P-12-08

Forsmark site investigation

Study of seismic background signals in the Forsmark area

Björn Lund, Reynir Böðvarsson
Hossein Shomali, Lars Dynesius

Department of Earth Sciences, Uppsala University

February 2012

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co

Box 250, SE-101 24 Stockholm
Phone +46 8 459 84 00

ISSN 1651-4416
SKB P-12-08

Forsmark site investigation

Study of seismic background signals in the Forsmark area

Björn Lund, Reynir Böðvarsson
Hossein Shomali, Lars Dynesius

Department of Earth Sciences, Uppsala University

February 2012

Keywords: Activity plan AP PF 400-09-015, Local seismic network, Noise, Forsmark power plant.

Summary

The proposed nuclear waste repository in Forsmark will be equipped with a high resolution seismic monitoring network. The network will monitor natural seismicity as well as seismicity induced by the construction, operation and closure of the repository and the subsequent development of the repository.

In order to determine which type of seismic sensors will give optimum performance in the repository area, and how these should be spaced, it is necessary to know the level and frequency content of the seismic background signals. Here we report on several different measurements of the seismic background in the Forsmark area.

The instrumentation available to us allows us to study frequencies up to 500 Hz. The seismic data show that the Forsmark nuclear power plants produce a significant amount of seismic energy. Most of this energy is emitted below 100 Hz, with pronounced peaks at 50 Hz and 100 Hz. There is, however, both significant energy in narrow bands further up in the spectrum as well as a generally elevated level of background noise compared to normal Swedish background levels. We also note that the amplitude of the power plant produced signals vary significantly in time.

In order to catch seismic events of low magnitude, the monitoring network will probably have sampling frequencies of the order of 2–4 kHz. As we could not access these high frequencies in this study, we propose that suitable instrumentation is acquired and tested in the Forsmark environment to study both performance and noise levels. The instruments can subsequently be included in the monitoring network. Once the construction of the network is commenced, we recommend that a backbone network is constructed from the surface, well in advance of the start of the construction of the repository, and that the network is expanded in stages during the construction, as deemed necessary by the seismic analysis. We include some recommendations on details of the network infrastructure in the report.

Sammanfattning

Det område i Forsmark där SKB planerar att etablera en slutförvarsanläggning för använt kärnbränsle kommer att utrustas med ett seismiskt nätverk för övervakning av seismiska händelser av mycket låg magnitud. Nätverket kommer att registrera naturlig seismicitet, men även artificiell seismicitet som induceras vid uppförande, drift och förslutning av förvaret, liksom seismiska händelser som uppkommer efter förslutning.

I syfte att utröna vilken typ av seismiska sensorer som har de mest optimala förutsättningarna att leverera data av god kvalitet i förvarsområdet, samt vilken instrumentkonfiguration som bör väljas vid utplacering i terrängen, är det nödvändigt att känna till nivå- och frekvensinnehållet hos de seismiska bakgrundssignalerna i Forsmark. I föreliggande rapport presenterar vi resultaten av flera olika mätningar av det seismiska bakgrundsbruset i Forsmark.

Tillgänglig instrumentuppsättning tillät oss vid denna undersökning att studera frekvenser upp till 500 Hz. Resulterande seismiska data visar att kärnkraftverken vid Forsmark producerar avsevärd seismisk energi. Merparten av denna energi emitteras vid frekvenser lägre än 100 Hz, med uttalade maxima vid 50 Hz och 100 Hz. Det föreligger emellertid betydande energiavgivning även i smala band högre upp i energispektrum, liksom en generellt förhöjd bakgrundsnivå jämfört med normala svenska bakgrundsnivåer. Vi kunde också konstatera att amplituden hos de kraftverksproducerade signalerna varierar avsevärt med tiden.

För att fånga upp seismiska händelser med låg magnitud, behöver det planerade seismiska nätverket arbeta med samplingsfrekvenser i storleksordningen 2–4 kHz. Eftersom vi inte hade tillgång till dessa höga frekvenser i föreliggande studie, föreslår vi att sådan utrustning införskaffas och testas i Forsmarksområdet i syfte att studera såväl instrumentens prestanda som brusnivåerna. Dessa instrument kan senare inlemmas i det seismiska nätverket.

När väl etableringen av nätverket ska påbörjas, rekommenderar vi att basen i systemet anläggs på markytan, i god tid före byggstarten för slutförvarsanläggningen, och att sedan nätverket får expandera i etapper under slutförvarsbygget. Hur expansionen sker, i termer av sensortäthet på djupet, får avgöras av den kontinuerligt utförda seismiska analysen. Vi ger också ett antal detaljerade rekommendationer med avseende på nätverkets infrastruktur i rapporten.

Contents

1 Introduction and Objectives

According to an agreement with the Swedish Nuclear Fuel and Waste Management Company (SKB) and Uppsala University, the Department of Earth Sciences continues to carry out observations and additional construction of new seismic stations within the Swedish National Seismic Network (SNSN). The work is carried out in accordance with activity plan AP PU 400-06-004, see Table 1-1.

Table 1-1. Controlling document for the performance of the activities within SNSN.

Activity plan	Number	Version
Drift av seismologiskt nät i Sverige	AP PU 400-06-004	1.0

The Swedish Nuclear Fuel and Waste Management Co. (SKB) has filed an application with the Swedish Government to build a nuclear waste repository in the Forsmark area, see the proposed layout in Figure 1-1. The repository will be equipped with a high resolution seismic monitoring system for the purpose of detecting and analysing both induced and natural seismicity. The system should ideally be installed prior to the commencement of the repository construction operations, in order both to establish a background seismic activity level and to be able to follow induced seismicity and rock destabilization during the construction phase. High resolution measurements during construction may help to identify the extent of weak zones and active faults and fractures, fluid migration paths in the rock mass and aid in the estimation of the stress field.

The Forsmark area has very low seismic activity (Bödvarsson et al. 2006), so in order to obtain seismic information from the crust, the seismic network needs to be very sensitive. In addition, the very small events that are likely to be induced during construction and operation of the repository will also require a highly sensitive network for proper detection and analysis. When designing such a network, the seismic background levels have to be taken into account in order to optimize the benefits of high gain versus number of sensors. The amplitudes of the background signals as well as their frequency content are important in this respect.

In this report we examine both newly collected seismic and electromagnetic data and older reflection seismic data in order to characterize the seismic background signals in the Forsmark area. Unfortunately, we did not have access to high frequency seismic data at this time, so the frequency analysis was restricted to frequencies below 500 Hz. We see from the map in Figure 1-1 that the planned repository will be located close to the existing power plants. This will be a challenge for the seismic network as the power plants, as we will see below, produce significant amounts of seismic noise.

The study of the background signals at Forsmark was performed in compliance with activity plan AP PF 400-09-015, see Table 1-2. Activity plans are internal SKB controlling documents.

Table 1-2. Controlling document for the performance of the Study of seismic background signals in the Forsmark area.

Activity plan	Number	Version
Seismisk brusmätning i Forsmark 2009	AP PF 400-09-015	1.0

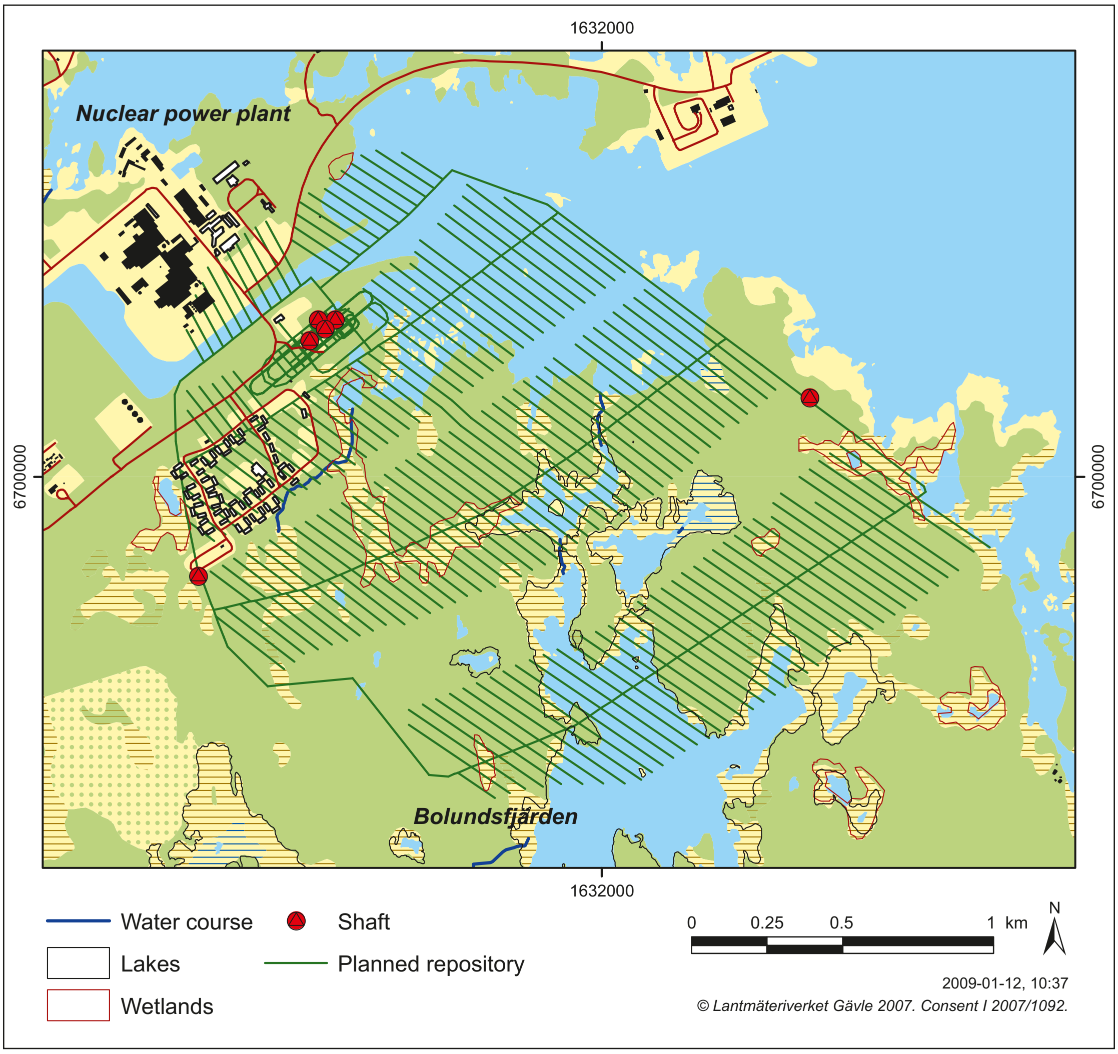

Figure 1-1. *Proposed layout (green) for the nuclear waste repository at Forsmark.*

2 Available data

For this study the Geophysics section at the Department of Earth Sciences, Uppsala University, collected two new seismic and one new electromagnetic data set, and used previously collected data and existing seismic station data. Figure 2-1 shows a map of the locations of seismic stations, reflection lines and electromagnetic measurement points in the Forsmark area.

The following data sets have been used:

Reflection seismic data collected in 2002 (Juhlin et al. 2002). The data were collected with 1 kHz sampling, but a 500 Hz hardware lowpass filter was used on the data. There are a large number of recordings in the seismic investigations, we have mainly looked at data from lines 1 and 4, primarily the receiver points close to the power plants. Four seconds of data were recorded for each shot, but as much of the data contain the response to the seismic source, we can only use the last second of data in each recording. This severely limits the usefulness of the data. In addition there are issues such as the coupling to the ground that make amplitude estimation very uncertain. We used the data mainly for the frequency content analysis.

Permanent seismic stations in the Swedish National Seismic Network (Bödvarsson and Lund 2003). We used the station FOR in Forsmark and the stations ASP in Äspö, Oskarshamn, and FAL in Falun. These broadband seismic instruments are sampled at 100 Hz and located in low noise underground vaults. The data were used for comparisons between Forsmark and other locations in Sweden.

Temporary seismic stations deployed between 28 December, 2009, and 20 January, 2010. These were 60 s – 100 Hz instruments, sampled at 400 Hz, and located on the ground surface with relatively simple covers. These data were used for frequency content and amplitude variation analysis.

Electromagnetic data. The data were sampled at 1 kHz and recorded 28–30 December, 2009. We looked at the two horizontal components of the magnetic field in order to correlate the electromagnetic field with the seismic.

Independently recording reflection seismic stations. These accelerometers record data from 0–1 kHz, using 2 kHz sampling, and were in operation continuously during various times between 23–24 February, 2011. These instruments were newly acquired and in a test phase. During the recording days there was a cold spell, with temperatures falling to –30°C, and the instrumentation suffered severe problems. We had power failures and various data quality issues which made the data unusable for the high frequency analysis that we had hoped to perform. However, the amplitude information gathered was enough to constrain the location of the seismic signals, see Chapter 4 below.

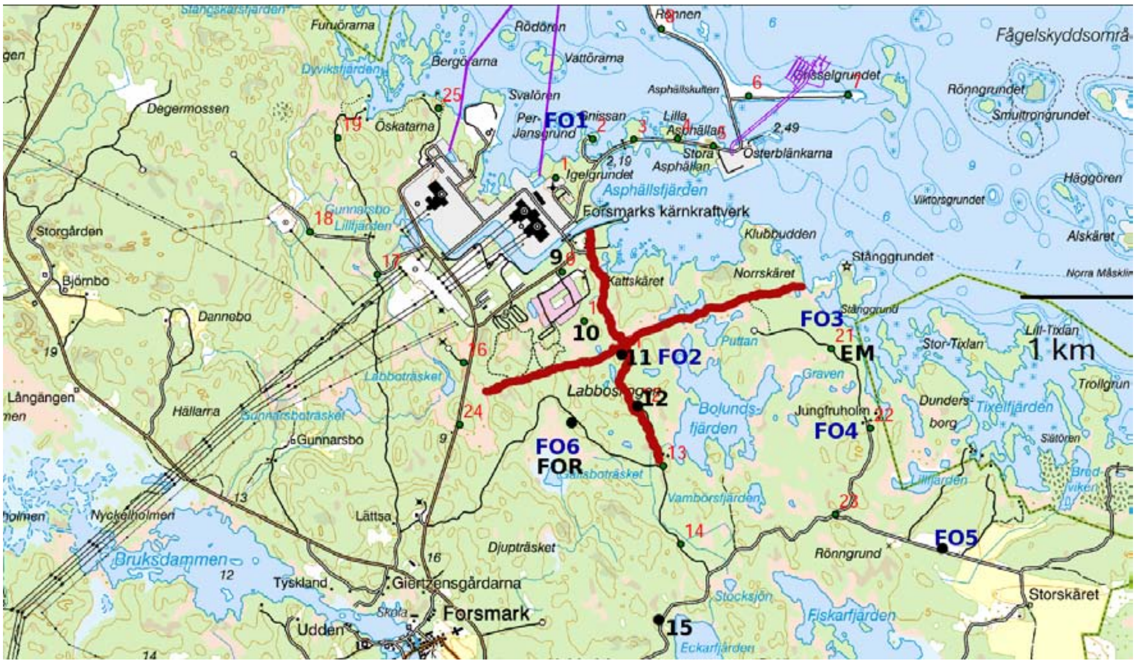

Figure 2‑1. *Map of the Forsmark area with data collection points. Red lines: reflection seismic profiles, line 4 runs NNW-SSE, line 1 runs WSW- ENE. FOR is the permanent SNSN station. Blue letters: temporary seismic stations, FO1–FO5. Red and black numbers: reflection seismic stations, 1–25. EM: electromagnetics.*

3 Frequency content of seismic signals

In this chapter we will compare the recorded seismic amplitude levels at Forsmark with those at other stations in Sweden and investigate the frequency content of the seismic signals.

3.1 Comparison of Forsmark to other locations in Sweden

The Swedish National Seismic Network (SNSN) operates 65 continuously recording seismic stations in Sweden. Comparisons of the background signals between the Forsmark station and other stations in Sweden show very clearly that there are elevated signal levels at frequencies higher than approximately 3 Hz in the Forsmark area, see Figure 3-1. In Figure 3-1 we show power spectral density (PSD) plots from five temporary seismic stations, F01–F05, sampled at 400 Hz, and data from three permanent seismic stations; Forsmark (F06), Äspö, Oskarshamn (ASP) and Falun (FAL). We calculated PSDs using the procedure in the USGS PQLX (McNamara and Buland 2004, USGS 2011) software, i.e. hour-long, continuous, and 50 percent over-lapping time-series segments are processed. There is no removal of earthquakes, system transients and (or) data glitches. The instrument response is removed from each segment, yielding ground acceleration (for easy comparison to the Low Noise Model, LNM).

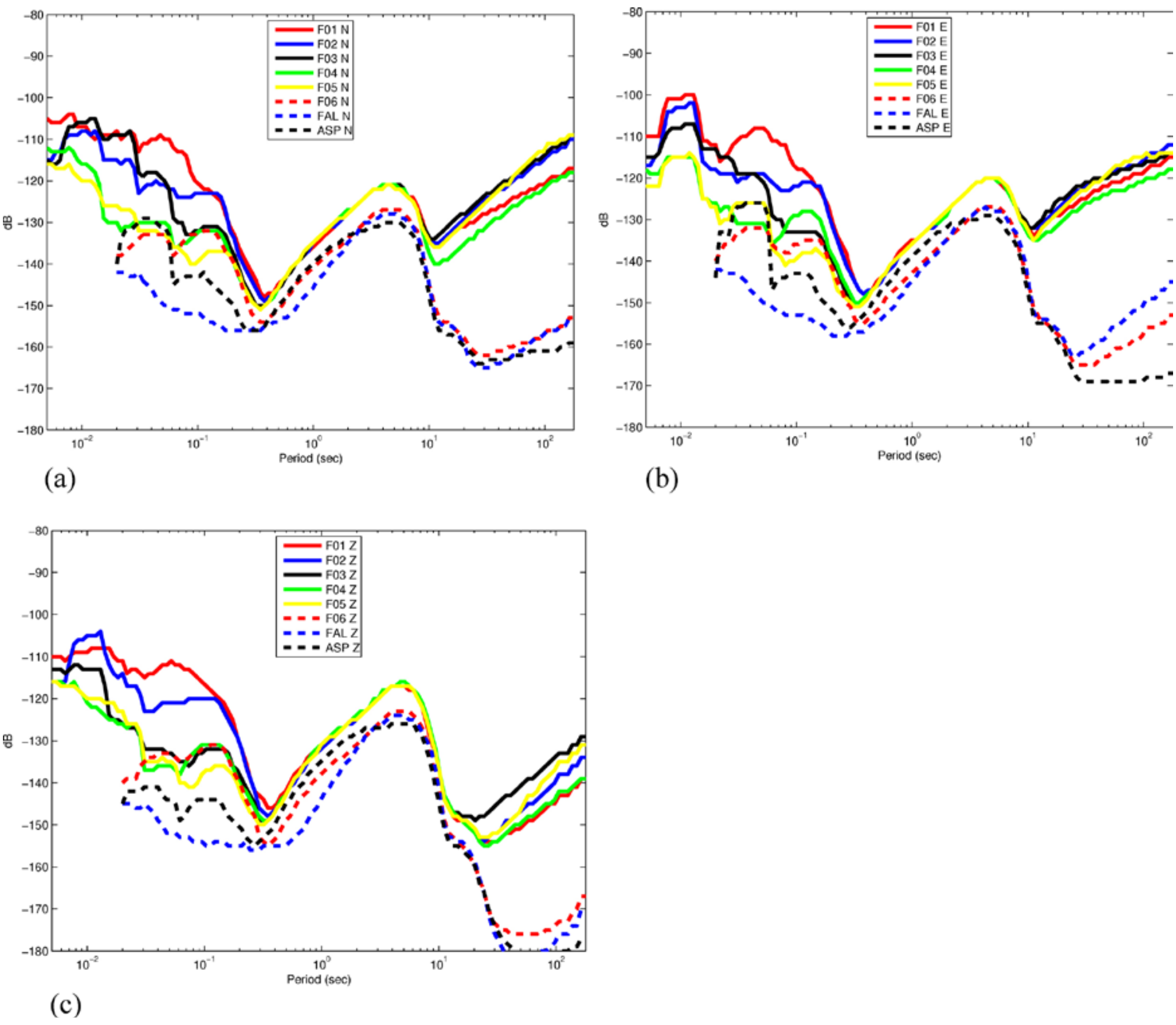

Figure 3-1. *Power spectral density plots of seismic background signals at six seismic stations in the Forsmark area, F01–F06, where F06 is the permanent SNSN station in Forsmark. ASP is the SNSN station on the island of Äspö, Oskarshamn, and FAL the station in Falun. Three components: (a) North-South, (b) East-West, (c) vertical.*

Each hour-long time series is divided into 13 segments, each about 15 minutes long and overlapping by 75 percent, with each segment processed by removing the mean; removing the long period trend; tapering using a 10 percent sine function; and transformation using an FFT algorithm (Bendat and Piersol 1971). Segments are then averaged to provide a PSD for each 1-hour time series segment. For each channel, raw frequency distributions are constructed by gathering individual PSDs in the following manner: binning periods in 1/8 octave intervals and binning power in 1 dB intervals. Each raw frequency distribution bin is normalized by the total number of PSDs to construct a PDF (Probability Density Function). The approach of this noise analysis method differs from many previous noise studies in that no attempt is made to screen the continuous waveforms to eliminate body and surface waves from earthquakes or transients and instrumental glitches such as data gaps, clipping, spikes, mass recentering or calibration pulses. These signals are included in our processing because they are low probability occurrences that do not contaminate high-probability ambient seismic noise observed in the PDFs.

The data shown in Figure 3-1 are median values over the approximately three weeks deployment of the temporary stations. Station ASP is located approximately 3.4 km away from the nearest of the Oskarshamn nuclear power plants, station F06 approximately 1.7 km away from the nearest of Forsmark nuclear power plants, and station FAL is an averagely quiet SNSN station. We see that all three permanent stations have fairly similar responses at frequencies below 1 Hz, except some differences in the East-West components at the lowest frequencies. At higher frequencies there are however marked differences, consistent on all three components. We see that the FAL station is the quietest of the three, and that ASP and F06 have similar structure in the high frequency content, with F06 having the largest amplitudes. Comparisons to other SNSN stations show a consistent picture, and we infer that the high frequency signals at ASP and F06 are due to the power plants.

The data from the temporary stations support the notion that there is significant background energy at frequencies up to 200 Hz around the Forsmark power plants. We see that stations F01 and F02 show the highest amplitudes, consistent with their location closest to the power plants. The seismic signals at stations F01 and F02 are on the order of 40 dB higher than the regular SNSN stations at frequencies between 10–50 Hz.

3.2 Frequency content of the seismic signals around Forsmark

We investigated the spectral content of the seismic recordings around Forsmark. As discussed in Chapter 2 above, we do not have much high frequency data to look at. The permanent SNSN station in Forsmark samples at 100 Hz, so these data are limited to below approximately 47 Hz. The temporary seismic stations sampled at 400 Hz, implying good control on frequencies up to approximately 185 Hz. In Figure 3-2 we show spectra from four of the temporary seismic stations. The instrument response has been corrected for, so data show ground motion in nm/s. These spectra contain 24 hours of data, from the 6th of January, 2010. At all stations, we see a broad peak at 5–15 Hz, very narrow peaks around 25 Hz, 50 Hz and 100 Hz, and additional wider peaks around 67 Hz, 85 Hz and 125 Hz. Station FO1 also indicates that there may be even higher frequency peaks in the data near the nuclear power plants, see Figure 3-2.

Figure 3-3 displays the spectrum from the station most distant from the nuclear power plants, FO5 (detail of Figure 3-2, lower right). We see that the background level of ground motion is on the order of 300 nm/s from about 90 Hz and higher. This is a fairly high seismic background level.

The seismic reflection lines acquired in 2002 were limited to 500 Hz and lower, and we can only use the last second of the 4 second traces, as the first 3 seconds contain the reflection seismic source signal. The amplitudes of the data also vary depending on the coupling of the geophones to the ground. These circumstances make it almost impossible to use the data to assess the existence of higher frequency energy. As an illustration, we show data from two geophones in line 4 close to the power plants, see Figure 3-4. We see that at point 93 there are indications of higher energy at 200, 250, 300 and 350 Hz, consistent with overtones from the 50 Hz power generation. Note that the y-scales, the power, are not comparable between the temporary stations and the reflection data. No attempt to correct for the instrument response has been done for these data.

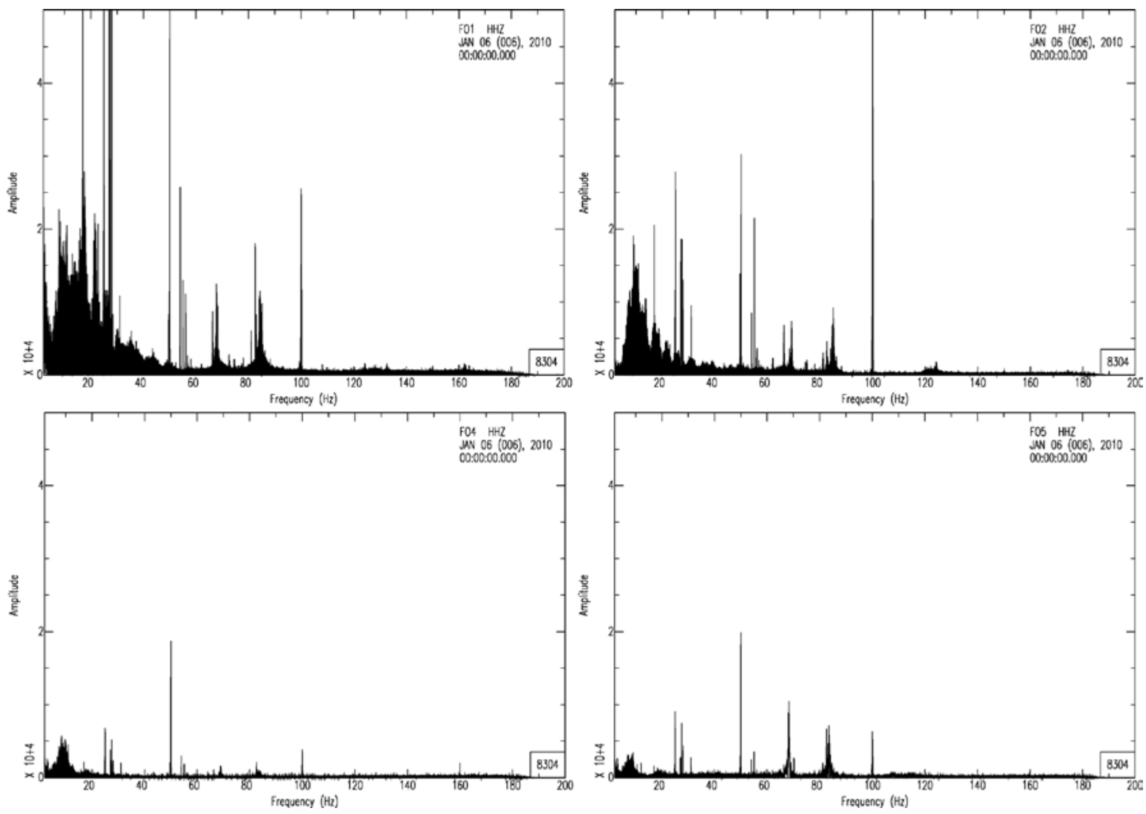

Figure 3-2. *Frequency content of the seismic signal recorded during 24 hours on January 6, 2010, at the four temporary seismic stations FO1 (upper left), FO2 (upper right), FO4 (lower left), and FO5 (lower right). The figures show true ground velocity in nm/s.*

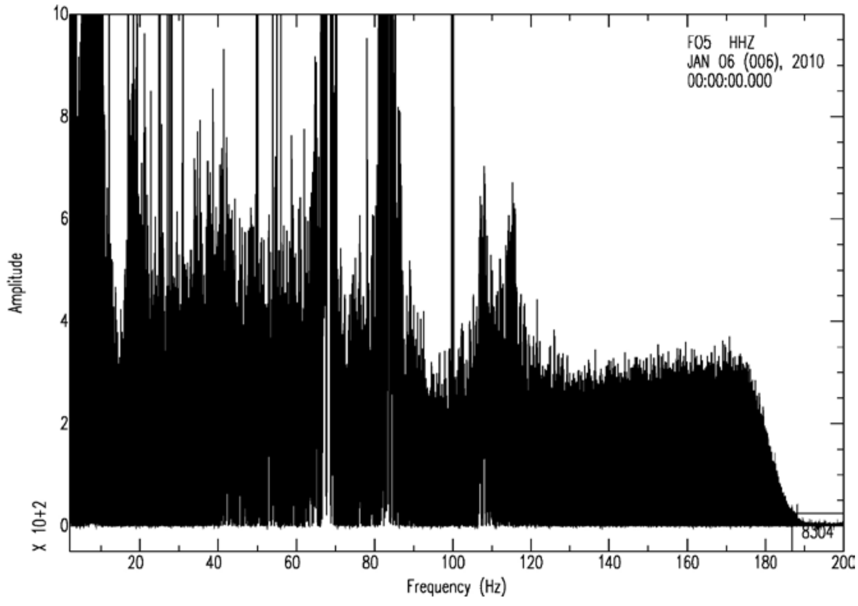

Figure 3-3. *Zoom in on the spectrum from station FO5 in Figure 3-2.*

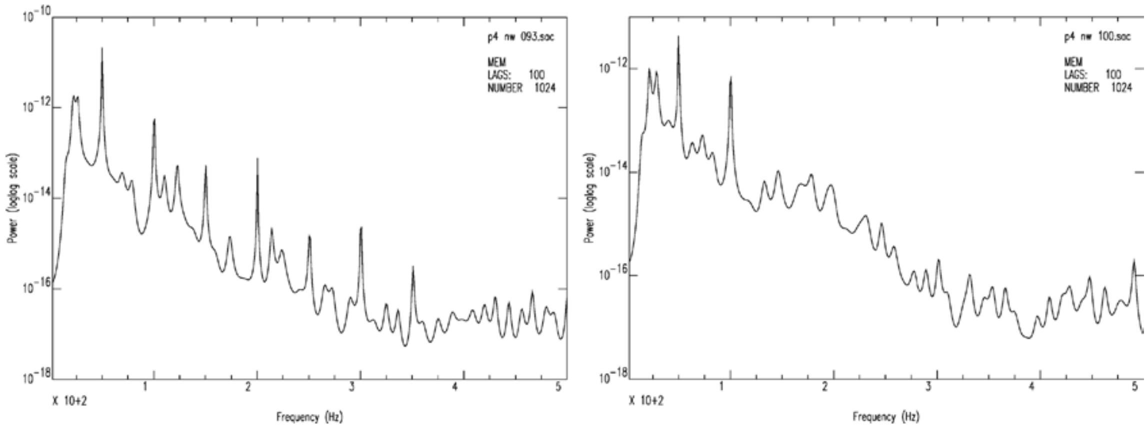

Figure 3-4. *Spectra from receiver points 93 (left) and 100 (right) in line 4 of the reflection seismic survey of 2002. Receiver 100 is closest to the nuclear power plants. 1 s of data. Maximum entropy method.*

3.3 Frequency content of electromagnetic signals

Measurements of the horizontal magnetic field in Forsmark on December 29, 2009, show strong spectral peaks at 50 Hz and harmonics (100 Hz, 150 Hz, 200 Hz etc.), see Figure 3-5. These are mostly due to the power generation in the nuclear power plants. There are also peaks at 16.67 Hz and harmonics, probably emanating from the closest electrified railway line, Uppsala-Gävle, situated about 37 km W of Forsmark, which adds energy also in the 50 Hz and harmonics peaks. The peaks at 66.7 Hz, 83.3 Hz, 116.7 Hz, 133.3 Hz etc are all harmonics to the 16.67 Hz fundamental frequency. Note, however, that these frequencies have significantly lower energy than the 50 Hz harmonics but are clearly visible in the spectra due to the logarithmic scale. There is no peak at 25 Hz in the magnetic data.

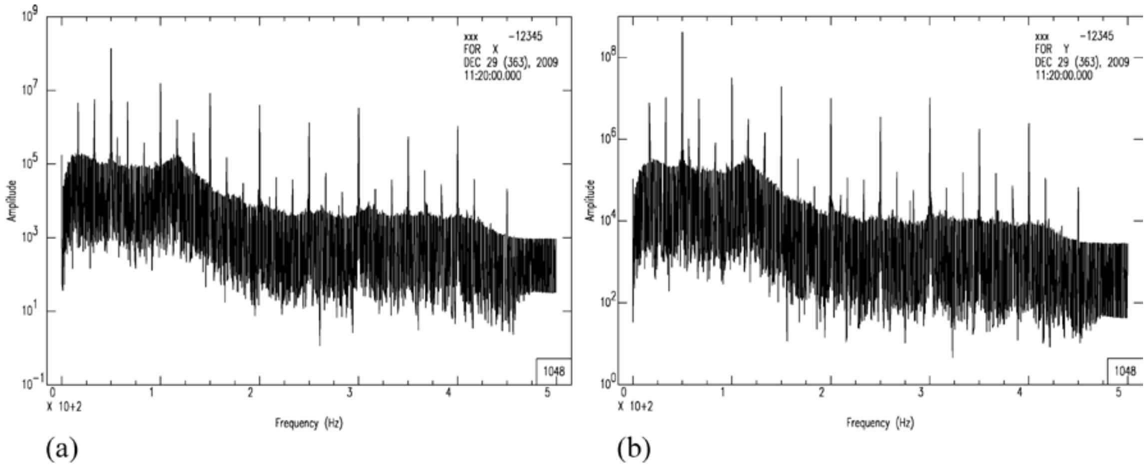

Figure 3-5. *Spectra (FFT) of the two horizontal components of the magnetic field at Forsmark at 11:20 to 11:40 on December 29, 2009. (a) magnetic north) and (b) magnetic east.*

3.4 Summary

Comparing the magnetic and seismic measurements, we note that the lower frequency seismic signals are not directly coupled to the 50 Hz power generated at the Forsmark power plants. These signals, the broad 5–15 Hz noise and the 25 Hz peak, are probably related both to the general operations at the plants and to some specific piece of machinery that generates 25 Hz signals. The 50 Hz and harmonics seen in the seismic recordings are probably more directly related to turbines or generators for the 50 Hz electricity. It is interesting to note that there are relatively broad seismic spectral peaks around 67 Hz and 83 Hz, coincident with the railway power harmonics. The cause of these is unclear to us.

At the temporary seismic stations close to the power plants (FO1 and FO2) there are indications of seismic energy at the 150 Hz harmonic. The geophones in the reflection seismic profile located close to the plants also indicate energy at the harmonics up to 350 Hz, albeit with low power. It is not unlikely that a sensitive high frequency seismic system close to the power plants will record even higher harmonics of the 50 Hz power generation.

The amplitudes of the seismic signals from the nuclear power plants are high. Our measurements indicate that the level is more than 40 db, i.e. a factor 100 higher than at regular SNSN stations between 10–50 Hz, and it is likely that the difference in amplitude is as high or higher at the 50 Hz harmonics. We also observe high seismic background levels at the station furthest away from the power plants, indicating that all of the intended repository site will be affected by the seismic noise from the power plant.

4 Location of the source of characteristic signals

So far in this report we have just assumed that the high amplitude signals emanate from the nuclear power plants. In February 2011 we deployed a 25 station network of instruments mainly used in reflection seismic data acquisition, as described in Chapter 2. Using these stations we wanted to locate the source of the signals by comparing the decrease in amplitude in various frequency bands. The recorded amplitudes depend on the strength of the signal and its attenuation in the crust, but also on the quality of the rock beneath the sensor and the coupling of the sensors to the ground. Due to the severe weather conditions we encountered problems which added to the uncertainty in the data and made two stations fail. Nevertheless, we performed an analysis of relative signal strength (relative to station 11) at the sensors, in three different frequency bands, and we conclude that it is most likely that these signals originate from the power generation.

4.1 Signals between 5 and 15 Hz

Station 9 records the highest amplitude, and we see that there is a general trend of decreasing amplitudes away from the power plants, although this trend is not always consistent from station to station, Figure 4-1. The 5–15 Hz frequency band often contains various sources of cultural noise, so it is conceivable that there are other contributors to the amplitudes at the stations.

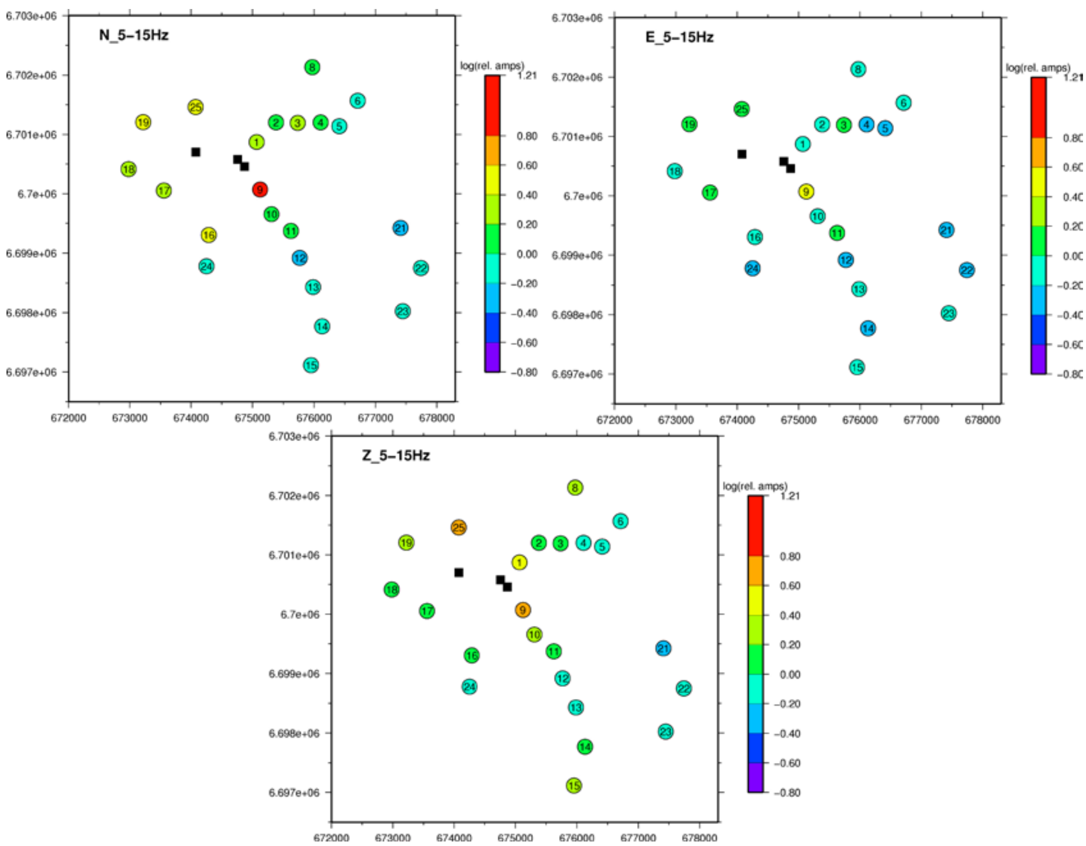

Figure 4-1. *Relative amplitudes in the 5–15 Hz band at 23 seismic sensors in the Forsmark area. North component (upper left), East component (upper right) and vertical component (lower). The numbered circles denote the sensors, the black squares are the three power plants. Note that we use the logarithm of the amplitudes.*

4.2 The 50 Hz signal

In the 50 Hz band the signals clearly come from the power plants, Figure 4-2. We see very high amplitudes close to the plants and the amplitudes decrease rapidly, especially for the north and vertical components, to the stations further away. Note again that the amplitudes are normalized to the amplitudes at station 11, individually for each component.

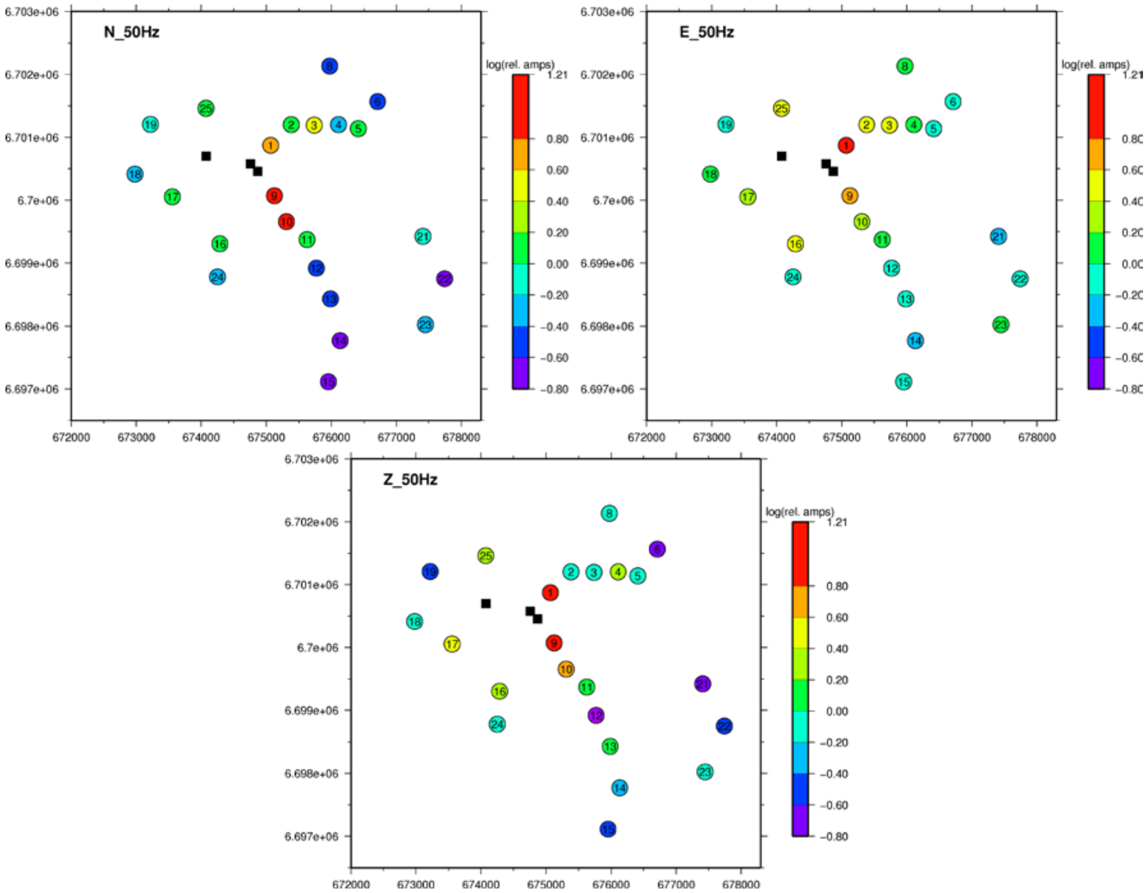

Figure 4-2. *Relative amplitudes in the 50 Hz band at 23 seismic sensors in the Forsmark area. North component (upper left), East component (upper right) and vertical component (lower). The numbered circles denote the sensors, the black squares are the three power plants. Note that we use the logarithm of the amplitudes.*

4.3 The 100 Hz signal

Again, stations 9 and 1 record very high amplitudes in the 100 Hz band, and the signal decays rapidly away from the power plants, Figure 4-3.

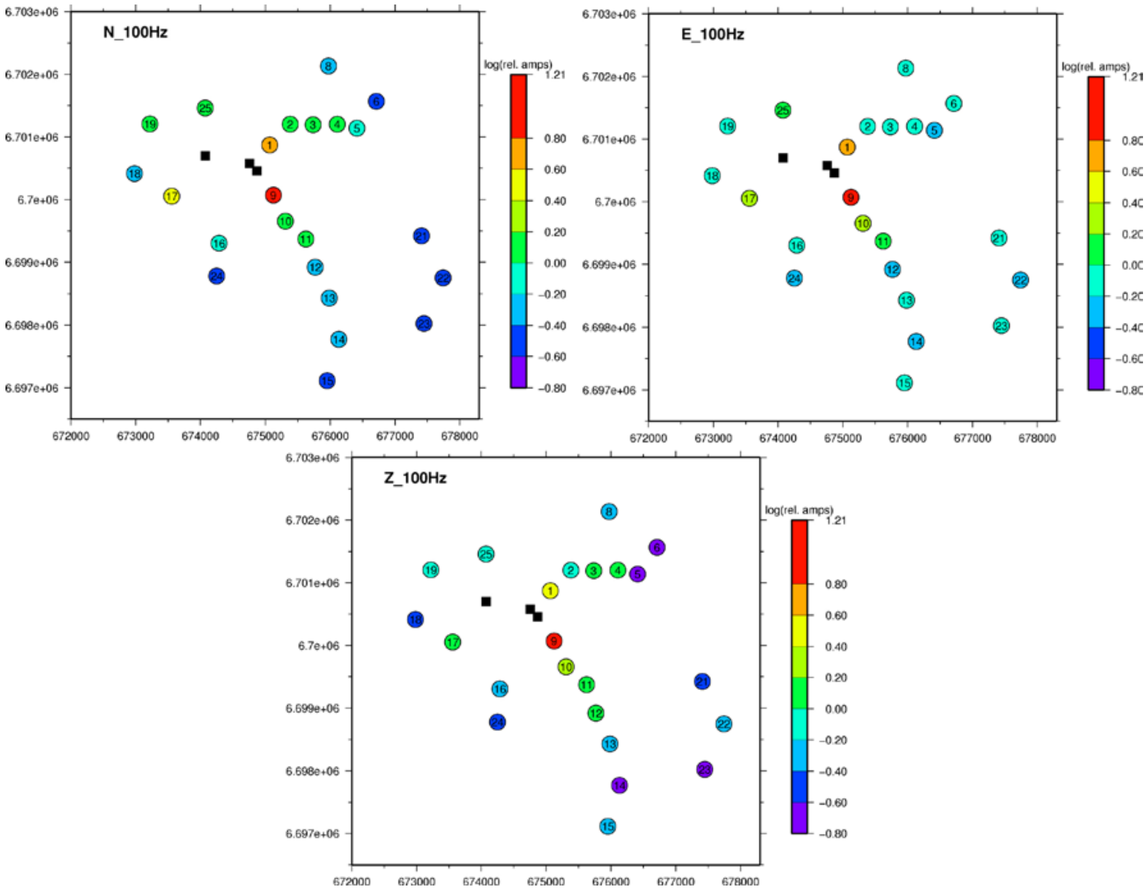

Figure 4-3. *Relative amplitudes in the 100 Hz band at 23 seismic sensors in the Forsmark area. North component (upper left), East component (upper right) and vertical component (lower). The numbered circles denote the sensors, the black squares are the three power plants. Note that we use the logarithm of the amplitudes.*

5 Temporal amplitude variations

The temporary station deployment in 2009–2010 allows us to study the temporal variation in signal strength over a 22 days period. The amplitudes will probably depend on the production at the nuclear power plants, especially in the 50 Hz band. In Figure 5-1 we show the amplitudes in the frequency bands 5–15 Hz, 25 Hz and 50 Hz.

We see variations in the 5–15 Hz band which may be related to the work week (decreases on Sundays the 2nd, 9th and 16th) but may have other work intensity related causes. There is also an overall increasing trend during the 22 days. In the 25 Hz band we see very little variation. The 50 Hz band, on the contrary, has significant variation which may be related to the energy output from the power plants to the grid. These variations are faster and there is transient behaviour in the data. The data show that we can expect significantly varying amplitudes in the different frequency bands during a longer time period of observation.

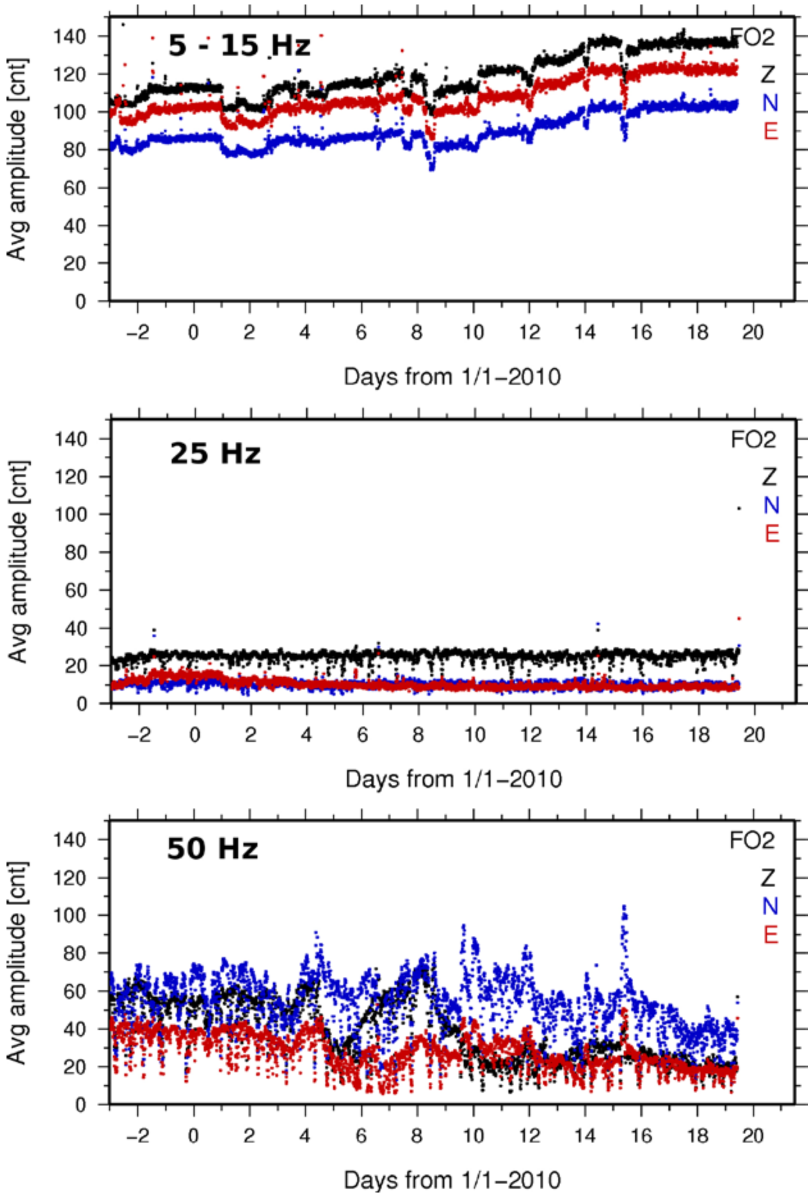

Figure 5-1. *Temporal variation in amplitude (counts) at temporary station FO2. The time period covered is December 29, 2009, to January 19, 2010, with zero in the time line being the start of January 1. Black line is the vertical component, blue line the North component and red line the East component.*

6 Instrumentation for high frequency seismic monitoring

It is obvious from the measurements reported in previous chapters that the noise in the Forsmark area is considerably higher than would be optimal for seismic monitoring. In order to select optimal sensors for the seismic monitoring of the repository site we propose that instrument tests are conducted in the area. We have been in contact with ISS International Ltd. because of their long experience in dedicated instrumentation for microseismic networks in mines. The company has been designing, manufacturing and supporting its primary product, the ISS seismic monitoring system, since 1990. Over 140 ISS systems are currently in daily use in 28 countries around the world (www.issi.co.za).

In April 2010 we had a meeting with an ISS representative in Uppsala, where we discussed a layout for an instrument setup for measurements of ambient seismic noise levels in the frequency band 50–3,000 Hz. It was proposed that ISS should provide the complete instrumentation package with sensors and a data acquisition unit, where the sensors are specially designed to increase the sensitivity for better resolution. The goal of the measurement is to investigate if the instrumentation is sufficient enough to resolve the minimum ground motion in the frequency band of interest at the measurement site.

The design of the sensor unit is a tube containing five geophones connected in serial and one accelerometer, where all sensors are of type uni-axial in vertical mode. With the right type of selected geophones the frequency response can be reliable up to one, maximum two, kilohertz without spurious resonances from the internal mechanical parts. Above two kilohertz an accelerometer is preferable due to the lack of resonances and higher sensitivity.

The sensors will be connected to a six channels, 24 bits, seismic data acquisition unit, DAU, data recorder with GPS synchronization.

At the measurement site the sensors would be placed in three one metre deep drill holes, equally spaced on a circle with 0.5 metre radius. The recording unit is placed close to the sensor setup to avoid noise pickup in the cable. Three similar sensors would be installed so that cross correlation techniques can be used to separate ground motion from sensor and electronic noise in the frequency band of interest. The measurements would take place at different times during day and night over a certain period.

Due to the special electrical conditions in the ground close to the nuclear power plants, with large variations and high levels in the electromagnetic potential, we note that long copper cables for data transmission must be avoided, and especially so for analogue signals. Induced signals and noise contamination in such cables is likely to be significant. We also note that for the high sampling rates considered for this system, high timing accuracy is vital for subsequent successful analysis of the events.

7 Recommendations for further studies

Before the final stage of the network design, some tests of sensors should be performed in the Forsmark area. Sensors and other equipment acquired for these tests will probably be possible to use in the network at a later stage. It is likely that the relatively sparse backbone of the network will be equipped with several serially connected geophones and possibly also accelerometers at the same places. This part (P1) of the network would be constructed and put into operation, together with the closest stations in the SNSN, one or two years before the start of the tunnel construction for base-line monitoring purposes. At later stages, more sensors would be gradually added, probably often inside the tunnel, to increase the sensitivity of the network. These parts (P2-Pn) of the network would be added at each stage of tunnel construction after careful pragmatic analysis and evaluation of the possible benefits. The final stage would then be reached when the benefits of one additional part is too small.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

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

Bödvarsson R, Lund B, 2003. The SIL seismological data acquisition system – as operated in Iceland and in Sweden. In Takanami T, Kitagawa G (eds). Methods and applications of signal processing in seismic network operations. Berlin: Springer. (Lecture notes in earth sciences 98), 131–148.

Bödvarsson R, Lund B, Roberts R, Slunga R, 2006. Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn. SKB R-06-67, Svensk Kärnbränslehantering AB.

Juhlin C, Bergman B, Palm H, 2002. Reflection seismic studies in the Forsmark area — stage 1. SKB R-02-43, Svensk Kärnbränslehantering AB.

McNamara D E, Buland R P, 2004. Ambient noise levels in the continental United States. Bulletin of the Seismological Society of America 94, 1517–1527.

USGS, 2011. PQLX: a software tool to evaluate seismic station performance. Available at: http://earthquake.usgs.gov/research/software/pqlx.php [12 March 2012].