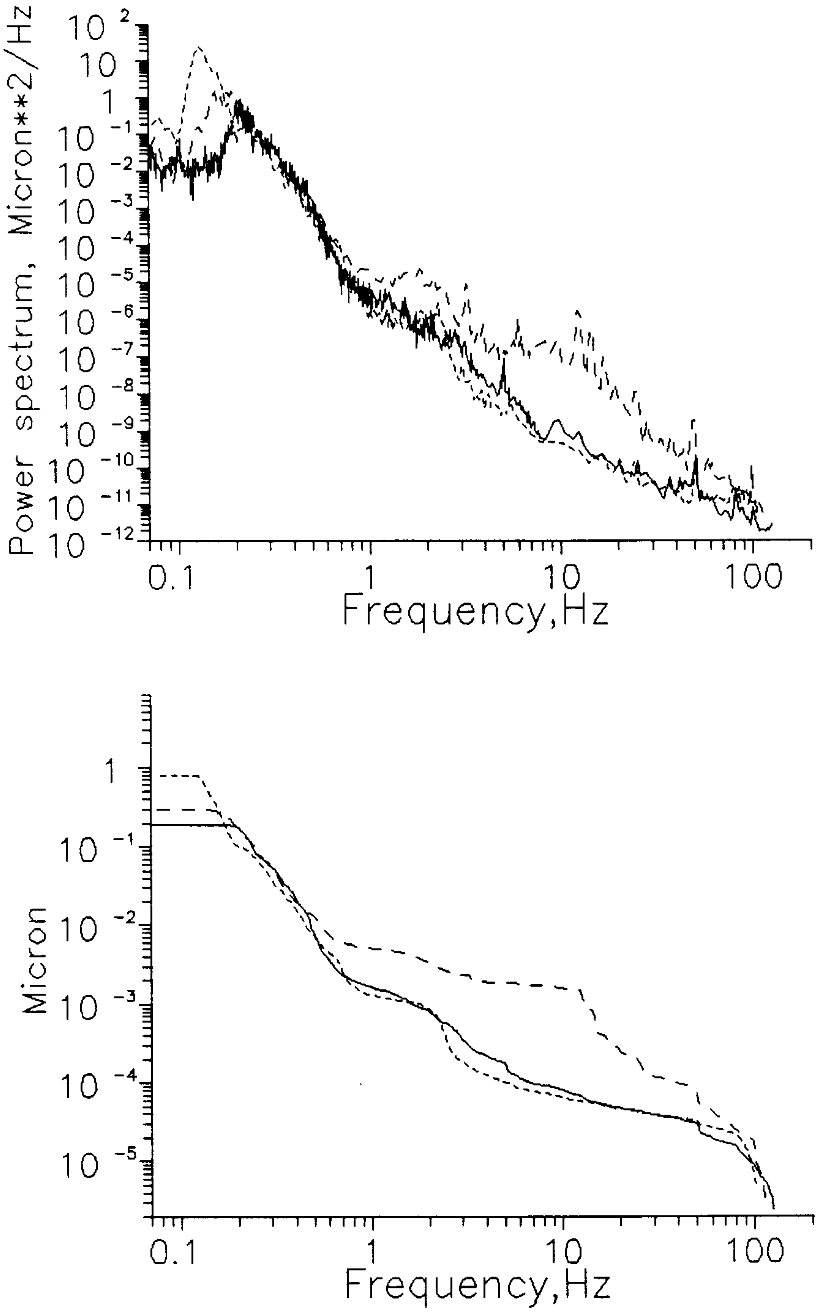


Fig.2 Power and integrated amplitude spectra of vertical vibrations measured in quiet conditions. CERN LEP tunnel. Tuesday 23-03-93, 1 a.m. - short dashed line. CERN TT2A tunnel. Sunday 22-11-92, 3 a.m. - long dashed line. Protvino UNK tunnel. Sunday 01-11-92, 2 a.m. - solid line.

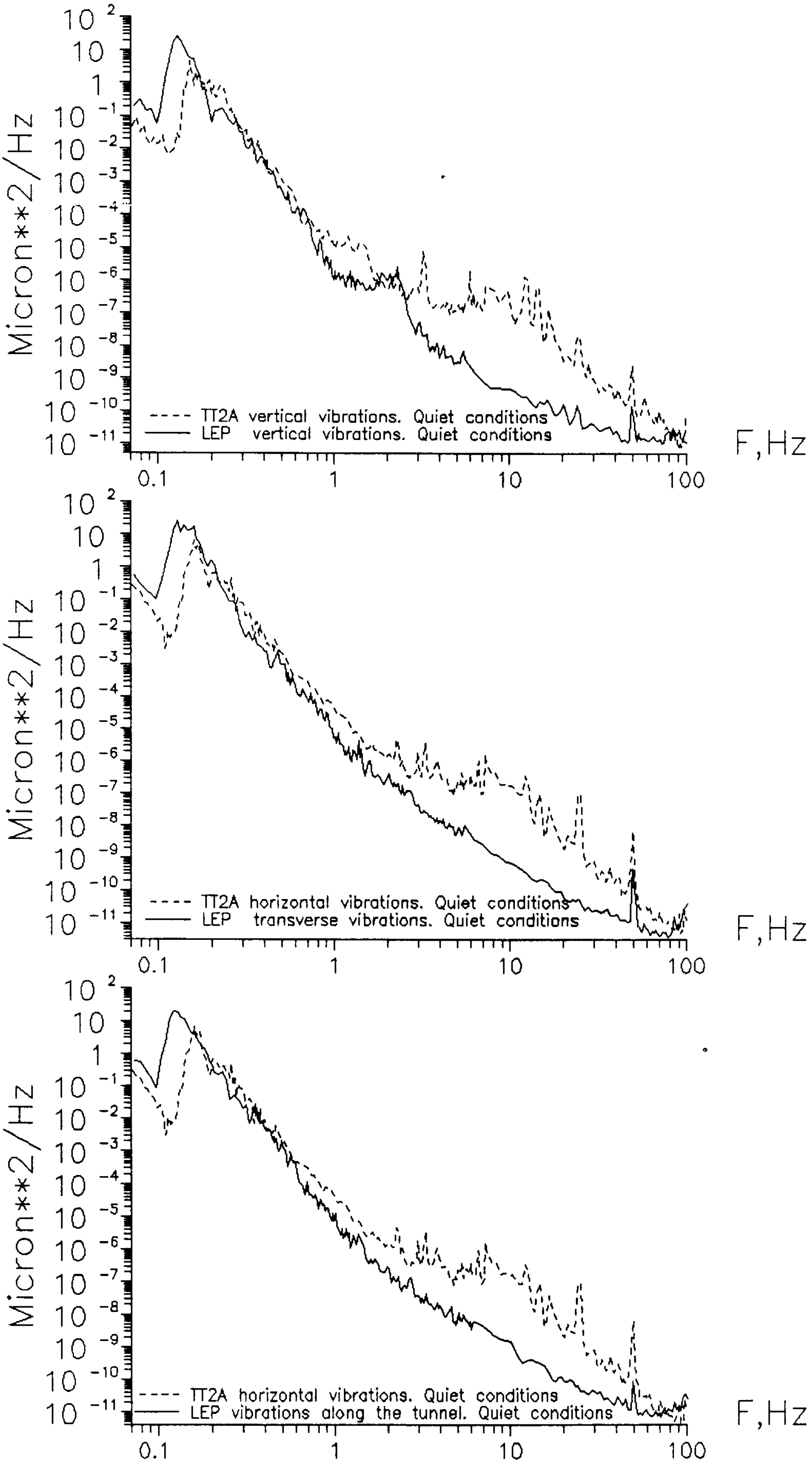


Fig.3 Comparison of power spectra measured in the CERN LEP (solid line) and TT2A (dashed line) tunnels in quiet conditions for vertical, horizontal (along the tunnel) and horizontal (transverse to the tunnel) vibrations.

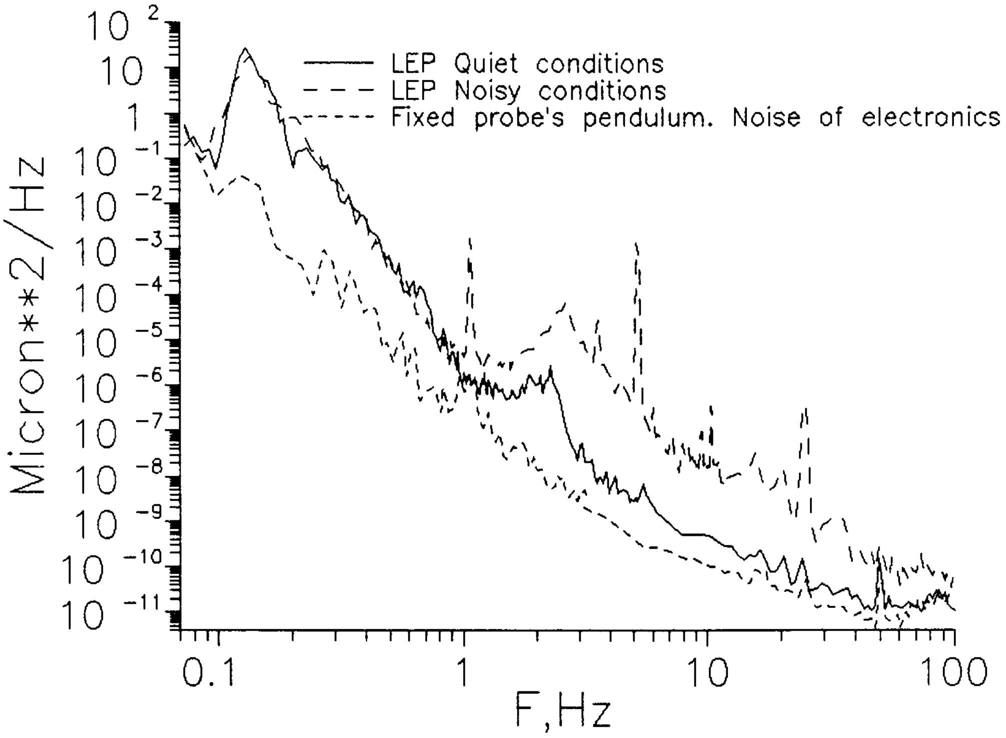


Fig.4 Comparison of the seismic signal and the noise of electronics. The "noise of electronics" was measured by the probe with its coils and pendulum fixed.

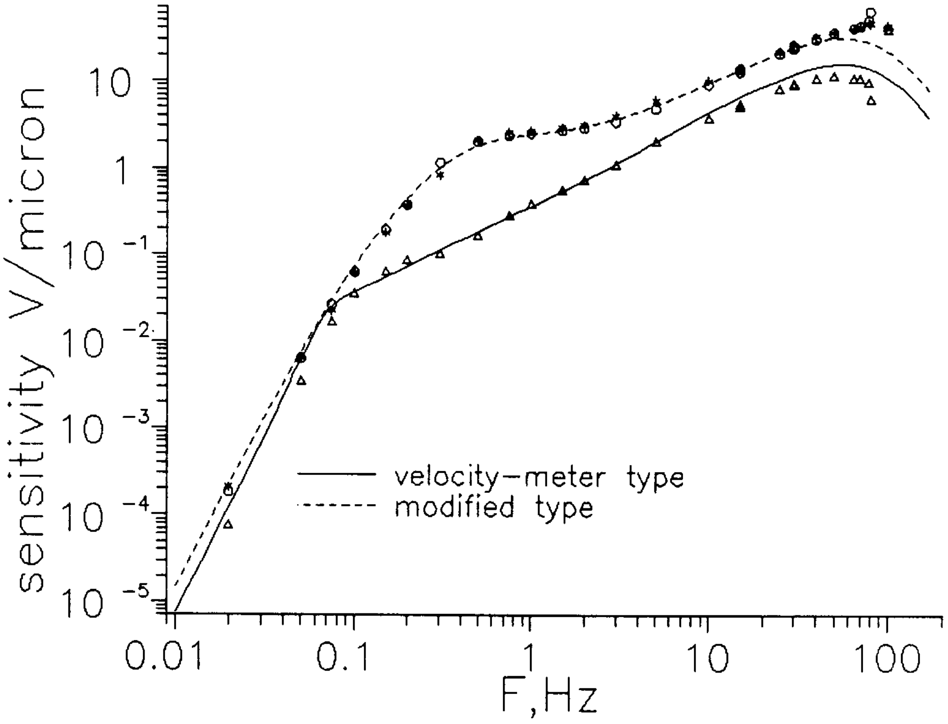


Fig.5 Sensitivity of the SM-3KV probe. Solid line and triangles show velocity-type characteristic. Dashed line, circles and stars - modified type. Lines - calculated, symbols - measured.

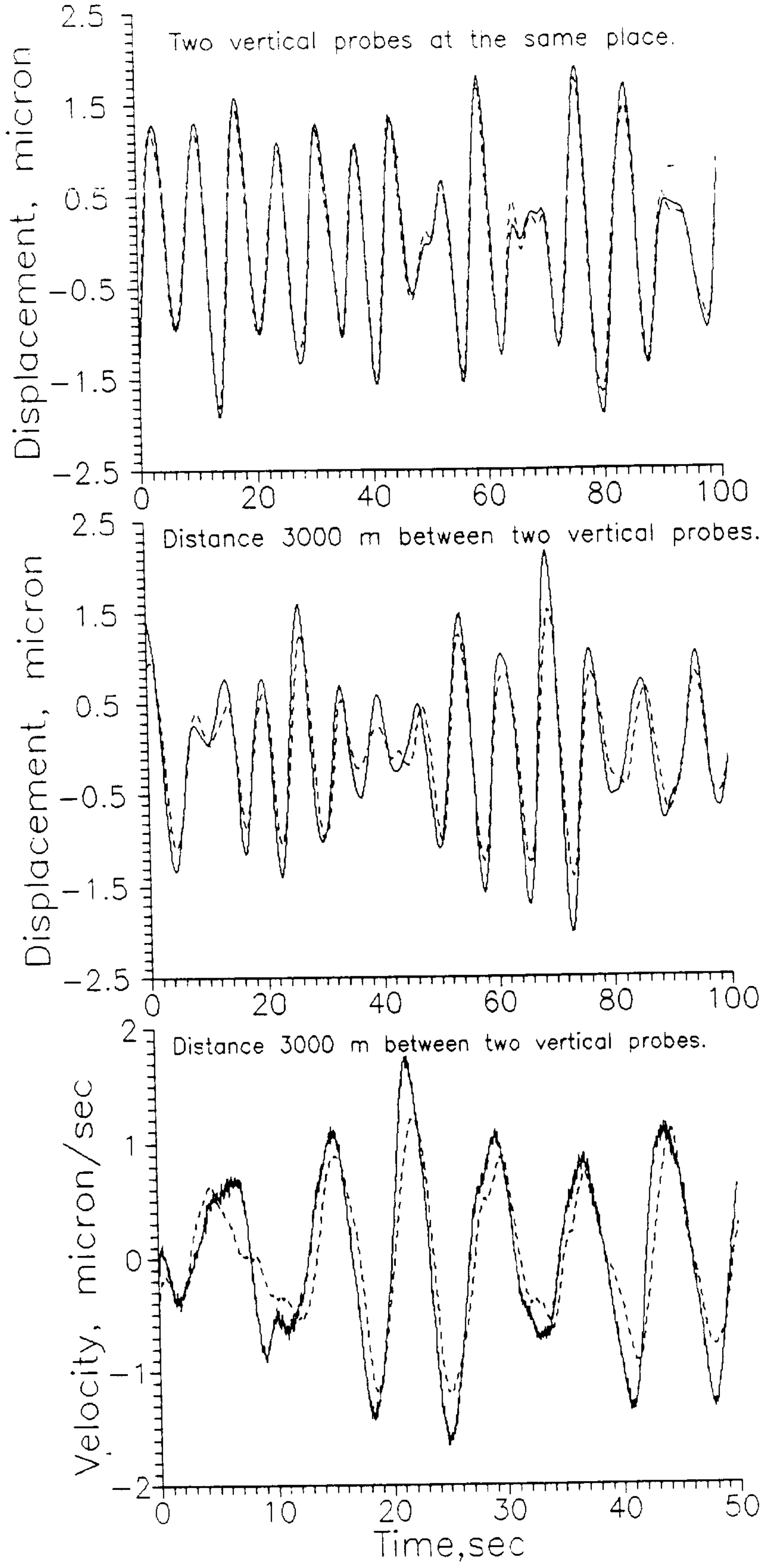


Fig.6 Vertical vibrations measured by two probes in the LEP tunnel. The distance between probes is 0m (top picture) and 3000m (middle and bottom picture).

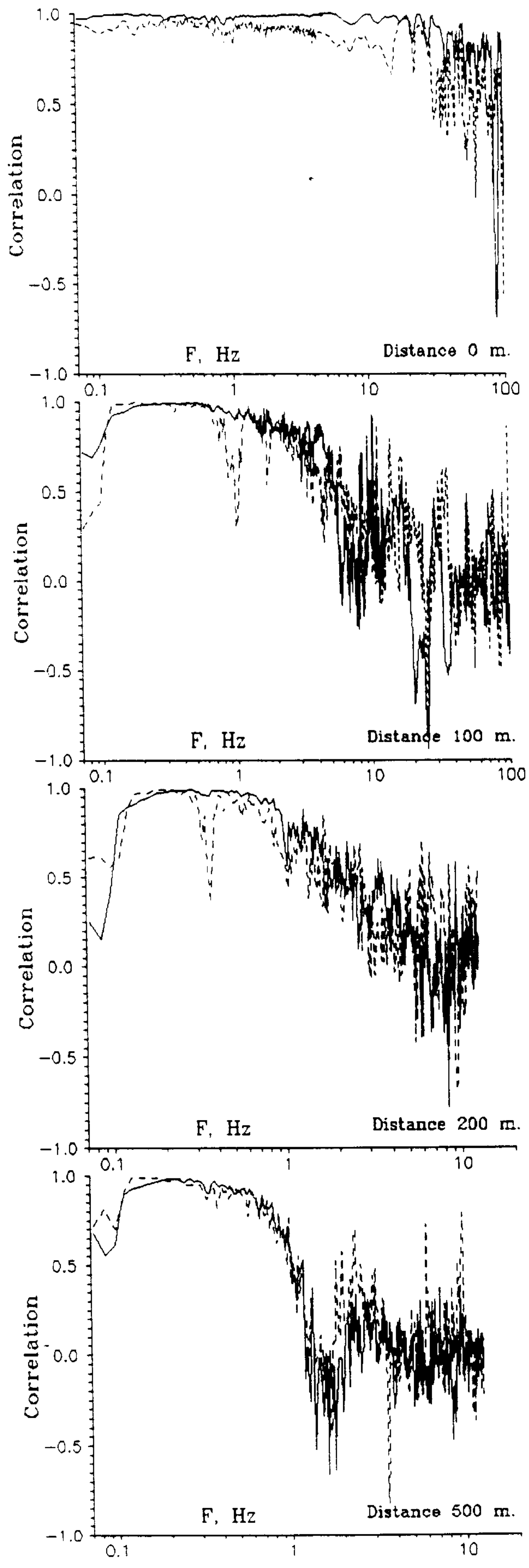


Fig.7 Correlation (real part) between two horizontal probes oriented transverse to the LEP tunnel. Probes are 0m, 100 m, 200 m and 500 m apart.

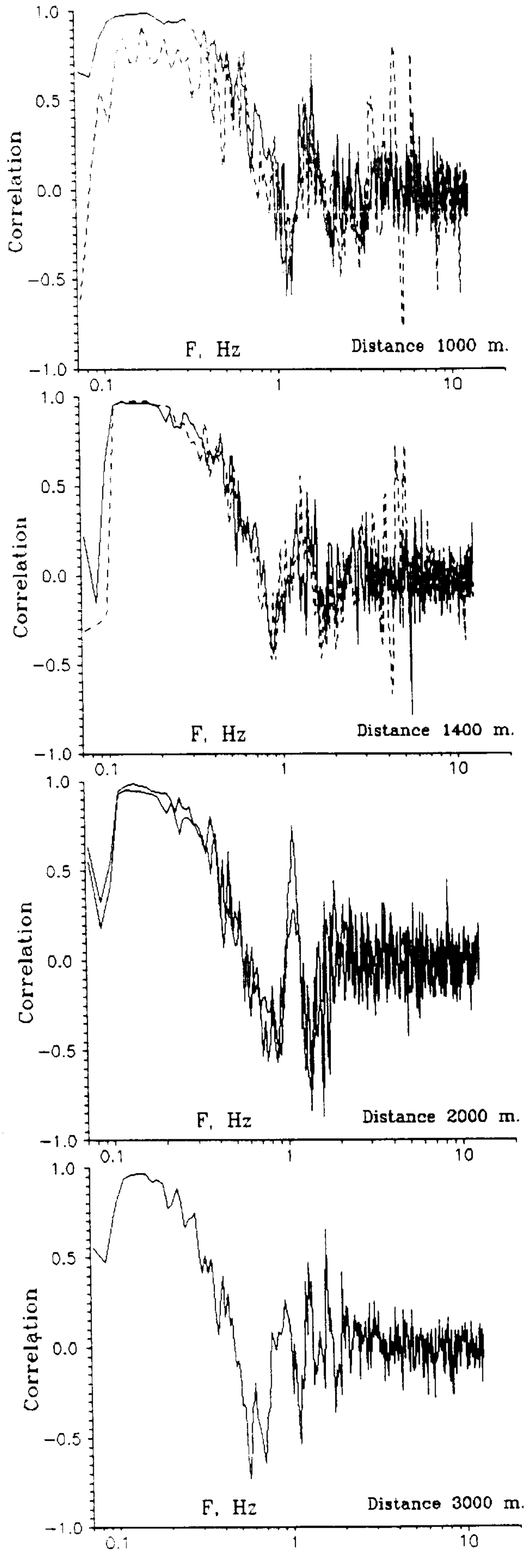


Fig.8 Correlation (real part) between two horizontal probes oriented transverse to the LEP tunnel. Probes are 1000 m, 1400 m, 2000 m and 3000 m apart.

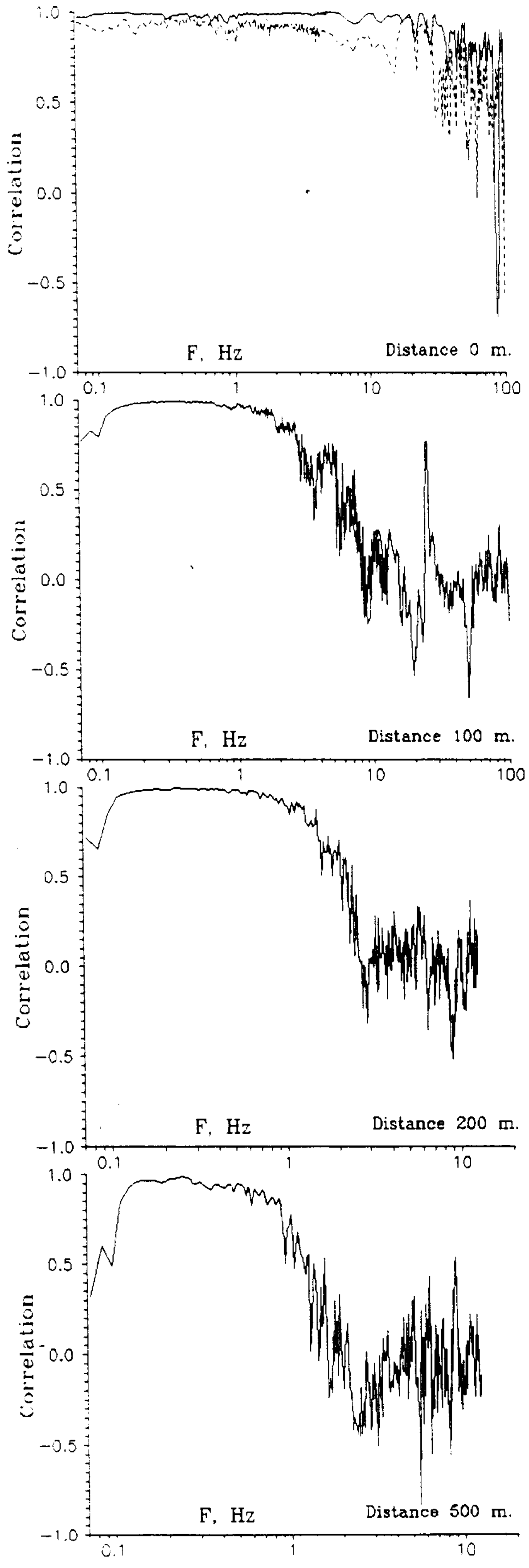


Fig.9 Correlation (real part) between two horizontal probes oriented along the LEP tunnel. Probes are 0m, 100 m, 200 m and 500 m apart.

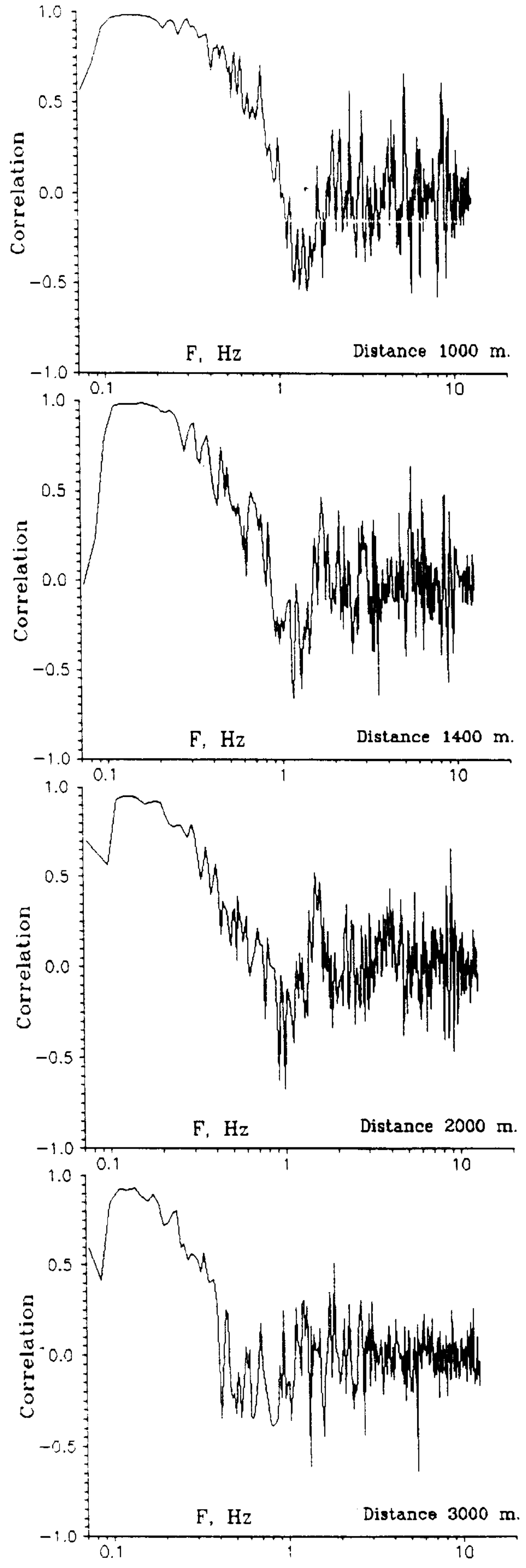


Fig.10 Correlation (real part) between two horizontal probes oriented along the LEP tunnel. Probes are 1000 m, 1400 m, 2000 m and 3000 m apart.

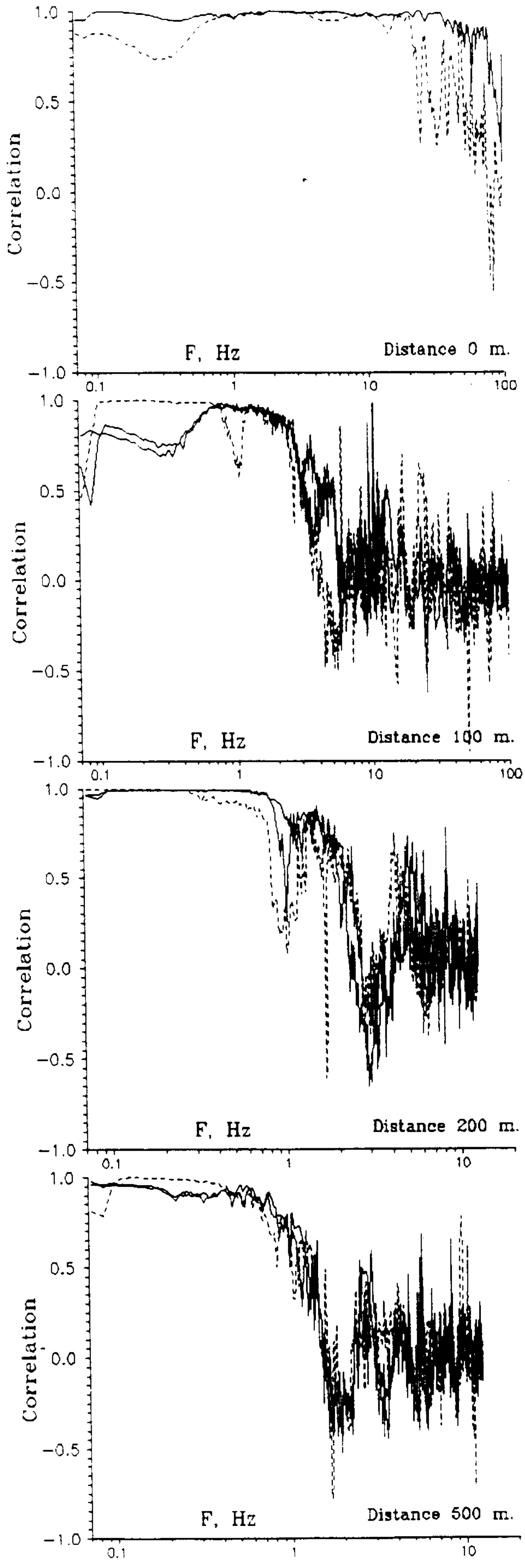


Fig.11 Correlation (real part) between two vertical probes in the LEP tunnel. Probes are 0m, 100 m, 200 m and 500 m apart.

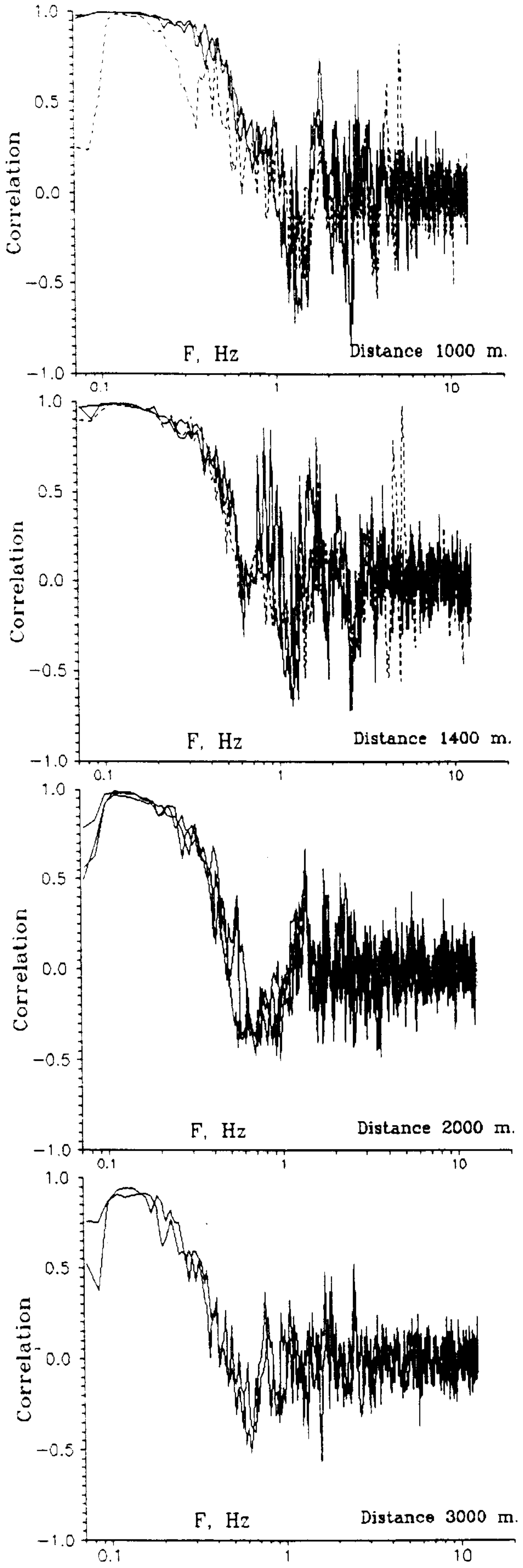


Fig.12 Correlation (real part) between two vertical probes in the LEP tunnel. Probes are 1000 m, 1400 m, 2000 m and 3000 m apart.

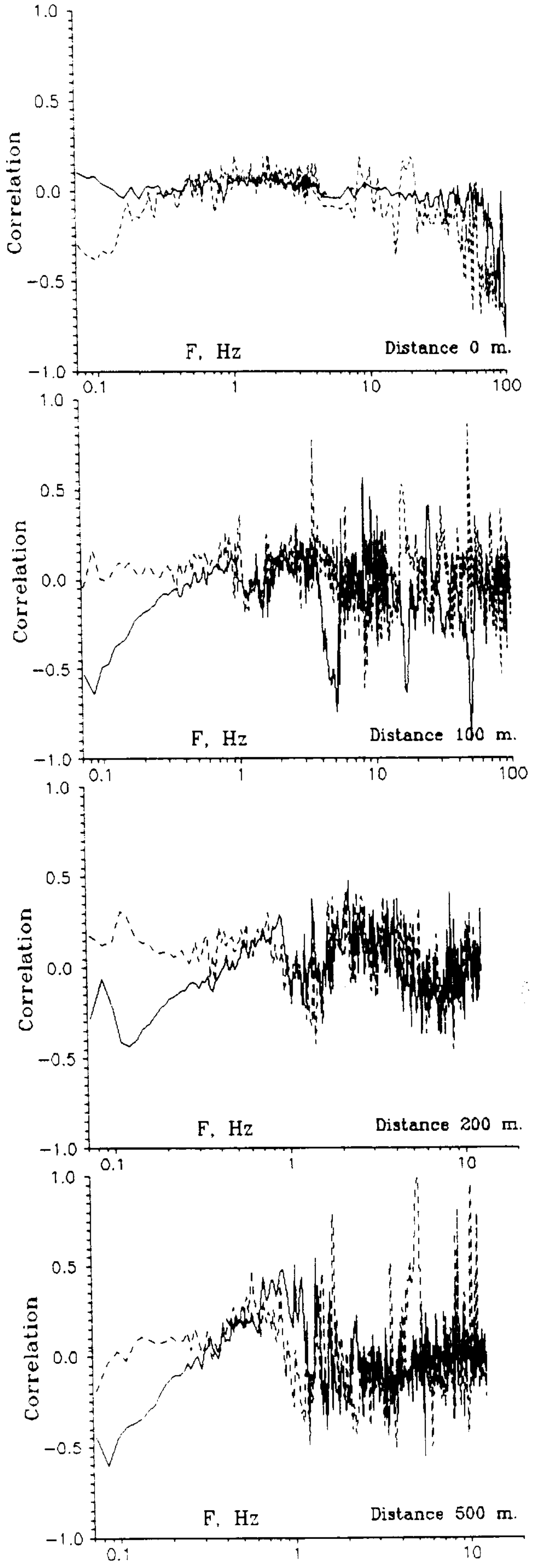


Fig.13 Correlation (imaginary part) between two horizontal probes oriented transverse to the LEP tunnel. Probes are 0m, 100 m, 200 m and 500 m apart.

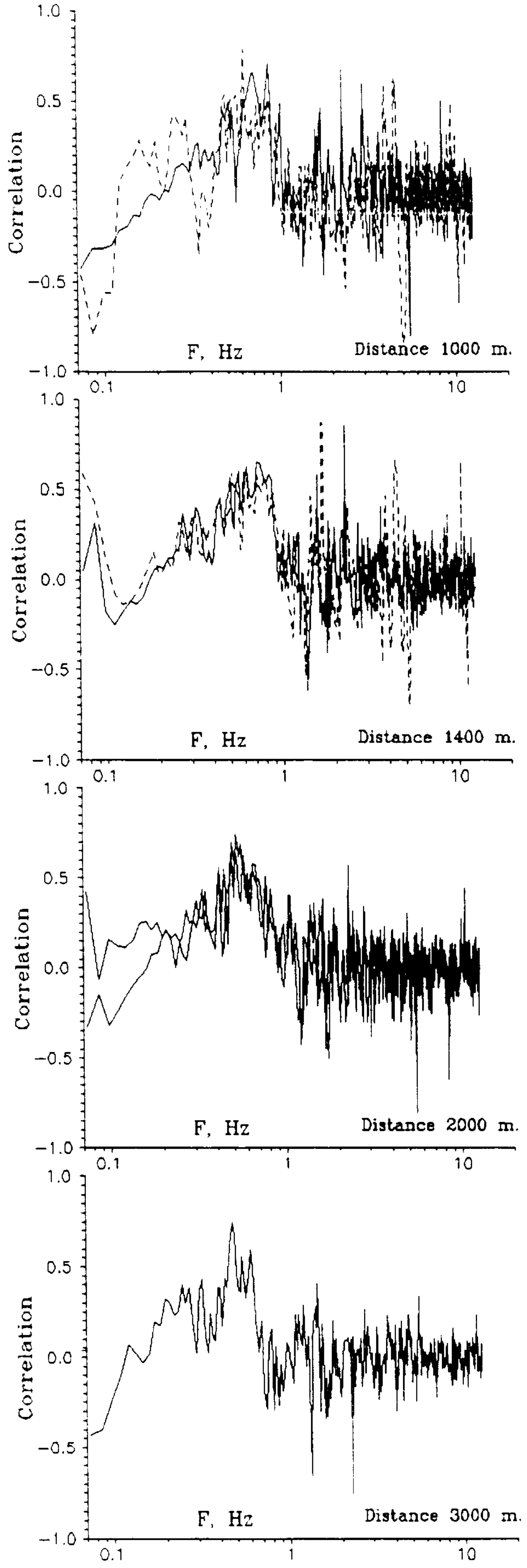


Fig.14 Correlation (imaginary part) between two horizontal probes oriented transverse to the LEP tunnel. Probes are 1000 m, 1400 m, 2000 m and 3000 m apart.

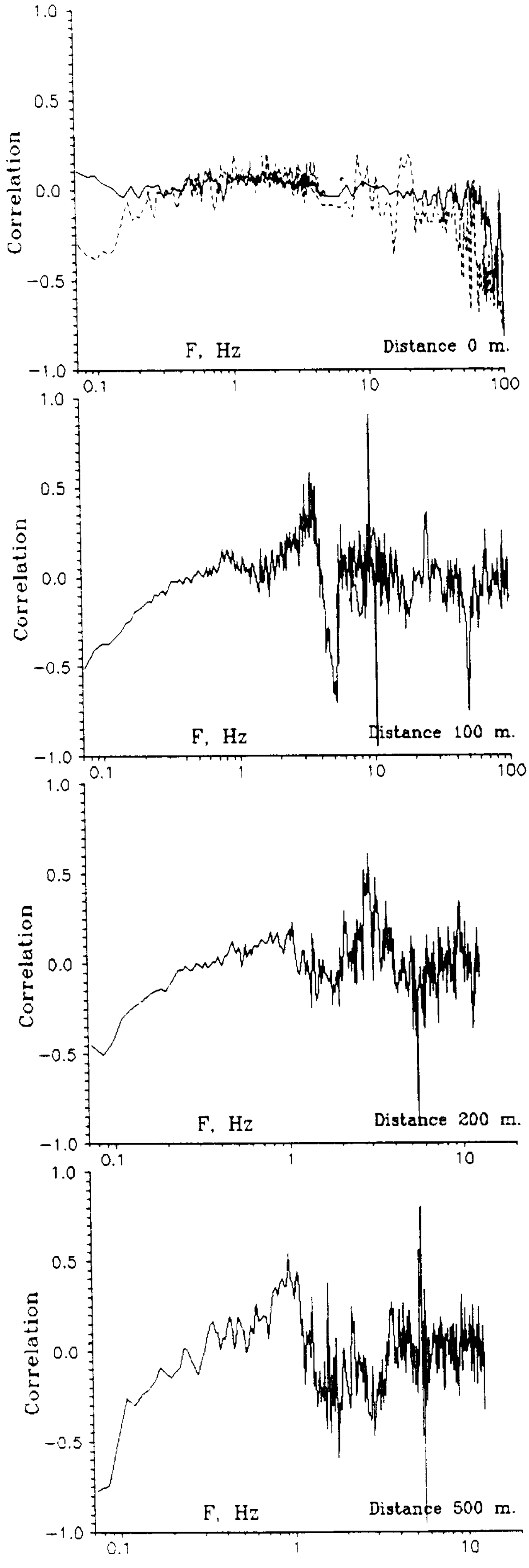


Fig.15 Correlation (imaginary part) between two horizontal probes oriented along the LEP tunnel. Probes are 0m, 100 m, 200 m and 500 m apart.

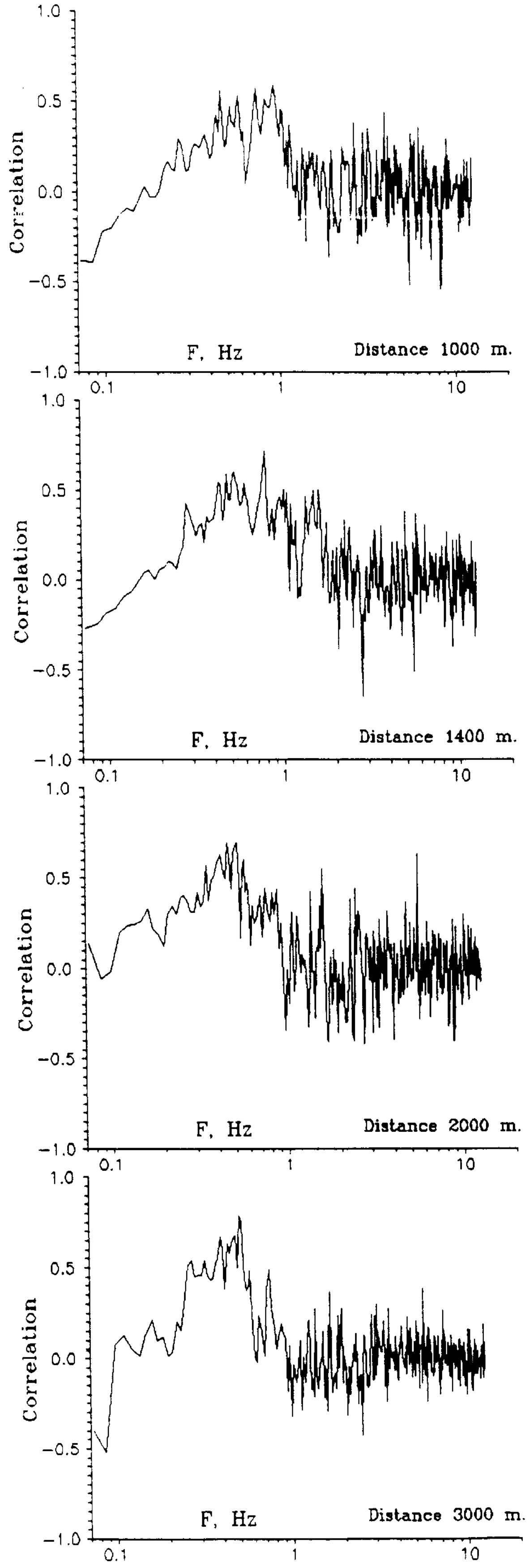


Fig.16 Correlation (imaginary part) between two horizontal probes oriented along the LEP tunnel. Probes are 1000 m, 1400 m, 2000 m and 3000 m apart.

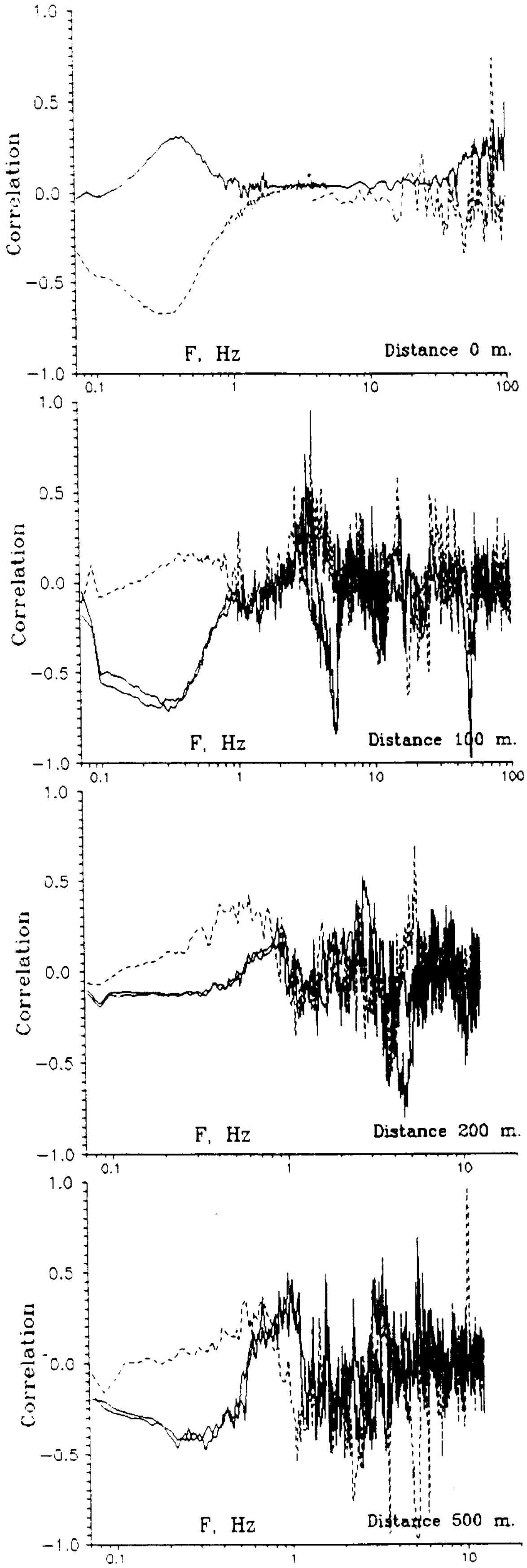


Fig.17 Correlation (imaginary part) between two vertical probes in the LEP tunnel. Probes are 0m, 100 m, 200 m and 500 m apart.

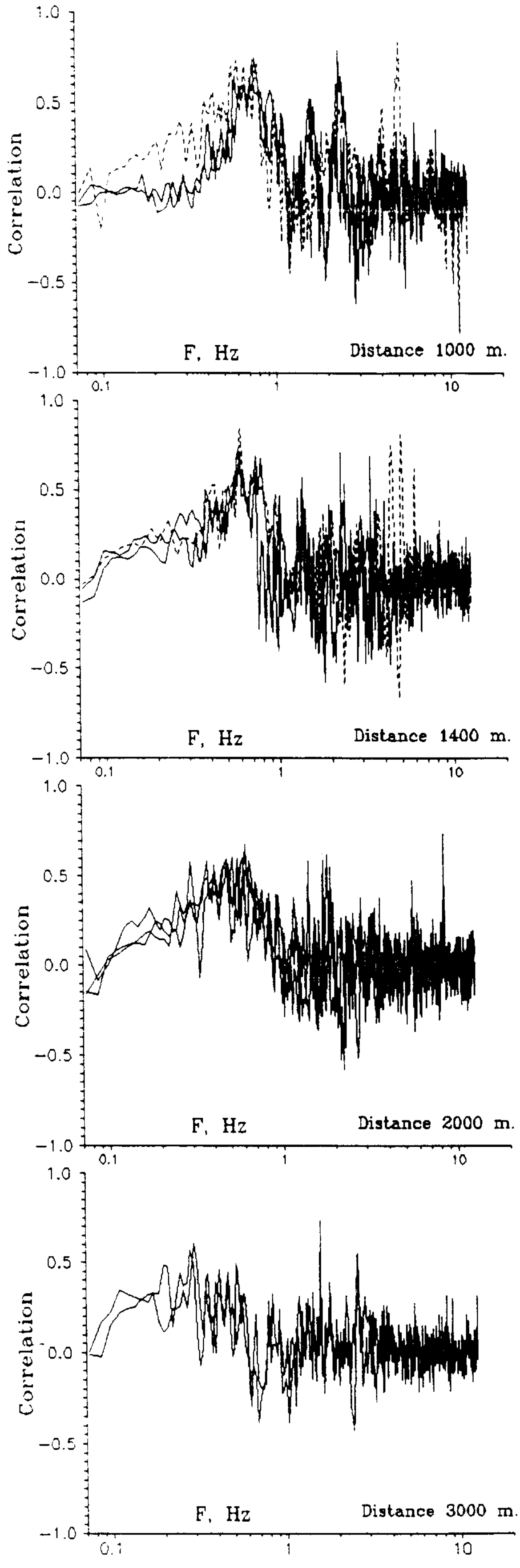


Fig.18 Correlation (imaginary part) between two vertical probes in the LEP tunnel. Probes are 1000 m, 1400 m, 2000 m and 3000 m apart.

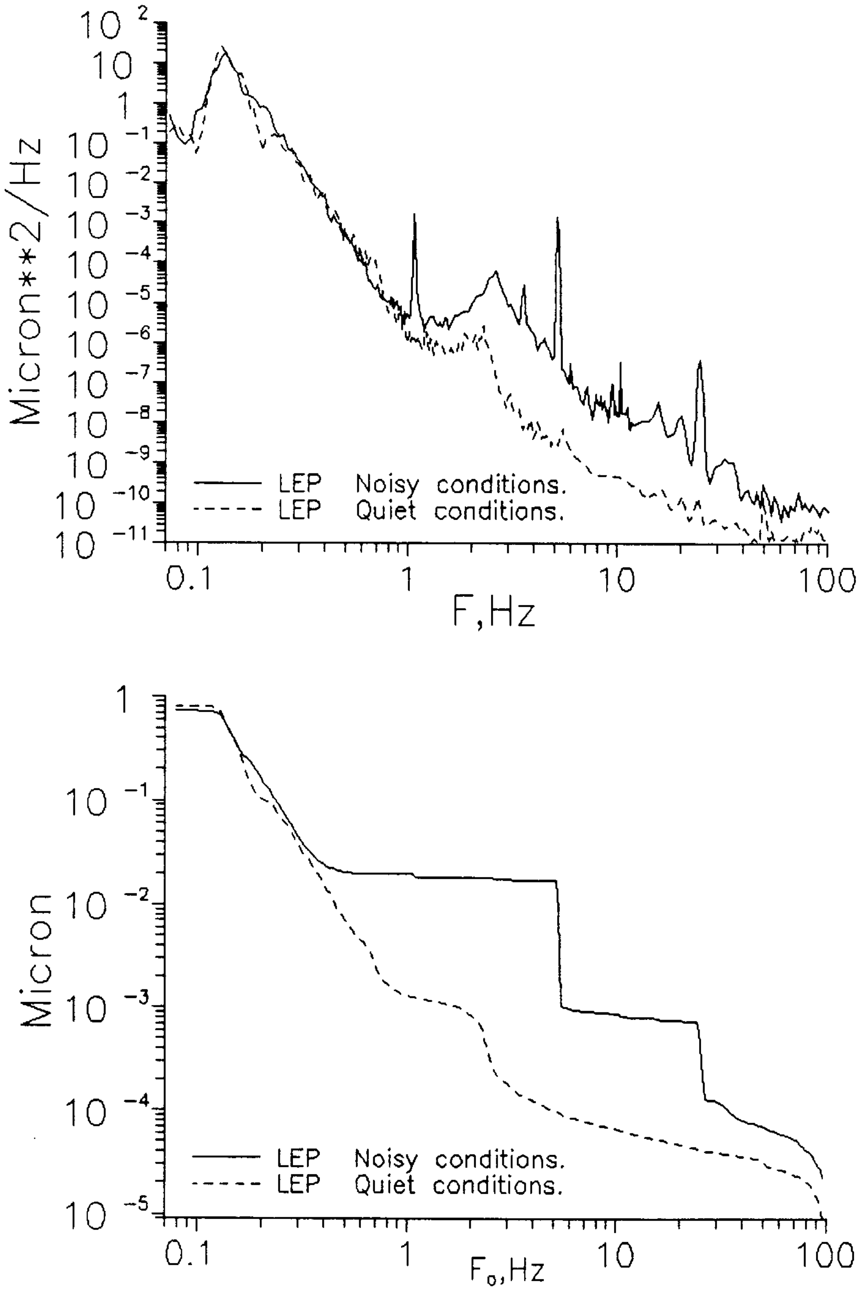


Fig.19 Power spectra (top picture) and integrated amplitude spectra (bottom picture) of vertical vibrations in the LEP tunnel in quiet and noisy conditions.

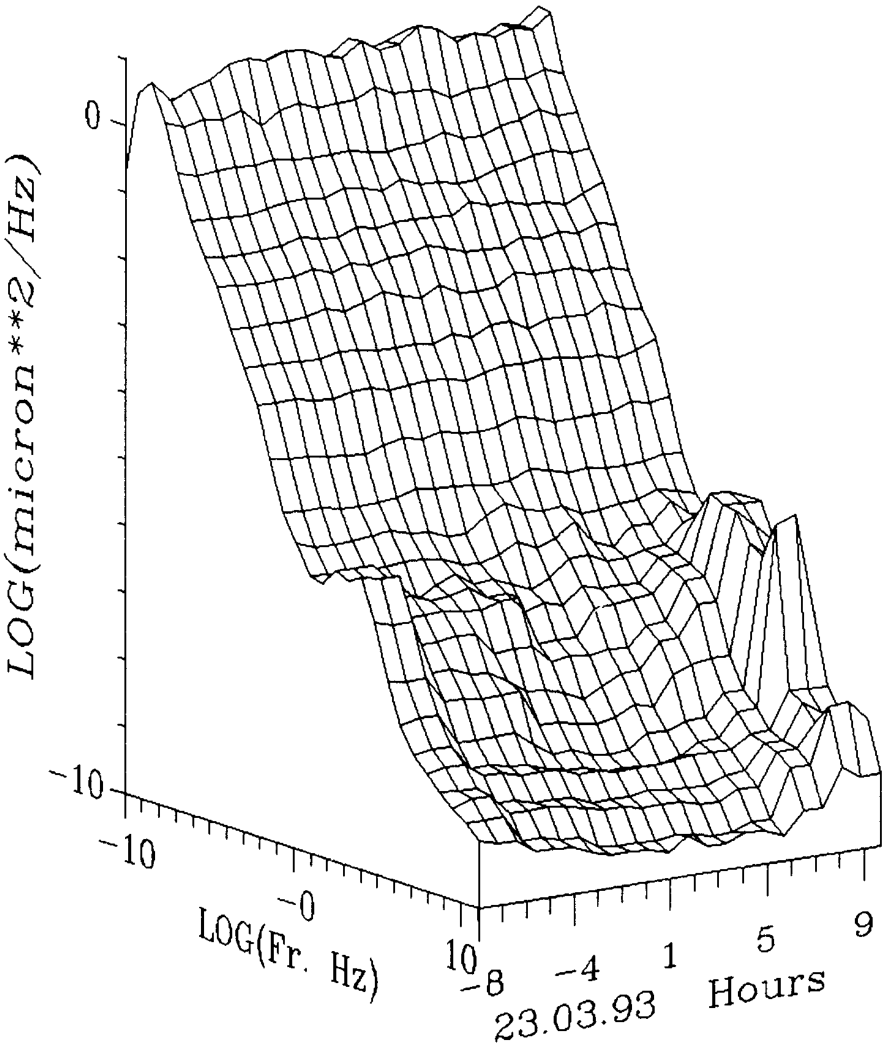
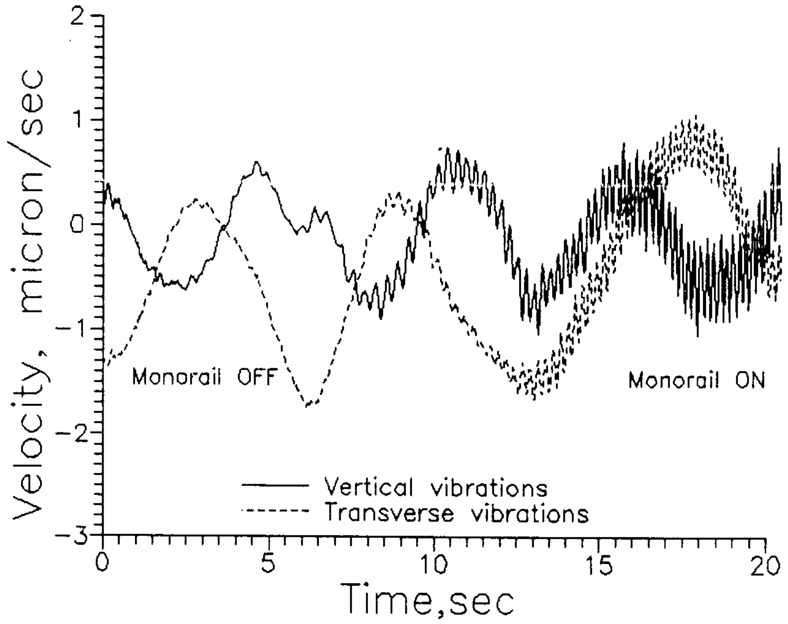


Fig.20 Three-dimensional presentation of the power spectrum of vertical vibrations in the LEP tunnel measured during 18 hours.



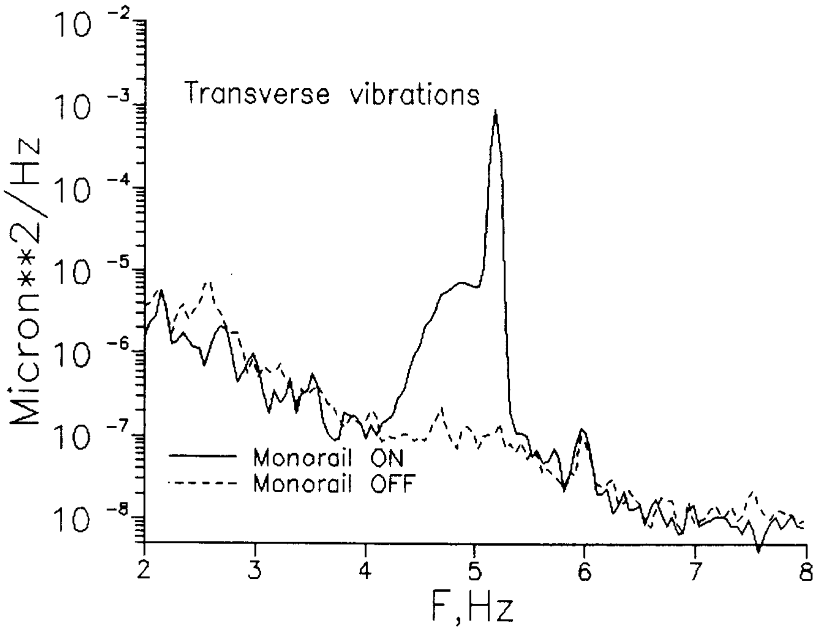


Fig.21 Influence of the moving monorail in the LEP tunnel on the vibrations (top picture) and on the power spectrum (bottom picture).

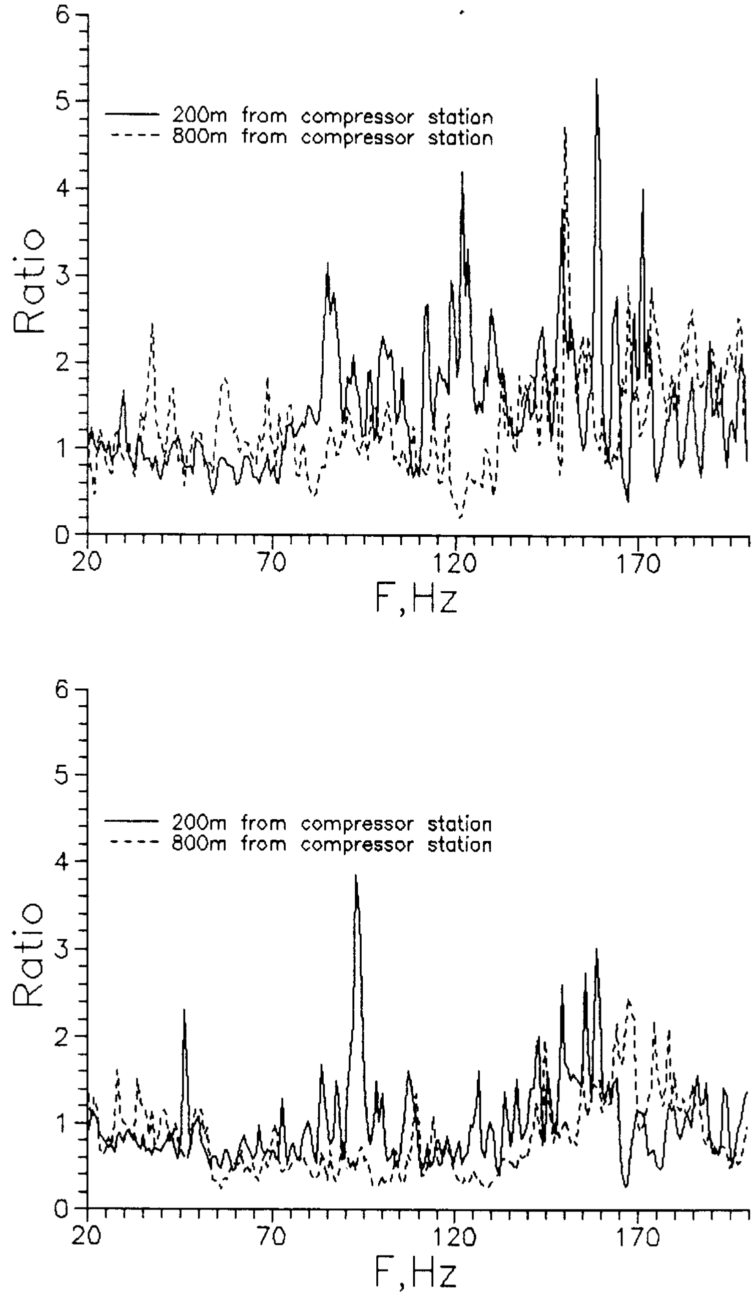


Fig.22 Influence of the cooling water compressor station on vertical vibrations (top picture) and vibrations transverse to the LEP tunnel (bottom picture).

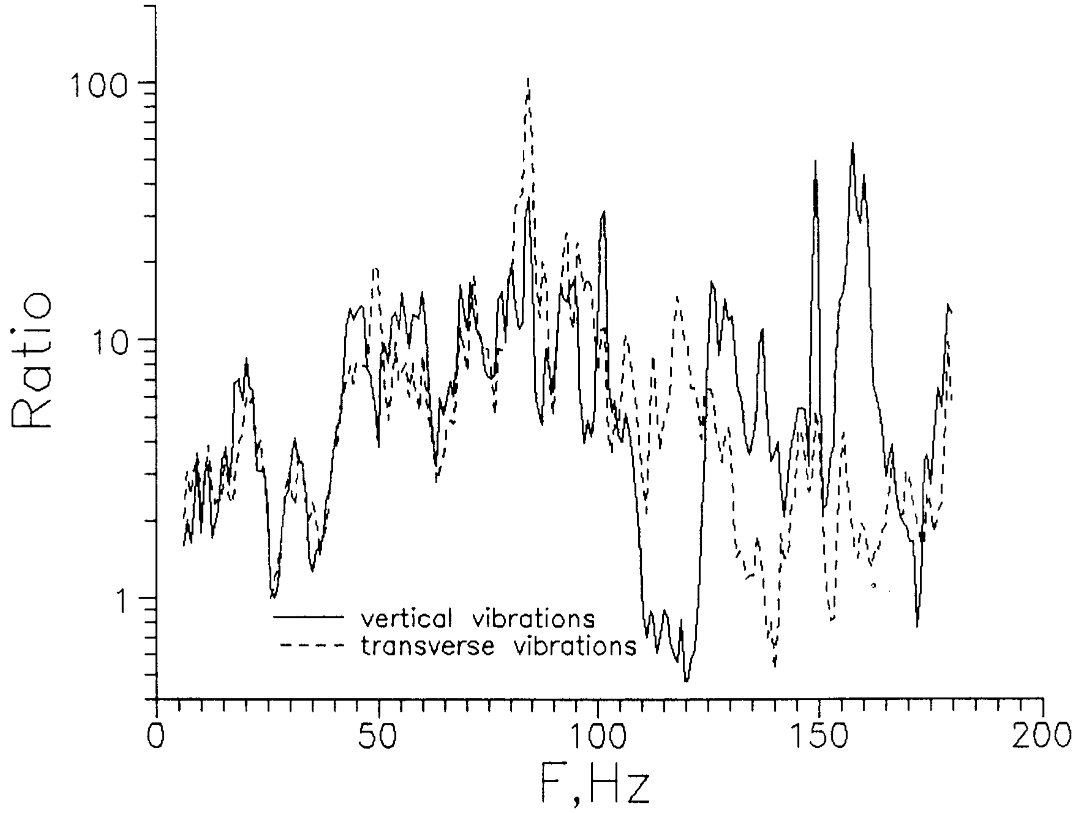


Fig.23 Influence of the ventilation system on the vertical and transverse vibrations.