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Noise Characteristics of the Upgraded FINESS Array

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Abstract

The FINESS array in southern Finland has gone through a technical upgrade in 1993. The quality of the data was strongly improved in the upgrade. The level of instrumental noise is lower and data of substations are more uniform. The array provides high quality data for seismic monitoring and research purposes. When compared to 5 nearest seismic stations in the distance range from 70 km to 160 km FINESS had the lowest noise level. At 1 Hz the median of FINESS noise level was at 1.70 nm^2*/Hz computed from noise samples of 47 days. The 5th and 95th percentiles were at 0.1 nm*^{2}*/Hz and at 13 nm*^{2}*/Hz. The spectral slope below 2 Hz was found to be 26 dB/octave and 9.5 dB/octave at higher frequencies during night. At daytime the slopes were nearly similar except a more moderate slope between 1.5 Hz and 2.0 Hz and higher noise level above 7.0 Hz. Diurnal variation of noise was strong during working days. The average difference at 1 Hz between 6 quietest hours during night and 10 busiest working hours was 0.6 dB. Above 2 Hz it varied between 3 dB and 5 dB. The spatial noise characteristics and possibilities to improve beamforming processes were examined by computing cross-correlograms as function of intersensor distance with different frequency bands. The correlation curves had negative minima, at different intersensor distances depending on the frequency. The results were ensured by computing noise suppression spectra with several array subconfigurations with different average intersensor distances. Extra noise suppression can be gained in beamforming by selecting subsets of sensors with optimum intersensor distances for different frequency bands. The sources of short term alterations of seismic noise field were studied by examining the low velocity detections. The detections had two major directions, 272° and 332°. No explicit sources could be designated. Strong candidates are small scale industrial activity relatively close to the array and traffic on a major road 4 km west from the array.*

Key words: seismology, small aperture arrays, seismic noise, noise suppression, detections

1. Introduction

The FINESS array lies in southern Finland in Sysmä. It has been designed for detecting and locating local and regional events (*Korhonen et al.*, 1987), but it has proved to be very efficient also in detecting teleseismic events (*Tarvainen et al.*, 1994). The array has taken part in international data exchange experiment Group of Scientific Experts Technical Test

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2 (GSETT-2) (*Bratt*, 1993) and it is one of the alpha-stations, which form the backbone of the system in the next test, GSETT-3 (*Ringdal*, 1994), starting Jan. 1. 1995. The array design resembles those of NORESS and ARCESS arrays in Norway (*Mykkeltveit*, 1985) and GERESS in Germany (*Harjes*, 1990). The array consists of 16 substations; 15 vertical short period (SP) instruments assembled in 3 rings with a 3-component SP station at the center. The diameter of the array is about 2 km (Fig. 1). The array has gone through a technical upgrade in 1993. New sitings were built for all substations and the location of 2 substations was changed. New telephone lines were built from substations to central station. All electronic equipment was modernized. The old 16 bit A/D converters were changed to 24bit AIM24 converters manufactured by Science Horizons, Inc. At the old array the instrumental noise was higher due to the old amplifiers and long analogous line transfer. Previously the data was digitized at the central station. Now it is digitized at the vault of each substation. The instrumental noise is now about 20 dB lower than average seismic noise. Earlier the instrumental noise was significant compared with the seismic noise. After the upgrade the name of the array was changed from FINESA to FINESS. The quality of the data was strongly improved in the upgrade. The data of FINESS is much more uniform (Fig. 2.) than

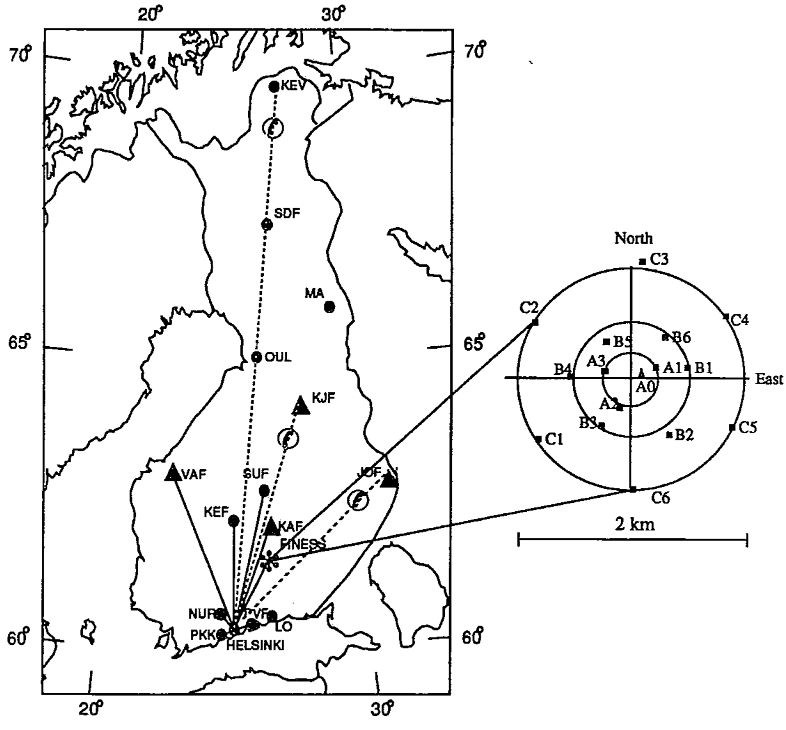


Fig. 1. Location and configuration of the FINESS array. Also other seismic stations in Finland are marked on the map. Triangles denote 3-component stations and circles vertical component stations. Solid lines indicate continuous online data transfer and dashed lines dial-up connections.

at the old array (*Tiira et al.*, 1994). Instrumental noise and leakages in analogous line transfer caused clearly observable noise of different amplitude and nature at some of the old substations. It was not feasible to test the possible change in noise levels between the old and new array installation due to arbitrary alterations in local noise conditions.

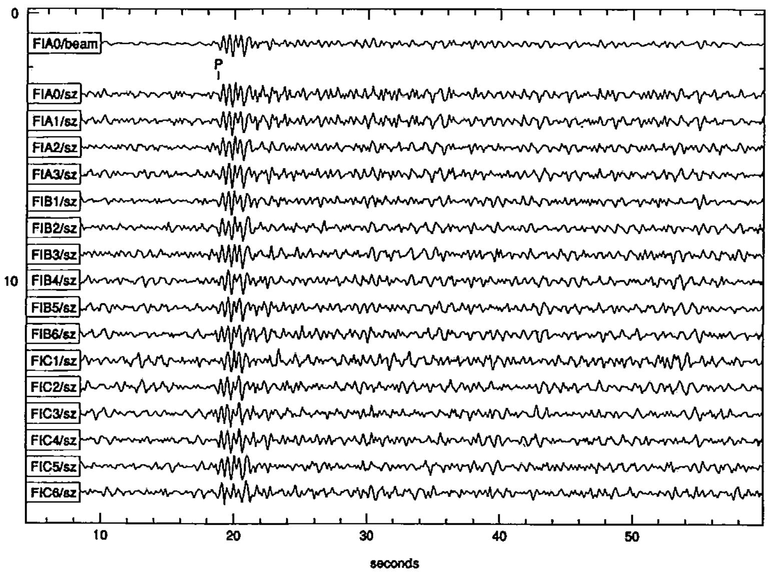
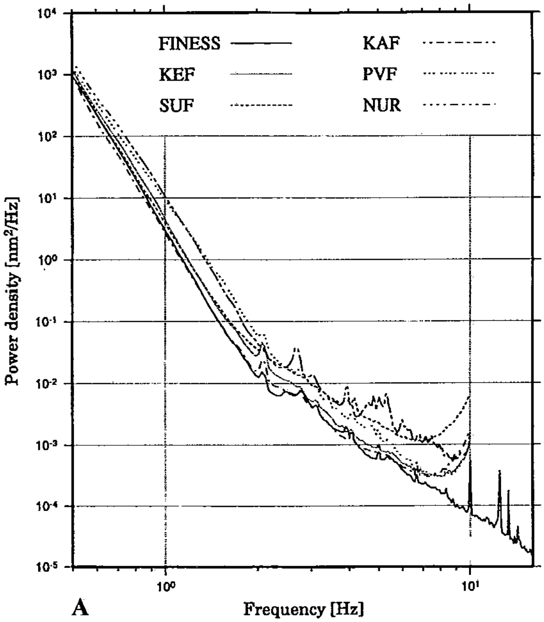


Fig. 2. Beam and recordings of vertical channels of each substation from a teleseismic event. The event is an earthquake on Kuril Islands Mar 3 1995 07:46:45, lat 43.98°N, lon 147.83°E, depth 47.5 km, mb 3.8. Distance to FINESS 64.89°. The epicentre information is from Center for Monitoring Research.

2. *Seismic noise level at the FINESS array*

The noise levels of the FINESS array and 5 nearest seismic stations in Finland were compared by computing noise spectra every hour during 47 days in winter and in spring. The average noise spectra for daytime and night-time are displayed in Fig. 3. The sampling rate in FINESS is 40 Hz. Stations KEF, SUF, KAF, PVF and NUR have sampling rate 20 Hz. These 5 stations have much lower amplification than FINESS. Consequently, their noise spectra start to rise near 10 Hz due to instrumental noise corrected with response. At most of the band between 1 Hz and 10 Hz FINESS had the lowest noise level during night (Fig. 3a). At daytime FINESS noise spectra had a peak between 3 Hz and 4 Hz caused by temporary logging operation in the near by woods (Fig. 3b). Otherwise FINESS still had comparably low noise level. NUR and PVF lie close to Gulf of Finland and densely populated areas. This explains the higher noise levels of these stations. KEF, SUF, and KAF lie in quiet areas in central Finland. The station KAF, which is situated closest to FINESS, had the lowest noise levels of the other 5 stations.



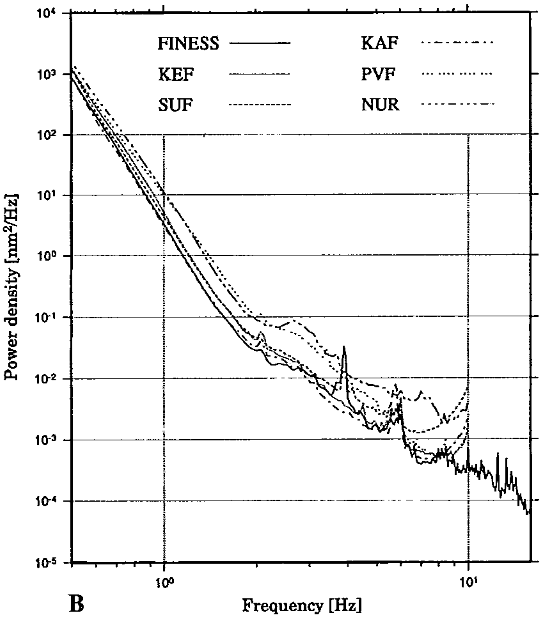


Fig. 3. Average noise power spectra of 47 days collected between December 1993 and May 1994. Noise samples of 204.8 s were taken every hour. a) Average spectra at night 00:00-03:00. b) Average spectra at daytime 08:00-18:00. The FINESS noise spectra were computed from single substation FIA1 to make the spectra comparable.

At 1 Hz the average of FINESS noise level was at 3.65 nm^2/Hz and the median was at 1.70 nm^2/Hz computed from noise samples of 47 days. The 5th percentile was at 0.1 nm^2/Hz and 95th percentile at 13 nm^2/Hz. The 10th and 90th percentiles were consequently at 0.2 nm^2/Hz and 8 nm^2/Hz. The spectra were computed from 8192 samples and were not smoothed. The unsmoothness of spectra contributes to the large variation in noise levels.

The FINESS power density noise spectra are characterized by a steep slope at low frequencies, a transition area around 2 Hz and a more moderate slope at high frequencies. During night the spectral slope is 26 dB/octave below 2 Hz and above 2 Hz 9.5 db/octave. During daytime the slope is similar in low frequencies, but only to 1.5 Hz. Between 1.5 Hz and 2.0 Hz the slope is more moderate. At high frequencies, between 2 Hz and 7 Hz, the slope is at daytime 9.3 db/octave. The major difference in spectral slopes between day and night are from 1.5 Hz to 2.0 Hz and above 7 Hz.

3. *Diurnal and weekly variation of FINESS noise*

The weekly variation of noise was studied by computing spectra of 204.8 s noise samples from every hour of one week. The percential variation of noise was computed by comparing each spectrum to the average of the whole week (Fig. 4). The spectra are heavily smoothed. The diurnal variation in the ground motion power spectra is clear in working days. Only a few hours during night have low average noise level. During working days there is a period of high noise level between 7 am and 7 pm local time. At lower frequencies this pattern breaks, showing that below 1 Hz most of the noise is not of cultural origin. The noise at low frequencies is evidently caused by weather conditions e.g. wind and sea waves. Above 2 Hz the noise levels during night at working days were comparable with daytime noise levels at the weekend. The strong variation around 4 Hz is mostly caused by the logging operation in the vicinity of the array.

The average difference at 1 Hz between the 6 most quiet hours during night and 10 busiest working hours was 0.6 dB. At 2 Hz it was 3.5 dB and at 5 Hz and 9 Hz 3.3 dB and 4.4 dB, respectively.

4. *Spatial characteristics of the FINESS noise field*

The spatial noise characteristics have an important role in tuning the beamforming processes of an array. The signal-to-noise ratio is enhanced in array data processing by beamforming, i.e. adding the sensor outputs of the substations. In theory the beamforming divides the incoherent noise by a factor of $N^{1/2}$, where N is number of substations, but different array configurations may give extra suppression in some frequency ranges (*Kværna*, 1989). To illustrate this cross-correlations of noise samples from all substations were computed as function of intersensor distance. The correlations were computed with zero lag. The results show that varied sensor separations have minimum at different frequency ranges (Fig. 5). At frequency band from 1.5 to 2.0 Hz the minimum is at 1380 m.

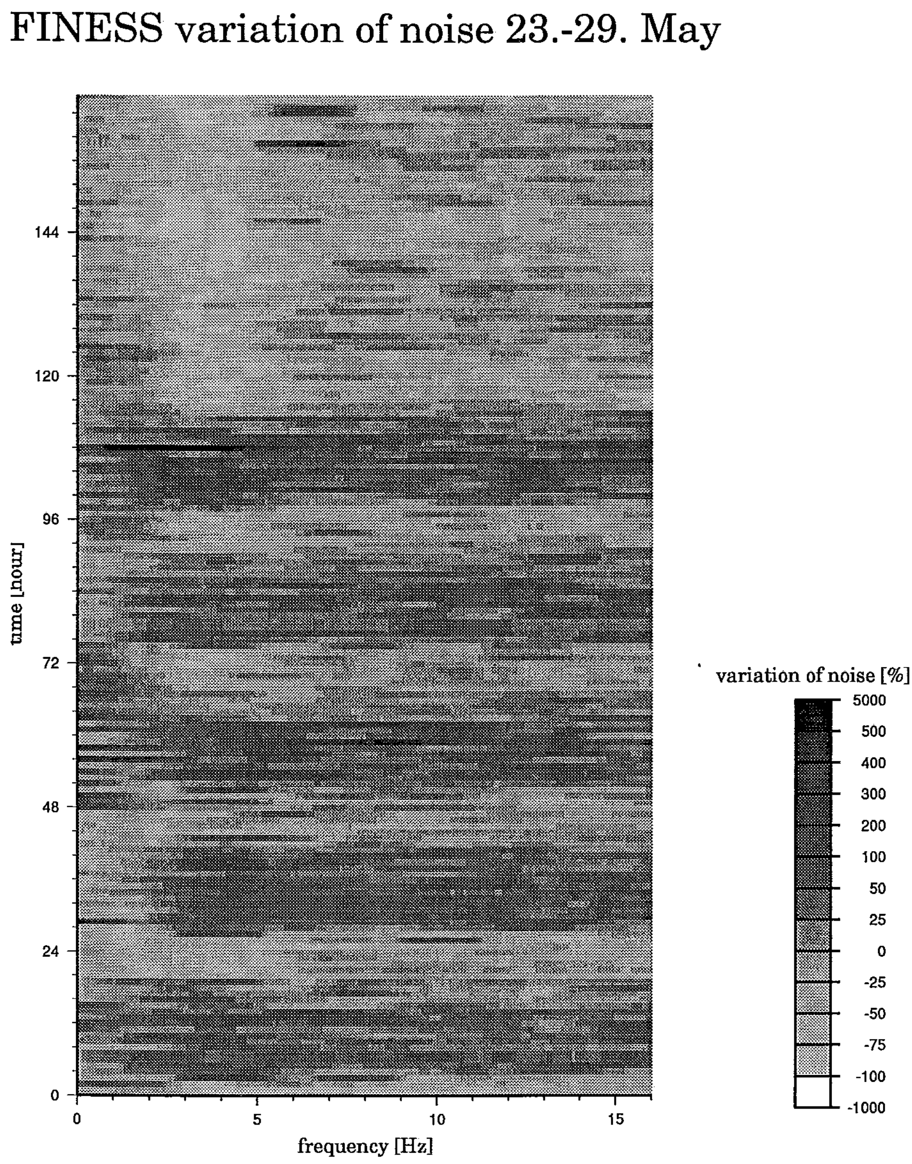


Fig. 4. Percential variation of noise at week 21/1994. Time period of one week from Monday to Sunday is on the vertical axis. Noise samples were taken every hour. The time is GMT+3. The gray shades imply percential variation of noise power spectra compared to average of the whole week.

At band from 3 to 4 Hz it is at 600 m. The theoretical correlation function is a Bessel function of zeroth order for noise with uniform wavenumber spectrum (*Mykkeltveit et al.* 1983). The higher the frequency the shorter the optimum distance of sensors is. In a study using NORESS data *Mykkeltveit et al.* (1990) found that the distance corresponding to the minimum of correlation is roughly inversely proportional to lower cut-off of the frequency band. With FINESS data the dependency was slightly different. Towards higher frequencies the change in the point of optimum intersensor distance grew smaller than with simple inverse proportionality between the factors. The frequency bands were obtained by filtering the data with very sharp finite impulse response low- and highpass filters with 255 coefficients. When 3rd order Butterworth filters were applied, the smoother sidelobes of the filters created smoother peaks in noise suppression.

Further, the noise suppression spectra were computed for different sensor configurations to reveal optimum arrangements for different frequency bands. The noise suppression was computed as the ratio of the beam power spectrum $B(f)$ to the average of the spectra of all sensors $M(f)$ (*Mykkeltveit et al.*, 1990).

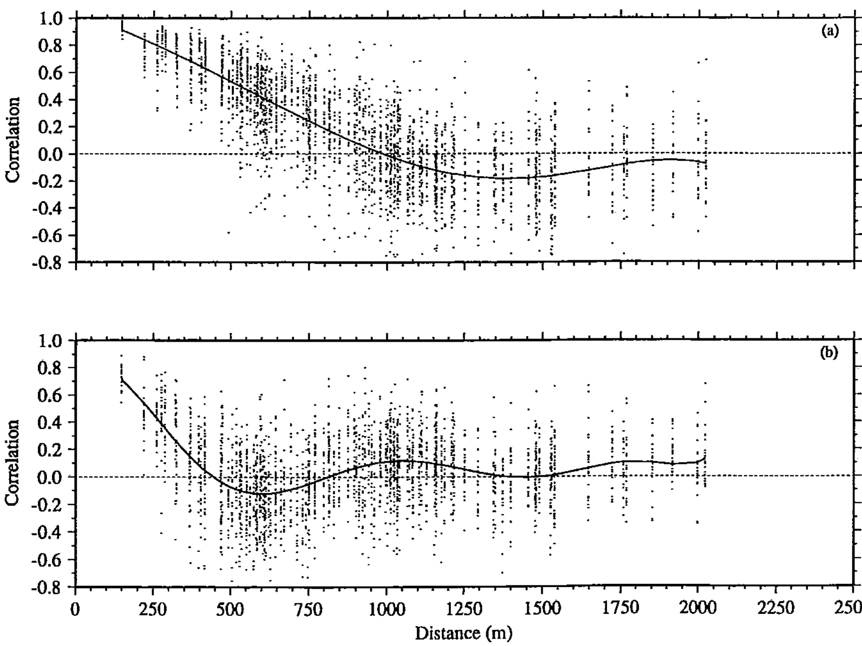
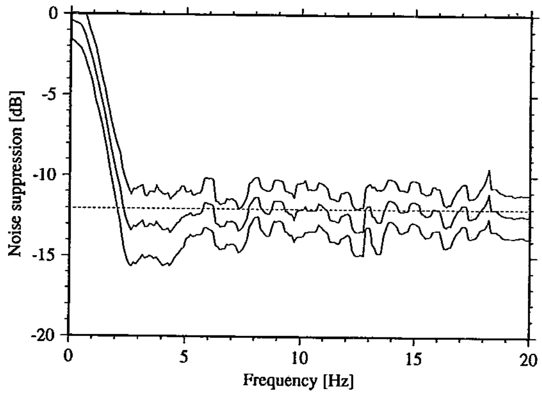


Fig. 5. FINESS noise correlations versus interstation separation in meters for frequency bands 1.5 Hz - 2.0 Hz (a) and 3.0 Hz - 4.0 Hz (b). The fitted curves are polynomial regression models of fifth order.

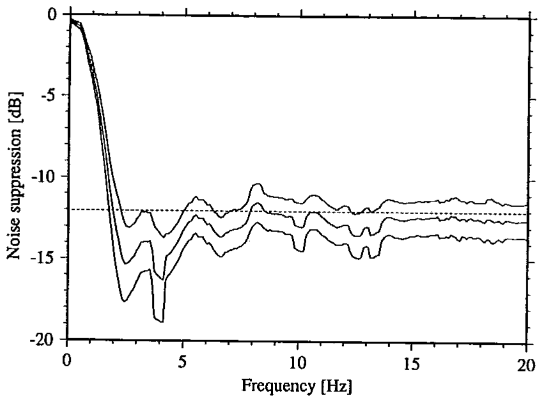
$$SUPP(f) = 10logS(f) = 10logB(f) - 10logM(f)$$

In Fig. 6 there are average noise suppression spectra for two weeks with different noise conditions. In both cases the noise suppression goes clearly below the theoretically expected line between 2 Hz to 5 Hz, which is an important area in detecting local and regional phases. During the first week of January the noise level was lower, especially between 2 Hz and 5 Hz. Also, the noise suppression was weaker in this week. The amount of noise suppression seems to follow the noise levels. At its maximum the noise suppression was close to 19 dB.

Extra noise suppression can be gained by selecting subsets of sensors which have different average intersensor distances, though smaller number of sensors weakens the noise suppression at most of the frequency range. Noise suppression spectra were computed with several array configurations for week 1/1994 (Fig. 6). At low frequencies, below 1.8 Hz, the strongest noise suppression was gained with the 6 instruments of C-ring with substation A0 at the center of the array. From 1.8 Hz to 2.7 Hz the A- and C-rings gave best results.



b)



a)

Fig. 6. a) Average noise suppression spectra with plus/minus one standard deviation for week 1/1994. The noise samples were collected every hour. b) Similar picture for week 21/1994. The theoretical line 12.04 of

At higher frequencies the whole array had strongest noise suppression. These results can be utilized in selecting more efficient array configurations for beamforming. Array's capability to detect weak events depends on the amount of noise suppression. So it is important to find the optimum array subconfigurations for different frequency ranges.

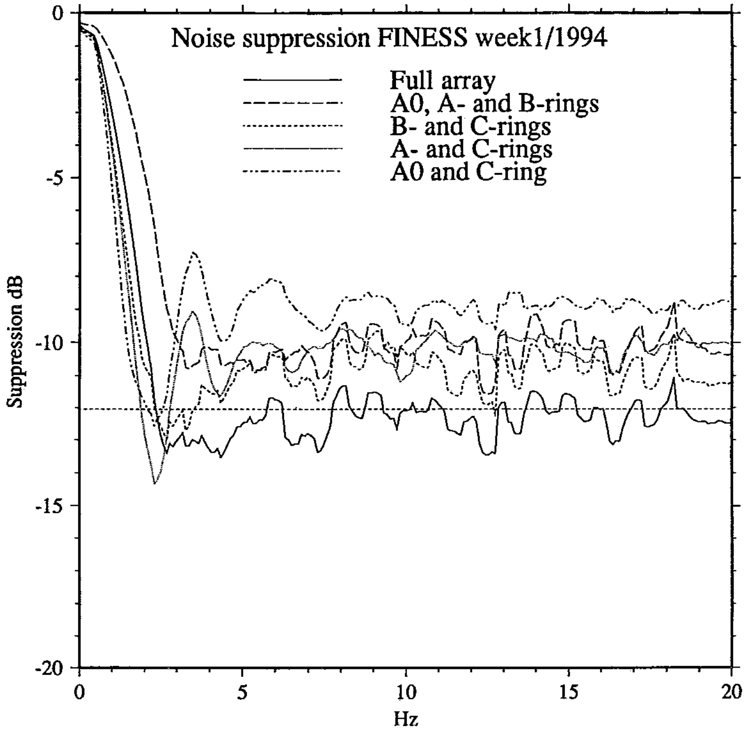


Fig. 7. Average noise suppression spectra for week 1/1994 with full array (16 sensors) and 4 different subconfigurations. A0, A- and B-rings (10 sensors); B- and C-rings (12 sensors); A- and C-rings (9 sensors); A0 and C-ring (7 sensors).

Some diurnal variation was observed in noise suppression levels, when average noise suppression between 2 Hz and 3 Hz was computed for one week (Fig. 8). The noise suppression was stronger at working days. Also, the diurnal variation was more clear at working days. The noise suppression was much stronger during working hours and had sudden drop at midnight local time.

5. *Short term alterations of seismic noise*

Sources of cultural noise in the vicinity of the array have a significant role in temporal noise variations. Array data processing techniques provide very applicable information for analysis of sources of short-term alterations in the seismic noise field. The beamforming

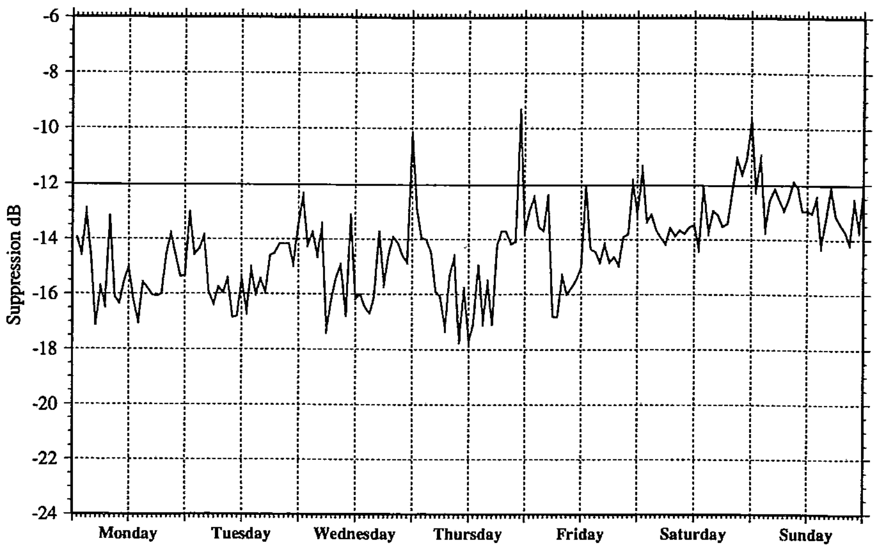


Fig. 8. Average noise suppression from 2 Hz to 3 Hz for each hour of the week 21/1994. Theoretical level of noise suppression with 16 substations is marked in the picture.

empowers the detection of weak noise bursts. Frequency-wavenumber analysis produces accurate estimates of apparent velocity and azimuth. The temporal variations in the seismic noise levels were examined by analysing the output of the detector system. All detections with apparent velocity 3 km/s were collected from January to August 1994. The incoming detections had two major directions, 272° and 332° (Fig. 9). The noise bursts with low velocity are not preceded by detections with higher velocities. Also, in visual inspection no P-waves are found before them. According to low apparent velocities these bursts of noise may be interpreted to be Rayleigh waves. When coherency was plotted as function of frequency (Fig. 10) the detections formed clear clusters. The frequency distribution of detections from 332° had a peak just above 4 Hz and had a heavy tail towards higher frequencies ending at 5.5 Hz. The detections from northeast direction had more concise coherency distribution with higher average level. There is another smaller separate cluster with slightly lower frequencies and coherencies and a distribution of detection with wide frequency range at low coherencies. The latter are probably random noise from different origins. The westward oriented detections had a sharp frequency distribution with a peak at 3.95 Hz and a tail at high frequencies ending above 5 Hz. The coherency values are mostly between 0.6 and 0.3. Another concentration lies around 7 Hz with coherency values below 0.4. Also in this direction random noise detections are seen at low coherencies. In both cases vast majority of the detection is in the main cluster.

Long term temporal analysis showed that number of detections from west was slightly higher during winter. There is a drop in number of detections in mid April. Possibly it is

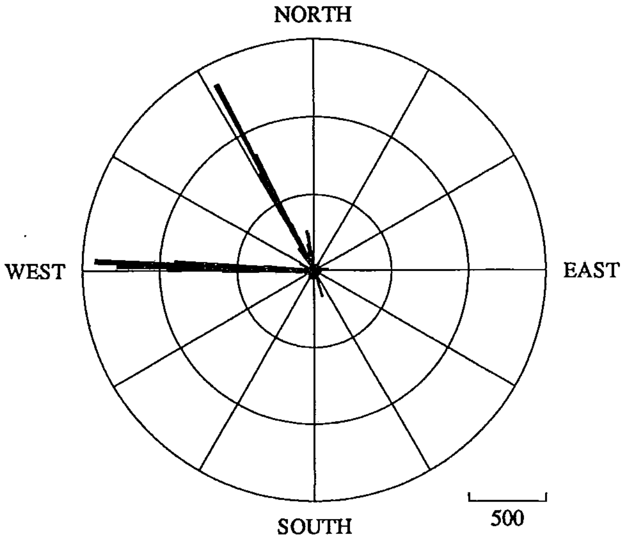


Fig. 9. Number of low velocity (≤ 3.0 km/h) detections in 1 azimuth windows from January 25 to August 31 1994.

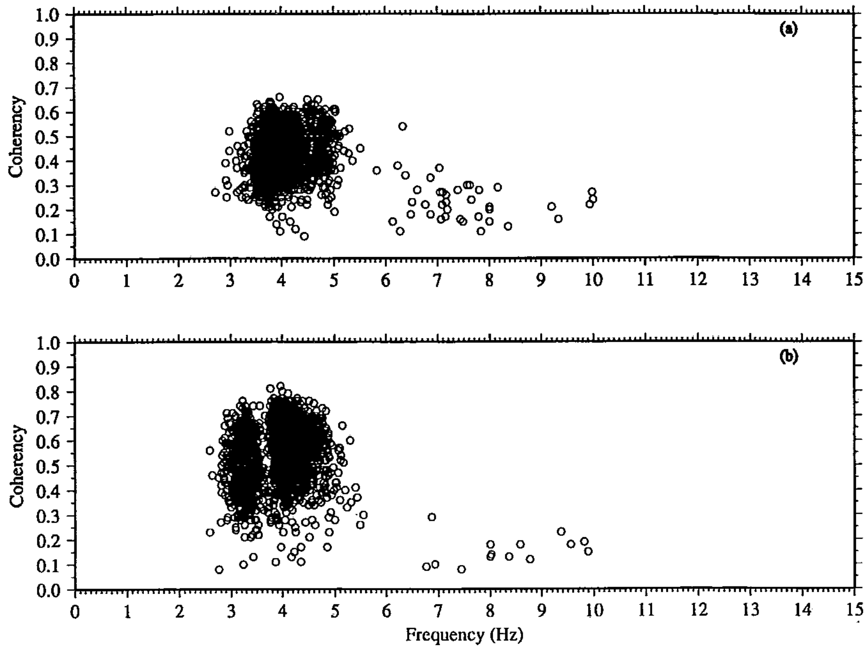


Fig. 10. Coherency plotted as function of frequency. a) Low velocity (≤ 3.0 km/s) detections from 272° ± 1°. b) Low velocity (< 3.0 km/s) detections from 332° ± 1°.

caused by melting of frost, which has been observed to enhance some noise sources. The number of detections from direction 332° rises notably at April 10 (day number 100). After an emergent burst of detections ending at April 29 (day number 119), the number of detections stays at higher level than in winter to the end of the observing period. The diurnal variation of low velocity detections showed that most of them were made during night. This applied to both directions. Though, detections were made also at daytime. Since most of the detections had a low STA/ LTA ratio, close to the detection threshold, it is probable that these bursts of noise were partly embedded by other cultural noise during daytime (Fig. 11).

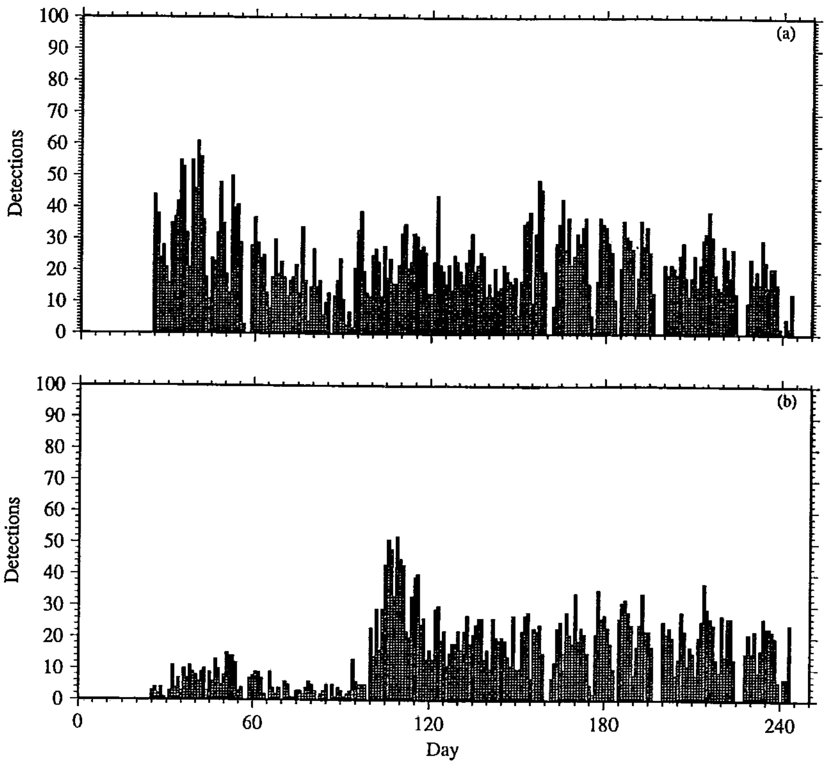


Fig. 11. Temporal distribution of low velocity (≤ 3.0 km/s) detections. a) Detections from 272° ± 1°. b) Detections from 332° ± 1°.

6. *Discussion and conclusions*

The technical upgrade has clearly improved the quality of the data. The instrumental noise is at lower level and the data of substations are more uniform. FINESS had the lowest noise level compared to 5 nearest seismic stations in Central and southern Finland. The array lies far enough from Gulf of Finland to prevent sea waves generating excess to noise level. There are no large towns or industrial sites in the vicinity of the array. At 1 Hz the median of noise was 1.70 nm^2/Hz and 5th and 95th percentiles at 0.1 nm^2/Hz and 13 nm^2/Hz. The results are comparable to those of *Bungum et al.* (1985), who found that at NORESS site in southern Norway the 1 Hz noise level was usually between 1 nm^2/Hz and 10 nm^2/Hz and that noise levels were slightly lower in Finland than in Norway.

The strong noise peaks at high frequency part of the FINESS noise spectra are evidently caused by inductive interference with 50 Hz power lines and electric equipment. With Nyqvist frequency of 20 Hz harmonic foldings lie exactly at 12.5 Hz and 10 Hz. The last folding would be at 5 Hz, but it is embedded by seismic noise. Only a small peak is observed at this point.

The diurnal variation of noise was much stronger in working days than at weekends as expected. The diurnal variation was observed above 2 Hz, but below 1 Hz it was nonexistent. This suggests, that noise above 2 Hz has mostly cultural origin. Local weather conditions have influence on the noise level between 0.5 Hz and 2.0 Hz (*Luosto*, 1976).

The possibilities to improve the beams of the detector system were studied by analysing spatial noise characteristics of the FINESS array. Cross-correlations with zero lag between all substation were formed from noise samples taken hourly. The results showed clearly how different frequency ranges have different optimum intersensor distances affecting amount of suppression of incoherent noise in beamforming. This was confirmed, when noise suppression spectra were computed. Subconfigurations with larger average intersensor distances gave stronger noise suppression at lower frequencies as expected according to results from noise correlation study. Above 2.7 Hz the full array gave strongest noise suppression. Between 2 Hz and 5 Hz the noise suppression exceeded clearly the theoretical level. At high frequencies the suppression level was close to theoretical value and no extra suppression could be gained. The results show that beams of the detector system can be improved by selecting suitable array configurations for some frequency ranges, though more thorough study of different noise conditions at the array site must be carried out first. Diurnal, seasonal and temporary changes in noise conditions set different demands for beams of the detector system. However it may not be necessary to construct dedicated beams with different array configurations for each type of noise conditions, but to find some arrangement, which is sufficiently good in all noise conditions. Currently, the array operates with 80 coherent and 6 incoherent beams. In testing new beams a good reference can be found from event bulletins of the International Data Center (IDC) of GSETT-3 experiment (*Ringdal*, 1994). The IDC will provide fast near real time on-line bulletins continuously. So, the testing can be made with on-line data.

When short term fluctuations in the seismic noise level were studied, it was found that two narrow sectors dominated the azimuth distribution of the low velocity detections. The centres of these sectors were at 272° and 332°. In northerly directions from FINESS there are 3 other seismic stations in a distance range from 70 to 120 km. The bursts of noise causing these detections were not observed at other stations. There are several possible sources for these short term alterations causing low velocity detections. They could be generated by some small scale industrial activity relatively close to the array. Also traffic and water flow in a river have been considered as a possible source of these bursts of noise. Excessive sources of low velocity noise bursts are not uncommon in the vicinity of seismic stations in populated areas see e.g. *Kværna* (1990). The velocities suggest that these noise pulses are caused by propagating Rayleigh waves. The detections do not cause false locations, because they are not preceded by other phases, have low velocity, very sharp azimuth distribution and low STA/LTA ratio. Most of the noise bursts are probably not detected.

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