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Annual report for the Forsmark Seismic Network

Seismic activity and developments in 2024

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Summary

This report presents activities, developments and seismic events at the Forsmark Seismic Network (FSN) as participated in and analysed by Uppsala University during 2024 in accordance with the SKB activity plan (AP) "AP SFK-23-028, Drift och vetenskaplig utveckling av lokalt seismiskt nät i Forsmark".

Seismic network operations at the FSN were initiated late in 2023 and 2024 has been a year of tuning, configuration enhancements and gaining experience with the seismic environment in the Forsmark repository area. Significant activities during the year includes; the identification and solution of a problem with spikes in the data at all stations caused by digitizer overload, the replacement of a faulty sensor (H05A) with a new unit (H05B), and the downhole orientation of all sensors, enabling accurate metadata construction. Also, automatic analysis of the continuous data streams was implemented in the software SeisComp and a series of seven calibration blasts were conducted and will be presented in an upcoming report.

The seismic activity recorded by the FSN is categorized into earthquakes, controlled explosions, chemical explosions, induced events, anthropogenic events, other events and not locatable events. No local earthquakes or induced events were detected during the year. Seven controlled explosions were conducted in October 2024, and ten chemical explosions were recorded in September during the removal of a pier at Biotestsjön. The majority of detected events, totalling 23, were classified as "other".

Sammanfattning

Den här rapporten presenterar aktiviteter, utveckling och seismiska händelser i Forsmarks seismiska nät (FSN) som Uppsala universitet deltagit i samt analyserat under 2024, i enlighet med SKB:s aktivitetsplan (AP) "AP SFK-23-028, Drift och vetenskaplig utveckling av lokalt seismiskt nät i Forsmark".

FSN togs i drift i slutet av 2023 och 2024 har därmed varit ett år fokuserat på intrimning av systemet, konfigurationsförbättringar samt att lära känna den seismiska miljön i Forsmarksområdet. Betydande aktiviteter under året inkluderar; identifiering och åtgärdande av ett problem med dataspikar på alla mätstationer orsakade av överbelastning i digitizern, ersättning av en trasiga sensor (H05A) med en ny (H05B) och orientering av alla borrhålssensorer så att korrekt metadata kunde fastställas. Automatisk analys av det inkommande kontinuerliga datat startades med programpaketet SeisComp och en serie om sju kalibreringsprängningar genomfördes, vars data kommer att analyseras och presenteras i en kommande rapport.

Den seismiska aktiviteten registrerad av FSN kategoriseras som jordskalv, kontrollerade sprängningar, kemiska explosioner, inducerade händelser, övriga händelser och icke lokalisierbara händelser. Inga lokala jordskalv eller inducerade händelser har identifierats under året. Sju kontrollerade sprängningar genomfördes i oktober 2024, och tio kemiska explosioner registrerades i september i samband med borttagning av en pir vid Biotestsjön. Majoriteten av de registrerade händelserna, totalt 23 stycken, klassificerades i kategorin "övriga".

Content

1	Progress overview	3
2	Uptime for stations during 2024	4
3	Background noise levels	6
4	Activities and development over the year	11
4.1	Spikes in data	11
4.2	Velocity model	11
4.3	Metadata	12
4.4	New sensor at HMF05.....	13
4.5	Calibration blasting	14
5	Detected seismic events	15
5.1	Earthquakes	15
5.2	Controlled explosions.....	15
5.3	Chemical explosions	18
5.4	Induced events.....	21
5.5	Other.....	21
5.6	Not locatable	29
5.7	Anthropogenic source – construction work.....	31
6	Conclusions	34
7	References	35

1 Progress overview

Processing and analysis of the seismic data from the Forsmark Seismic Network (FSN) are conducted at the Swedish National Seismic Network (SNSN) at Uppsala University in accordance with the activity plan (AP) “AP SFK-23-028, Drift och vetenskaplig utveckling av lokalt seismiskt nät i Forsmark”. During 2024, several staff members at the SNSN have been involved in the work at FSN: Eva Lindblom has managed daily monitoring, data handling and analysis, as well as performed specialized analyses and reporting; Hossein Shomali, Michael Roth, and Björn Lund have participated in various aspects of analysis and reporting, and Michael Schieschke has contributed with hardware-specific expertise.

The commissioning phase outlined in the AP is now largely complete, which consisted of:

- Configuration of digitizers
- Configuration and commissioning of the data acquisition server
- Configuration and commissioning of data transfer between SKB’s server and SNSN
- Calibration of sensor orientation, see Chapter 4.3
- Organization of station metadata, see Chapter 4.3
- Analysis of noise conditions at each measurement point, see Chapter 3
- Configuration and commissioning of the analysis tool
- Testing with various tools in SeisComP to find optimal settings
- Evaluation of network functionality (integration testing)

Both automatic and manual event analysis are fully operational using the SeisComP system, although ongoing optimization will continue as additional calibration data become available. The analysis has entered routine operation, with monthly reports submitted to SKB. Knowledge of background seismic activity in the Forsmark area, as captured by the FSN network, is gradually increasing. However, it is not always possible to determine the origin of all recorded events.

Waveform data are streamed from SKB to SNSN at 2,000 and 200 samples per second (Hz). The 2,000 Hz data are stored in a ring buffer that retains three months of recordings. For seismic events which have been manually analysed, 2,000 Hz data segments are stored for the duration of the FSN project. The 200 Hz data is stored at SNSN for one year.

2 Uptime for stations during 2024

The FSN has been running with 12 recording sensors in operation since autumn 2023, with the instruments placed in nine different boreholes in the vicinity of the planned nuclear waste repository, see Figure 2-1. The stations are equipped with high sensitivity 14 Hz borehole geophones from the Institute of Mine Seismology (IMS) together with Güralp Affinity digitizers. All stations but one have three-component sensors, H42C has only a vertical sensor. Data are sent to a server at SKB and via seedlink also to SNSN in Uppsala.

Since its installation, sensor H05A, at 190 m depth in borehole HMF05, has been non-functional. The root cause of the malfunction remains unclear and could be due to sensor failure, wiring issues, or other factors. To resolve this, a new sensor (H05B) was installed on 18 October 2024, at a depth of 20 meters, see Chapter 4.4 for more details.

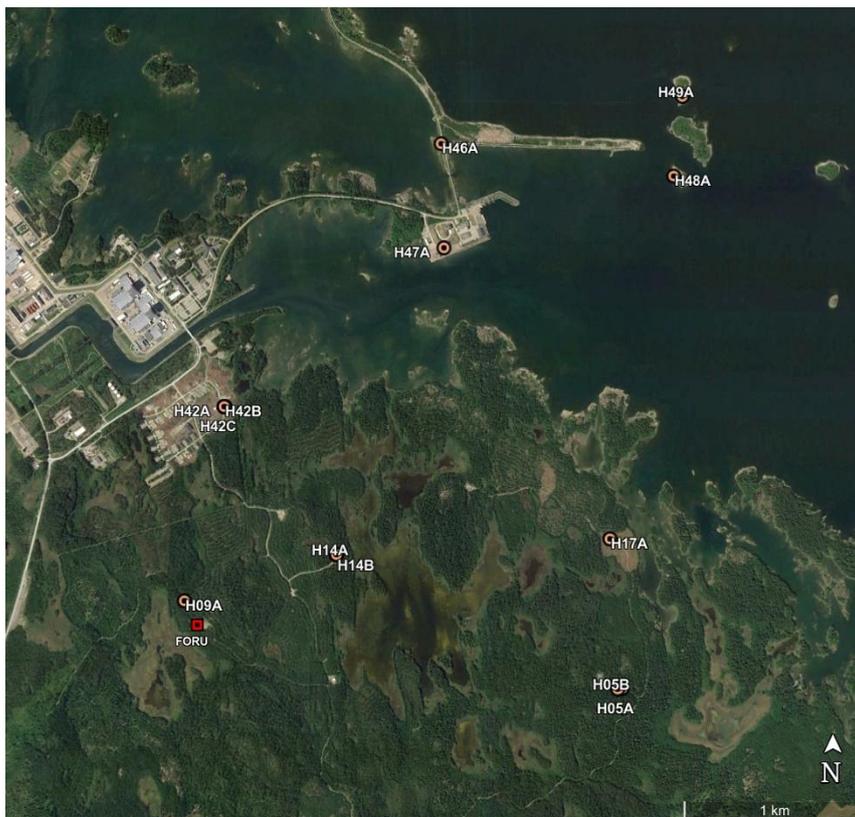


Figure 2-1. Borehole geophones (orange circles) and the permanent SNSN station FORU (red square).

In terms of power supply, all stations are connected to the main power distribution grid, except for station H17A. That station relies on solar panels and a wind turbine connected to batteries. During the winter months, additional battery charging support has been required to maintain operation for this station when there is little wind and the sunlight is limited.

Data transmission across the network is facilitated through varying methods. The majority of stations are connected to fibre optic links, while two stations (H17A and H49A) transmit data using wireless communication. All stations operate at a sampling frequency of 2,000 Hz.

While many stations maintained consistent operation, certain stations experienced periods of downtime due to technical issues, including power failures, cable damage, and necessary equipment upgrades. All stations except the island station H49A had an average uptime above 90 % during 2024. Table 2-1 summarizes the monthly and annual uptime for each station in the FSN.

Station H49A experienced downtime in the spring due to a broken power cable, followed by issues with a broken fibre cable. Downtime at several stations in FSN occurred in late spring and early summer due to switch replacements. Station H17A was offline during the winter due to a power failure caused by insufficient solar and wind energy. Station H05B was successfully installed on 18 October 2024 and has remained operational since then. Stations H42A, H42B, and H42C encountered data gaps during the spring, which were resolved by performing a hard reboot of the station.

To improve station uptime, we suggest replacement of the power cable to H49A and the installation of a new solar panel at H17A.

Table 2-1. Percentage uptime for all stations in FSN during 2024. Station H05B replaced the broken station H05A. It was installed 18th October 2024.

Station	January	February	March	April	May	June
H05B	x	x	x	x	x	x
H09A	100	90.3	99	100	79.2	73.9
H14A	100	90.3	98.7	100	76.1	73.9
H14B	100	90.3	98.7	100	76.1	73.9
H17A	76.3	99.4	100	100	93.5	100
H42A	94.7	79.3	97.8	86.9	82.9	100
H42B	95	80	97.8	88.2	82.9	100
H42C	95.1	79.9	97.3	88.4	82.9	100
H46A	100	99.4	100	100	98	74
H47A	100	99.4	100	77.3	98	66.2
H48A	100	98.9	100	70.3	98	74
H49A	100	98.9	50.9	0	28.8	74

Station	July	August	September	October	November	December	Total 2024
H05B	x	x	x	100	100	100	100.0
H09A	100	100	100	84.2	100	100	93.9
H14A	100	100	100	100	100	100	95.0
H14B	100	100	100	100	100	100	95.0
H17A	100	100	100	100	81.5	85.4	90.7
H42A	100	100	100	100	100	100	90.3
H42B	100	100	100	100	100	100	90.5
H42C	100	100	100	100	100	100	90.5
H46A	100	99.6	100	100	100	100	97.6
H47A	99.5	100	100	100	100	100	95.1
H48A	100	100	100	100	100	100	95.2
H49A	62.2	50.2	100	100	100	100	72.0

3 Background noise levels

The background noise levels at the FSN stations vary, with H42A, B and C being the noisiest due to their proximity to the power plant. In contrast, H49 and H48, located on small islands, are the quietest. All stations suffer from 50 Hz monochromatic noise, along with many overtones, reflecting the influence of the power plants across the network. Figure 3-1 presents a snapshot of the noise spectrum up to 300 Hz for all FSN stations during a period of seismic inactivity, clearly showing that H42A, B, and C have the highest background noise levels, while H48A and H49A have the lowest. Beyond 300 Hz and up to 1000 Hz, the noise spectrum shows less variation, differing only in the number and intensity of monochromatic peaks.

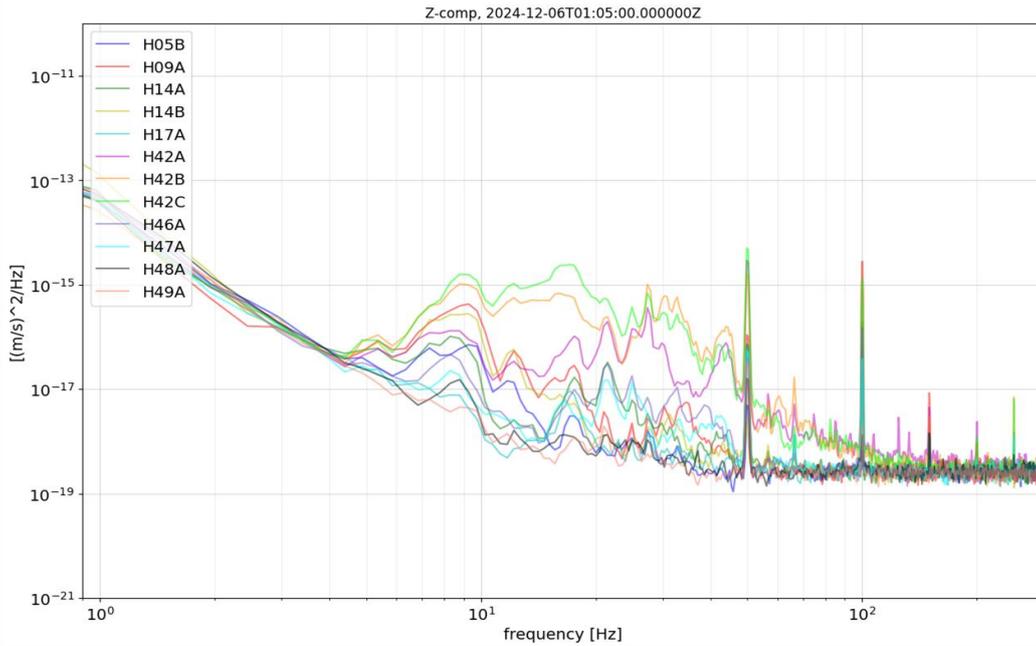


Figure 3-1. Spectrum of 30 sec of Z-component data for all stations in FSN at 01:05 UTC on 6 December when no seismic activity was observed. The clear 50 Hz and 100 Hz peaks are clearly visible as well as some overtones at higher frequencies. Instrument response is removed.

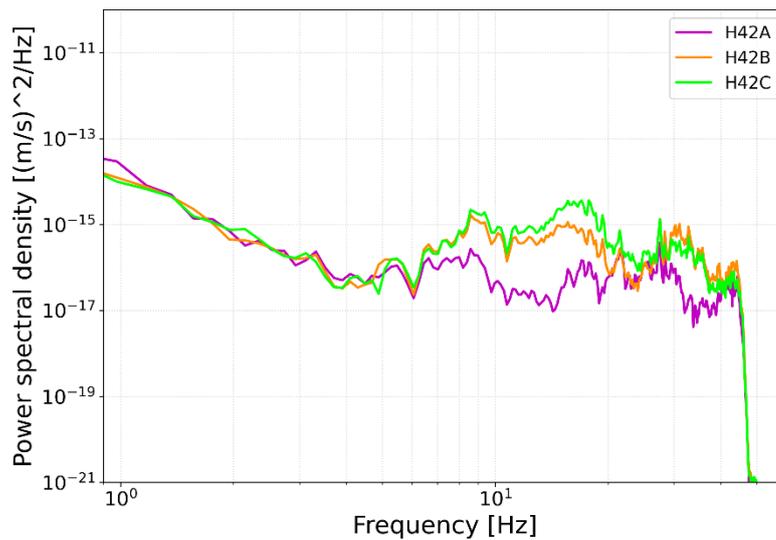


Figure 3-2. Spectrum of 30 sec of Z-component data for stations H42A-C at 01:05 UTC on 5 May 2022. Instrument response removed.

The instruments at station H42 were in operation between August 2018 and May 2022, and during the latter years data at 100 Hz sample rate were archived at SNSN. In Figure 3-2 we show noise data at H42 at the same time of day as in Figure 3-1 but in May 2022. We see that the noise levels are very similarly distributed in frequency during both time periods, and that H42A, the deepest sensor, has significantly less noise in the bands 10 - 20 Hz and 30 - 40 Hz compared to H42B and H42C.

In order to assess background noise levels at the stations and monitor changes over time, such as sensor performance or variations in noise characteristics, monthly Power Spectral Density (PSD) plots are provided by SNSN to SKB. These plots are generated daily, adding data day by day to build up a monthly overview such as those in Figure 3-3 to Figure 3-5. The PSD plots are generated through the following scheme:

The seismic channels are checked for completeness and, if there are at least 20 min of data, we compute an hourly PSD as follows:

- take the raw data and split the 3600s time window into 200s time windows with 100s overlap (i.e. 35 time windows).
- compute the PSD using Welch's method.
- interpolate the PSD onto an evenly spaced log₁₀ frequency axis.
- divide the PSD by the squared acceleration system response (i.e. convert the raw data PSD (units in counts²/Hz) into ground acceleration PSD (units of m²/s⁴/Hz)).
- the hourly PSDs are stored in a temporary archive to be used to generate the monthly overview plots.

Once per day the monthly PSD plots are updated as follows:

- read all hourly acceleration PSDs for the respective month.
- transform the units of the PSD in dB by using $10 \cdot \log_{10}(\text{PSD})$.
- compute an average PSD from all hourly PSD and plot the average PSD curve and its associated axis in red colour in the overviews.
- compute the residual of each hourly PSD from the average PSD and display the residual color-coded from blue (values below the average PSD) to red (values above average PSD).

This report includes three examples of PSD plots for October 2024, shown in Figure 3-3, Figure 3-4, and Figure 3-5. For Figure 3-3 and Figure 3-4, which display data from two FSN stations, the calculations were based on 2,000 Hz data. In contrast, Figure 3-5, featuring data from the permanent SNSN station FORU, uses 100 Hz data. All plots represent instrument corrected data. The yellow lines in the plots show the global high and low noise models, Peterson (1993).

Figure 3-3 shows the lowermost of the sensors in the H42 borehole, H42A, where noise levels are high and distinct peaks in the average PSD reveal continuous monochromatic noise originating from the power plant. The calibration blasts conducted on October 30 are evident as vertical lines with amplitudes up to 20 dB higher than the average PSD and residuals visible up to approximately 500 Hz. Additional work day noise is also visible occasionally, with higher than the average noise levels.

Figure 3-4 presents the PSD for station H47A, located near an extensive surface construction site. The PSD reveals distinct noise bands between 10 and 200-300 Hz, visible only during daytime hours on workdays and absent on weekends, reflecting the influence of the construction activity.

Figure 3-5 shows a PSD for the permanent SNSN station FORU, which is equipped with a broadband instrument rather than the 14 Hz geophones used at the FSN stations. Note that the y-axis limits differ between this figure and those for the FSN stations, reflecting the broader frequency band of the broadband instrument. The figure shows both the 25 Hz noise peak from the power plants and the increased noise around 6 - 9 Hz, in agreement with the FSN instruments. In addition, microseisms generated by storms in the Atlantic Ocean is clearly visible at lower frequencies, particularly around 0.1 and 0.2 Hz.

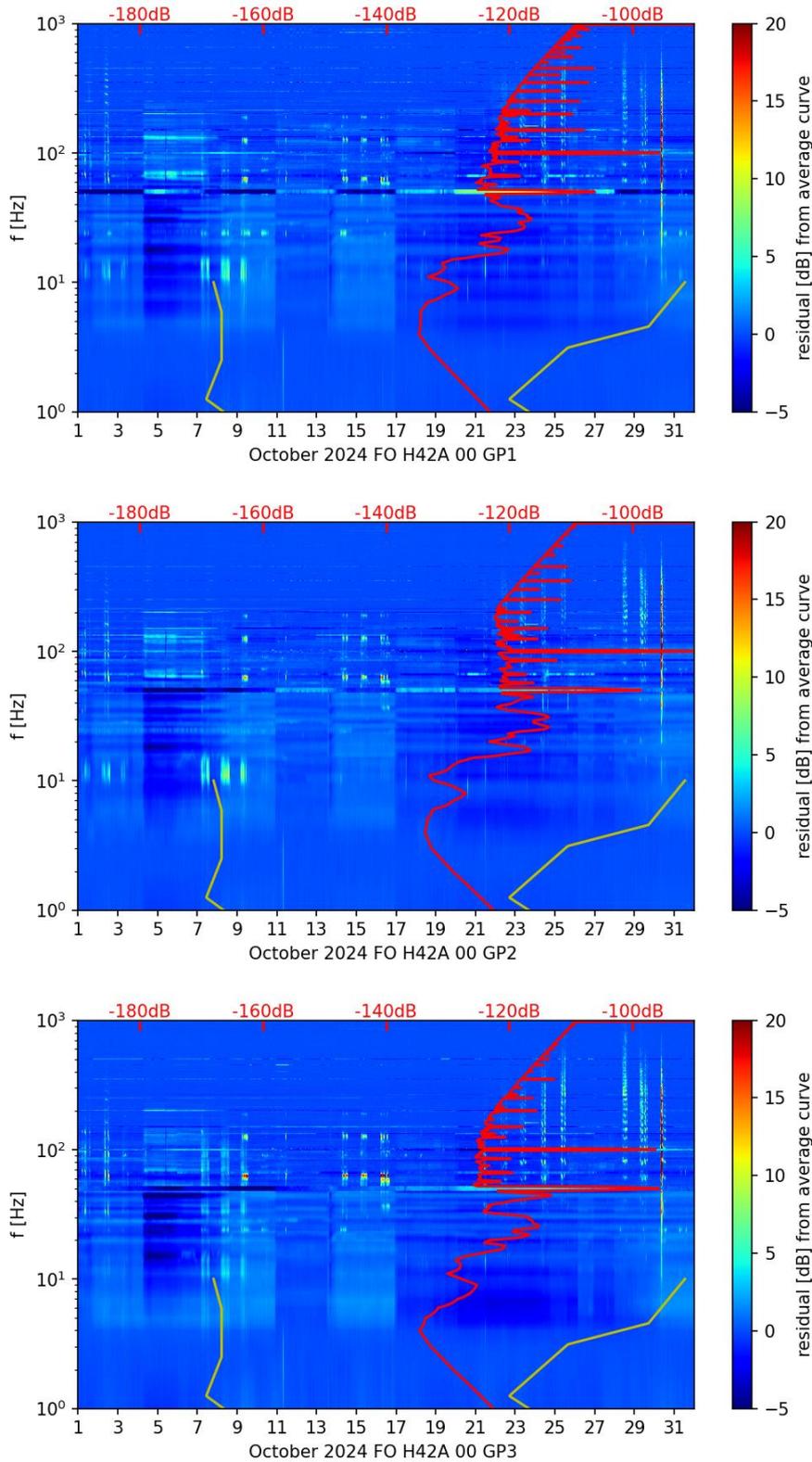


Figure 3-3 . Power Spectral Density (PSD) for station H42A and October 2024. The red line shows the average ground acceleration PSD for all of October in units of dB, the yellow lines show the global high and low noise models (Peterson, 1993) and the colour scale shows the deviation in dB from the monthly average PSD. The components GP1-3 are the in the local borehole system, with GP3 closest to vertical, as in Section 4.3.

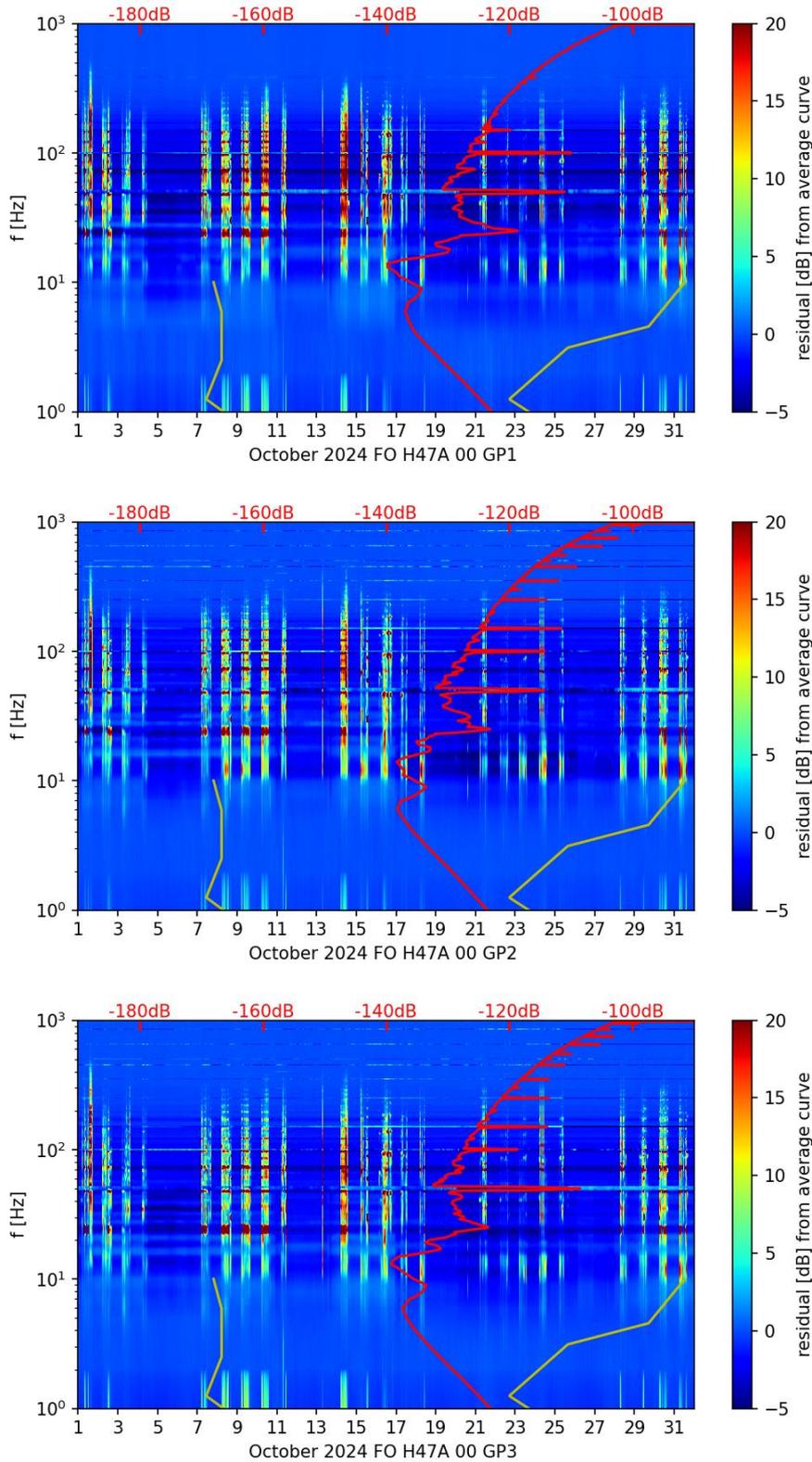


Figure 3-4. Power Spectral Density (PSD) for station H47A and October 2024. The red line shows the average ground acceleration PSD for all of October in units of dB, the yellow lines show the global high and low noise models (Peterson, 1993) and the colour scale shows the deviation in dB from the monthly average PSD. The components GP1-3 are the in the local borehole system, with GP3 closest to vertical, as in Section 4.3.

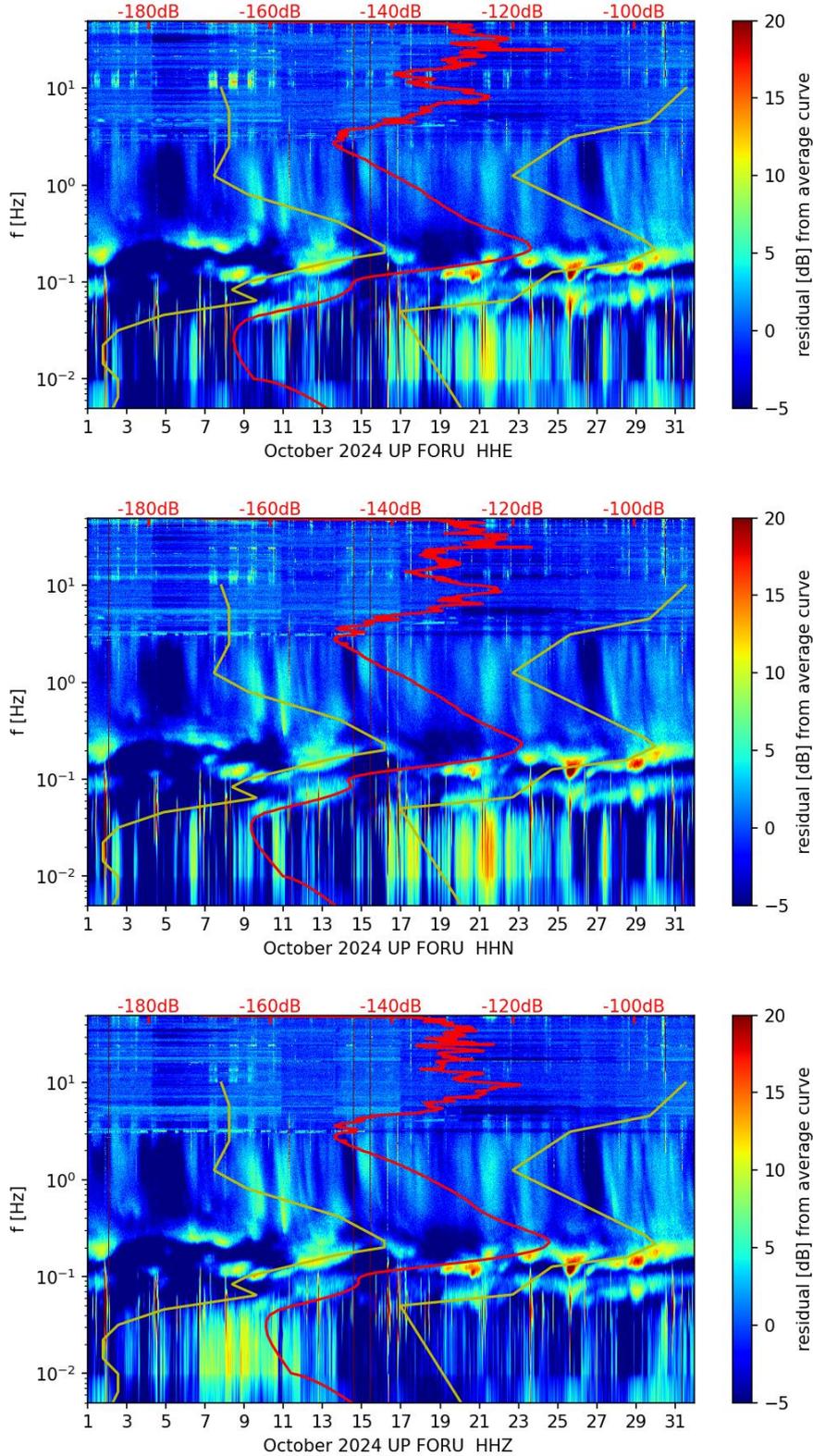


Figure 3-5. Power Spectral Density (PSD) for station H42A and October 2024. The red line shows the average ground acceleration PSD for all of October in units of dB, the yellow lines show the global high and low noise models (Peterson, 1993) and the colour scale shows the deviation in dB from the monthly average PSD. The components GP1-3 are the in the local borehole system, with GP3 closest to vertical, as in Section 4.3.

4 Activities and development over the year

During 2024, significant development occurred in the FSN, detailed in the subsequent chapters and reported together with detected seismicity in FSN in monthly reports to SKB for each month during 2024. Persistent data spikes observed early in the year were identified as resulting from digitizer overload. The orientations of all sensors were determined through polarization analysis, enabling the construction of accurate metadata. From calibration shots that were conducted in October 2023 a simple homogeneous velocity model for the area was established and used both in the automatic and the manual analysis of events in SeisComP. The malfunctioning sensor (H05A) was replaced with a new sensor (H05B) to restore functionality. Finally, a series of seven calibration blasts were conducted in October 2024, and a detailed analysis is to be presented in an upcoming report.

4.1 Spikes in data

During the starting period of FSN there were spikes in data from all stations and all channels, from a few per day up to 20-30 per day. Data were recorded at both 2,000 and 200 samples per second (Hz) at all stations. In May we experimented with stopping the 2,000 Hz data streams for stations H42 A, B and C and H17A for approximately one week. This resulted in no spikes in the 200 Hz data. Thereafter, the 2,000 Hz data streams were started again, and the spikes were back. Then the 200 Hz data streams were stopped, and the spikes disappeared again. Hence, it seems that the digitizers can handle one frequency but not more than that (at least not including the high 2,000 Hz sample rate) without an overload and the spikes occur as a consequence of the overload.

Therefore, it was decided to stop the 200 Hz channels at all stations and only sample at 2,000 Hz, transmitting that data from the digitizers to the SKB data server. 200 Hz data is then created by decimation on the data server. The 200 Hz channels were closed on 4 June 2024. The decimation of 2,000 Hz data to 200 Hz was carried out both at SKB and in Uppsala until 17 September, thereafter exclusively at SKB.

As of today, both 200 Hz and 2,000 Hz data are transmitted to Uppsala. The 200 Hz data is stored at SNSN for one year, while the 2,000 Hz data is stored in a ring buffer that retains three months of recordings. Segments with 2,000 Hz data for all manually analysed events are stored for the duration of the FSN project. All data is analysed at SNSN, and information on detected events are communicated to SKB in monthly reports.

4.2 Velocity model

A simple homogeneous velocity model has been developed based on the P-wave travel times from the calibration shots conducted over two days in October 2023, in combination with earlier velocity studies in the area. The calibration shots consisted of 500 kg weight drops as well as hammer blows out on the small islands where sensors H48A and H49A are located. Figure 4-1 presents the travel times versus distance for these calibration shots. The line of best fit through the data points indicates a P-wave velocity of 5633 m/s.

The velocity structure in the Forsmark area has been studied before by e.g. Juhlin et al (2002), Cosma et al (2005) and Lund et al (2025). The results from Juhlin et al (2002) show a P-wave velocity from approximately 5000 m/s at a very shallow depth up to about 6150 m/s at 400 m depth.

Cosma et al (2005) performed a Vertical Seismic Profiling (VSP) survey in two boreholes in Forsmark and their result shows a P-wave velocity of 5750 m/s on average. The surveys were conducted to a borehole length of 775 m in each borehole.

Similar results were found by Lund et al (2025) where a P-wave velocity of 5800 m/s and S-wave velocity of 3250 m/s were found at a depth of approximately 200 m and a P-wave velocity of 5500 m/s and S-wave velocity of 3000 m/s at a depth of 75 m.

The current processing and analysis of data in SeisComP is using a simple uniform velocity model with a P-wave velocity of 5,700 m/s and a vp/vs ratio of 1.73, resulting in an S-wave velocity of 3,300 m/s. This model was derived from the results presented above. More data for a review of the velocity model was acquired during the calibration shots in October 2024, which will be presented in an upcoming report.

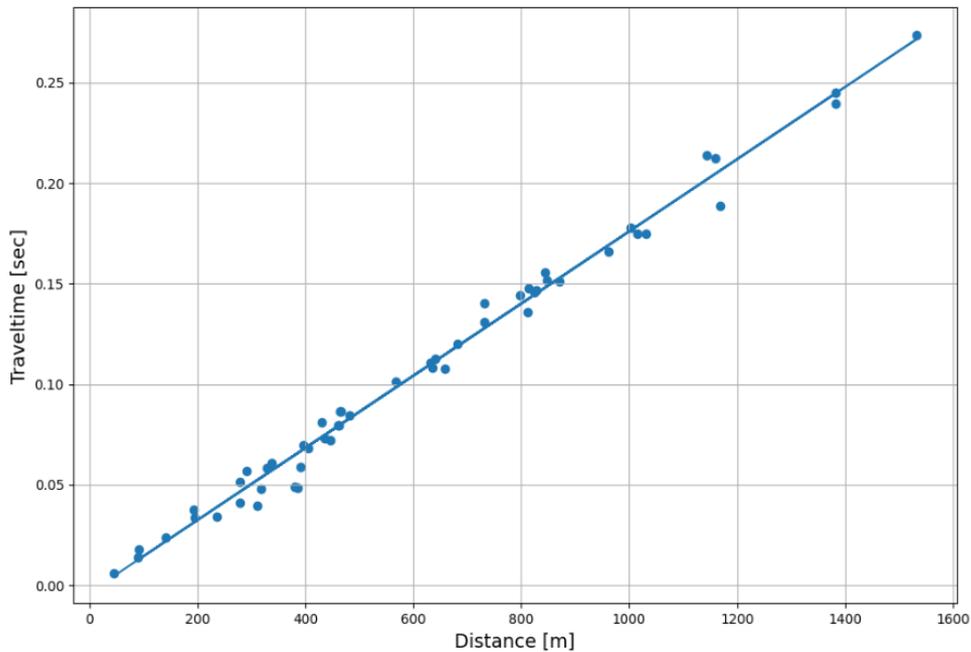


Figure 4-1. Traveltime versus distance for calibration shots carried out in Forsmark during October 2023. The best fitting line gives a P-wave velocity of 5633 m/s.

4.3 Metadata

All sensors in the FSN are three-component sensors, except at station H42C, where a one-component sensor is installed. The components of the three-component sensors are designated as the 1-, 2-, and 3-components. All geophones are deployed in boreholes, with the 3-component aligned along the borehole axis and the 1- and 2-components perpendicular to the borehole axis.

Initially, the orientations of the 1- and 2-components were unknown. The polarization studies performed on waveform data collected from calibration shots conducted in October 2023 and October 2024 yielded the angle between true geographical north and the sensor's 1-component, referred to as the horizontal correction angle.

The azimuth and dip for each component (1, 2, and 3) were calculated based on the borehole's azimuth and inclination, as well as the horizontal correction angle. Table 4-1 presents the borehole azimuth, inclination, and horizontal correction angles for each station.

To align the sensor with the geographical coordinate system, the sensor must first be rotated to align vertically. Subsequently, the 1- and 2-components are rotated counter-clockwise by the horizontal correction angle.

The resulting dip and azimuth for each component and station are provided in Table 4-2. The 1-component is the component rotated into the North-component. The 2-component is the component rotated into the East-component. The 3-component is the component rotated into the Vertical-component.

The dip and azimuth have been added to a station metadata repository in SeisComP format, which also includes coordinates and instrument response information.

Table 4-1. The horizontal correction angles found from polarizations analysis of calibration shots in 2023 and 2024 and the azimuth and vertical inclination of the borehole at the location of the sensor are shown in the table. Sensor H05B installed during 2024.

Station	average horizontal correction angle	inclination of borehole at sensor	Azimuth of borehole at sensor
H05B	23	-85.84	4.16
H09A	57	-66.7	23.3
H14A	120	-58.97	31.03
H14B	165	-62.7	27.3
H17A	308	-76.18	13.82
H42A	58	-89.68	0.32
H42B	28	-88.28	1.72
H42C	-	-85.82	4.18
H46A	200	-79.98	10.02
H47A	212	-47.04	42.96
H48A	150	-90	0
H49A	92	-90	0

Table 4-2. Dip and azimuth for the three components at all stations in FSN. The components are rotated like this: 1→N, 2→E, 3→Z.

Station	Component 3		Component 1		Component 2	
	Dip	Azimuth	Dip	Azimuth	Dip	Azimuth
H05B	-85.84	144.65	-4.06	337.03	0.89	66.97
H09A	-66.7	323.45	21.75	301.35	7.94	34.54
H14A	-58.97	129.53	-10.39	237.27	-28.88	333.07
H14B	-62.7	142.14	16.08	198.2	-21.45	281.7
H17A	-76.18	247.16	-13.33	51.57	-3.58	142.42
H42A	-89.68	35.47	-0.02	302	0.32	32
H42B	-88.28	12.23	1.31	331.99	1.11	62.01
H42C	-85.82	33.76	-	-	-	-
H46A	-79.98	339.23	-10.02	160.01	0.13	249.99
H47A	-47.04	308.88	-40.08	154.23	12.9	233.12
H48A	-90	0	0	210	0	300
H49A	-90	0	0	268	0	358

4.4 New sensor at HMF05

Since the installation, sensor H05A in borehole HMF05 has been non-functional. The root cause of this malfunction remains unclear; it may be due to sensor failure, wiring issues, or some other factor.

To address this issue, a new sensor (H05B) was installed on 18 October 2024, at a depth of 20 meters. The H05B sensor is placed within a protective plastic housing where the sensor is on one side and an inflatable cuff on the other side. When pressurized, this cuff pushes the sensor firmly against the borehole wall. The pressure can be adjusted and monitored to ensure optimal contact and positioning. See the document "AP SFK-24-045 FSN – installation av ny geofon i HFM05" for more information about the installation of H05B.

The new sensor at H05B is functioning effectively and appears to provide data of comparable quality to that of the other stations, despite its installation using an inflatable cuff. For a comparison of the spectrum across all FSN stations, see Figure 3-1.

4.5 Calibration blasting

On 30 October, calibration blasts were conducted as outlined in the activity plan AP SFK-24-043, "Surface Calibration Blasts for the Forsmark Seismic Network (FSN)". Originally, six blasts were scheduled; however, an additional blast was executed due to an error in the timing system, resulting in a total of seven blasts, see Chapter 5.2 for more details. The analysis of the blast data will be presented in an upcoming report.

5 Detected seismic events

The recorded events in the FSN are classified based on previous experience of the SNSN analysts, which look at location, depth, waveform (S/P ratio, coda, surface waves) and spectral characteristics. The high-frequency instrument characteristics and the busy Forsmark seismic environment makes classification non-trivial and for certain classifications we need more known, or calibration, events, of the various kinds. The FSN events have so far been classified into the following categories:

- **Earthquakes:** Naturally occurring real earthquakes.
- **Controlled explosions:** Blasts with precisely known time and location.
- **Chemical explosions:** Blasts with unknown time and location.
- **Induced events:** Seismic events triggered in the ground by human activity other than blasting, above or below ground.
- **Anthropogenic events:** Events directly caused by human activity e.g. construction work.
- **Others:** Events with unidentified source.
- **Not locatable:** Events visible on several stations but currently not possible to locate.

5.1 Earthquakes

No events classified as earthquakes have been detected in the Forsmark area covered by the FSN during 2024.

5.2 Controlled explosions

On 30 October 2024, calibration blasts were conducted as outlined in the activity plan “AP SFK-24-043, Surface Calibration Blasts for the Forsmark Seismic Network (FSN)”. Originally, six blasts were scheduled; however, an additional blast was executed due to an error in the timing system, resulting in a total of seven blasts. Figure 5-1 displays the blast locations, and Table 5-1 provides detailed information on the position and timing of each blast. All detonations occurred at 3 m depth below the ground surface, except for shot 1 which occurred at 20 m depth, and times in the report are given in UTC. The first three shot points (Shots 1, 2, and 4) were situated centrally within the FSN and charged with 1 kg of explosives each. To ensure adequate signal strength across the network, shot points 3, 5, and 6, located at the FSN boundaries, were charged with 1.5 kg.

All FSN stations recorded the blasts, capturing clear P-wave arrivals for each shot as well as most S-wave arrivals, see Figure 5-2. Prior to the blasting, 27 additional seismic sensors were deployed within the FSN area, see Figure 5-1 for their location. These sensors included both 1- and 3-component 5 Hz SmartSolo geophones, which were installed by pressing the geophone spikes directly into the ground. The additional geophones were strategically placed to enhance the spatial coverage of the network to seismic signals generated by the blasts.

The blast locations determined by the StdLoc locator plugin in SeisComP with both the FSN stations as well as the SmartSolo geophones are presented in Figure 5-1, with all epicentral positions falling between 15 to 106 meters of their true locations. A comprehensive analysis of the blast data will be provided in a subsequent report.

Table 5-1. Time of blasts together with their location and size of the charge for each shot point. All blasts were carried out in 3 m deep boreholes except shot 1 that was in a 20 m deep borehole. The sea level surface is the zero level for the depth according the RH2000 reference height system in Sweden.

Shot point	Date	Time	Latitude	Longitude	Depth [m]	Charge	Comment
Shot 1	30/10/24	08:29:20.29	60.4003	18.1824	17.31	1 kg	
Shot 2a	30/10/24	08:54:48	-	-	-	1 kg	No exact time or location
Shot 2b	30/10/24	09:24:32.65	60.4002	18.1826	1.16	1 kg	
Shot 4	30/10/24	10:04:34.62	60.3936	18.2058	-2.77	1 kg	
Shot 5	30/10/24	10:36:16.61	60.3847	18.2224	-6.9	1.5 kg	
Shot 3	30/10/24	12:21:49.70	60.3848	18.1872	-3.35	1.5 kg	
Shot 6	30/10/24	12:48:03.32	60.3787	18.2330	-3.59	1.5 kg	

Table 5-2. Blast origin time and location parameters as determined through seismic analysis using the SeisComP system. The column “Epicentral distance” gives the epicentral distance between the true location of the shot and the location from SeisComP. The last column lists the number of P- and S-phases used for the solution. Notice that shot 2a has no exact location.

Shot point	Date	Origin time	Latitude	Longitude	Depth [m]	Epicentral distance [m]	Phases
Shot 1	30/10/24	08:29:20.35	60.4005	18.1844	84	106	36
Shot 2a	30/10/24	08:54:48.61	60.3999	18.1855	79	-	37
Shot 2b	30/10/24	09:24:32.69	60.4002	18.1836	79	54	39
Shot 4	30/10/24	10:04:34.65	60.3937	18.2056	63	15	40
Shot 5	30/10/24	10:36:16.63	60.3852	18.2217	23	66	40
Shot 3	30/10/24	12:21:49.75	60.3849	18.1874	157	14	38
Shot 6	30/10/24	12:48:03.38	60.3792	18.2321	310	70	41

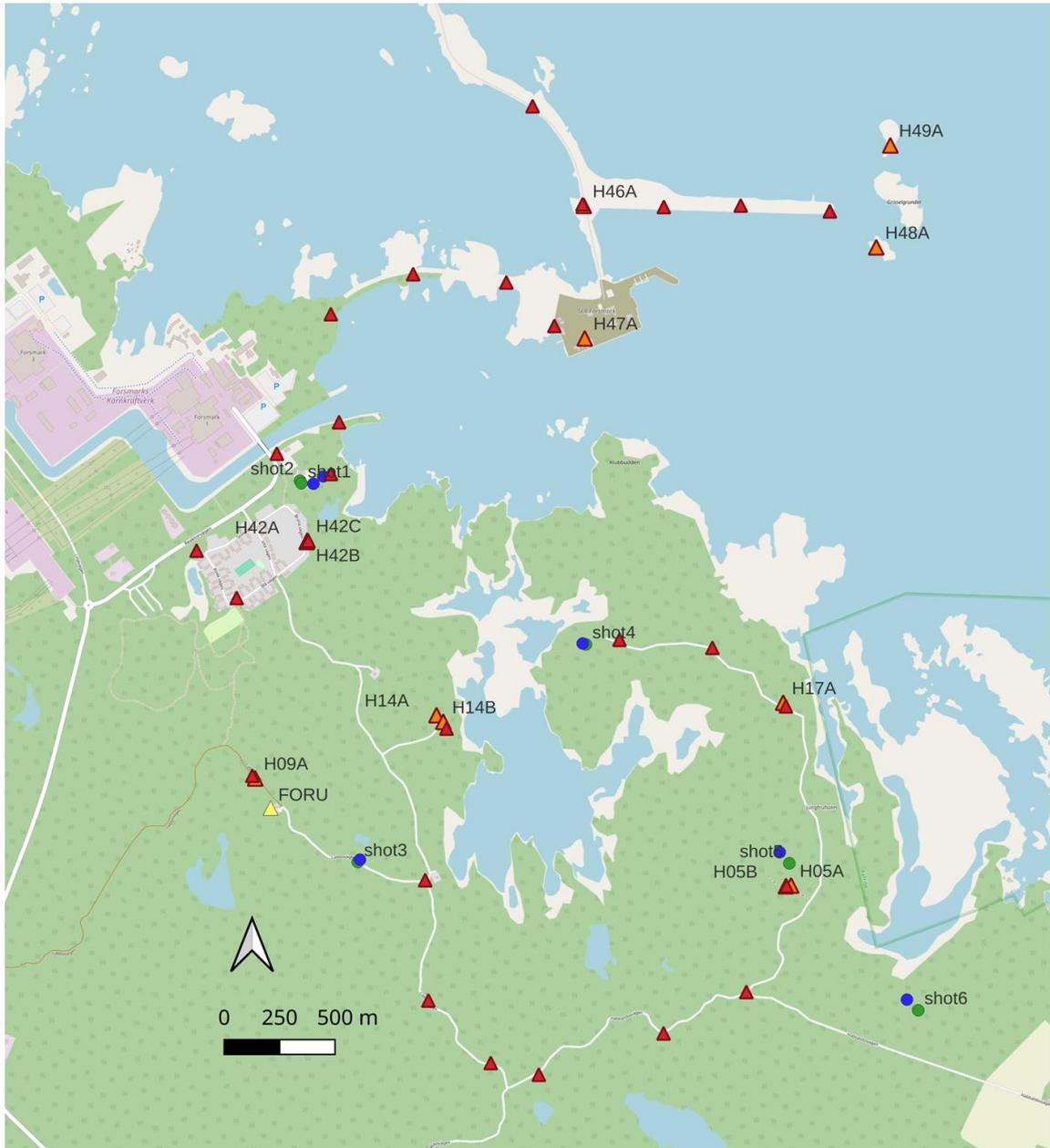


Figure 5-1. Map showing shot points for the calibration shots. The green and blue filled circles show the actual shot points and the location from SeisComP, respectively. The yellow, orange and red triangles show the location of the permanent SNSN station, the FSN stations and the temporary SmartSolo instruments, respectively.

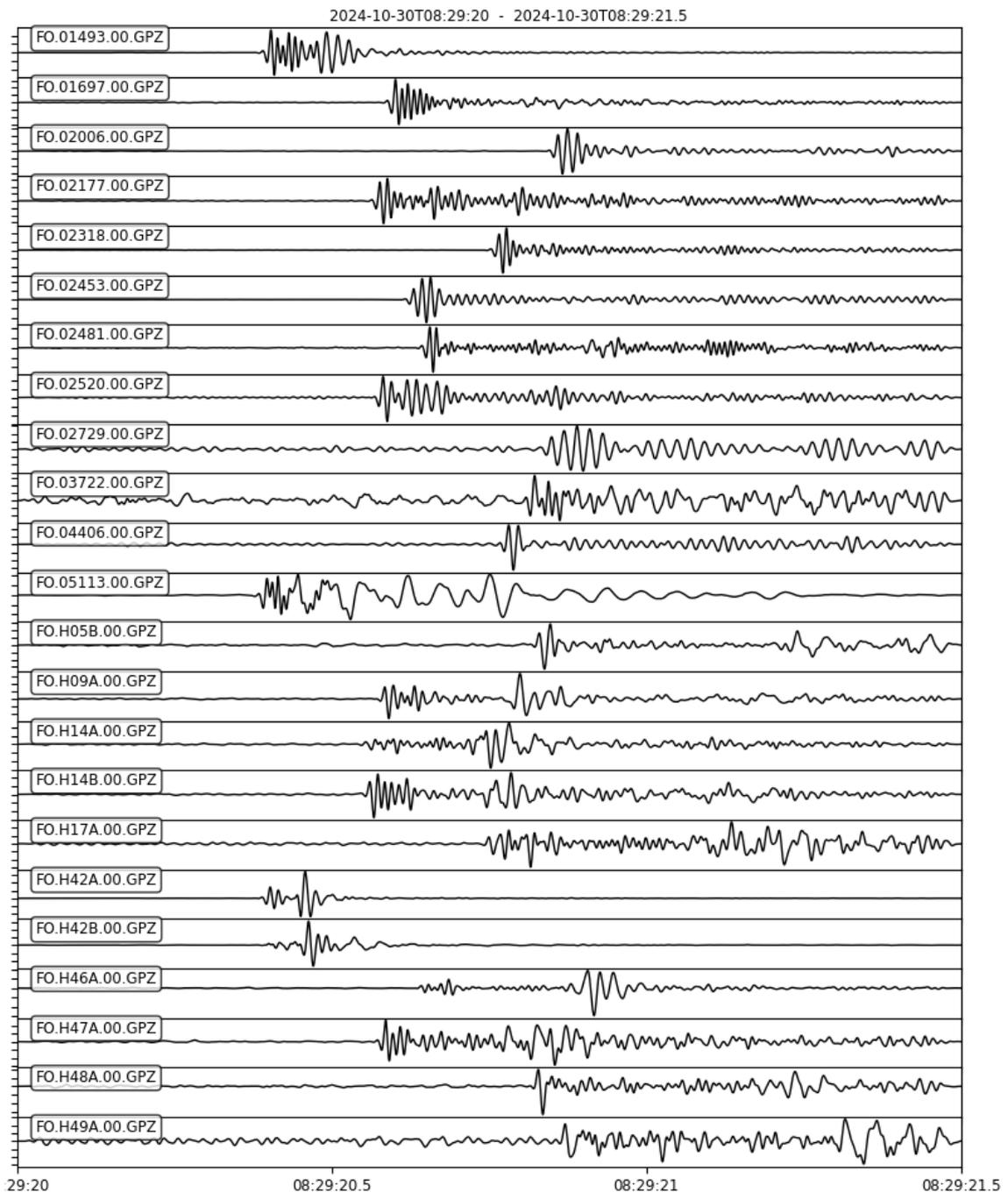


Figure 5-2. Z-component at all stations in FSN (FO.H05B to FO.H49A) as well as the 12 3C temporary SmartSolo geophones showing the waveforms from shot 1. Data is bandpass filtered between 10 and 90 Hz. The SmartSolo data are shown in the top 12 traces. Traces have individual scaling.

5.3 Chemical explosions

In September, ten chemical explosions were conducted to remove a pier at Biotestsjön, approximately three kilometres north of the FSN. The magnitudes of these blasts varied, as shown in Table 5-3. While the explosions were detectable across the FSN, the accuracy of the epicentral locations was limited, and the depths of the explosions were poorly constrained. Although the actual blasts occurred at the surface, SeisComP reported depths ranging from approximately 500 to 1500 meters, and the epicentral locations showed deviations from the true positions of up to about 500 m. Fixing the depth to zero in the location process did not significantly improve the epicentral locations. Figure 5-3 displays the actual location of the removed pier along with the positions

determined by SeisComP. The errors in both depth and epicentral location are largely due to the fact that the explosions occurred outside the FSN, significantly reducing the network's ability to precisely determine the location, particularly depth.

The blast on 18 September at 19:05 appears to have been reported with an incorrect time stamp, as it was instead identified in the data at 07:05 on the same day. This 12-hour discrepancy suggests a possible error in the reporting process.

Table 5-3. Information from the blasting company about time of blasts together with their location and size of the charge for each shot.

Date	Origin time	Number of holes	max kg/interval	Total kg
03/09/24	14:19	36	2.5	50
05/09/24	12:37	68	3.5	155.8
05/09/24	13:10	6	3.2	19.2
10/09/24	11:20	96	5.0	325
12/09/24	12:32	135	5.0	425
17/09/24	09:10	57	3.0	115
17/09/24	14:05	35	3.0	85
18/09/24	19:05	43	3.0	75
18/09/24	14:31	43	3.0	90
19/09/24	07:15	10	1.5	10

Table 5-4. Blast origin time and location parameters determined through seismic analysis using the SeisComP system. The column "Epicentral distance" gives the epicentral distance between the true location of the blast and the location from SeisComP. The last column lists the number of P- and S-phases used for the solution.

Date	Origin time	Latitude	Longitude	Epicentral distance [m]	Phases
03/09/24	14:18:43	60.4348	18.1991	330	24
05/09/24	12:37:05	60.4403	18.1870	586	24
05/09/24	13:10:48	60.4379	18.1960	210	24
10/09/24	11:21:57	60.4369	18.1951	92	24
12/09/24	12:33:59	60.4382	18.1938	211	24
17/09/24	09:08:49	60.4387	18.1956	282	23
17/09/24	14:04:32	60.4337	18.1988	395	24
18/09/24	07:05:05	60.4353	18.1990	300	24
18/09/24	14:31:40	60.4336	18.1954	311	24
19/09/24	07:18:24	60.4324	18.2002	555	23



Figure 5-3. The green filled circle shows the true location of the pier that was removed with ten blasts in September 2024. The blue filled circles show the location of the ten explosions as located with SeisComp. The orange and yellow triangles show the location of the FSN stations and the permanent SNSN station, respectively.

5.4 Induced events

No events classified as induced have been detected in the area during 2024.

5.5 Other

During two days in February 2024, two distinct series of events were detected near or within the power plant. These events occurred over approximately half an hour on both days, with intervals of a few minutes between them. The structured timing and repetitive pattern strongly suggest that the source of these events is linked to activity within the power plant or other human activity in its vicinity.

Table 5-5 and Figure 5-4 present the locations determined by SeisComP, while Figure 5-5 provides an example of waveform data for one of the events observed during the two days in February.

Three additional isolated seismic events were recorded during the year and are categorized as "Other". Figures 5-6 to 5-11 display the waveforms and amplitude spectra for the three nearest stations with clearly identifiable signals for each of the events.

For the event on 13 August, located near station H17A, large surface waves are seen and signal energy above the background noise level up to approximately 50 Hz.

The 10 September event, also detected near station H17A, differs slightly in appearance. The amplitude spectrum indicates signal energy extending up to around 100 Hz and the used P-wave arrivals are only distinguishable at a few stations.

The event on 10 November, situated slightly north of the nuclear power plant, is most likely related to activities at the facility. However, its precise location is uncertain due to ambiguity in the arrival of P- and S-waves.

Table 5-5. Event origin time and location parameters determined through seismic analysis using the SeisComP system. The second last column lists the number of P- and S-phases used for the solution. The last column shows the colour of the event in Figure 5-4.

Date	Origin time	Latitude	Longitude	Phases	Colour
09/02/24	19:18:58	60.4000	18.1746	18	Blue
09/02/24	19:24:45	60.4033	18.1777	18	Blue
09/02/24	19:27:05	60.4015	18.1792	19	Blue
09/02/24	19:30:02	60.4034	18.1702	21	Blue
09/02/24	19:32:02	60.4034	18.1655	18	Blue
09/02/24	19:34:06	60.4064	18.1564	18	Blue
09/02/24	19:35:29	60.4010	18.1832	15	Blue
09/02/24	19:37:38	60.4046	18.1560	17	Blue
09/02/24	19:39:22	60.4074	18.1488	17	Blue
09/02/24	19:41:26	60.4066	18.1642	19	Blue
09/02/24	19:43:37	60.4013	18.1800	15	Blue
09/02/24	19:45:17	60.4054	18.1693	20	Blue
11/02/24	10:02:02	60.4039	18.1726	16	Green
11/02/24	10:05:29	60.4026	18.1784	15	Green
11/02/24	10:09:19	60.4080	18.1470	11	Green
11/02/24	10:13:07	60.4025	18.1774	16	Green
11/02/24	10:17:21	60.4017	18.1858	13	Green

Date	Origin time	Latitude	Longitude	Phases	Colour
11/02/24	10:21:08	60.4021	18.1805	13	Green
11/02/24	10:24:59	60.4031	18.1832	18	Green
11/02/24	10:29:21	60.4040	18.1701	14	Green
13/08/24	09:46:52	60.3860	18.2286	14	Purple
10/09/24	19:22:41	60.3952	18.2223	12	Purple
10/11/24	16:15:23	60.4144	18.1643	17	Purple

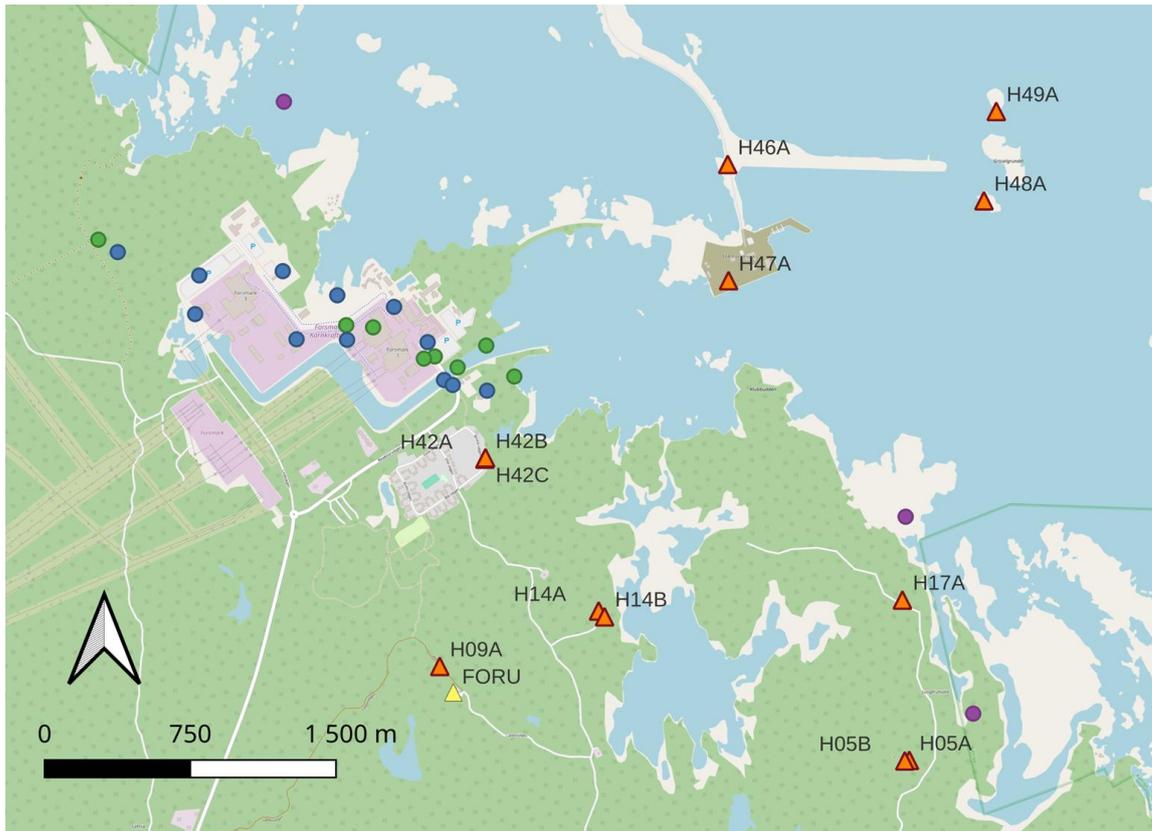


Figure 5-4. The blue, green and purple filled circles show the locations by SeisComP for the events that occurred on February 9, February 11 and the three remaining events, respectively. The stations in FSN are denoted by orange triangles and the permanent SNSN station by a yellow triangle, respectively.

For all the three latter events the P- and S-waves are difficult to identify, particle motion analysis indicates that it is unclear even if the picked phases are indeed body waves. This difficult in identification is to a large degree due to the very low signal-to-noise ratio (SNR), in many cases SNR is not much larger than 1 and identification is based on a change in frequency content. This of course adds to the classification difficulties. As seen in Figures 5-6 to 5-11, many stations show some degree of larger lower frequency phases, suggested by the polarisation analysis to be surface waves. The amplitude ration of the surface waves to the body waves is high.

We cannot determine the source of these three events. The large surface waves could indicate a surface source, but a source below ground cannot be ruled out.

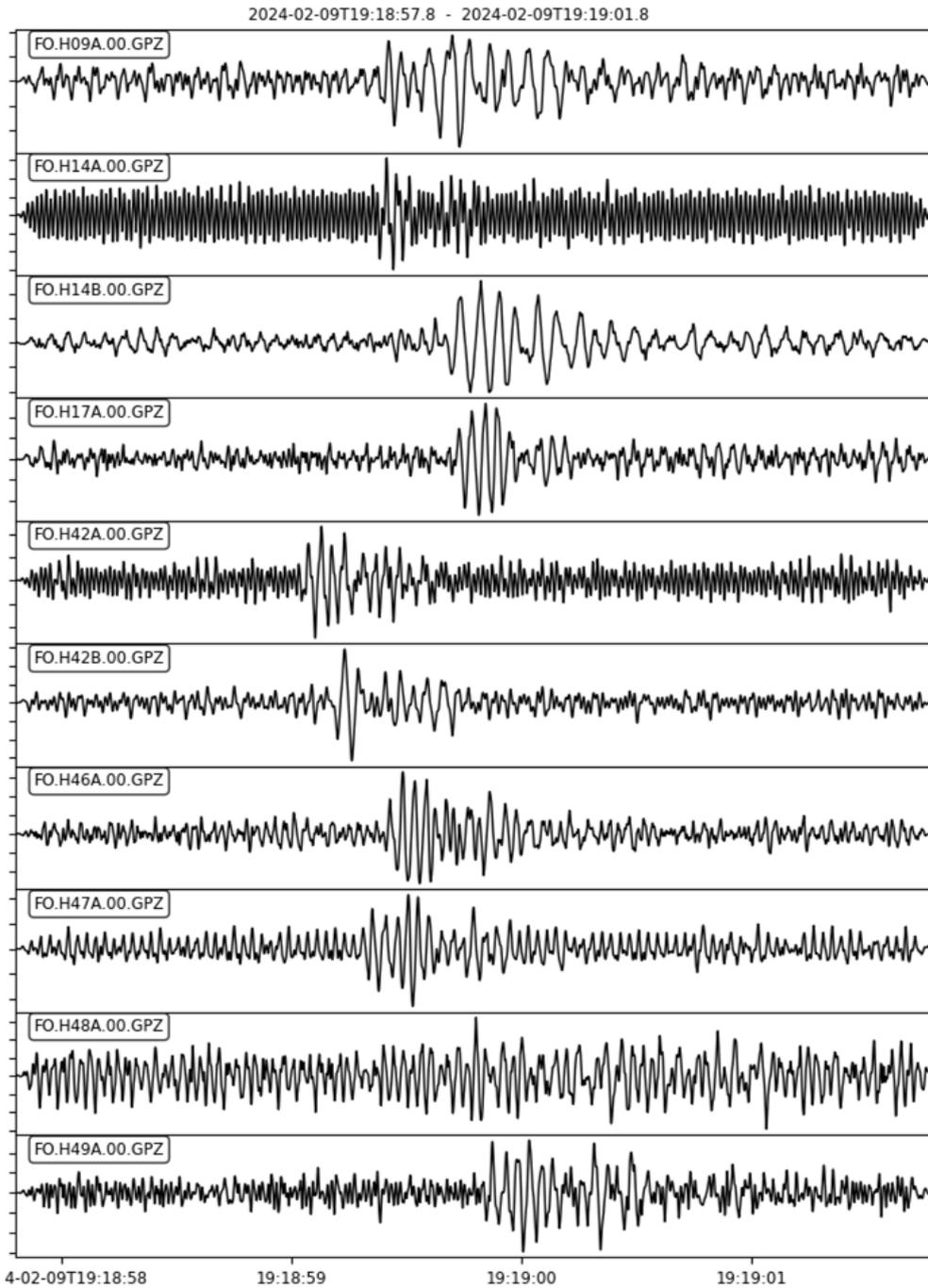


Figure 5-5. Z-component at the different stations in FSN showing one of the events that occurred on February 9 and 11 2024. All the events on February 9 and 11 looks similar. Data is bandpass filtered between 10 and 90 Hz. Traces have individual scaling.

2024-08-13T09:46:51 - 2024-08-13T09:46:55

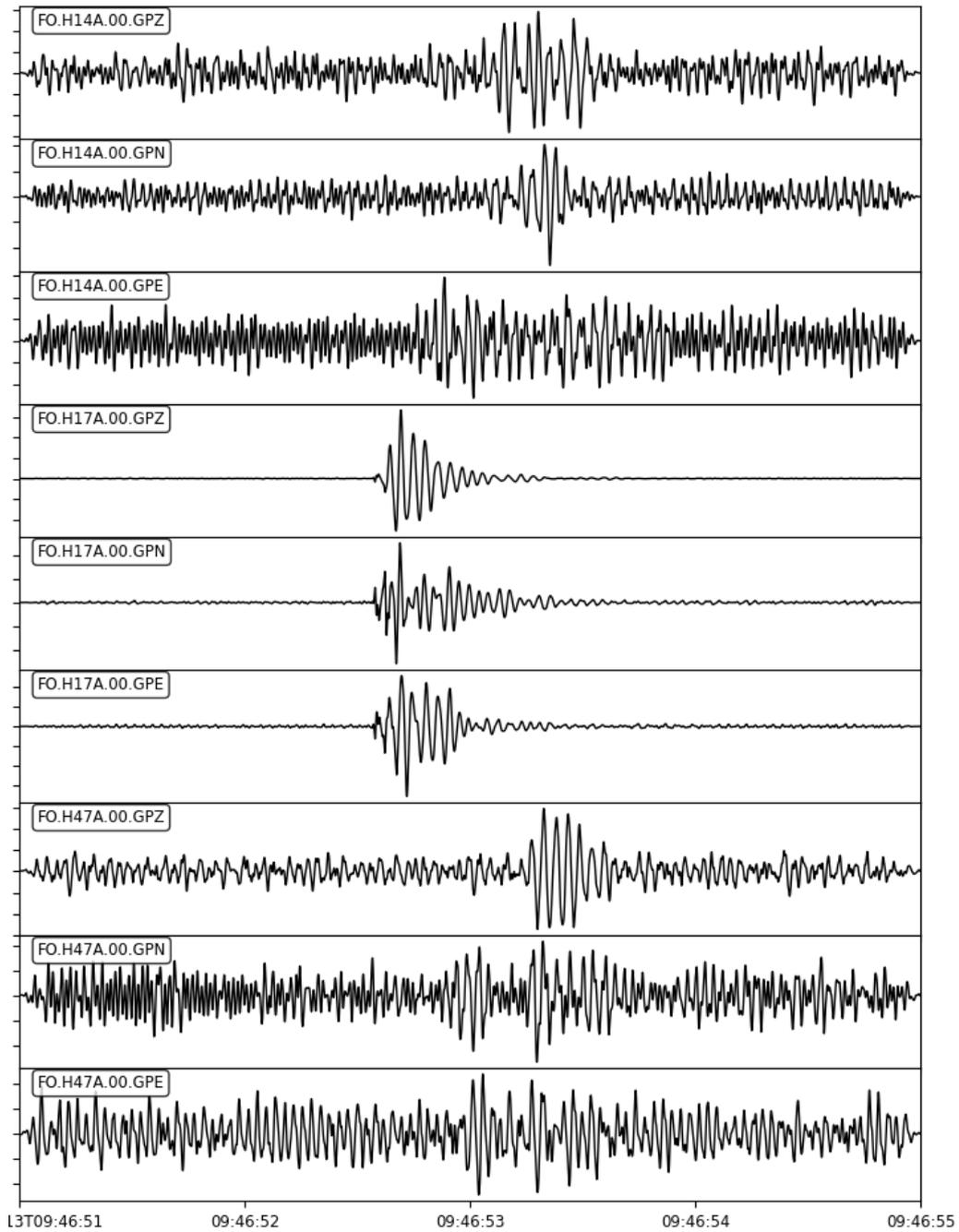


Figure 5-6. The three closest station to the event on August 13. The data is bandpass filtered between 10 and 90 Hz. Traces have individual scaling.

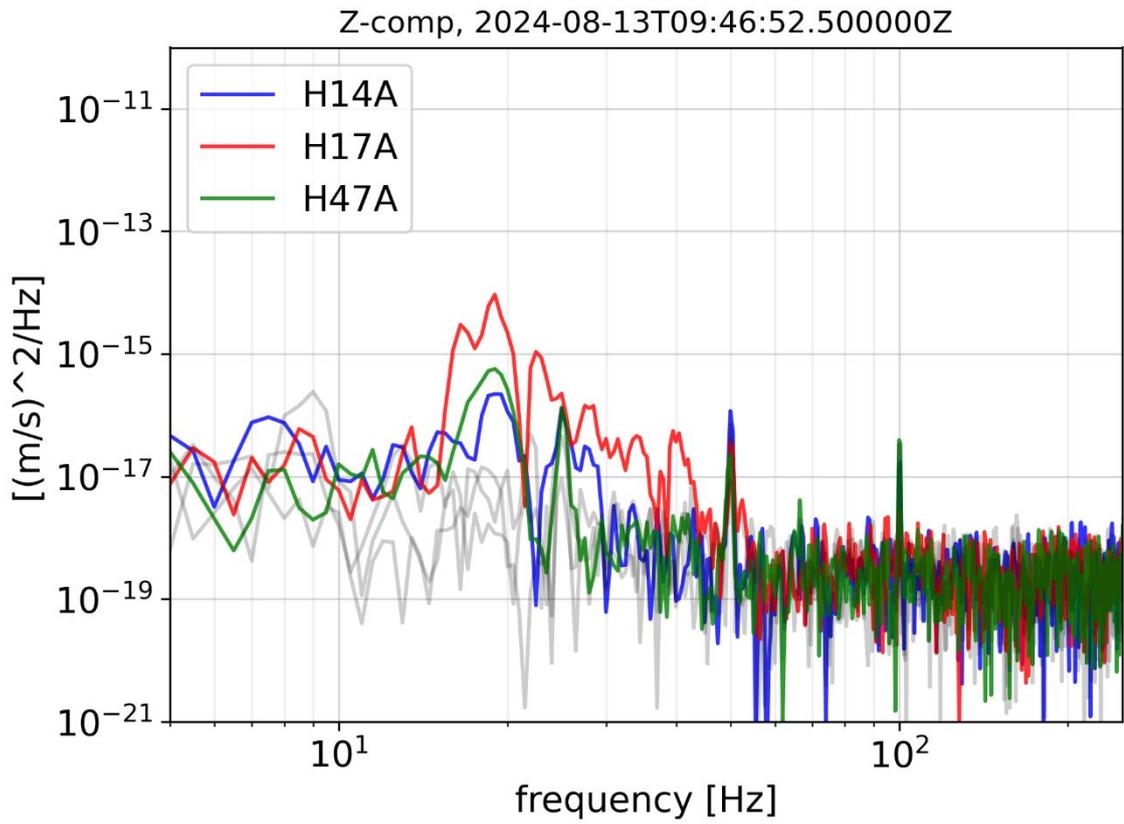


Figure 5-7. Spectrum for Z-component at the three closest station for the event on August 13. The shaded grey lines show the background noise level at the station, it is the spectrum for 2 sec of data just before the event.

2024-09-10T19:22:39.8 - 2024-09-10T19:22:43.8

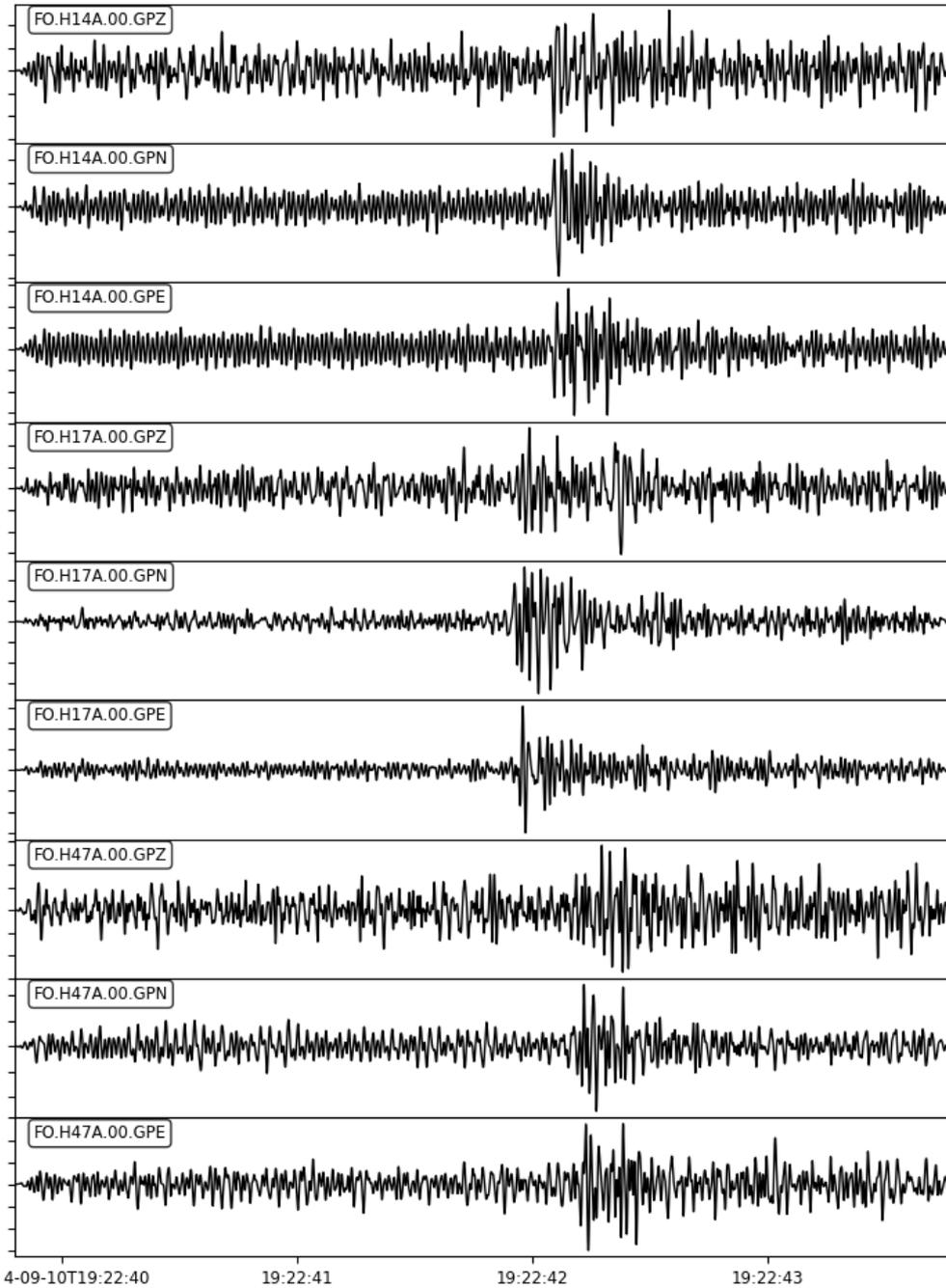


Figure 5-8. The three closest station to the event on September 10. The data is bandpass filtered between 10 and 90 Hz. Traces have individual scaling.

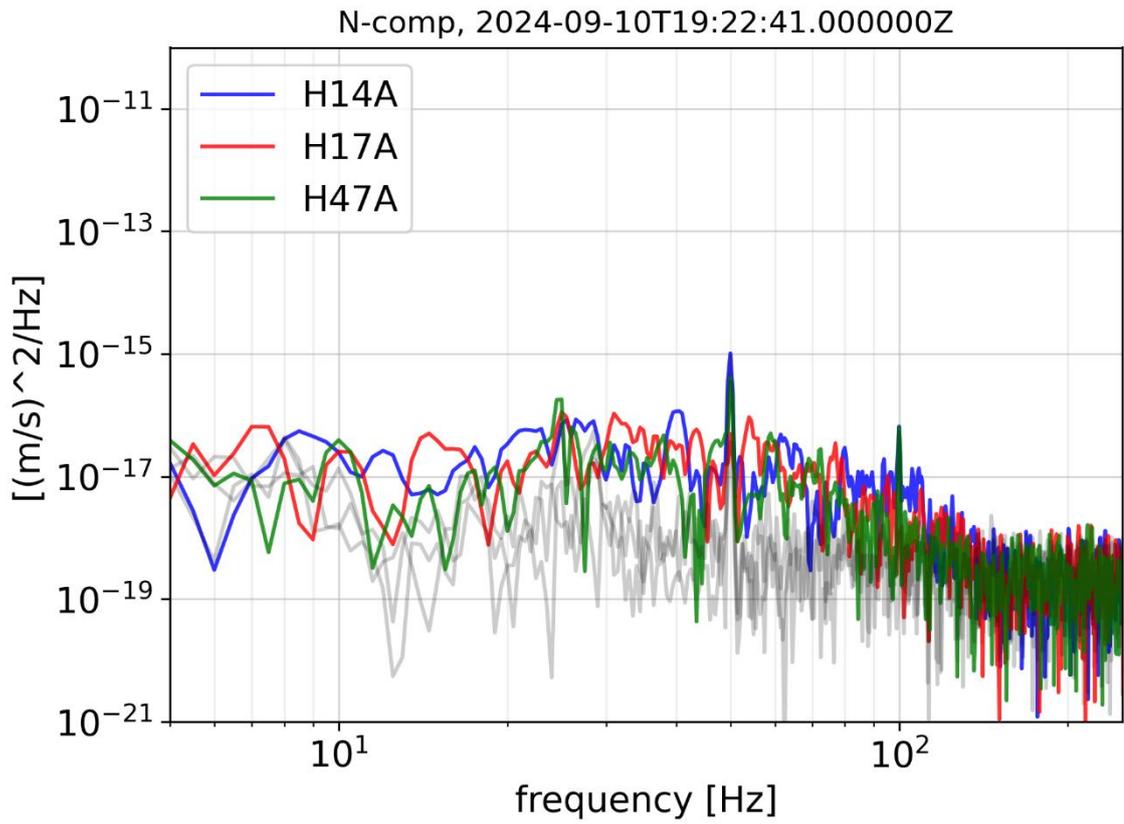


Figure 5-9. Spectrum for N-component at the three closest station for the event on September 10. The shaded grey lines show the background noise level at the station, it is the spectrum for 2 sec of data just before the event.

2024-11-10T16:15:23 - 2024-11-10T16:15:27

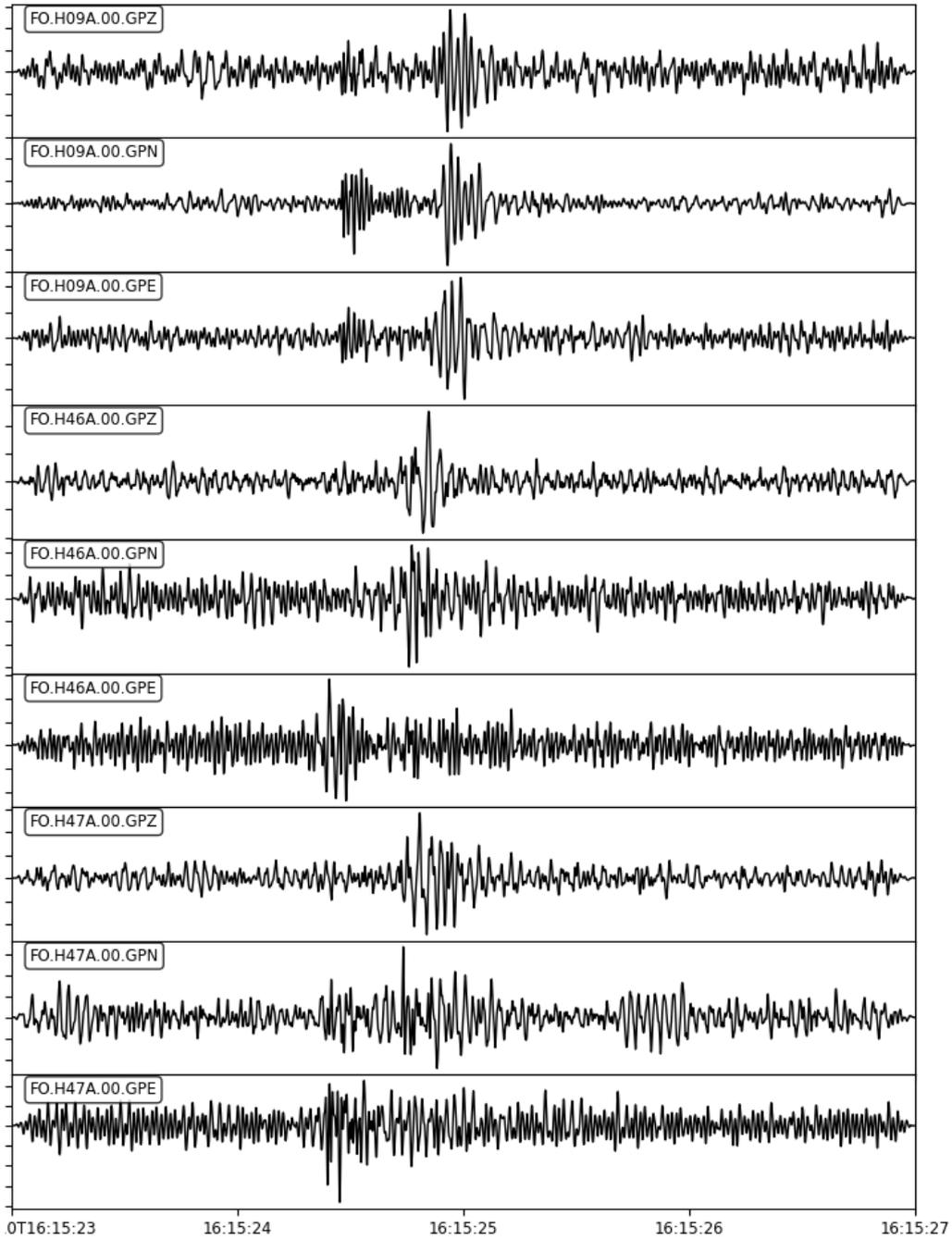


Figure 5-10. The three closest station to the event on November 10. The data is bandpass filtered between 10 and 90 Hz. Traces have individual scaling.

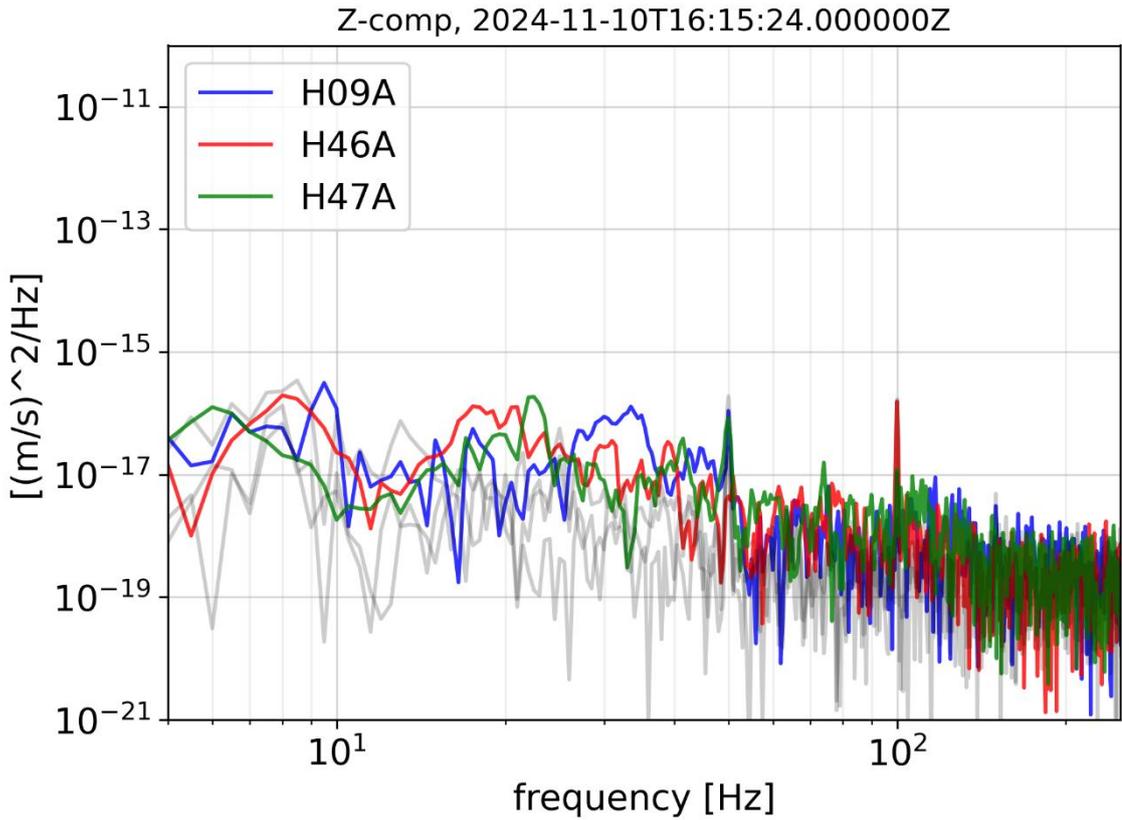


Figure 5-11. Spectrum for Z-component at the three closest station for the event on November 10. The shaded grey lines show the background noise level at the station, it is the spectrum for 2 sec of data just before the event.

5.6 Not locatable

During 2024, a significant number of events were observed in the southern part of the network, predominantly during December. These events were detected at some or all of the following stations: H05B, H09A, H14A and B, H17A, and FORU. On certain days, multiple events occurred every hour, while at other times, there were several days between occurrences. Although these events were recorded on some or all of the aforementioned stations, identifying P- and or S-wave arrivals was difficult, making it difficult to locate the events with any degree of accuracy. Figure 5-12 provides an example of one such event from December 10, we see that signal-to-noise ratios for body-waves are rather low.

The cause of these events remains unknown; however, there appears to be a correlation between temperature changes, and specially temperature drops below zero degrees, and their occurrence, as illustrated in Figure 5-13. This observation suggests that environmental factors, such as freezing-related processes, may be the cause in triggering these events. The temperature data shown in Figure 5-13 is measured at a meteorological mast located in an open area within the forest in Forsmark. The mast is situated on a gravel surface. The temperature is measured 2 meters above ground using a temperature sensor protected from solar radiation and weather conditions.

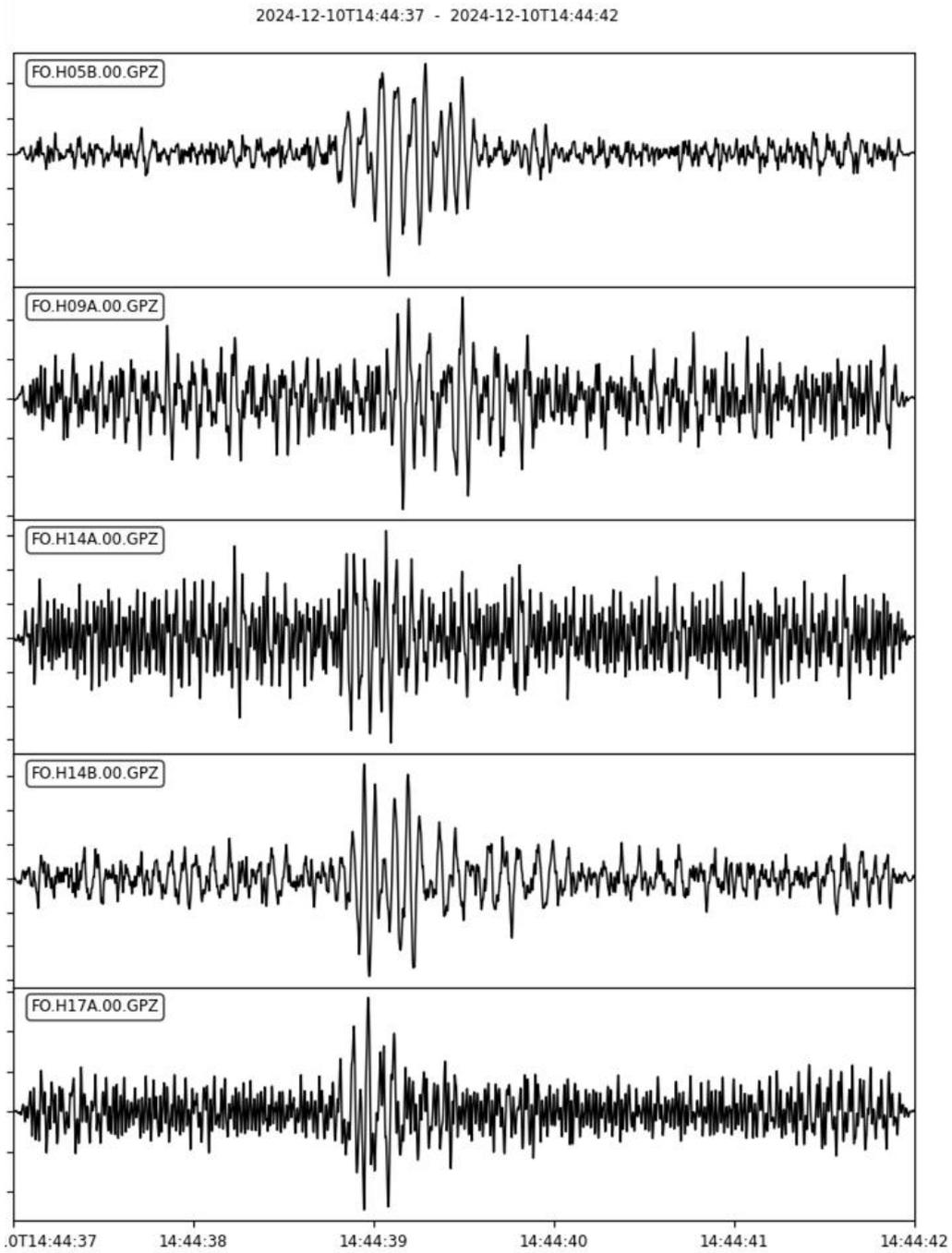


Figure 5-12. Z-component at station H05B, H09A, H14A, H14B and H17A for one of the frequently occurring events during December. Data is bandpass filtered between 10 and 90 Hz. Traces have individual scaling.

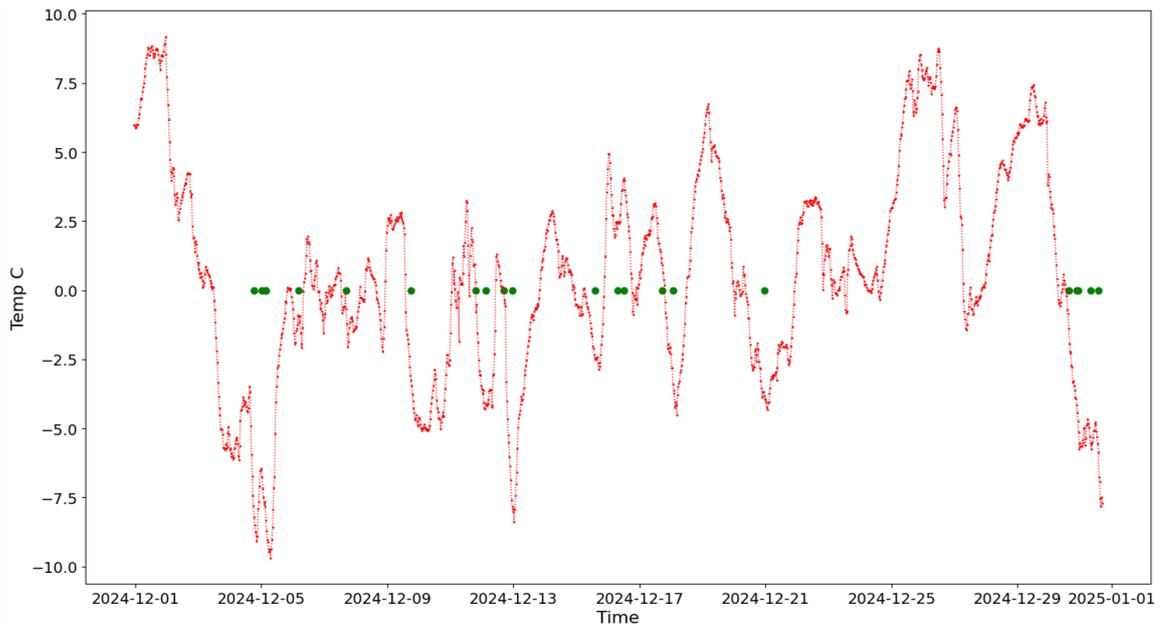


Figure 5-13. The red line shows temperature values in Celsius during December in Forsmark. The green dots show the time of when there has been one or several events repeating closely in time in the southern part of the network

5.7 Anthropogenic source – construction work

Human activity, such as construction work, is often clearly visible on the seismic stations in the FSN, particularly at stations H46A and H47A, where significant building activity is ongoing. This activity generates distinctive seismic signals, characterized by repetitive and structured vibration patterns that are easily distinguishable from background noise. Figure 5-14 illustrates an example of seismic signals produced by construction work, presumably at the surface, close to station H46A and H47A. The corresponding spectrum is shown in Figure 5-15 with data from station H47A. Note that the construction work data comes from around 11 UTC day time while the noise data is from 01:00 night time on the same day. The time difference likely explains the difference in the amplitudes of the 25 and 50 Hz power plant peaks between day and night.

2024-12-18T11:03:30 - 2024-12-18T11:06:00

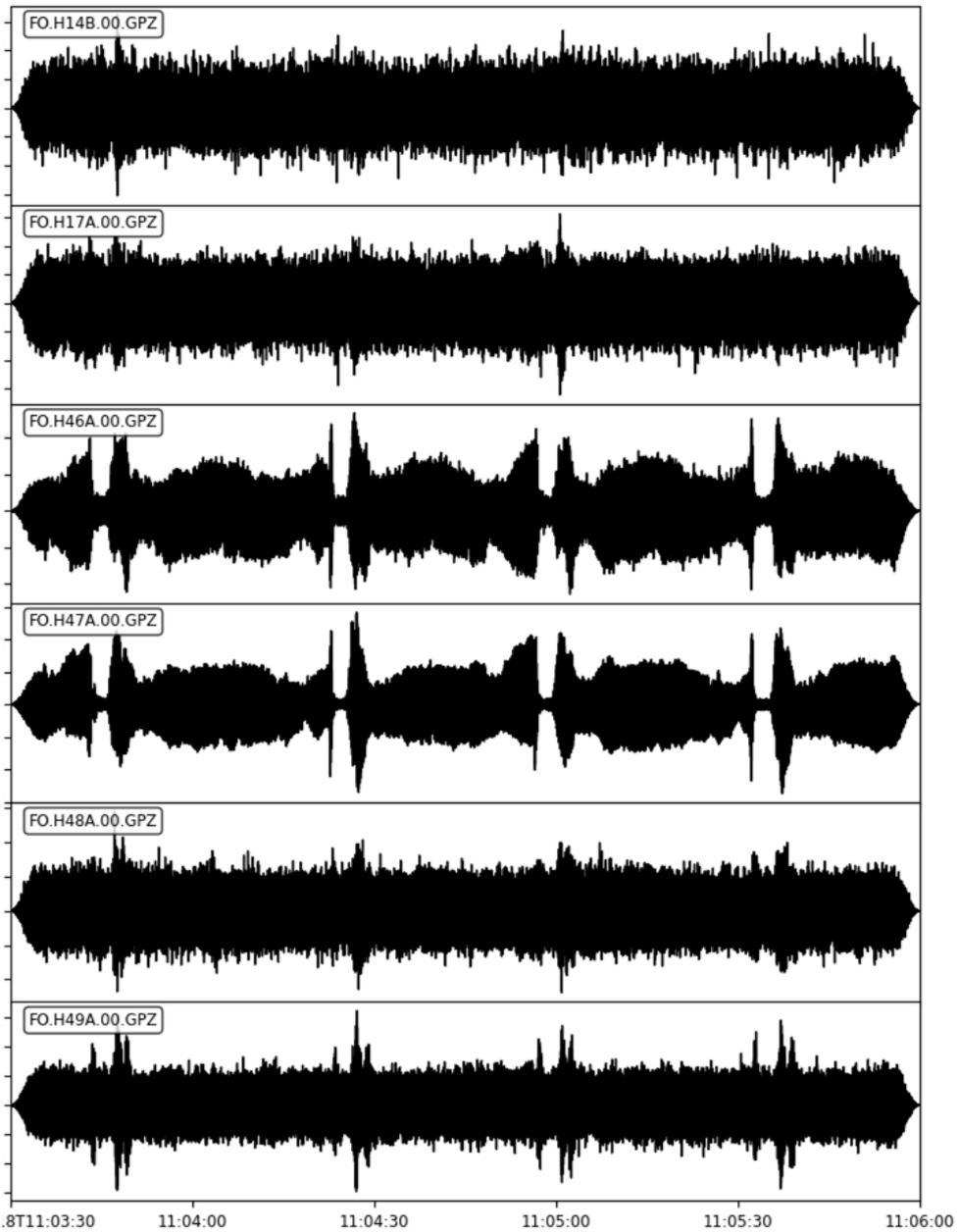


Figure 5-14. Z-component at the northern most stations in FSN showing the clear signal from construction work carried out around station H46A and H47A on 18 December. Traces have individual scaling.

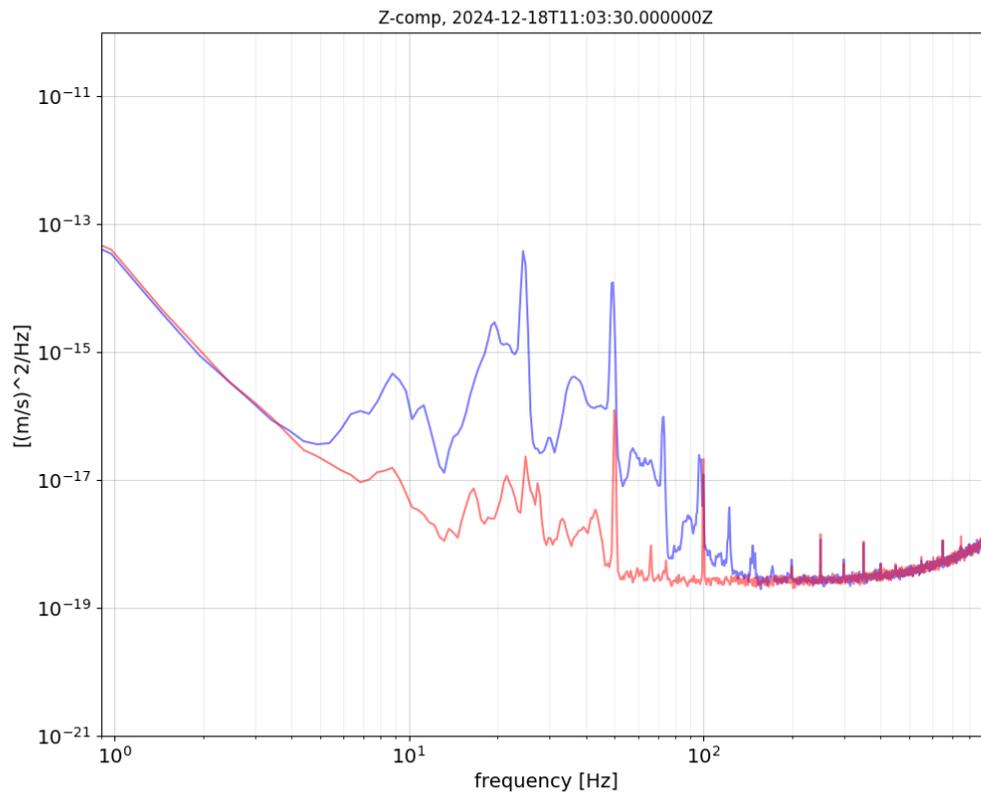


Figure 5-15. The blue line shows the amplitude spectrum for station H47A, same time window as data in Figure 5-14. The red line shows background noise level for station H47A, 150 sec of data from 01:00 UTC December 18. Instrument response is removed.

6 Conclusions

During 2024, the overall performance of the Forsmark Seismic Network was satisfactory, with station uptimes exceeding 90% for all stations except H49A. That station experienced power outages due to a damaged cable, which should be replaced to restore full operational capacity. Furthermore, replacing the solar panel at station H17A is recommended to improve its reliability, particularly during the winter months.

The newly installed sensor at station H05B is operating effectively and delivers data quality comparable to that of other stations, even though it is installed using an inflatable cuff and not grouted into the borehole.

Throughout the year, the FSN recorded a total of seven controlled explosions, ten chemical explosions related to the demolition of a pier, and twenty events classified as "Other" that were linked to activity at the nuclear power plant. Additionally, three isolated events were also categorized as "Other." The source of these three events is not clear, large surface waves may hint at a surface source but we cannot rule out a subsurface source.

The capability of the FSN to monitor activity in the Forsmark area was demonstrated during the pier demolition at Biotestsjön. One of the blasts was reported at a time, 19:05, when no seismic activity was observed, however, a blast in that area was detected on the same day at 07:05, indicating a 12-hour mishap in the reporting.

We see that detection and location of seismic events in the Forsmark area to a large degree is operational. The FSN detects events that we know of and expect the network to detect, such as the calibration blasts and the blasting operations at Biotestsjön. It is clear that an event equivalent to 1 kg of explosives is clearly seen at all stations, if detonated in bedrock within the network. We also see infrastructure work on the surface, events from the power plants and frost related events. We note, however, that the depth locations are associated with significant uncertainties. We also note that some events remain difficult to detect, locate and classify.

In order to improve the detection and analysis of seismic events in Forsmark there are a number of approaches that can be taken.

- Additional seismic stations, especially one or two north of the power plants, would significantly aid the location of power plant related events, and reduce the uncertainty of what their origin is.
- Additional seismic data acquisition in the repository area may also be necessary to enhance the location and depth control of events there. These could be more seismic sensors but could also be the deployment of one or more fibre-optic cables, with Distributed Acoustic Sensing (DAS) technology, in boreholes and/or along the ground, with appropriate interrogators.
- As construction reaches deeper levels in the spent fuel repository, seismic sensors or DAS technology in the tunnel would significantly increase detectability and locatability.
- Calibration events are crucial to enhance the velocity model for increased accuracy, and test hypocenter and depth location processes.
- A library of known events of various sorts should be established for the FSN. These would include blasts, but also other common events such as construction work, transports, power plant impulsive sources etc. Such a library, with times and verified event types, can then be used to aid classification of the recorded seismic events.
- Machine learning should be introduced into the FSN, both in tests for improved detection and location, but also for classification purposes. For the classification there are both denoising methods available that can reduce known noise sources in the data and methods to train models to identify specific sources.

7 References

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