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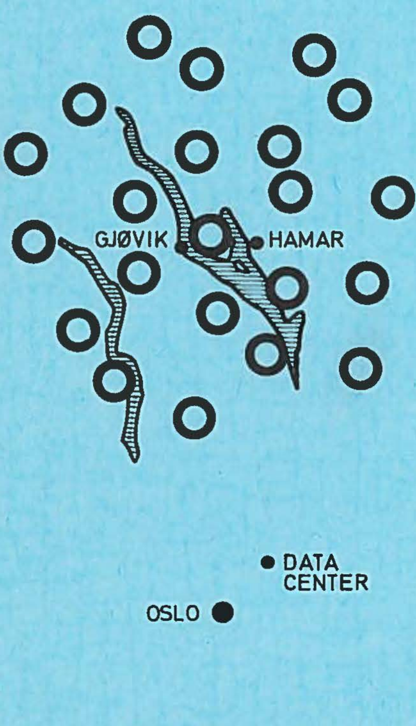
Royal Norwegian Council for Scientific and Industrial Research

ARRAY STATIONS AS A TOOL FOR MICROSEISMIC RESEARCH

by

Hilmar Bungum



NORWEGIAN SEISMIC ARRAY

NORSAR

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ABSTRACT

Some of the advantages of using large seismic arrays in microseismic research are pointed out, and examples of various kinds of noise analyses on both long period and short period NORSAR data are presented.

INTRODUCTION

As some authors previously have pointed out (Iyer 1964, Haubrich and McCamy 1969), there are few areas within seismology which have attracted more attention and produced more papers than the problems about the seismic background noise of the earth. However, not all of these works have advanced the subject equally much, and there might be several reasons for this. One of them is obviously that the observational instruments have been too inadequate as compared to the complexity of the problem, and also that the theoretical side of the problem has not attracted enough attention.

A step forward in microseismic research came by the introduction of the large aperture seismic arrays. These stations have digital recording which makes the data, with a good time and amplitude resolution, easily ready for computer analysis. The most important, however, as compared to the conventional stations, is that sampling is done both in time and space. That means that one can analyze the complete noise field, and thereby test different theoretical models for the noise.

A commonly used and fruitful model is based on the description of the noise as being generated from a stationary, normally-distributed random process, in which case it can be shown (Lee 1960, Yaglom 1962) that the probability structure is completely described by the covariance functions. The most common way to present that information is to take it via a Fourier transform out in frequency domain as power spectral density. For propagating noise, sampled in time and two space dimensions by a seismic array, the equivalent characterizing function is the covariance matrix, usually presented through its three-dimensional Fourier transform as a power spectral density in frequency-wavenumber space. A high-resolution technique has been established for the estimation of this function (Capon 1969a), which describes the velocity and frequency properties of the noise field. Recently there have been presented several works based on such frequency-wavenumber analysis (Vinnik 1967, Toksöz and Lacoss 1968, Capon 1969b, Haubrich and McCamy 1969, Lacoss et al 1969, Bungum et al 1971b), and one can surely say that this technique has some definite advantages over the traditional way of analyzing microseisms.

CASE STUDIES

Most of the empirical works in microseisms have been case studies, where one or a few short time periods have been studied in detail, especially with respect to the relation between large-scale meteorological disturbances and seismic noise. For analyses of that kind large seismic arrays are well suited, and especially NORSAR, since that array is located quite close to a long coastline where meteorological storms are approaching in large numbers.

In this paper there will be presented some examples of different kinds of noise analyses performed at NORSAR. One of the simplest ways of analyzing noise is to compute power spectra, which gives the power as a function of frequency for individual seismometers. Fig 1 (left) shows a power spectrum from a time period when there is a meteorological storm all along the Norwegian coast. The weather chart for this day, 12 October 1971, is presented in Fig 2. The first and second peaks of microseisms are clearly visible, at frequencies around 0.08 and 0.16 Hz on the uncorrected spectrum. Both of those peaks are gone in the spectrum to the right in Fig 1, which presents an unusually quiet day. However, at

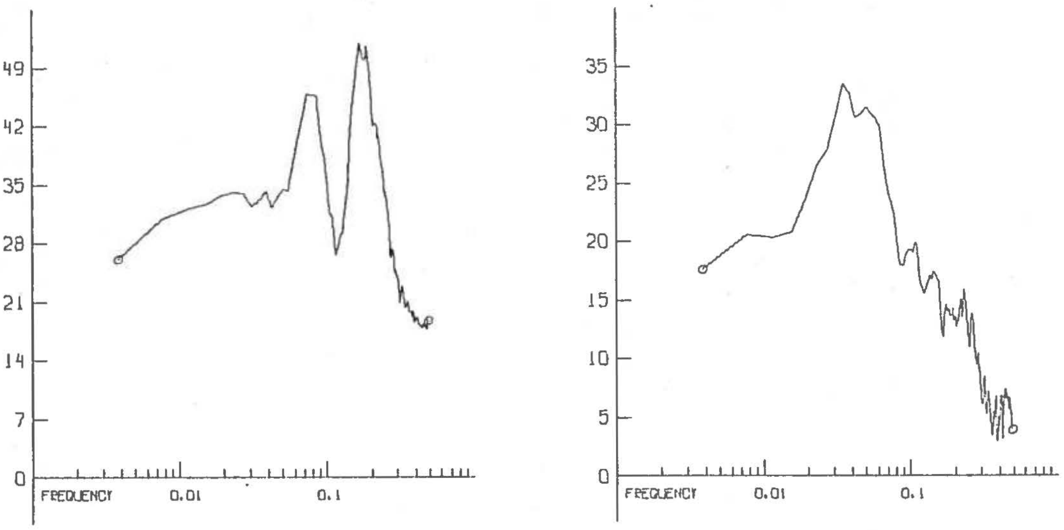


Fig 1. Long period power spectral density for a single vertical seismometer from 12 October 1971, 0530 GMT (left) and 13 Sep 1972, 0000 GMT (right). The vertical axis is in dB relative to 1 nm^2/Hz at 0.05 Hz. Estimated with 5 blocks á 256 samples of 1 Hz data. The spectra are not corrected for frequency response.

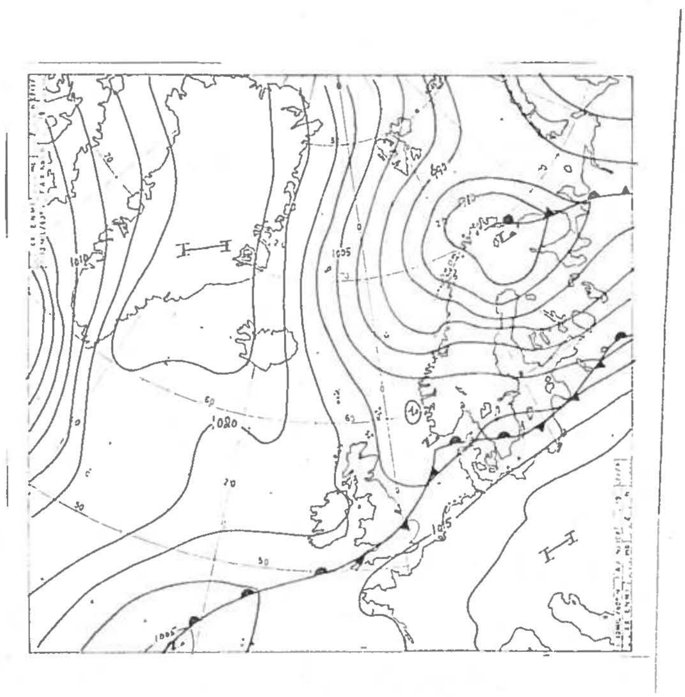


Fig 2. Weather chart from 12 October 1971, 0600 GMT.

0.05 Hz the noise level is not much different in the two cases, around 30-35 dB above 1 nm^2/Hz. Based on the analysis of a number of such situations, it is our impression that the noise level at 0.05 Hz never varies much, while around 6 seconds the variation may be as large as 40 dB, as in Fig 1. Furthermore, it is unusual that the first peak is very clear, and also that the second peak is completely gone, so the two spectra in Fig 1 are therefore extreme cases.

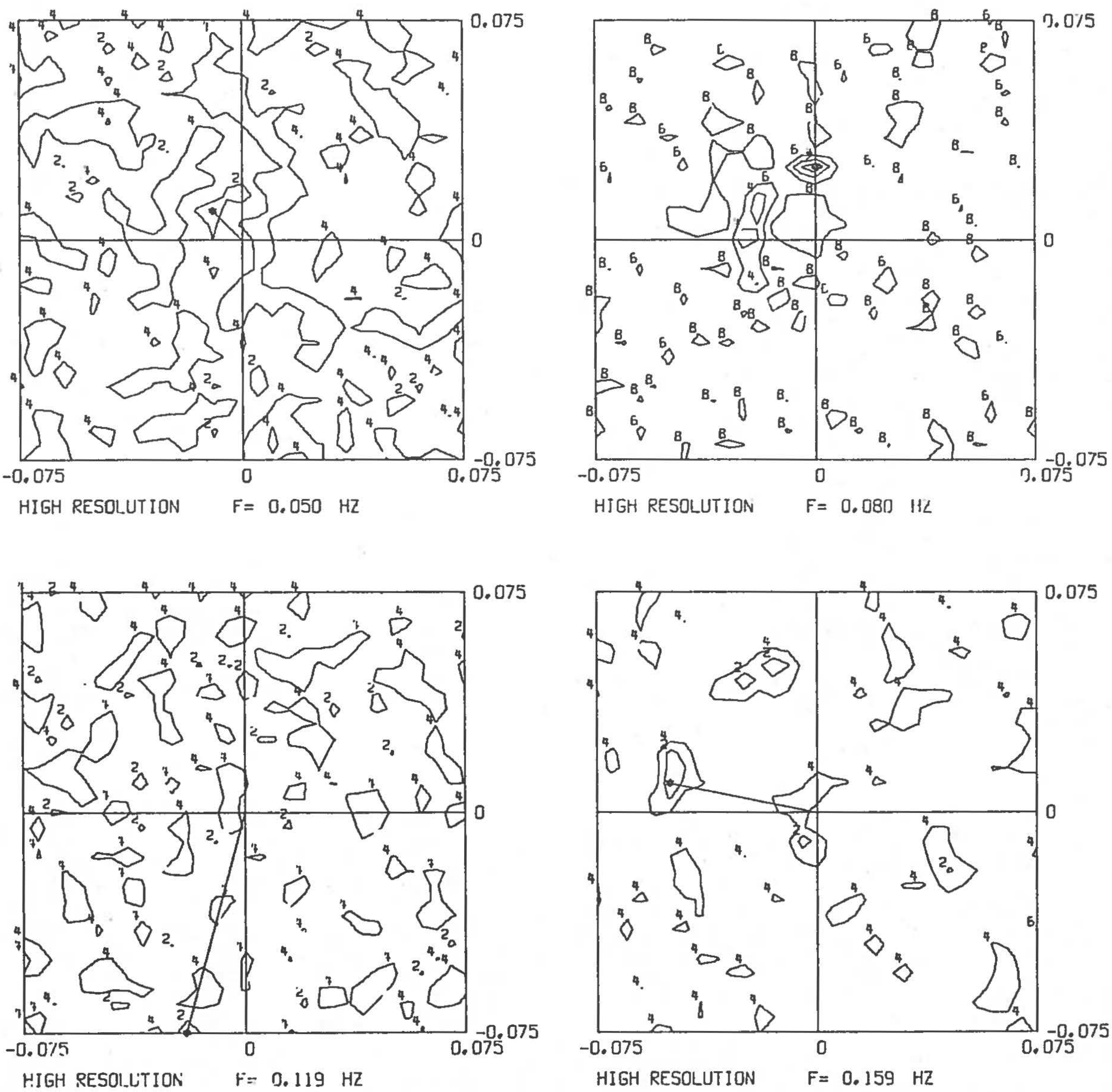


Fig 3. Long period high-resolution frequency-wavenumber power spectral density based on data from 22 vertical seismometers on 12 October 1971, 0530 GMT, for the frequencies 0.05, 0.08, 0.12 and 0.18 Hz. Axes are in cyclic wavenumber (c/km) and the contour levels are in dB down from maximum. Estimated with 5 blocks á 256 samples of 1 Hz data.

The next step would naturally be to analyze the structure of the noise resolved in velocity and azimuth. Fig 3 shows here wavenumber spectra for 0.05, 0.08, 0.12 and 0.18 Hz, for the same data as to the left in Fig 1, and one can observe clear changes in the direction and intensity of the propagating noise as a function of frequency. At 0.05 Hz the noise is almost all non-propagating, while at 0.08 Hz the main direction is from the north with some contribution also from the west. At 0.12 Hz, which is the frequency of the trough in Fig 1 (left), there are no propagating waves at all, while at 0.18 Hz the double frequency peak dominates with contribution from two different directions, the main source being to the west. The phase velocities in all cases have been between 3 and 4 km/sec. Observations of that kind should give a good background for studying the generation mechanisms of microseisms.

In addition to the analysis of the velocity structure for different frequencies as demonstrated above, the same method can also be used in order to follow a situation over time. In this way one can get a fairly precise picture of how the structure of the noise changes with the meteorological situations. But of course, from a frequency-wavenumber analysis one can only get the direction and velocity of the noise for different frequencies, and not normally the distance to the generating area.

There is, however, one important exception to this statement about the distance to the source. The high-resolution analysis always gives as a bi-product an estimate of the power ratio between propagating and non-propagating waves, and a preliminary analysis shows that the latter seems to be dominating when there is a cold-front passing over the array. It is therefore reasonable to believe that the non-propagating noise in these situations is generated through a direct atmospheric loading on the surface in the array siting area.

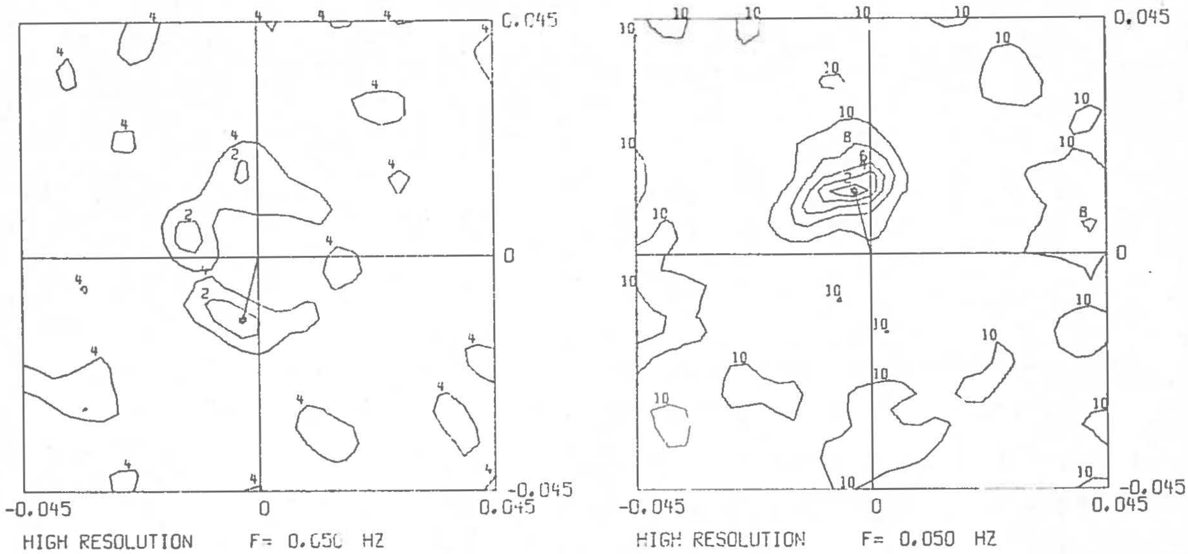


Fig 4. Long period high-resolution frequency-wavenumber power spectral density based on data from 22 vertical seismometers on 30 Aug 1971, 0600 GMT (left) and 19 October 1972, 1130 GMT (right), both for the frequency 0.05 Hz. Axes are in cyclic wavenumber (c/km) and the contour levels are in dB down from maximum. Estimated with 5 blocks á 256 samples of 1 Hz data.

At NORSAR, where the noise is analyzed also because one is interested in reducing its adverse effects on detectability, not only storm microseisms are studied. Fig 4 (left) gives an example from a situation when the absolute noise level is fairly low, the propagating noise in this case is only 4 dB above the background, and the noise is more or less isotropic, with a slight dominance from the south-west. A severe problem in the analyses of such situations is that there is a high risk that a seismic event would interfere with the noise, i.e., that signal-generated noise could be interpreted as microseisms. This is difficult to avoid since the signal often cannot be seen directly on the seismic traces, and when the noise level is at the extreme low, the long period detectability is so good that one cannot be sure to eliminate all events through a study of seismic bulletins.

Generally, the danger of interpreting seismic signals as microseisms is present at all noise levels. This is because there is no fundamental difference between the wavenumber structure of signals and noise in the signal frequency band, and cases have been found where the microseisms show as good a point-source structure as certain earthquakes. An example of that kind is given to the right in Fig 4, which could equally well be (but is not) an earthquake. Also discovered are situations when surface waves from earthquakes appear right on top of a strong microseismic storm in wavenumber space.

So far this paper has only discussed analysis of long period noise. Also for short period data the noise clearly has a negative effect on detectability, but there is the big advantage that noise and signals in the short period band are well-separated in wavenumber space. This allows beamforming to be used as the main technique for signal enhancement, and the NORSAR array was therefore constructed such that the minimum distance between short period seismometers should give a negligible noise coherency. Since the coherency matrix and the wavenumber spectrum both are transformations of the covariance matrix, it follows that NORSAR is difficult to use for wavenumber analysis of short period seismic noise. An ideal array for such analysis would have a minimum station separation of less than one km and not 3 km as for NORSAR. (The short period noise analysis presented by Bungum et al (1971) was based on data from a test array which is no longer in operation.)

There are, however, many other ways in which one can study the structure of short period seismic noise. One example of this is given below.

LONG TERM ANALYSIS

In the on-line detection processing system of NORSAR (Bungum et al 1971a), a short term average (STA) and a long term average

(LTA) are calculated for each individual beam, and a detection is declared whenever the ratio between the two exceeds a certain level. The STA is calculated through a rectify-integrate procedure,

$$STA(t) = \sum_{i=0}^{L-1} |S(t-i\cdot\Delta t)|$$

where S(t) is beam amplitude, L is integration window length (around 2 seconds) and Δt is the sampling interval. The LTA is calculated through a recursive filter,

$$LTA(t') = (1-2^{-\eta})\cdot LTA(t'-L\cdot\Delta t)+2^{-\sigma}\cdot STA(t'-L\cdot\Delta t)$$

where t' is LTA sampling time (around 1 second intervals), η is a time constant and σ a scaling parameter. The parameters have been set such that the half-time is around 40 seconds.

The LTA, being a running estimate of the noise level within the processing frequency band (presently 1.2-3.2 Hz), is calculated on-line on at present 318 array beams. For the purpose of noise analysis, all these LTA-values are stored on magnetic tape once per minute. For the analysis presented in this paper, the LTA is again resampled, this time at a rate of 20 samples per day. A thorough analysis showed that this would be sufficient in order to describe the long term variations of the short period seismic noise.

The LTA, calculated as described above, is presented in Fig 5 for the first 5 months of 1972. The curve shows the average of all 318 beams, which again means that it presented a sort of average over all 132 short period seismometers. That

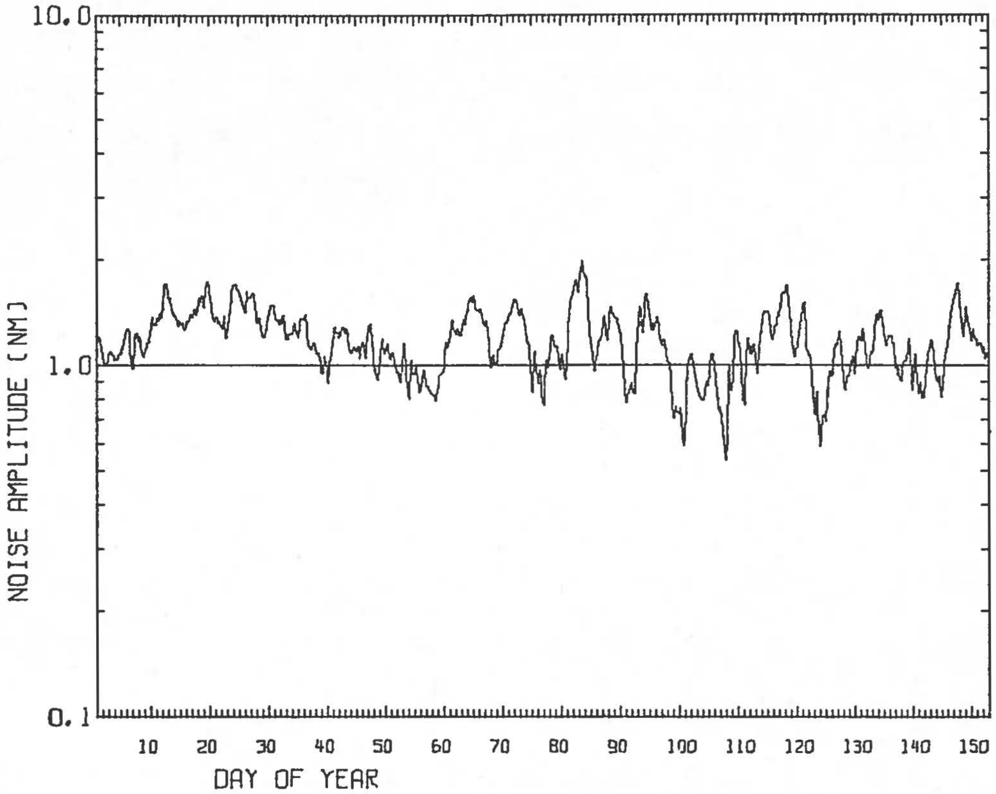
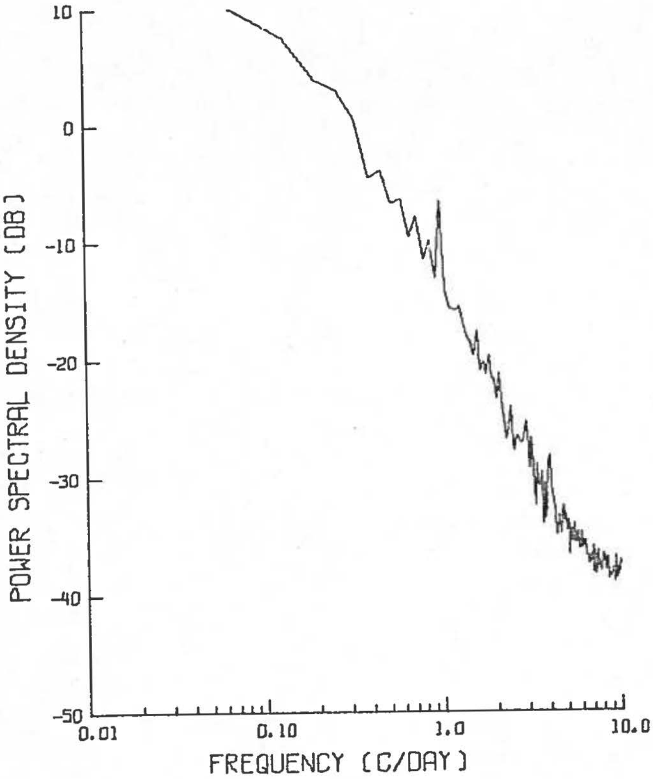


Fig 5. Average noise level (LTA) within the frequency band 1.2-3.2 Hz for the time period January-May 1972.

guarantees that local site effects are smoothed out, and that the curve should be representative for the general siting area. In Fig 5 there is no clear pattern extractable just by looking at the data. Therefore, the power spectral density was calculated, as presented in Fig 6. The spectrum is exponentially shaped, which indicates randomness in the generation process. That is also confirmed by the fact that the correlation time is very short. The other dominating feature is the peak in the spectrum at exactly 1 c/day. The peak is significant on a 90% probability level, and reflects the diurnal variation of the noise in this frequency band, 1.2-3.2 Hz. A similar study from 5 months in the autumn of



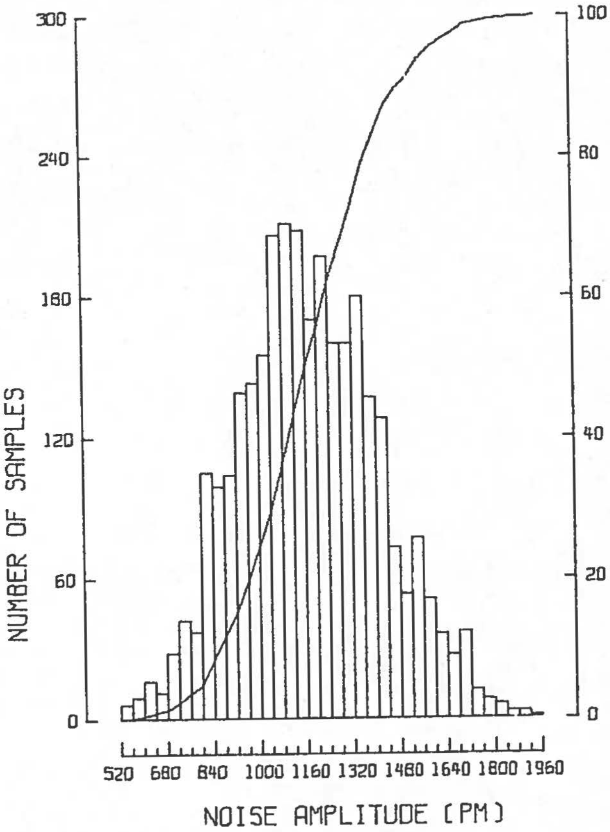


Fig 6. Power spectral density of the average noise level presented in Fig 5. Estimated with 10 blocks á 15.3 days of data, sampling rate 20 samples/day.

Fig 7. Incremental and cumulative distribution of the average noise level presented in Fig 5.

1971, with filter 0.9-3.5 Hz showed no such peak, which indicates that diurnal variation is a phenomenon which takes place at frequencies above 1 Hz, approximately.

One of the reasons why this LTA study was initiated was to get the statistical distribution of the short period noise over a long time interval within the on-line processing frequency band. That distribution, for the same data as in Fig 5, is presented in Fig 7, both incremental and cumulative. The ground motion conversion is somewhat uncertain in this case, since the LTA is a measure of integrated linear power. However, the median noise level has been found at 1.15 nm, the 90% level is 2.0 dB above and the 10% level is 2.7 dB below the median, and the LTA can be well approximated by a Gaussian distribution. Since there is no simple inverse linear relationship between noise level and detectability (Lacoss 1972), it is difficult to determine how much effect this has on detectability, but with some additional approximations one can say that the noise fluctuations equivalate a standard variation of roughly ± 0.1 magnitude units in the detection threshold (Bungum 1972 a and b).

Recently, a similar LTA analysis has been initiated for the long period data, and the first results indicate that the variations here are much larger. One obvious thing is also that the short period and the long period LTA correlate at times very well, which means that the 6-second peak, which often dominates the long period records, also leaks into the processing frequency band, where 1.2 and 3.2 Hz represent the half-power points of a filter with falloff 24 dB/octave.

This paper does not claim to be complete with respect to presenting the possibilities of large seismic arrays in microseismic research. Also, several of the analyses discussed above are not unique for arrays, but only convenient when high-quality digital data are available.

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