An analysis of ground and instrumental short-period noise

R. CONSOLE * - A. ROVELLI *

Received on October 25th, 1978

ABSTRACT

The main causes of background noise on seismic recordings are considered. For this purpose, numerical spectral analysis techniques are applied to records obtained from an analogue-digital converter.

Firstly, the causes of noise due to the data acquisition system itself, particularly to the FM magnetic recording apparatus, are analysed.

Subsequently, an analysis is made of seismic ground noise samples taken under various environmental conditions and recorded either in the field, or by telemetry, or on magnetic tape.

RIASSUNTO

Vengono prese in esame le principali cause di rumore di fondo su registrazioni sismiche. A questo scopo vengono adoperate tecniche numeriche di analisi spettrale su registrazioni ottenute da un convertitore analogico-digitale. Dapprima si analizzano le cause di rumore provenienti

---

* Istituto Nazionale di Geofisica, Roma.

dal sistema di acquisizione stesso, ed in particolare dal complesso di registrazione magnetica FM. Successivamente vengono analizzati campioni di rumore di fondo sismico, prelevati in varie condizioni ambientali e registrati direttamente sul posto, oppure mediante telemetria, o anche su nastro magnetico.

INTRODUCTION

Anyone who has had anything to do with the installation of seismic recording instruments has had to face the problem of ground noise. This interference is the main cause which everywhere limits the effectice sensitivity of apparatus by reducing the distance at which an earthquake of a given magnitude may be usefully recorded.

Indeed, each site may be said to have its own peculiar behaviour as far as microtremors are concerned.

Even though the latter varies as a function of time in both amplitude and spectral composition, there are also systematic differences as a result of which certain locations are to be preferred to others as sites for seismic stations.

Microtremors are produced by perturbation sources both in the vicinity of, and distant from, the recording site. Furthermore, the geological conditions peculiar to the site may either damp or heighten the amplitude.

Examples of extremely local causes of microseismic agitation consist of the movements of persons or machines in the buildings housing the seismographs, or wind action on their structures. These causes may be removed fairly easily by setting up the seismic sensors in shallow holes or in rather low constructions separated from the buildings in which there are people.

Depending on the nature of the ground, interference due to vehicle traffic on roads and to the motion of heavy factory machinery may be propagated over quite some distance. This interference appears as oscillation trains of rapidly varying amplitude and a frequency of a few hertz. The oscillations caused by gravel crushing and cement manufacturing plant are particularly annoying. Of interest in this connection is the work done by Walker et al. (1964), who detected clear-cut lines related to industrial machinery activity in recorded short-period noise spectra.

Of course, all interference connected with human activities is characterized by a periodic variation peaking during the day and with minimum intensity during the night. Occasionally also a weekly periodicity corresponding to the Sunday holiday may be observed.

Some interference may originate far away from the recording site. This type of interference is connected mainly with sea conditions and is characterized by a quasi sinusoidal motion with a period of several seconds. Over a period of hours or days, this motion may increase by one order of magnitude with respect to the values observed during calm periods. Generally speaking, these values are higher in winter months than during the summer, at least in Italy. Robertson (1965), for instance, has investigated the connection between short-period wind noise and geological and topographic factors, coming to the conclusion that short-period wind noise is more dependent on topography than on lithology.

In view of the material and labour costs involved, a seismic station should be built in such a way that the maximum amount of data may be obtained. This means that the records produced must have the highest possible signal-to-noise ratio. With this in mind it obviously becomes important to investigate background noise, also by means of spectral analysis. Such an investigation may serve two different purposes:

i) to check the suitability of a prospective site for a new seismic station;

ii) to provide some information on which to base the design of filters to improve the signal-noise ratio during recording or electronic data processing.

1. RECORDING TECHNIQUES

Seismic background noise must be recorded under the best possible conditions in order to facilitate subsequent processing. The signals are usually not recorded on paper but stored on magnetic tape aand subsequently reproduced in the laboratory in the form in which it is intended to perform the analysis.

Magnetic recording is always performed by means of the frequency modulation of a carrier signal in the acoustic range. In simpler recording devices, the signals from various channels are multiplexed by mixing different central frequencies before the signals are sent to the recording heads. In more complex recorders, the central frequency is the same for all channels and numerous recording head are used to record parallel signals.

Both analogue and digital techniques may be used for spectral analysis. In the former, the signal is transmitted to special bandpass filters which allow the amplitude associated with each frequency range to be determined visually. In the latter, after the required digitization of the signals has been carried out, the spectral transform of the signal is calculated numerically by the computer.

The technical characteristics of the instruments used are described in the following (see Fig. 1).

The sensors of the three components (two horizontal and one vertical) have a characteristic frequency of 1 Hz and are kept in a critical damping condition. Tey have a generator constant of about 600 V/m/s.

The amplifiers allow a variable gain of between 400 and 50.000, with a flat characteristic between 0.1 Hz and 5 Hz. Outside this band the fall-off is 12 db/octave.

The signals are fed into the input of a seven-track FM tape recorder with a tape speed of 15/16 inches per second with a flat characteristic up to 150 Hz. The ratio of input to output signals amplitude is 1:1.

Digitization of the signals reproduced by the tape is performed on an instrument that can act on eight channels simultaneously with a sampling rate of 100 per second for each one. The data are stored using 12 bit words on computer-compatible magnetic tape. By means of this system, voltage differences of about one millivolt may be detected with a maximum input of ± 2 volts.

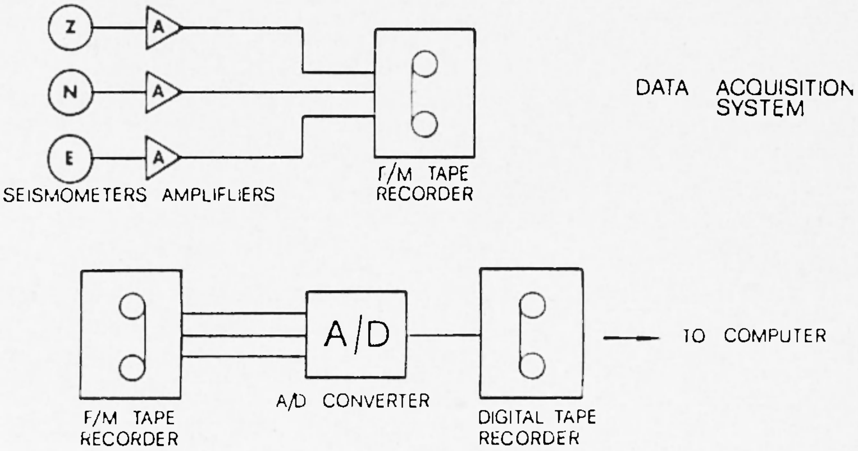

Fig 1

2. Numerical data processing

The advantage of the type of instrumentation described in § 1 above is that it supplies data in digital form ready for direct use in computers.

The values obtained from the digitizer are filtered to remove frequencies lying outside the band to be analysed. Numerical tests are then run to check for stationarity, a necessary condition for calculating the spectral density of background noise using standard stochastic process techniques (Bendat, 1958).

After the stationary conditions of the numerical sequences have been checked, the spectral contents may be calculated by the direct or indirect method (Bath, 1974). The former is used more frequently for processes of the deterministic type and consists in calculating the square-modulus of the Fourier transform of the record divided by the duration of the signal examined. For stochastic type processes, the results display considerable instabilities in certain cases. The indirect method is preferable for seismic noise; the autocorrelation function of the sequence recorded is calculated first, and then the power spectrum is obtained from the fast Fourier transform of the autocorrelation function. This technique affords the advantage of a much higher stability (Bendat-Piersol, 1971).

More in detail, the operations to be performed after the record has been digitized are as follows:

— Eliminate the continuous component (always present to some extent in FM records) from the initial data by transforming the starting series into a zero mean value series.

— Filter out any trends, or even spectral contents in the high-frequency band, likely to produce aliasing errors.

— Calculate the autocorrelation function on the pre-set interval T from the digital data using the expression:

$$C(\tau) = \frac{1}{2T}\int_{-T}^{+T} f(t)\, f(t+\tau)\, \mathrm{d}t$$

— Obtain the record power spectrum numerically from the expression:

$$E_r(\omega) = 2\int_{0}^{T} C(t)\, e^{-i\omega t}\, \mathrm{d}t$$

— Correct the record power spectrum using the seismograph response curve $H(\omega)$

$$E(\omega) = \frac{E_r(\omega)}{H(\omega)}$$

where the seismograph transfer function $H(\omega)$ takes into account frequency dependence due both to the seismometer and to the electronic components of the amplifier system.

— Lastly, in order to avoid instability due to signal truncation effects, suitable smoothing operators are used.

In recent years, in addition to these conventional spectral analysis methods, « data adaptive techniques » (Lacoss, 1971, Ulrych-Bishop, 1975) have begun to be used on a increasing scale.

One of these techniques, the maximum entropy method, has been successfully applied in seismology (Slicther, 1967 and Wiggins et al., 1972). Lacoss (1971), for instance, makes a comparison between long-period seismic noise spectra calculated by standard techniques and those using data adaptive methods.

The maximum entropy spectrum of a time sequence is calculated by the transfer function of a linear operator wich filters a white noise in order to give the sequence as output. If $F(\omega)$ is the spectral amplitude of the time series whitened by a filter with transfer function $\Gamma(\omega)$, it results

$$| \mathrm{F}(\omega)\, \Gamma(\omega) | = k$$

where k is a constant (Ulrych et al., 1973).

Consequently

$$| F(\omega) |^2 = \frac{k^2}{| \Gamma(\omega) |^2} = \frac{k^2}{| 1 - \sum_{j=1}^{M} \gamma_j \exp(-2\pi i j \omega \Delta t) |^2}$$

M is the filter length, Δt is the sampling rate and γ_j are the filter coefficients, calculated using least squares criterion. Andersen (1974) furnishes a faster algorithm.

A comparison between the two methods seems rather interesting (fig. 11).

3. CHECKING OF ELECTRONIC NOISE INTRODUCED BY THE RECORDING CHAIN

Before starting on the actual analysis of the background noise in seismic records, a check was carried out on the reliability of our data acquisition system. The intention was to check the possible existence and size of any output signals from the recording chain not produced by the motion of the ground on which the sensor was placed. These signals may originate in the electronic components of the amplifier, particularly in the FM magnetic recording system.

For the purpose of our investigation, an indirect method was chosen in which certain noise sources were deliberately excluded.

The first test consiste of analysing the background noise produced inside the analogue-digital converter. The test was run by simply sampling for a period of about 3 minutes with the digitizer input circuit open.

As a result, the numerical values produced by the analogue-digital converter remained constant at a non-zero mean value (owing to amplifier polarization), displaying random shifting away from this value by a maximum of plus or minus one digitation unit.

The autocorrelation function of these signals (fig. 2a) is characterized by white noise, and the spectrum of the record obtained is practically flat over all frequencies. The spectrum of the ground equivalent signal for this noise (fig. 2a') obviously reproduces the inverse of the transfer function of the system.

In the second test, the noise introduced by the amplifier group was examined by digitizing the output signal after the sensor mass had been stopped, thereby simulating the condition of actual zero ground motion as the seismometer could no longer provide any output signal.

The amplitude of the signals recorded was around 0.010 V. The spectrum of this record peaked at 50 Hz (fig. 2 b') The presence of the 50 Hz frequency is noticeable also in the auto-

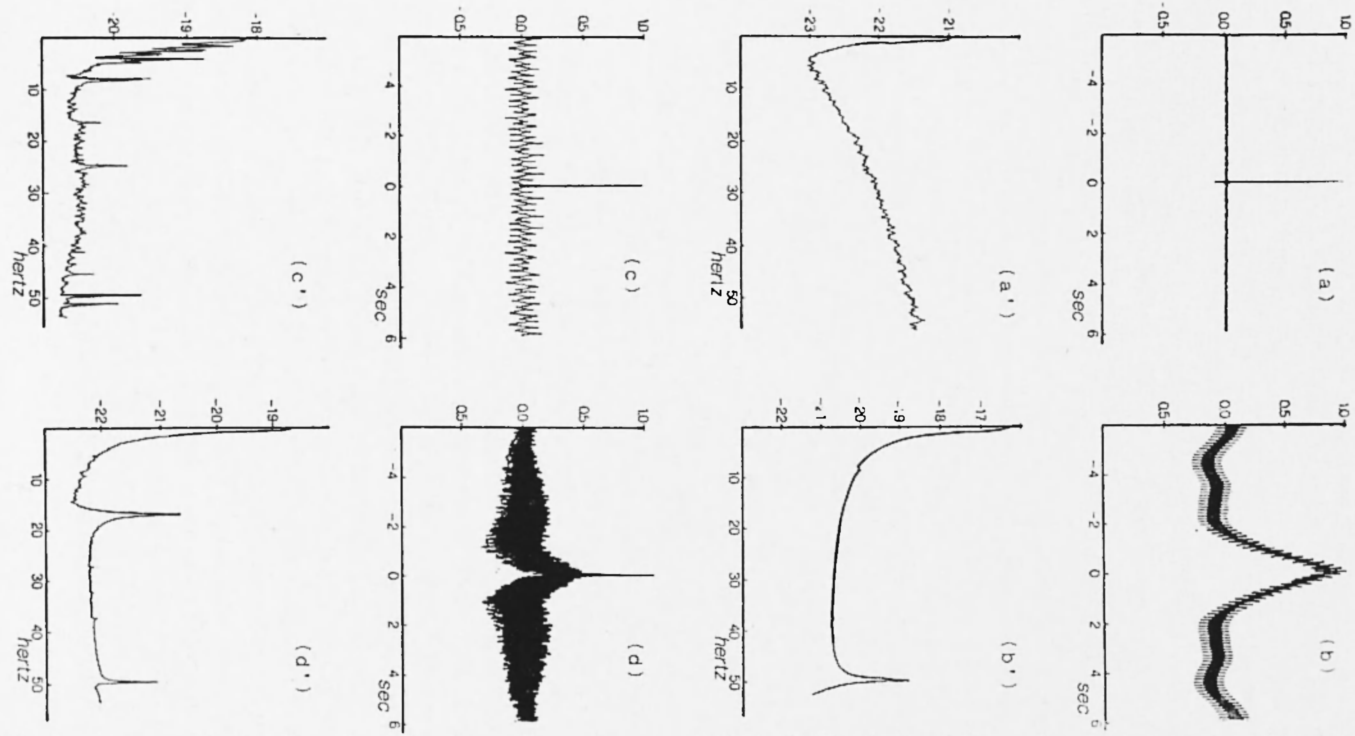

FIG. 2 - Autocorrelation functions (a, b, c, d) and power (a', b', c', d') obtained from electronic noise produced by different recording techniques: directly from the electronic components of the digitizer (case a and a'), from direct digital recording with stopped mass (case b and b') by frequency modulation with stopped mass (case c and c') and by telephone cable, again with stopped mass (case d and d').

correlation function, fig. 2 b) and a beat effect is set up with the Nyquist frequency of $\sim$ 52 Hz, as can be seen even more clearly in fig. 3b.

An analysis was then made of the noise produced by the FM tape recorder. In this case. what was obtained from the reproduction of the tape was digitized using the normal amplification system and blocking the sensor masses. This test revealed the presence of signals of appreciable amplitude at the analogue-digital converter input. Observed voltages fluctuated between plus or minus 0.030 V, while the FM tape recorder dynamics afforded a linear output up to values not exceeding $\pm$ 2V.

Numerical analysis by computer revealed a high degree of autocorrelation in these signals (2c). In fact, the power spectrum displays very distinct peaks that we believe to be related to the periodicity with which the motor and driving mechanism pivots revolve inside the FM tape recorder, or to over-shoots of the speed control system. The trend of the shift spectrum referring to the actual ground motion equivalent to the digitized signals is rather high at low frequencies (fig. 2c'). This trend is the minimum level for which any ground motion may be usefully detected as a function of frequency by the acquisition system being used. In this connection, the « seismic » background noise is taken as the useful signal to be analysed. Obviously, it will also be a negative factor tending to mask the true signals when the system is used to detect seismic events.

In order to extend the investigation to other sources of electronic noise, tests were run on the cable transmission systems using frequency modulation currently being used between the Central Geophysical Observatory and several peripheral stations. Also in this case, care was taken to block the mass of the sensor (situated at the Aquila Observatory) and the output signal from the electronic chain formed by the preamplifier, modulator, telephone line and demodulator, was digitized. In the record spectrum, and thus also in the ground displacement spectrum (fig. 2d'), a very conspicuous peak is visible at a frequency of 17 Hz, in addition to the mains frequency. It is probably due to the modulator-demodulator couple. The autocorrelation function is shown in fig. 2d.

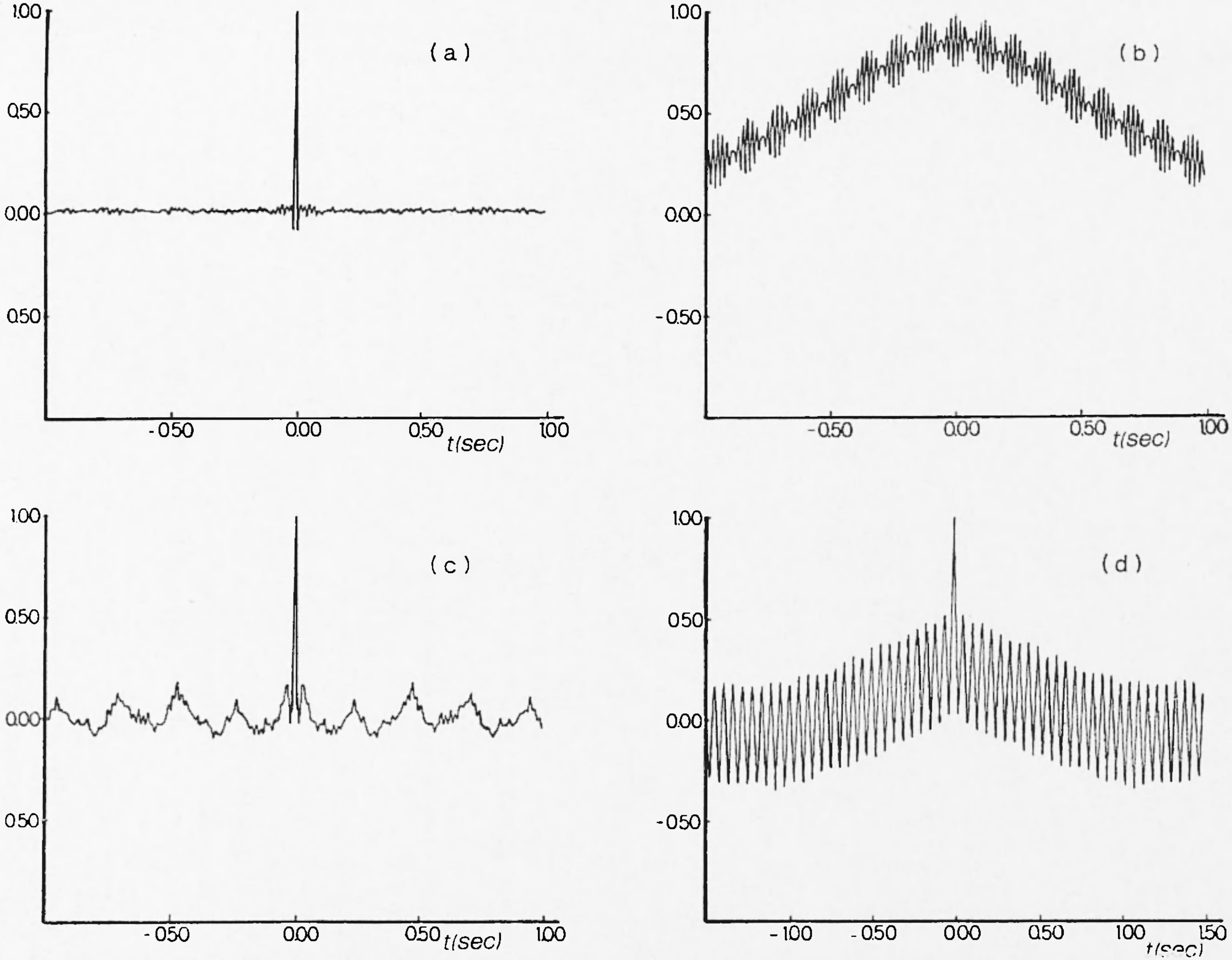

FIG. 3 - Autocorrelation functions of electronic noise for time lags not exceedng 1.5 secs. In case b, beat effect between the 50 Hz of the mains and the Nyquist frequency of 52 Hz, superimposed on a long-period pattern, is shown.

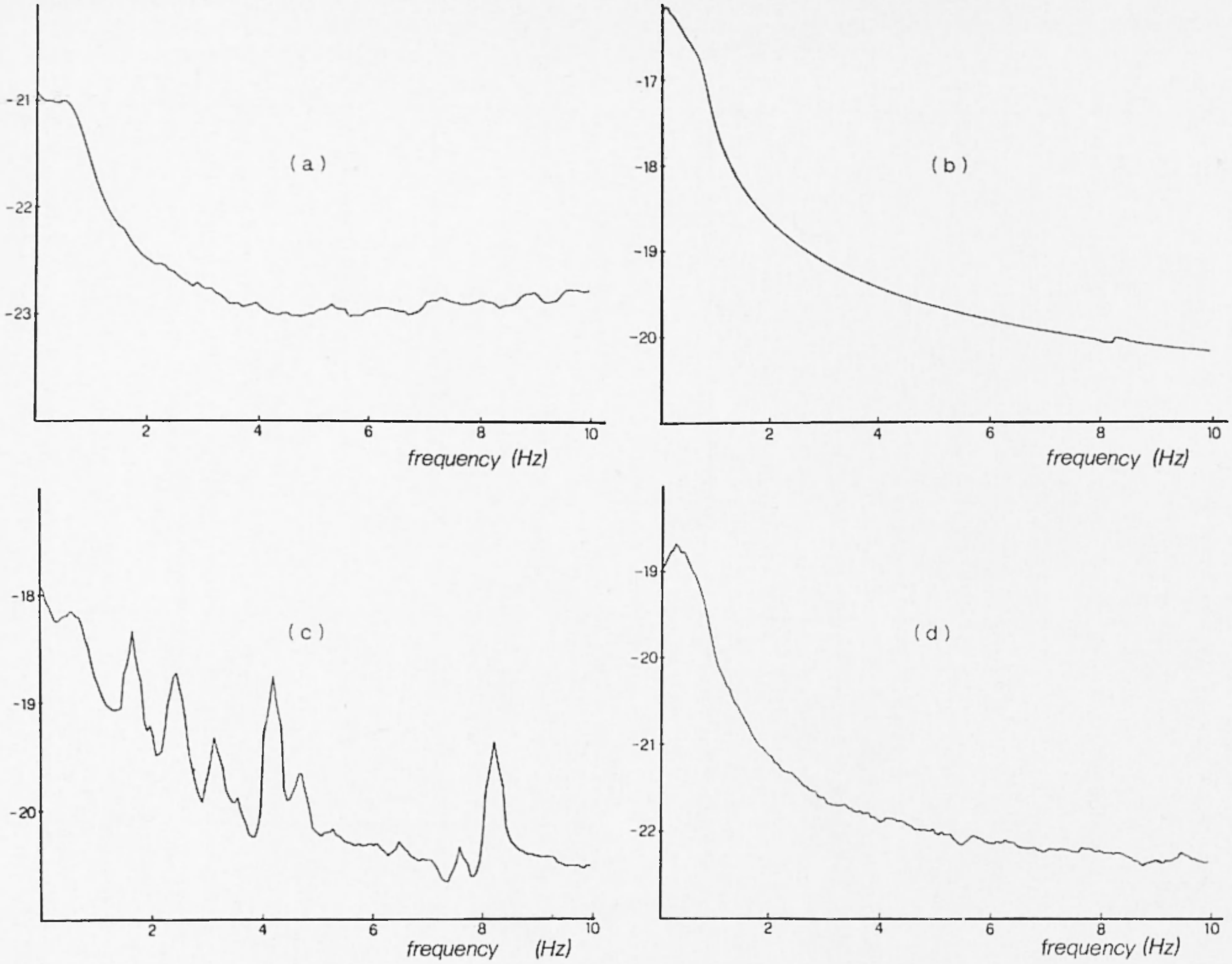

FIG. 4 - Power spectra of electronic noise in the 0 — 10 Hz band. Only in case c sharp lines may be observed with a high spectral contents for frequencies lower than 10 Hz.

It could be of interest to analyse the autocorrelation function in fig. 2 in greater detail. If only time lags of less than 1 second are considered, the patterns for the various circumstances are those shown in fig. 3. The frequencies discussed earlier are thus easier to discern.

A more thorough analysis may be made also as far as frequencies are concerned (fig. 4) by examining the 0-10 Hz band, i.e. the one of greatest interest in seismology, using a higher resolution. Within this range, it may be observed that only in case 4c is there any interference with high frequency peaks that could be added to the seismic signals and alter things because of their high amplitude.

4. SEISMIC BACKGROUND NOISE

The subsequent tests were run on recordings of background noise samples taken in different places and under different environmental conditions. Some of these tests were run outside the Central Geophysical Observatory of Monte Porzio Catone, and required the use of an FM magnetic tape recorder.

Others were run by digitizing signals directly in real time using remote sensing by radio or telephone cable.

Figs. $5c_1$, c_2, c_3 show the ground displacement spectra of tracks a_1, a_2, a_3 recorded on seismograph S13 duringo a survey carried out in Calabria to ascertain the suitability of certain sites as locations for seismic stations. The signals were first recorded using the FM technique and then digitized. The autocorrelation functions are shoun in figs. $5b_1$, b_2, b_3.

Visible in the first and second recording is a small seismic agitation (figs. $5a_1$ and a_2) with fairly small amplitudes.

The effects of meteorological interference (wind, rough seas, etc.) may be see in fig. $5a_3$. A further example of recording by

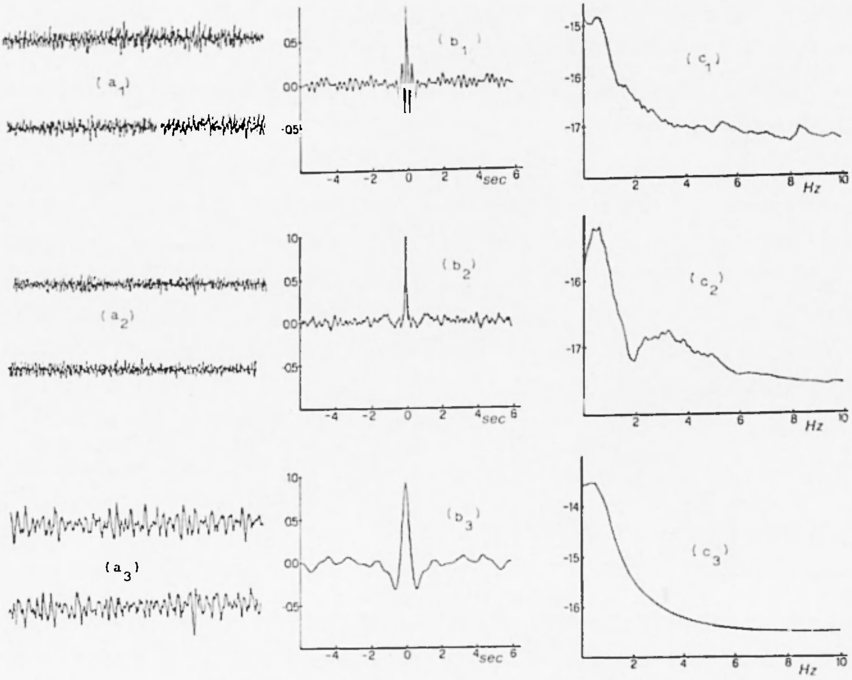

FIG. 5 - Seismic noise with related autocorrelation functions and ground motion spectra, recorded by the FM technique in different parts of Calabria. (a_1) Martino; (a_2) Pian della Corona; (a_3) Monte Liccio.

the FM technique was carried out inside the Central Geophysical Observatory (fig. 6). In this case, it was possible to compare three digital sequences directly recorded in real time (fig. 7). Both in the FM recording (fig. 6) and in case (1) in fig. 7, the frequency peaks at 1.4 Hz, probably as a result of industrial machinery in operation. The noise level is, however, much higher in the FM recordings.

In the case of track (1) and (2) in fig. 7 referring, respectively, to days with low and high meteorological interference, both the two autocorrelation functions and the energy distrib-

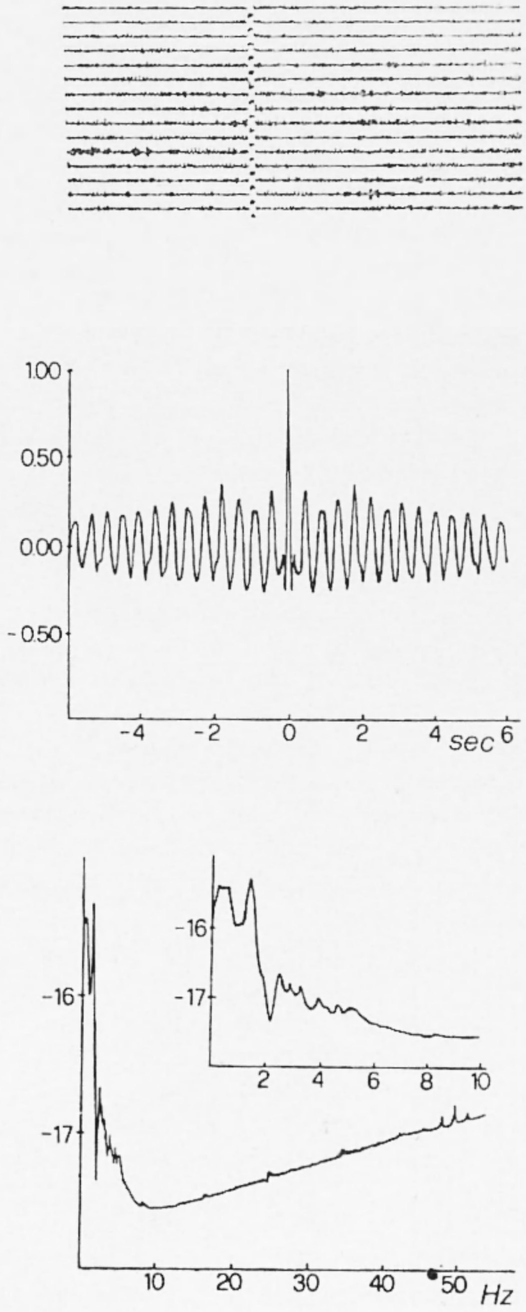

FIG. 6 - Seismic noise, with related autocorrelation functions and ground motion spectra recorded by FM technique at the Central Geophysical Observatory of Monte Porzio Catone.

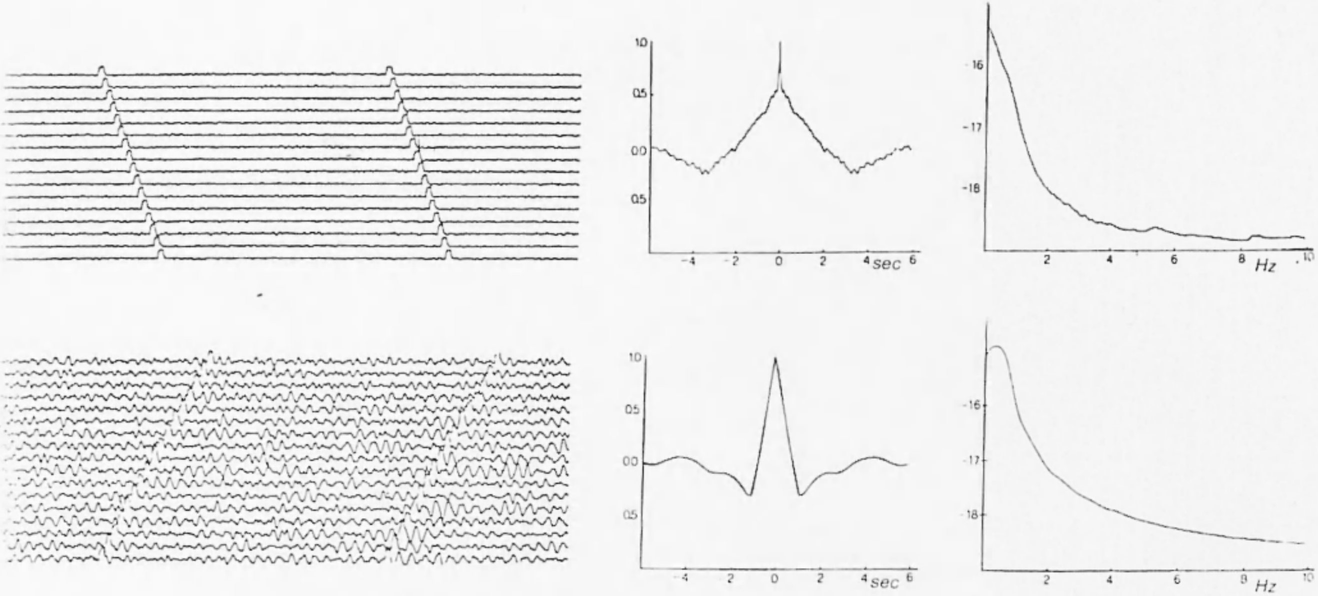

FIG. 7 - Seismic noise of two recordings made at the Monte Porzio Catone station, near Rome: 1) "calm" situation with slight, industrial noise; 2) high meteorological noise.

ution displayed by the two power spectra clearly reveal the presence of different frequencies with different amplitudes. In case (1) the spectral contents are very high in the 3-5 Hz band, and there is a considerable noise level at 10 Hz. In case (2), the spectral contents all lie in the 0.5-10 Hz band with a very sharp spectral contenas show a very sharp drop after 1 Hz (fig. 7).

The results concerning the background noise telemetered from the Montasola station are given in fig. 8. Tracks (1) and (2) in fig. 8 are contemporaneous respectvely with trains (1) and (2) in fig. 7. However, as the noise level at th eMontasola station is very low, there is not much observable difference between the two spectra and the two autocorrelation functions. Also for the Duronia station two recordings were made, simultaneous at Roma Monte Porzio and Montasola. Ttrasmission was by telephone cable (fig. 9). For Duronia, track (1), which refers to a day with comparatively little interference, displays a considerably lower noise level (by about a factor of ten) than track (2) in the low frequency band. In track (2), on the other hand, there is a rapid fall for frequencies greater than 0.5-1 Hz. The spectral contents in the band around 5 Hz, so conspicuous in track (1), now disappear.

The tracks in fig. 10 refer to recordings, again simultaneous with the others in figs. 7, 8 and 9, carried out in the Aquila station and also transmitted by telephone cable to the Central Geophysical Observatory. Both the noise level and the spectral pattern are virtually the same in case (1) and (2).

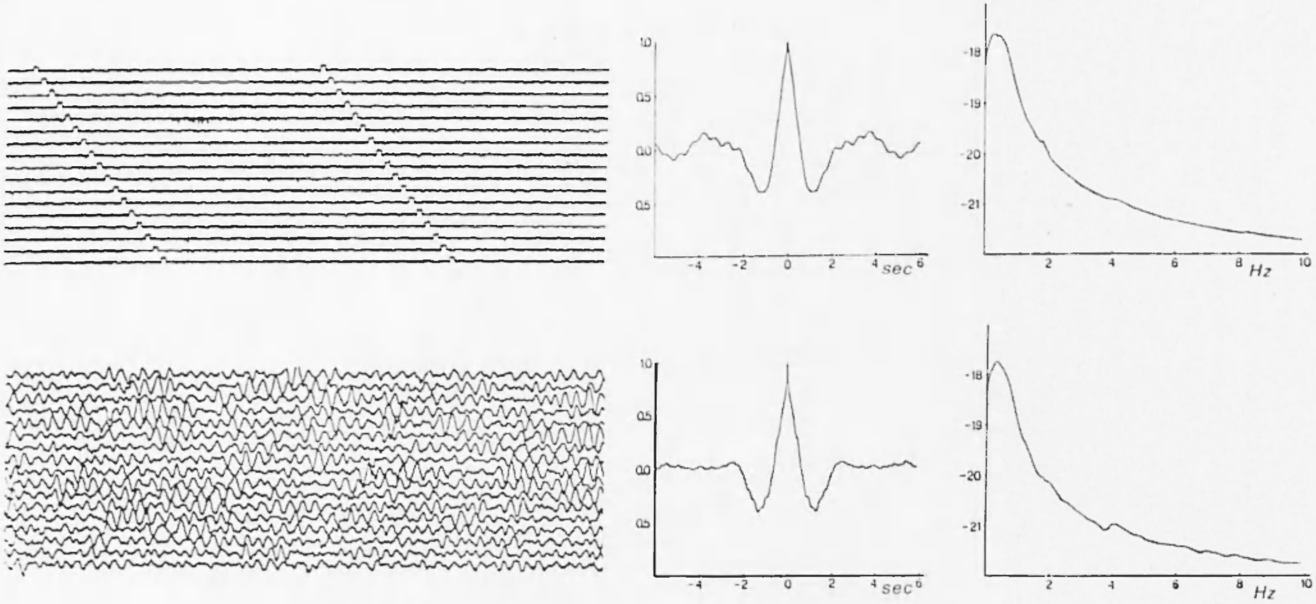

FIG. 8 - Seismic noise of two recordings made at Duronia station, near Rome: 1) "calm" situation with slight, industrial noise; 2) high meteorological noise.

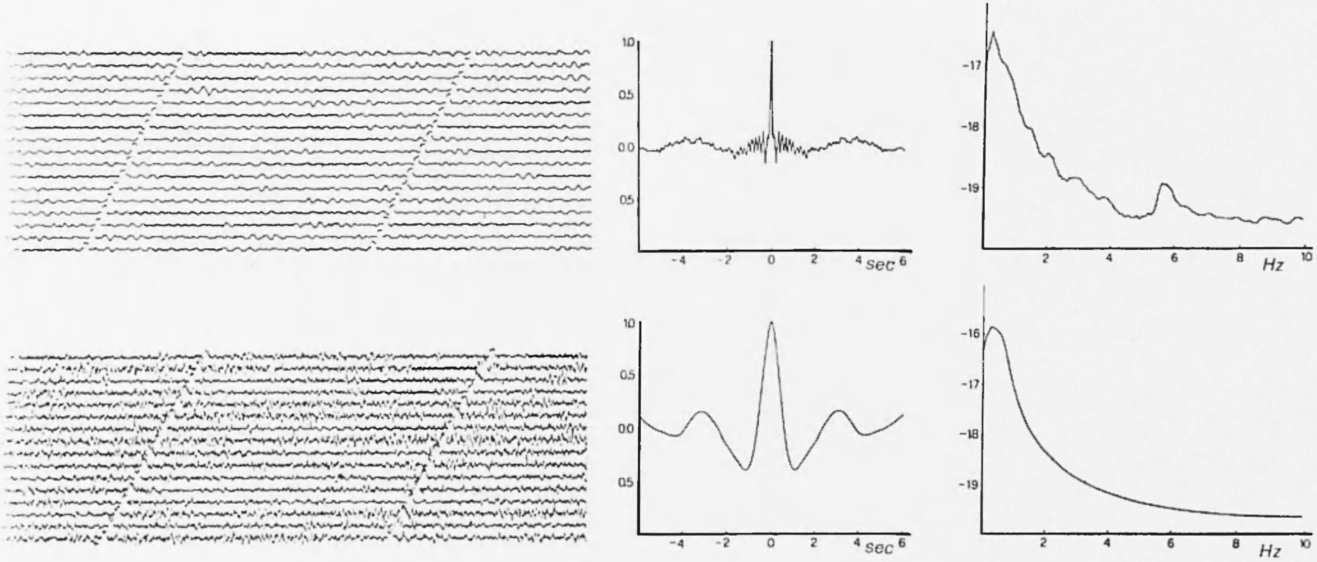

FIG. 9 - Seismic noise of two recordings made at Montasola station, near Rome: 1) "calm" situation with slight, industrial noise; 2) high meteorological noise.

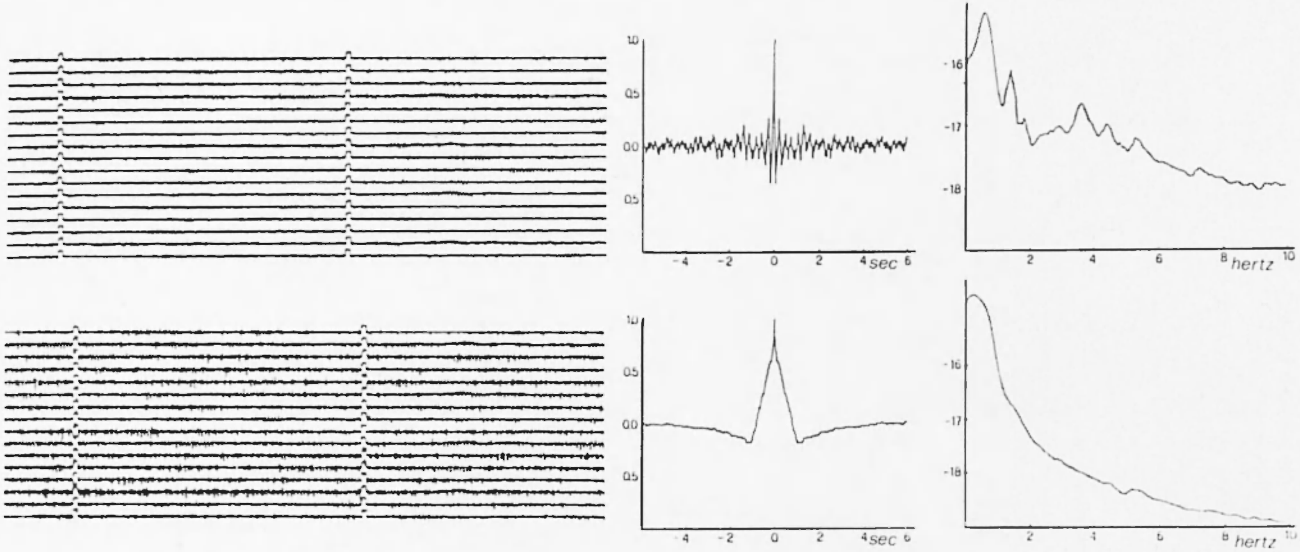

FIG. 10 - Seismic noise of two recordings made at Observatory of L'Aquila, near Rome: 1) "calm" situation with slight, industrial noise; 2) high meteorological noise.

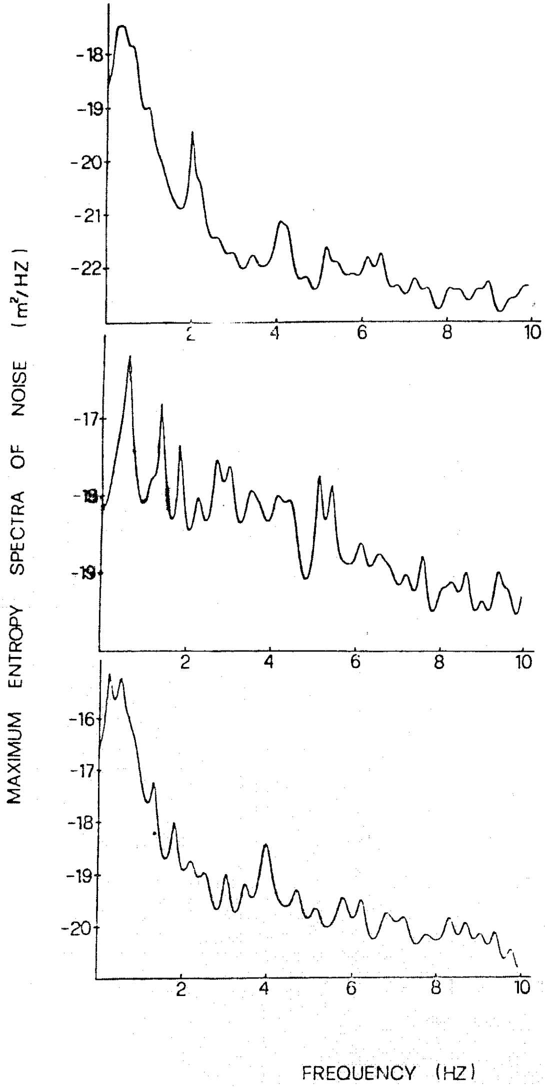

FIG. 11 - Maximum entropy spectra of recordings in Figs 7(2), 8(2), 9(2).

5. CONCLUSION

It could be seen that, in a recording system wich included both a modulator-demodulator couple and a tape recorder, the main trouble was due to the latter. The effect is mainly evidenced by noise, the spectrum of wich brings out peculiar frequencies that do not exist when the recording is done without mechanical means.

It is advisable that, putting into operation a seismic station working by means of such instrumentation, the level of the amplification given to the output signal of the seismometer be enough to overcome by at least an order of magnitude the instrumental nois (i.e. the noise present in the output when the mobile coil of the transducer is stopped).

Only if one operates the right way, it is possible to evidence the real features of the natural seismic noise. In the choice of a site to be used for a new seismic station, some preliminar tests concerning background noise are necessary. When a spectral analysis is available, it can give information about the nature of the background noise and the best design of electronic filters. Of course, both the amplitude and the spectral composition of the noise can change. So, several test scarried out in different conditions and at different day times are advisable in order to get a full knowledge of the microseismic noise of a site.

REFERENCES

Andersen H., 1974 - *On the calculation of filter coefficients for maximum entropy analysis.* « Geophysics », 39, 1, pp. 69-72.

Bath M., 1974 - *Spectral analysis in geophysics.* Elsevier Scient. Publish. Company, New York.

Bendat J.S., 1958 - *Principles and applications of randon noise theory.* Elsevier Scient. Pubblish. Company, New York.

Bendat J.S., Piersol A.G., 1971 - *Random data: analysis and measurement procedures.* Wiley Interscience, New York.

Lacoss R.T., 1971 - *Data adaptive spectral analysis methods.* « Geophysics », 36, 4, pp. 661-675.

Robertson H., 1965 - *Physical and topographic factors as related to short-period wind noise.* « Bull. Seism. Soc. Am. », 55, 5, pp. 863-877.

Slicther L.B., 1967 - *Spherical oscillations of the earth.* « Geophys. Journ. », 14, 1, pp. 171-177.

Ulrych T.J., Bishop T.N. - *Maximum entropy spectral analysis and autoregressive decomposition.* «Reviews of Geophysics and Space Physics», 13, 1, pp. 183-200.

Ulrych T.J., Smyle D.E., Jensen O.G., Clarke G.K.C., 1973 - *Predictive filtering and smoothing of short records by using maximum entropy.* « Journ. of Geophysical Research », 78, 23, pp. 4959-4964.

Walker R.A., Menard J.Z., Bogert B.P., 1964 - *Real-time, high resolution spectroscopy of seismic background noise.* « Bull. Seism. Soc. Am. », 54, 2, pp. 501-509.

Wiggins R.A., Miller S.P., 1972 - *New noise-reduction technique applied to long-period oscillations from the Alaskan earthquake.* « Bull. Seism. Soc. Amer. », 62, 2, pp. 471-479.