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Assessing Station Performance in the AdriaArray: A Study of CSS Deployments

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Abstract

The Croatian Seismological Survey (CSS) plays a central role in seismic monitoring throughout Croatia with its permanent, temporary and mobile station networks. As part of the AdriaArray initiative, the CSS has expanded its capabilities by integrating its stations into a regional framework aimed at improving seismic coverage. In this study, the performance of three representative stations MOSL (permanent), 7433 (temporary) and BATN (mobile) is evaluated by analyzing the probabilistic power spectral density (PPSD). Results indicate that the permanent station exhibits superior performance, with noise levels better aligned with the New Low Noise Model (NLNM), whereas temporary and mobile stations show significantly higher noise at periods of 0.07-1 s. However, signal quality is affected by significant issues such as insufficient thermal and barometric insulation and shallow installations. While temporary and mobile stations show lesser performance overall, in range of 1-10 s they are comparable to permanent stations in some aspects. Further, they exhibit higher noise levels at periods of 10-100 s, which is influenced by environmental and anthropogenic factors. Improving seismic network performance in Croatia requires upgrading equipment, implementing deeper vault designs, and optimizing station locations to minimize noise interference. These results provide important insights for the modernization of seismic monitoring in Croatia and its integration into international initiatives.

Keywords: Croatian Seismological Survey (CSS); AdriaArray Initiative; Seismic Monitoring; Noise Analysis; Seismic Network Modernization

1. Introduction

Seismic monitoring networks play a crucial role in understanding tectonic processes, assessing seismic hazards and ensuring public safety (National Academies of Sciences, Engineering, and Medicine, 2006). In the tectonically active region of the central Mediterranean, the Adriatic plate and its surrounding margins pose unique geodynamic challenges and risks (Le Breton et al., 2017). The Adria Array initiative, a multinational collaboration, aims to improve seismic monitoring in this region by integrating permanent and temporary seismic stations across national borders (Kolinsky et al., 2025).

In Croatia, seismic monitoring is carried out by the Croatian Seismological Survey (CSS), which has the legal mandate to establish and maintain the national network of seismic stations (Official Gazette, 1985). The CSS has recognized the importance of international cooperation and has joined forces with the AdriaArray Initiative (Kolinsky et al., 2025) to improve seismic network coverage in Croatia and neighboring regions. In 2021, CSS secured funding for the CROSSNET project (Crossnet, 2025), a major infrastructure initiative aimed at modernizing Croatia's seismic monitoring capabilities. This collaboration is in line with CSS's ongoing efforts to modernize its network through the CROSSNET project. This article focuses on the contributions of CSS and its collaboration with the AdriaArray Initiative.

Despite the joint efforts described above, certain areas of Croatia are still not sufficiently monitored due to the sparse distribution of stations and the lack of modern infrastructure. To address these challenges and support the AdriaArray Initiative, the CSS has set up more than 20 temporary seismic stations, both strong-motion and broadband, with later including stations in wider Petrinja area, Cestica, Bilogora, Batina and island of Palagruža. These stations have a dual role: they increase the station density of the AdriaArray and close gaps in the coverage of the national seismic network in Croatia.

This study assesses CSS station performance within the AdriaArray, focusing on noise characteristics via Probabilistic Power Spectral Density (PPSD) (McNamara et al., 2004) analysis relative to global noise models (NLNM and NHNM) (Peterson, 1993). The aim is to identify trends and factors that influence the performance of the stations and thus gain insights for the optimization of future seismic networks.

Currently, the national network of seismic stations operated by CSS in Croatia comprises three different types of networks, all of which are operated under the network code CR: (1) the national network of permanent seismic Stations, (2) the mobile pool around Petrinja, which was deployed for monitoring after the 2020 M_w 6.4 Petrinja earthquake (Markušić et al., 2021) and subsequently for the Berkovici aftershock series (Dasović et al., 2024), and (3) the temporary CROSSNET installations, which were established as part of the CROSSNET project to modernize Croatia's seismic monitoring capabilities. Each of these networks includes both broadband and strong-motion instruments. The permanent national network mainly uses Guralp instruments and a smaller number of Kinemetrics sensors for strong motion (Ivančić et al., 2018). In contrast, the mobile pool and CROSSNET installations are predominantly equipped with Kinemetrics instruments (Fiket et al., 2023; Fiket, T. 2023). Figure 1 illustrates the current status and distribution of all CSS installations.

The transition to digital instrumentation began in 2000, with the first deployments focusing on upgrading sites previously managed by residents (Ivančić, 2023). In the analog era, these residents were responsible for routine maintenance tasks such as changing recording paper and refilling ink. These sites were the logical choice for digital upgrades given their established infrastructure and CSS's limited budget.

Despite the importance of seismic monitoring in Croatia, there are still problems with long-term funding. Even major seismic events such as the 1995 Ston/Slano earthquake (Herak, 1998) did not provide sufficient financial support to improve the seismic network. As a result, the CSS often resorted to cost-effective installations, preferring sites with existing buildings, power supplies and communication lines to minimize costs.

Most of the current equipment was purchased in the early 2000s, with Guralp equipment being preferred due to its favorable price/performance ratio. These devices formed the backbone of the CSS network and enabled seismic monitoring despite the financial constraints.

Since the establishment of the permanent seismic network, data acquisition has relied primarily on Guralp's proprietary Scream! software (Guralp, 2025) to acquire data directly from the station. With the subsequent implementation of SeisComP systems (GFZ, 2008), the data acquisition infrastructure was expanded by connecting the seedlink protocol (FDSN, 2025) to the central Scream server. All data are archived at the CSS center in Zagreb, the permanent stations (Guralp devices) are recorded via the Scream! 4.6. software on a special server, with data recorded in Guralp's own gcf format, and all others via the SeisComP system and the Seedlink protocol. The recording scheme is shown in Fig. 2.

After the 2020 Petrinja earthquake (December 29, 2020) (Markušić et al., 2021), the Croatian Seismological Survey (CSS) received its first major delivery of new instruments as well as a significant budget increase from the Croatian government. This marked a turning point for CSS and enabled the establishment of a mobile pool designed for rapid deployment in epicentral areas. The mobile pool consists of a combination of broadband (BB) and strong motion (SM) instruments that enhance CSS's capacity for post-seismic monitoring and data acquisition.

The newly acquired devices include: Kinemetrics MBB-2 broadband sensors, Quantera Q330S+ digitizers and Etna2 strong motion devices. In total 20 devices of each type were purchased. These instruments were initially deployed in the wider Petrinja area to monitor aftershocks and other seismic activity following the main earthquake.

The transition to a mobile seismic network required significant improvements in data transmission methods. Unlike Guralp's Scream! software, which sends data to a server with a known IP address, SeisComP obtains data from stations with fixed IP addresses. This means that the stations require stable and known IP addresses for reliable operation. To meet these requirements, the following options were tested: Public IPs in mobile networks, dynamic DNS, VPN connection. We will briefly describe all the options mentioned:

Although Public IP option was possible, it was not practical in Croatia due to the high cost of public IP addresses in mobile networks. CSS tested dynamic DNS services offered by mobile network operators. However, these proved to be unreliable due to high latency times and frequent data transmission failures. Therefore, CSS opted for an OpenVPN server installed on one of its computers. The routers at each station were equipped with certificates to be able to use this VPN connection. This approach provided a highly reliable and efficient communication channel and overcame the limitations of previous methods. The VPN-based solution initially implemented for the Petrinja mobile pool has since been adopted for all subsequent deployments, including those within the CROSSNET project.

In April 2022, part of the Petrinja mobile pool was relocated to monitor the aftershock series of the Berkovici earthquake (Dasović et al., 2024), and stations were set up in: Prud, Lisac and Kliševo.

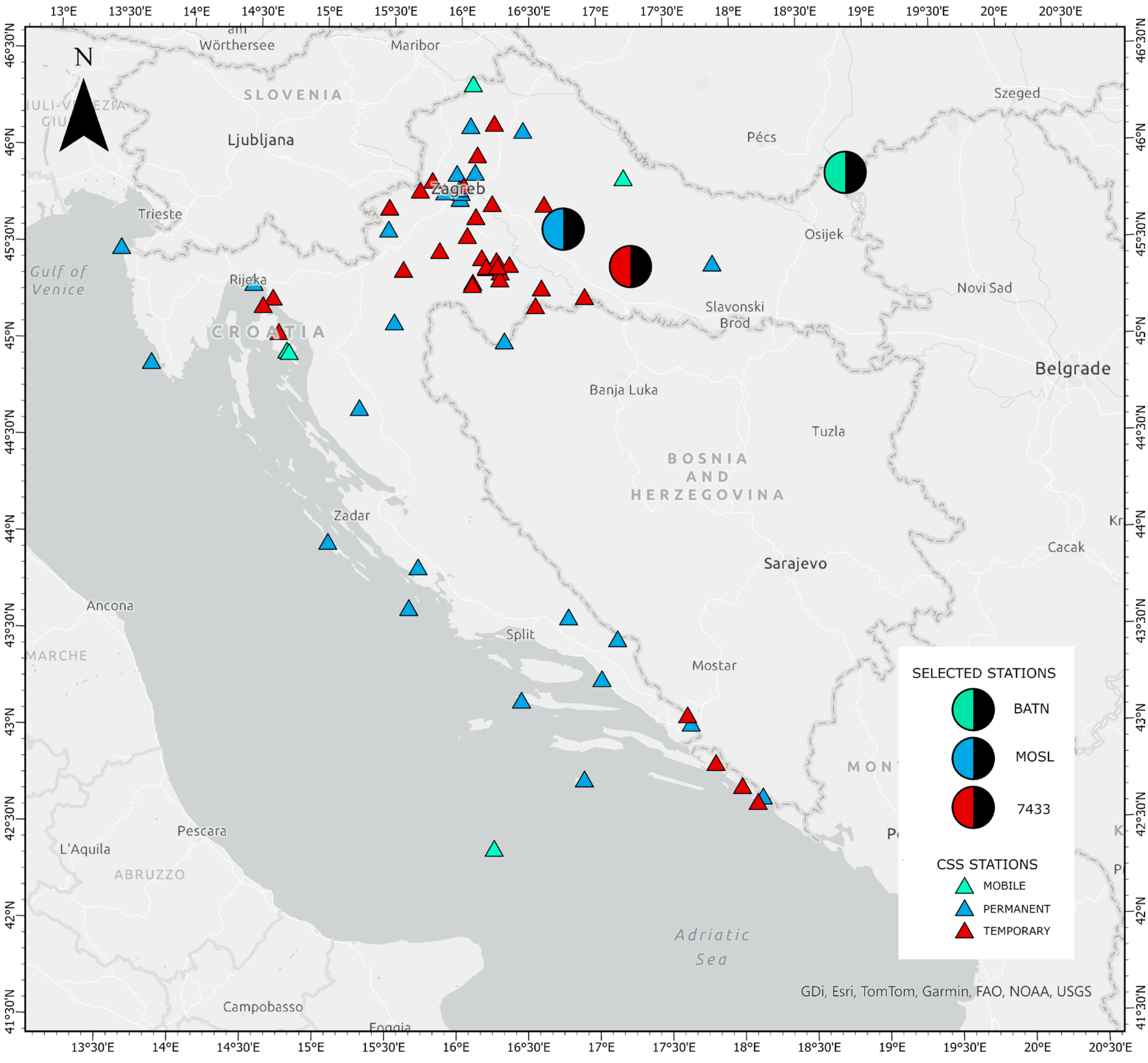


Figure 1. Current status of the seismic stations managed by the Croatian Seismological Survey. The triangles are SM and BB stations (permanent blue, temporary red, mobile green), while the stations BATN, 7433 and MOSL (looking from E to W) are marked with color/black circles depending on type.

The mobile Petrinja pool, originally set up in response to the 2020 earthquake, has become an important tool for CSS operations. Its reliable data transmission system and versatile instrumentation have enabled CSS to respond quickly to seismic events and provide valuable data for monitoring aftershocks and conducting seismic studies.

As part of CROSSNET project, the following equipment was purchased: 100 Kinemetrics Etna2 strong motion instruments, 20 Streckeisen/Kinemetrics STS 2.5 broadband seismometers, 25 Kinemetrics MBB-2 broadband seismometers, 50 combined Kinemetrics Omnisensor strong motion and broadband instruments, 120 Kinemetrics Quantera Q8 digitizers, 20 mobile sets for rapid deployment and microtremor studies (Kinemetrics, MBB-2 sensors and Q8 digitizers), 10 OBS instruments: Nammu units from K.U.M. Kiel, equipped with Nanometrics broadband sensors and 6D6 digitizers.By early 2023, all instruments were delivered and enabled CSS to significantly expand its monitoring capabilities.The earthquake on the island of Krk M_L 4.8 in February 16, 2023 (Faculty of Science, 2025) was the first deployment of the newly acquired CROSSNET instruments. Stations were installed in the wider area around Krk, demonstrating the flexibility and efficiency of the mobile pool in managing seismic events in different regions.

As part of its collaboration with the AdriaArray initiative, CSS has made all of these stations available to AdriaArray participants, providing unrestricted access to its network data. This open access policy underlines CSS's commitment to advancing regional seismic monitoring and promoting international cooperation.

2. Methodology of deployment, data collection and noise analysis

CSS deployments can be roughly divided into two types: permanent and temporary installations. With very limited resources available prior to the 2020 earthquakes, the permanent installations were in many cases of similar quality and design to the temporary installations used elsewhere in the earthquake community.

2.1 Deployment

2.1.1 Permanent installations

Of the permanent facilities, only a few are equipped with a special infrastructure for optimal seismic monitoring. We can roughly divide the existing infrastructure of the stations into four groups as follows:

1) Concrete piers – only two stations (Kijevo and Puntijarka) have special concrete piers for the installation of seismometers,
2) Shallow vaults – six stations (Lastovo, Moslavina, Makarska, Ričice, Rijeka and Ozalj) are housed in shallow vaults,
3) Horizontal shafts – the Kalnik and Dubrovnik stations are housed in small horizontal shafts built into the rock faces of the mountains,
4) Existing structures – most of the stations are housed in existing buildings or basements where the existing infrastructure (e.g. power and communication lines) can be easily utilized.

Equipment is a variety of Guralp's seismometers and digitizers.

2.1.2 Temporary installations

Temporary stations are housed in existing structures, with sensors insulated using styrofoam boxes where possible. Equipment includes Quantera Q330S+ digitizers and Kinemetrics/Metrozet MBB-2 seismometers, recording at 100 and 200 samples per second.

2.1.3 Mobile stations (CROSSNET mobile pool)

Mobile stations deployed as part of the CROSSNET project are housed in existing structures, with sensors insulated using styrofoam boxes where possible, Equipment includes Quantera Q8 digitizers and Kinemetrics/Metrozet MBB-2 seismometers, recording at 100 and 200 samples per second.

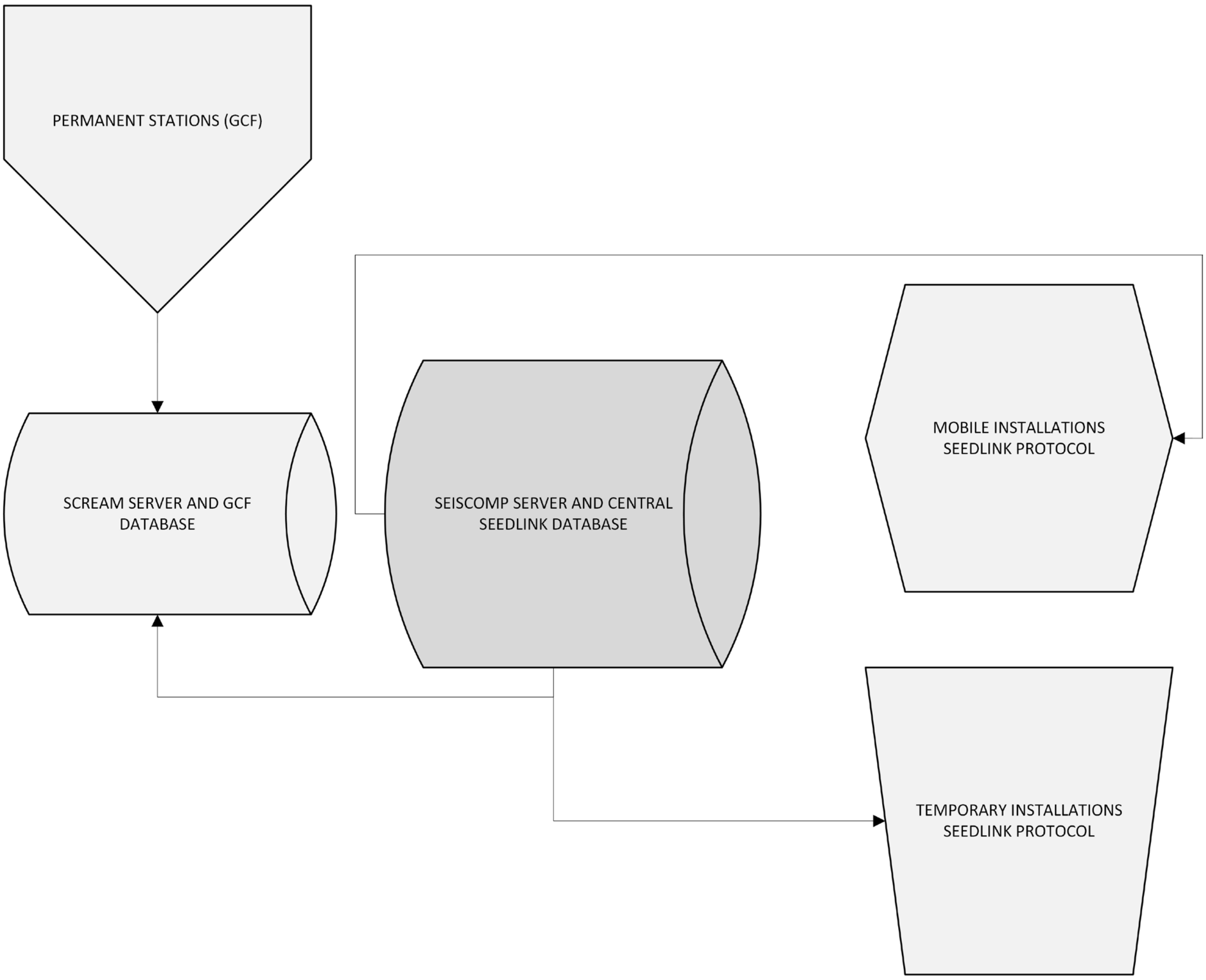


Figure 2. Recording scheme at the CSS headquarters. Direction of arrows shows whether the data is pulled or pushed. SeisComP server pulls all of the data from known addresses.

2.2 Data collection

2.2.1 Permanent installations

Data are stored localy on a separate industrial computer running Guralp's Scream! 4.6 software in proprietary GCF format.

Data transmission to the central server is via a range of communication systems selected according to site availability: cellular networks for stations within range of mobile data coverage, fixed terrestrial lines where wired infrastructure such as DSL or fiber is available and Satellite Internet for remote locations where no other communication options are available. The IP of the station is generaly not known nor recorded. Remote access to station is possible via industrial computer using TeamViewer for remote access and then via serial port connection (RS232) to Guralp's digitizers.

2.2.2 Temporary installations

Data are archived localy on USB sticks (2 per each Q330S+) as multiplexed miniseed files. The communication link is via a mobile network with a Westermo MRD-405 router with OpenVPN tunnel to the SeisComP server at the CSS headquarters in Zagreb. VPN IP address of each modem is known and remote assistance is directly to Q330S+ digitizers, using variety of protocols (ssh, scp, ftp, http).

2.2.3 Mobile stations (CROSSNET mobile pool)

Data are archived localy on microSD card within Q8 as multiplexed miniseed files. The communication link is via a mobile network with a mix of Teltonika RUT200/Teltonika TCR100/Westermo MRD405/Advantech ICR-2031 routers with OpenVPN tunnel to the SeisComP server at the CSS headquarters in Zagreb. VPN IP address of each modem is known and remote assistance is directly to Q330S+ digitizers, using variety of protocols (ssh, scp, ftp, http).

2.3 Noise analysis

In order to quantify the quality of installations, the probabilistic power spectral density was chosen as a means of rapid quality control. Using the Obspy package version 1.2.1 (Beyreuther et al., 2010; Megies et al., 2011; Krischer et al., 2015; The Obspy Development Team, 2020), the analysis was performed with the PPSD analysis module, which is based on the McNamara method (McNamara et al., 2004). For the comparison of the different stations/setups, only the median curve of the PPSD was selected to get a better insight into the performance of the stations. To monitor the performance of each station in detail, a detailed PPSD analysis as well as some other parameters were visualized (e.g. median, inter-quantile range and similar). Chart for all stations grouped in three types (permanent, temporary, mobile) was created to give insight into the differences between stations. In graph, the NLNM and NHNM models are given for comparison, medians for each group were plotted as thicker lines in order to easily compare overall group performance. Annual data series were used to evaluate each facility and we chose not to remove seismic events from the analysis.

For each of the components, all available data collected in one year were prepared as an annual miniseed file. As already mentioned, the data was not filtered, events or failures removed, etc. The basic idea was to compare the worst-case scenario in order to gain insight into the quality of each deployment. In other words, neither earthquakes (that bias noise curves upward), nor cultural noise (i.e. not picking just quiet nightly hours), nor instrumental artifacts (calibration pulses, glitches, etc.) nor seasonal/weather effects were removed from input data, making it effectively a worst-case (or most noisy) scenario.

An FDSN inventory was created for all stations and Obspy routines were used to perform the PPSD analysis. For each station and channel, the PPSD was calculated and stored as compressed numpy binary (npz) files for later use in plotting the results. Median and mean curves were plotted for each PPSD analysis, as well as area under median PSD curve to NLNM, Pearson correlation coefficient and root mean square error. Separately, interquantille range was drawn for a quick assessment of site quality (primarily to support the selection of potential sites for future permanent stations in the CROSSNET project).

3. Results

For this study, three typical installations were selected that are representative for the three types of stations within the network which the CSS maintains. Station MOSL was selected for the permanent network, station 7433 for the Petrinja temporary installation and station BATN for the CROSSNET mobile pool stations. Figure 1 shows the geographical location of all three stations, while Table 1 summarizes the information about the stations and equipment.

For MOSL data were used the from January 2, 2022 to December 31, 2022, for station 7433 the period from January 1, 2022 to December 31, 2022 was selected and for BATN we used the period from February 7, 2024 to December 31, 2024. These periods were chosen because they had the most data available for analysis.

The results of the analysis for each of the stations are shown in Fig. 3, and the combined performance of the permanent, temporary and mobile network is shown in Fig. 4.

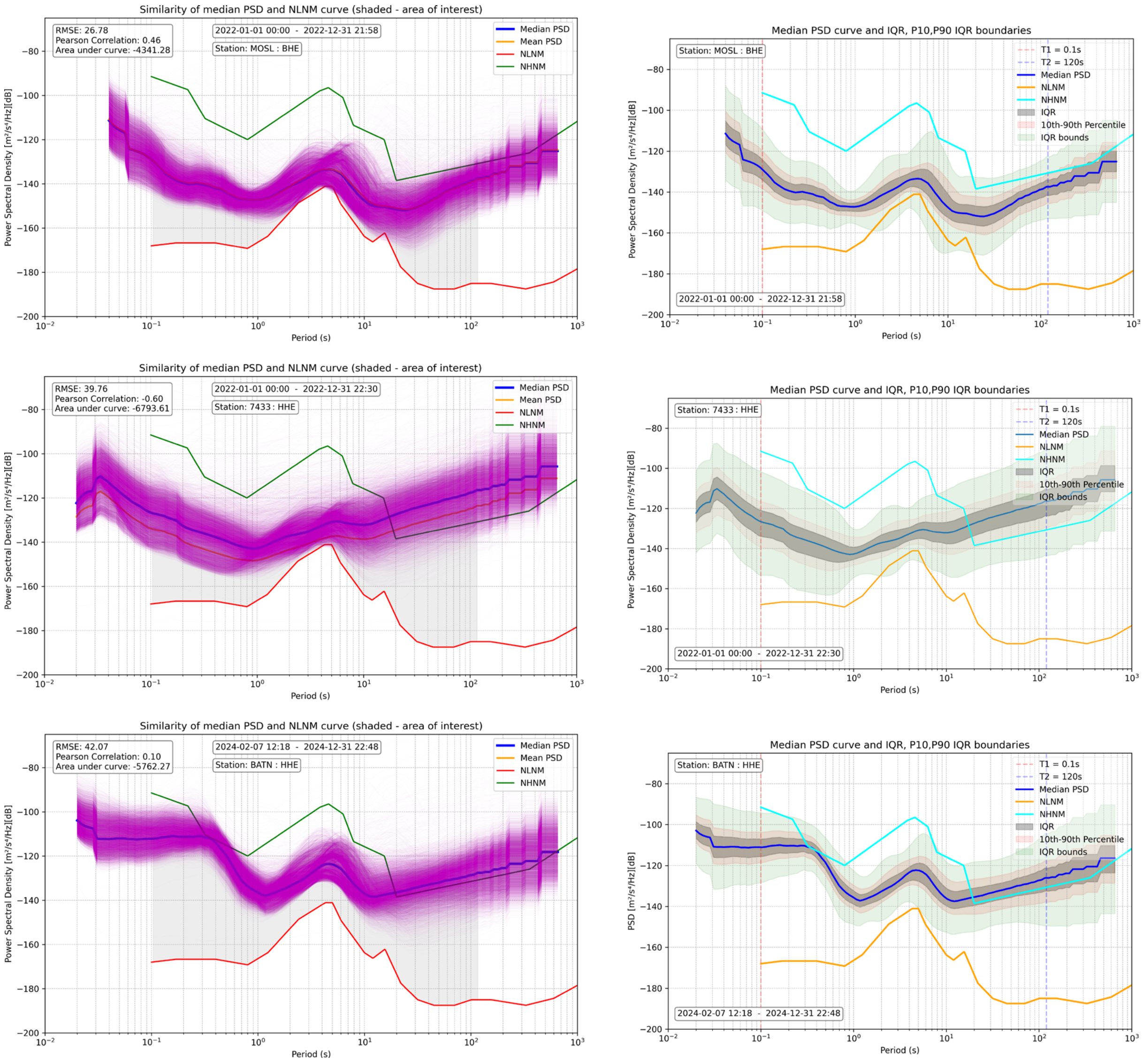
As shown in Fig. 3, the component noise characteristics separate the three sites clearly: MOSL tracks the NLNM most closely, with a low median PSD and a consistently narrow IQR/P10-P90 envelope across almost all periods; its microseism peak (~5-20 s) is well defined but moderate, and long periods remain near or below the NHNM. 7433 is noisier than MOSL, with a median shifted upward – especially at short periods (T < ~0.33-0.5 s) and a broader IQR that points to intermittent cultural influence; its microseism band is stronger than at MOSL and, for periods

≥16 s, the mean and median tend to approach or locally exceed the NHNM. BATN is the noisiest and most variable station overall: the median is elevated across bands, the microseism peak is highest, and the IQR/P10-P90 spread is widest – particularly at long periods (>20-30 s), where both mean and median rise markedly, consistent with tilt/wind sensitivity or installation coupling. In line with these patterns, the mean-median separation is smallest at MOSL, larger at 7433, and largest at BATN, reflecting increasing temporal variability from a well-behaved mountain site (MOSL) through a culturally influenced site (7433) to a site dominated by environmental/installation noise (BATN).

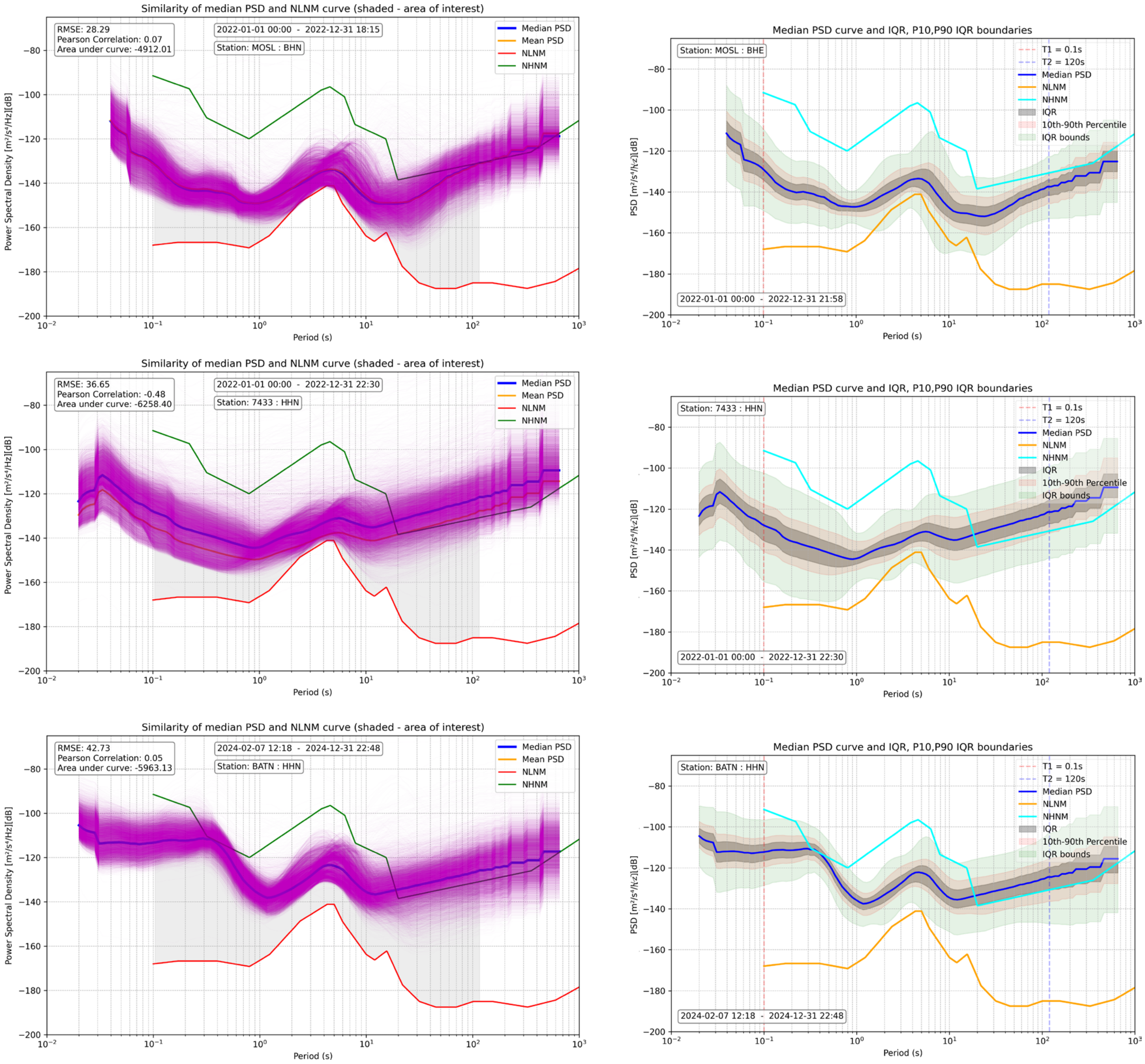
Table 1. Stations and equipment used.

Station code	Location	Latitude (°N)	Longitude (°E)	Elevation (km)	Type	Sensor	Digitizer	Comm.
MOSL	Moslavačka gora	45.6135	16.7544	0.480	Perm	CMG-3ESPC	CMG-DM24 S3	4G
7433	Omanovac	45.4174	17.2484	0.654	Temp	MBB-2	Q330S+	4G
BATN	Batina	45.8840	18.8470	0.205	Mobi	MBB-2	Q8	4G

(a)



(b)


Similarity of median PSD and NLNM curve (shaded - area of interest)
RMSE: 28.29
Pearson Correlation: 0.07
Area under curve: -4912.01
2022-01-01 00:00 - 2022-12-31 18:15
Station: MOSL : BHN
Median PSD
Mean PSD
NLNM
NHNM
Power Spectral Density [m²/s⁴/Hz][dB]
Period (s)
Median PSD curve and IQR, P10,P90 IQR boundaries
Station: MOSL : BHE
T1 = 0.1s
T2 = 120s
Median PSD
NLNM
NHNM
IQR
10th-90th Percentile
IQR bounds
2022-01-01 00:00 - 2022-12-31 21:58
PSD [m²/s⁴/Hz][dB]
Period (s)
Similarity of median PSD and NLNM curve (shaded - area of interest)
RMSE: 36.65
Pearson Correlation: -0.48
Area under curve: -6258.40
2022-01-01 00:00 - 2022-12-31 22:30
Station: 7433 : HHN
Median PSD curve and IQR, P10,P90 IQR boundaries
Station: 7433 : HHN
2022-01-01 00:00 - 2022-12-31 22:30
Similarity of median PSD and NLNM curve (shaded - area of interest)
RMSE: 42.73
Pearson Correlation: 0.05
Area under curve: -5963.13
2024-02-07 12:18 - 2024-12-31 22:48
Station: BATN : HHN
Median PSD curve and IQR, P10,P90 IQR boundaries
Station: BATN : HHN
2024-02-07 12:18 - 2024-12-31 22:48
−80
−100
−120
−140
−160
−180
−200
10⁻²
10⁻¹
10⁰
10¹
10²
10³

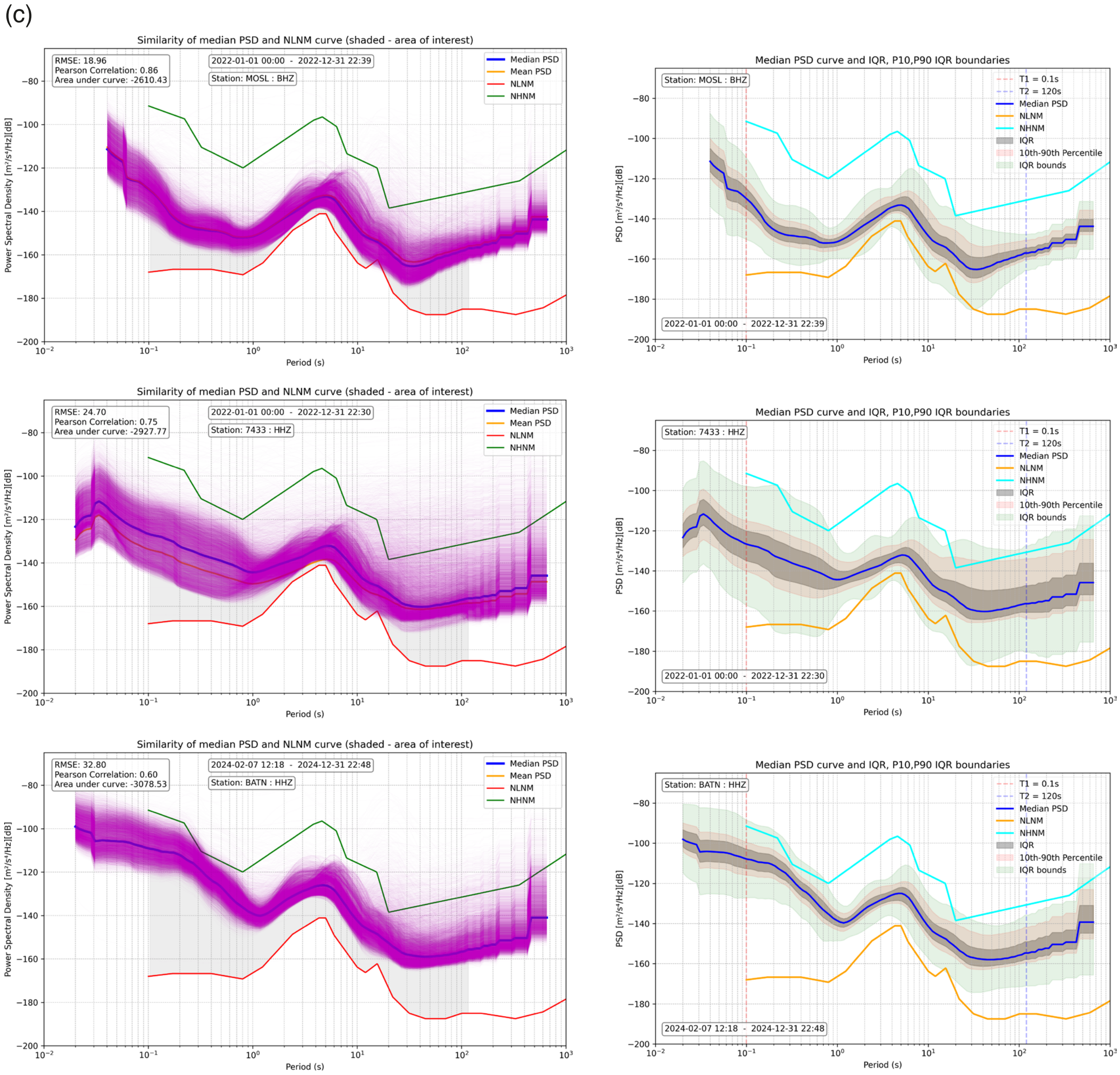
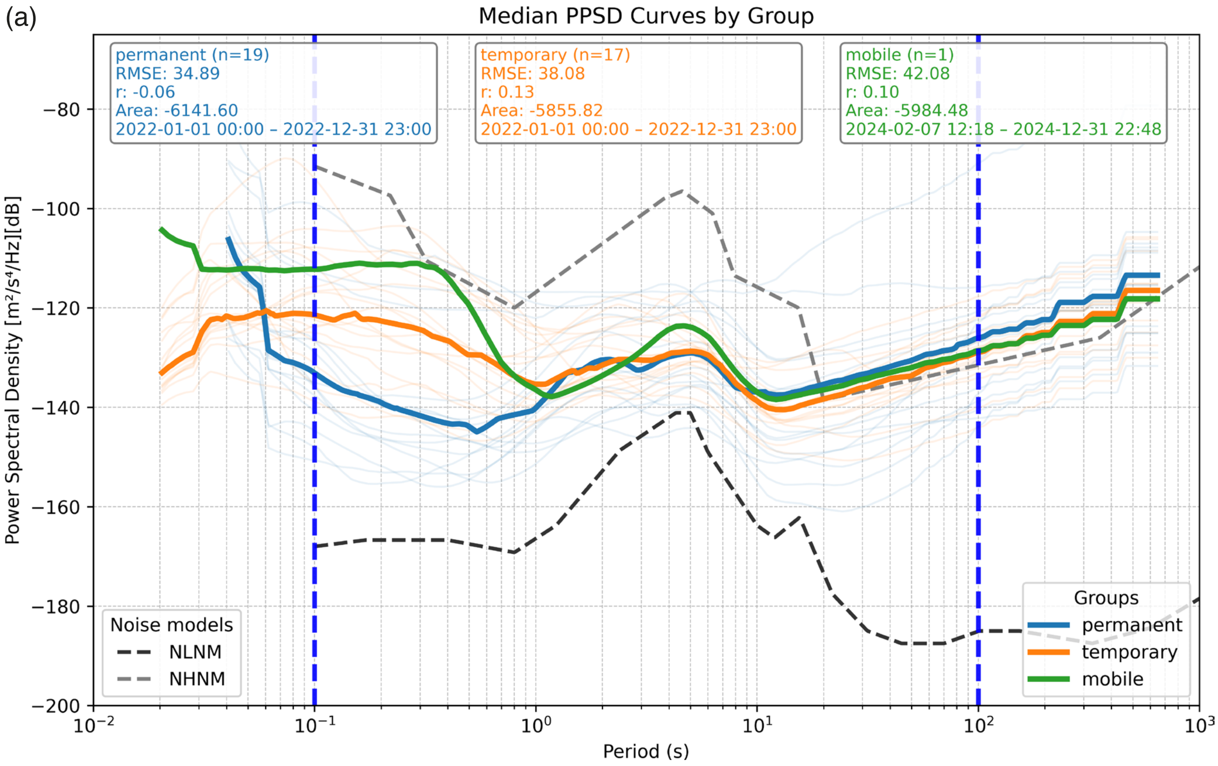
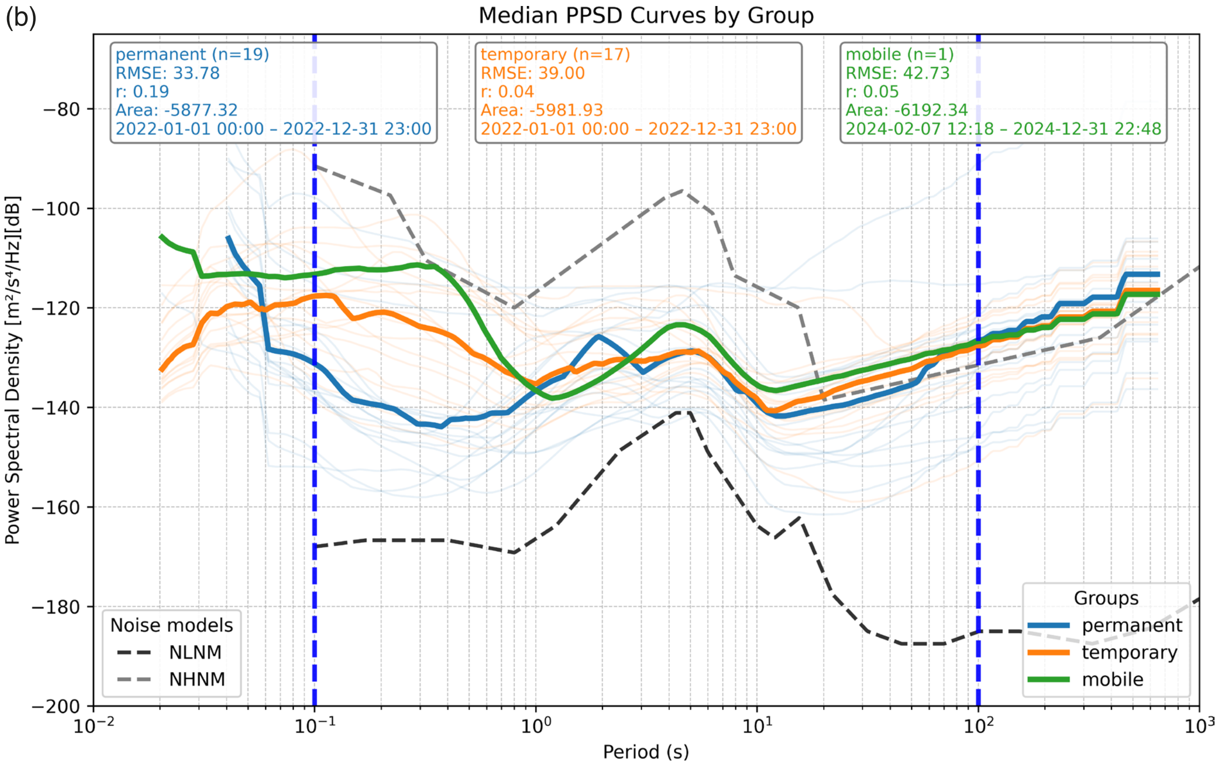


Figure 3. PPSD analysis results for stations MOSL, 7433 and BATN. Both classic PPSD graph and interquantile range (IQR) analysis graph are shown for each station. (a) E component, (b) N component, (c) Z component

Figure 4 shows the large variability of the median PSD curves for all types of installations. For the horizontal components E (Fig. 4a) and N (Fig. 4b), the permanent stations are clearly the quitest for periods up to 2 s. Between 2-12 s temporary and mobile stations dip slightly below the permanent median. From 30-50 s up permanent median rises more quickly than temporary pool. For the vertical component (Fig. 4c), the situation shifts. The temporary and mobile stations perform comparable and even better in part of 3-15 s, and they cluster more tightly than permanent stations. This can be expected, since Petrinja mobile pool stations are covering less diverse environment. For lower time periods (2s or less), most of the permanent stations have lower noise levels than the temporary and mobile stations.

Temporary stations reach better performance in vertical component in the range of more than 10 seconds than permanent stations when looking at the group median. That can be attributed to newer equipment in the temporary and mobile installations, as well as to the varying quality of permanent installations over the bigger territory and noisier enviroments (within cities, etc.). Roughly half of the permanent stations perform better than Petrinja's mobile pool stations for periods of more than 4 seconds. Summarized metrics is given in Table 2.


(a)
Median PPSD Curves by Group
permanent (n=19)
RMSE: 34.89
r: -0.06
Area: -6141.60
2022-01-01 00:00 – 2022-12-31 23:00
temporary (n=17)
RMSE: 38.08
r: 0.13
Area: -5855.82
2022-01-01 00:00 – 2022-12-31 23:00
mobile (n=1)
RMSE: 42.08
r: 0.10
Area: -5984.48
2024-02-07 12:18 – 2024-12-31 22:48
Power Spectral Density [m²/s⁴/Hz][dB]
−80
−100
−120
−140
−160
−180
−200
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Period (s)
Noise models
NLNM
NHNM
Groups
permanent
temporary
mobile


(b)
Median PPSD Curves by Group
permanent (n=19)
RMSE: 33.78
r: 0.19
Area: -5877.32
2022-01-01 00:00 – 2022-12-31 23:00
temporary (n=17)
RMSE: 39.00
r: 0.04
Area: -5981.93
2022-01-01 00:00 – 2022-12-31 23:00
mobile (n=1)
RMSE: 42.73
r: 0.05
Area: -6192.34
2024-02-07 12:18 – 2024-12-31 22:48
Power Spectral Density [m²/s⁴/Hz][dB]
−80
−100
−120
−140
−160
−180
−200
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Period (s)
Noise models
NLNM
NHNM
Groups
permanent
temporary
mobile

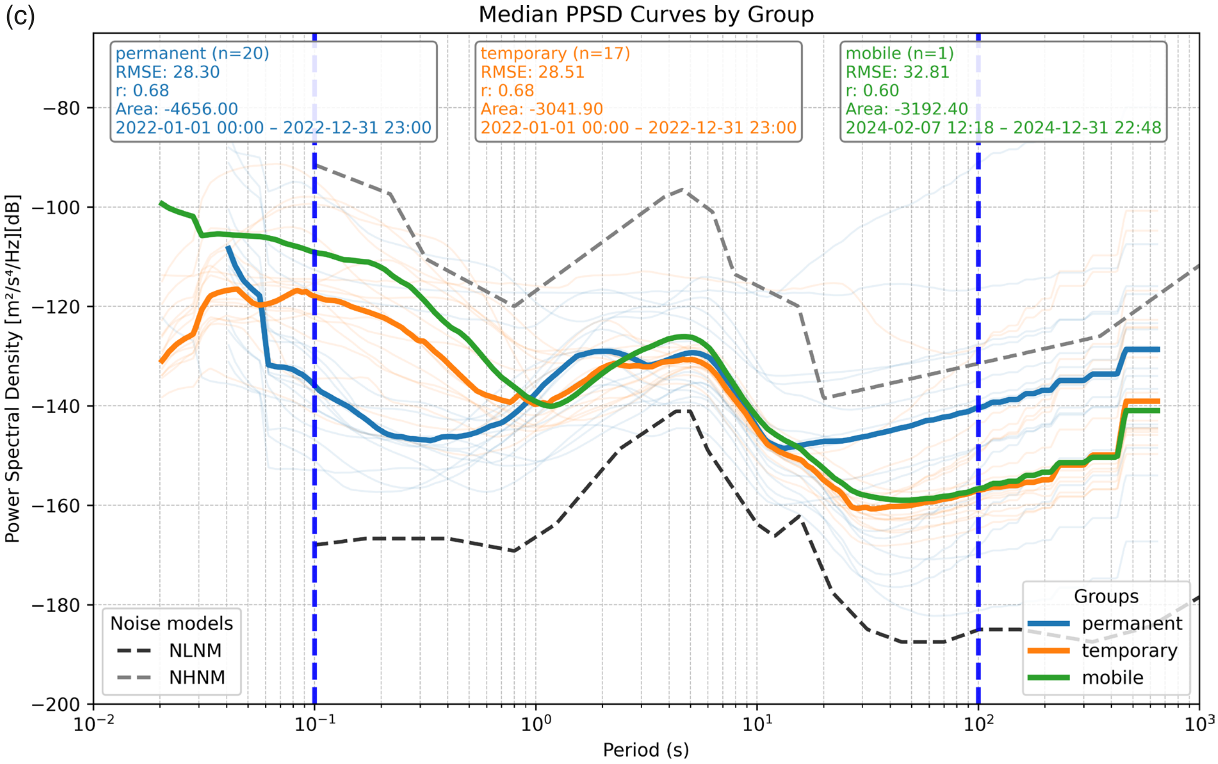


Figure 4. Median and individual PPSD graphs for permanent (blue), temporary (orange) mobile (green) network, (a) E component, (b) N component, (c) Z component. Thick lines represent median.

Table 2. Metrics per station.

Station Code	Type	Noise level (Microseism band)	P10-P90 range	Key Challenges
MOSL	Permanent	Lowest; near NLNM (microseism peaks moderate)	Narrow – moderate	Forestry road/hut nearby; comms relay; wind/thermal variations
7433	Temporary	Moderate; stronger than MOSL; long-periods (≥16-20 s) approach/exceed NHNM	Wide	Infrastructure proximity, nearby forest, anthropogenic noise, temperature variations, sensor too shalowly buried
BATN	Mobile	Highest; partly above NHNM	Narrow	Urban noise sources, wind noise, nearby river

4. Discussion

4.1 Influence of geological setting

The MOSL station is located in Moslavačka Gora (Latin: Mons Claudius), in the center of Croatia. Moslavačka Gora is an outstanding geological feature known for its diverse rock formations and significant mineral resources. The massif consists mainly of crystalline rock, including various igneous and metamorphic types that exhibit complex structural relationships. Geologically, the Moslavačka Gora represents one of the most important surface outcrops of the crystalline basement within the Tertiary sediments of the Pannonian Basin. The area is characterized by the presence of granitic rocks, especially monzogranite, containing minerals such as K-feldspar, oligoclase, quartz and biotite with secondary muscovite (Pamić, J. et al., 1984). The station is located on Moslavina Mountain in a forest area. Hard crystalline rock should give excellent sensor-ground coupling and low natural noise levels at 2 seconds and less. Further, thin regolith layer on top should reduce site amplification. However, station is buried in top soil layer without reaching bedrock. Near the station there is a forest road used for transporting timber masses with heavy machinery (within 10 meters from the station), as well as a mountaineering hut (about 30 meters from the station) and a communication relay station (within 100 meters from the station). It turns out that few times a year, the mountaineering hut is supplied with running water via the underground pipe nearby. All this affects the quality of the signal at this location, although it is one of the two stations (including the station on the island of Lastovo) installed in the open field, in a shallow vault, with solar panels as a power supply and is one of the few purpose-built seismic stations in the Republic of Croatia.

Station 7433 is located on Mount Psunj above Pakrac in central Croatia near the mountain hutOmanovac. Omanovac, located in the Psunj Mountains in Croatia, is geologically significant due to its granitoid formations. Studies have identified monzogranite in the Omanovac quarry, with U-Pb isotope dating indicating a concordia age of around 380 million years, placing its formation in the Devonian period (Horvat, 2018). The granitoids in this region, including those from the Papuk and Psunj-Krndija complexes, consist of quartz diorite, granodiorite and monzogranite (Horvat et al., 2004). Granitoid bedrock is preffered, but like in MOSL case, sensor is shalowely buried in topsoil layer, effectively masking the benefits of bedrock. As it is a temporary station for monitoring the aftershock series of the Petrinja earthquake, the sensor is buried shallowly in the ground next to the Omanovac mountain rescue station. Nearby is the woodshed where wood is chopped for the winter, which is clearly visible on the waveform. The digitizer and the power supply are located in this woodshed. The site is prone to thunderstorms and we had an incident where parasitic currents destroyed the battery after a thunderstorm hit the mountain rescue, but the rest of the equipment was undamaged.

The BATN station is located on the Gradac plateau on the border with the Republic of Serbia. This is the region of the mountain Bansko brdo. In this region there are basalt outcrops and basaltic breccias with congeneric deposits, loess and alluvium (Pikija et al., 2015). Basaltic breccias are not found on site, and loess and aluvium are the predominant noise amplifiers in the 0.1 s to 2 s range. As it is a test station for future deployments and a temporary station for the AdriaArray cooperation, the station is located in the Museum of the Battle of Batina, which is not used most of the year, and the sensor is covered with a polystyrene box to lower the temperature variations.

4.2 Comparative analysis of station performance

All three installation types leave considerable room for improvement. Because the sites are in continental Croatia on mountains within the Pannonian Basin, comparison under broadly similar geological conditions is meaningful. None achieved contact with undisturbed bedrock; all are set within a shallow soil layer. As expected, the permanent station performs slightly better overall, while the mobile temporary stations near Petrinja and the mobile station at Batina achieve broadly comparable performance in several bands.

At the permanent installation (MOSL), the noise level lies closer to the New Low-Noise Model (NLNM). Overall performance is good; however, the forested setting – with trees closer than roughly three tree heights – means wind-induced sway transmitted through roots cannot be fully eliminated, and the shallow soil emplacement further compounds this coupling. Across bands, MOSL is consistently the quietest. In the secondary microseism band (3-10 s), MOSL reaches about −137 dB, providing the best small-event SNR; 7433 follows at roughly −132 to −136 dB, and BATN is noisiest at about −126 dB. In the cultural band (<1 s), BATN is up to ~30 dB louder than MOSL on the horizontal (H) and vertical (Z) components, while 7433 is consistently up to ~8 dB above MOSL; the broader IQR at 7433 indicates strong day/night and weekday variability typical of anthropogenic activity. In the 0.5-2 s “structural” band, MOSL remains closest to low-noise levels with a tight IQR, 7433 is higher with a broader IQR, and BATN performs worst – consistent with local context (MOSL has only a dedicated equipment container within ~10 m, 7433 is adjacent to a mountaineering hut, and BATN is inside a museum). In the primary microseism band (10-20 s), the ranking largely holds, with the exception that BATN slightly outperforms 7433 on the Z component.

Given that MOSL’s equipment is older and near end-of-life, upgrading to modern broadband sensors and improving thermal and barometric isolation would likely yield a meaningful reduction in noise. The interquartile range (IQR) further indicates stability differences: BATN and 7433 exhibit greater variability than MOSL, plausibly due to stronger exposure to environmental forcing (wind, pressure, and temperature fluctuations). Deeper vaults in competent material and improved thermal insulation at these sites would markedly enhance performance.

A comparison of median PPSD curves for all permanent CSS stations against the temporary installations shows that temporary/mobile stations perform comparably in the 1-10 s range, while permanent stations retain an advantage below 1 s. The temporary deployments occupy a compact area and many are in floodplain settings around Petrinja, where anthropogenic noise is elevated, so similarities in PPSD shape are expected. The disparity in installation effort between temporary/mobile and permanent sites underscores the need to upgrade permanent stations where feasible – particularly improving bedrock coupling, vault depth, and environmental isolation – to close the remaining performance gap while preserving their short-period advantage.

5. Conclusions and recomendations

This study highlights key features of Croatian permanent seismic stations, particularly regarding vault depth, insulation, and environmental exposure. Since temporary and mobile stations are not as carefully planned and designed as future permanent stations, there are opportunities to improve the data quality. The main problems of the current seismic network are insufficient thermal insulation and lack of air pressure insulation, as well as shallow or non-existent vaults that are overly sensitive to vibrations transmitted from the top soil layer in the vicinity. The same applies to temporary and mobile installations, for which, however, we have lower expectations in terms of signal quality. It is expected that the signal-to-noise ratio of the future national seismic network can be significantly improved by placing instruments into deeper vaults, posthole or borehole installations and careful avoidance of as many sources of interference as possible. For temporary or mobile deployments, additional care should be taken to choose locations with as little anthropogenic noise as possible.

Data availability statement. Data can be downloaded at: https://zenodo.org/uploads/17120859.

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