

Milestone

Milestone 4.1 - Status of the seismocitizen network around the pilot geothermal sites

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Summary

Through the GeoTwins project, we are testing a new paradigm for the collaborative monitoring of geohazards in urban environments. This approach relies on the deployment of Dense Semi-permanent Seismic Networks (DSSNs) using low-cost seismic stations installed in internet-connected buildings and operated by non-seismologists. This new seismic network concept goes beyond the traditional choice between sparse permanent networks and very dense but temporary networks that cannot support long-term monitoring. DSSNs represent an opportunity for established seismic network operators (public research institutes or private companies) to benefit from a vast amount of complementary data.

Two DSSNs, composed of 72 stations in total, now monitor seismicity around the geothermal areas in Alsace, France: the Strasbourg Eurometropole region and the Outre-Forêt region. Initiated and deployed progressively between 2018 and 2024, they are now fully integrated into the operational workflows of the French national seismological survey (BCSF-Rénass). The on-going performance assessment of the Strasbourg network done through the GeoTwins project shows that although urban anthropogenic noise strongly affects detection capabilities, dense low-cost networks can still significantly enhance earthquake monitoring and support high-resolution seismic catalogs when combined with conventional stations.

1. Introduction

The implementation of our Dense Semi-permanent Seismic Networks (DSSNs), designed to bridge the gap between sparse permanent infrastructures and dense temporary arrays, relies on the use of Raspberry Shake stations. These low-cost sensors are straightforward to install, requiring only power, an internet connection, and basic leveling and orientation, making them well suited for large-scale deployments in urban environments. Several of these stations were already used by us in previous projects (in Alsace and on Mayotte, France) where they have proven their usefulness, notably during the 2021 seismic crisis near Strasbourg (Schmittbuhl et al., 2021), despite their installation in urban and noisy environments.

The stations are deployed in the homes of volunteer citizens with no seismological background who agreed to host a seismic station for a minimum duration of three years. The station hosts were recruited through a call for volunteers circulated via various channels such as newspapers, social networks, town-hall and local-association announcements, and flyers.

This deliverable describes the deployment and data-management process of two DSSNs in Alsace and provides information on the assessment of the impact of anthropogenic noise and station density on the performance of the network in detecting and locating earthquakes.

2. Seismocitizen network deployment around the geothermal sites

A total of 72 Raspberry Shake stations (<https://raspberrysshake.org/>) were acquired and deployed. All are 3D models, equipped with three orthogonal velocimetric components and designed exclusively for indoor installation. The stations were deployed in two regions: the Eurometropole of Strasbourg around the city of Strasbourg and the Outre-Forêt areas located about 40 km north of Strasbourg. Both areas were selected because they each host deep geothermal projects.

The Strasbourg Eurometropole area included two deep geothermal projects, one in Vendenheim and one in Illkirch. Operations at both sites were halted following the seismic crisis that culminated in a magnitude 3.9 earthquake on June 26, 2021 (Schmittbuhl et al, 2021). The Outre-Forêt region also hosts two deep geothermal projects, one in Soultz-sous-Forêts, one in Rittershoffen, where operations were recently suspended after a magnitude 2.5 event on December 4, 2025. A third project is starting with the drilling phase of the first well in Schwabwiller, in between Soultz-sous-Forêts and Rittershoffen.

The following two sections describe in detail the deployment process in these two areas.

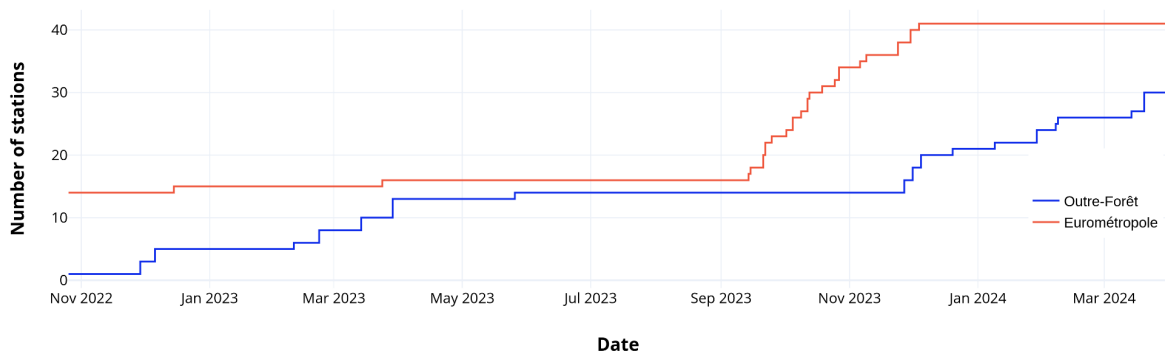


Figure 1: Evolution of the number of installed stations in the area of Strasbourg and Outre-Forêt.

2.1 Strasbourg area

2.1.1 First phase (2017 - 2018): preliminary tests

Starting from 2017, the BCSF-Rénass deployed seven Raspberry Shake stations in the area of Strasbourg Eurométropole where the observatory is located. These stations were installed in residences of EOST personnel or in some of their acquaintances. The objective was to test the feasibility of a low-cost seismic stations network deployed in an urban environment.

2.1.2 Second phase (end of 2019 - 2020): densification of the network during the Vendenheim seismic sequence

In November 2019, the first main induced seismic event (M3.0) related to the Geoven geothermal project of Fonroche-Géothermie occurred at 4 km depth and was felt largely by the Strasbourg population ([Schmittbuhl et al., 2021](#)). Following this earthquake, it was decided to densify the seismic network near the two geothermal projects in the Strasbourg Eurometropole. Five stations were deployed near the Geoven geothermal project, north of Strasbourg. Four stations were also installed near the ES-Géothermie geothermal project, south of Strasbourg. At the end of 2020, 16 Raspberry Shake stations were installed and were largely used to follow regional natural seismicity and the series of induced seismic events that occurred until January 2021.

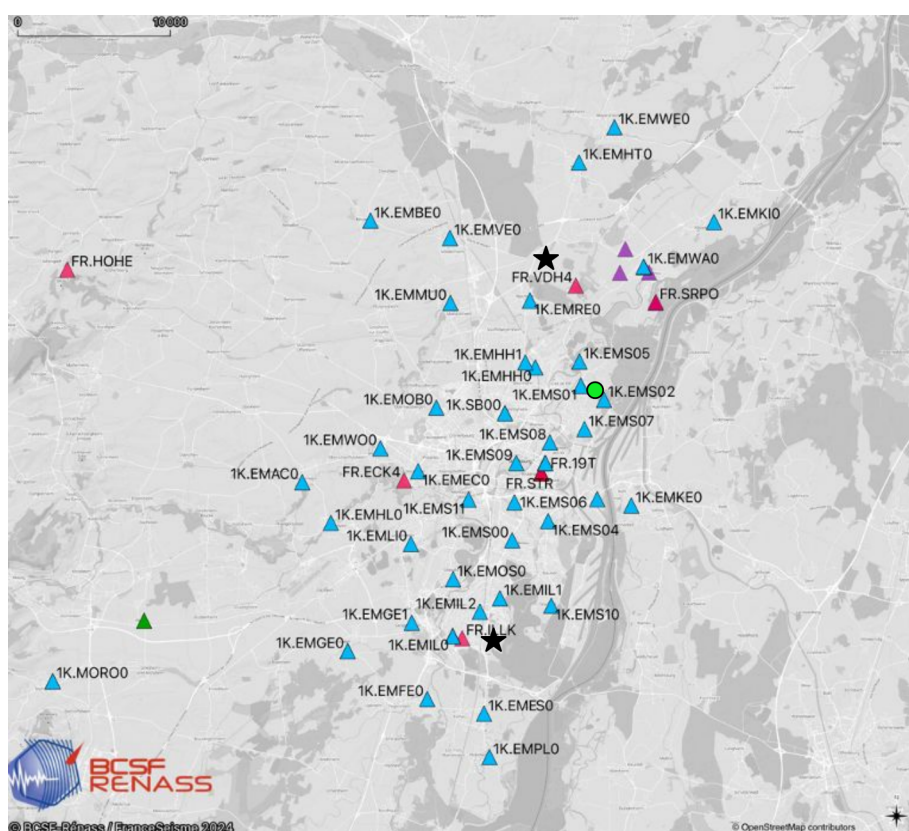


Figure 2: Map of the stations in Eurometropole. **Blue triangles:** Raspberry Shake stations. **Red triangles:** Epos-France permanent stations. **Purple triangles:** temporary EOST stations (no real time data). **Black stars:** deep geothermal sites not in operation. **Green point:** epicenter of the November 2019 M 3.0 event.

2.1.3 Third phase (end of 2022 - 2024): PrESENCE ANR project

2022 marks the start of the ANR PrESENCE project (2022-2026). It is an extension of a previous project (Sismocitoyen) of collaborative monitoring of geohazards in urban and peri-urban environments using a large number of Raspberry Shake stations to densify the French permanent seismic network. 25 additional stations were deployed in residences of voluntary citizens during the 2022-2024 period. At the end of 2024, 39 stations were installed in the Strasbourg Eurométropole area (Figures 1 and 2).

2.2 Soultz-sous-Forêts/Rittershoffen area

Raspberry Shake stations of the DSSN network in the Strasbourg Eurométropole area were deployed in three different phases from 2017 to 2023 by members of the BCSF-Rénass and EOST with the help of LISEC (Laboratoire Interuniversitaire des Sciences de l'Éducation et de la Communication).

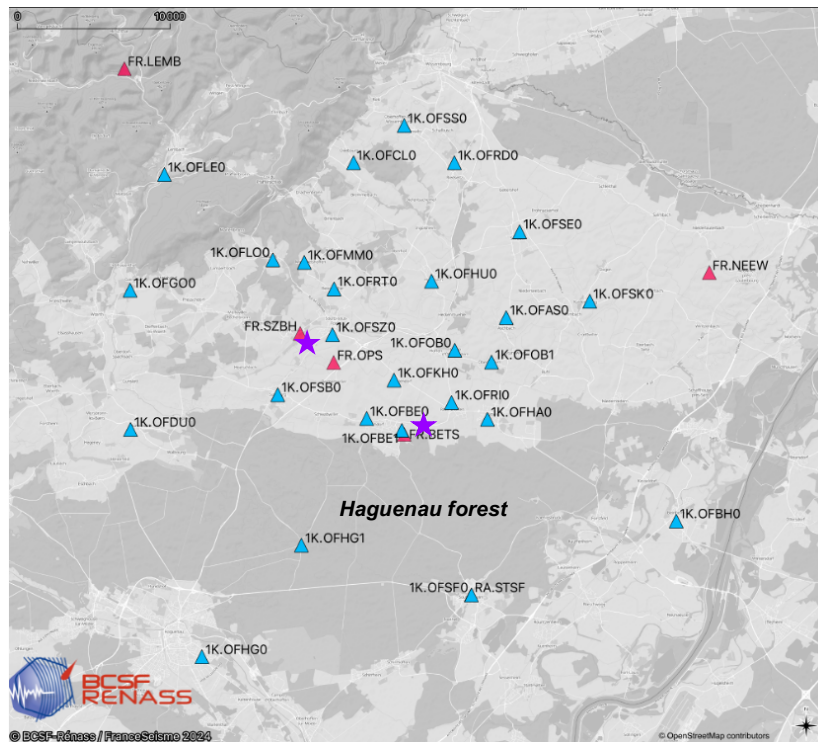


Figure 3: Map of the stations in Outre-Forêt. **Blue triangles:** Raspberry Shake stations. **Red triangles:** Epos-France permanent stations. **Purple stars:** deep geothermal sites in operation.

Within the framework of the PrESENCE ANR project, 30 stations were also installed in the Outre-Forêt area between 2022 and the end of 2024 (Figures 1 and 3). Unlike in Strasbourg, where the station distribution is roughly uniform, the deployment in Outre-Forêt features two zones with low station density. The first is the central part of the area, north of the two deep geothermal projects (around the OFHU0 station in Figure 3). This zone lacks stations because no volunteers were found in the relevant villages. The second low-density area is located south of the geothermal sites. Coverage is sparse there due to the absence of suitable indoor locations with electricity and internet access, as this zone largely corresponds to the Haguenau Forest.

We also note that finding hosts in the Outre-Forêt region proved significantly more difficult than in the Strasbourg Eurometropole. After two months, only 20 volunteers had applied, offering limited options for station placement. Local contacts and word-of-mouth were therefore necessary to reach the envisioned number of stations. One hypothesis for the lower participation in Outre-Forêt is the absence of a unifying media outlet capable of relaying information to a large audience, unlike in the Eurometropole. Indeed, a significant fraction of volunteers in the Strasbourg area learned about the project through a post on the official Facebook page of the Eurometropole of Strasbourg, which has approximately 120,000 followers.

2.3 Data management

From 2017 to 2022, real-time waveform data was sent to Raspberry Shake using the CAPS protocol and retrieved from their server (<https://raspberrysake.org/data-center>). However, relying on this system had two main drawbacks. First, real-time data transfer from Raspberry Shake to our server incurred a fee of €1 per channel per month, corresponding to €36 per year for a 3D station. With the increasing number of Raspberry Shake stations in our network, the total cost became substantial, exceeding €2,000 per year. Second, the use of this acquisition system depends on the availability of the Raspberry Shake data center and may result in data gaps.

For these reasons, since 2022, we have switched to using a VPN (WireGuard) and the SeedLink protocol to directly transfer and access waveform data from the BCSF-Rénass server. All stations installed within the framework of the ANR PrESENCE project were equipped with VPN data transmission. Older stations were progressively updated with the VPN from October 2022 to December 2023.

Direct connection access to the stations with the VPN facilitates their monitoring and their maintenance. We use Ansible (an open source IT automation platform - <https://docs.ansible.com/>) to facilitate the deployment of Raspberry Shake stations configuration and management tasks, ensuring rapid and consistent production deployment. Using this tool, we were able to quickly update the hardware watchdog configuration on all deployed stations. In the event of most system failures, the watchdog mechanism ensures that the machine is automatically restarted, preventing potential data loss. A cron job routine was also implemented with Ansible to check and restart the VPN in case the station cannot reach our server.

An important benefit of using our own servers is the direct integration with the BCSF-Rénass monitoring activities. As a result, the data are processed through the same automatic workflows used for stations that are part of the permanent French seismic network.

We note that the Raspberry Shake data are not currently available through the Epos-France data-center, but can be accessed through the official Raspberry Shake datacenter (network code AM). In addition, the exact locations of the stations cannot be disclosed, in accordance with the agreement made with hosts to preserve their privacy. The reported locations must therefore be randomly shifted within a 1 km radius of the true positions.

3. Evaluation of the performance of the Strasbourg DSSN

Using the data from the Strasbourg Eurométropole DSSN, we explored the advantages and limitations of recording seismicity in urban areas using a DSSN composed of low-cost sensors (Minetto et al, 2025). In particular, our objectives are to:

1. Compare the detection performance of Raspberry Shake stations and permanent stations installed within the Strasbourg Eurométropole.
2. Evaluate the benefits of recording seismicity in a heavily urbanized area, or, in other words, if stations closer to the expected epicenters but in a noisy environment can offer better detection performance than stations farther from the epicenter but installed in a less noisy environment (Figure 4).
3. Determine how increasing the number of stations affects the detection and location performance of the network under different noise conditions.

To assess the detection and location performance of the DSSN, we examine how the magnitude of completeness (M_c) and location uncertainty of modeled earthquakes, whose source properties are calibrated using the source properties of the events recorded during the 2018-2021 Vendenheim sequence, vary in response to diurnal fluctuations in the noise levels recorded at the DSSN stations.

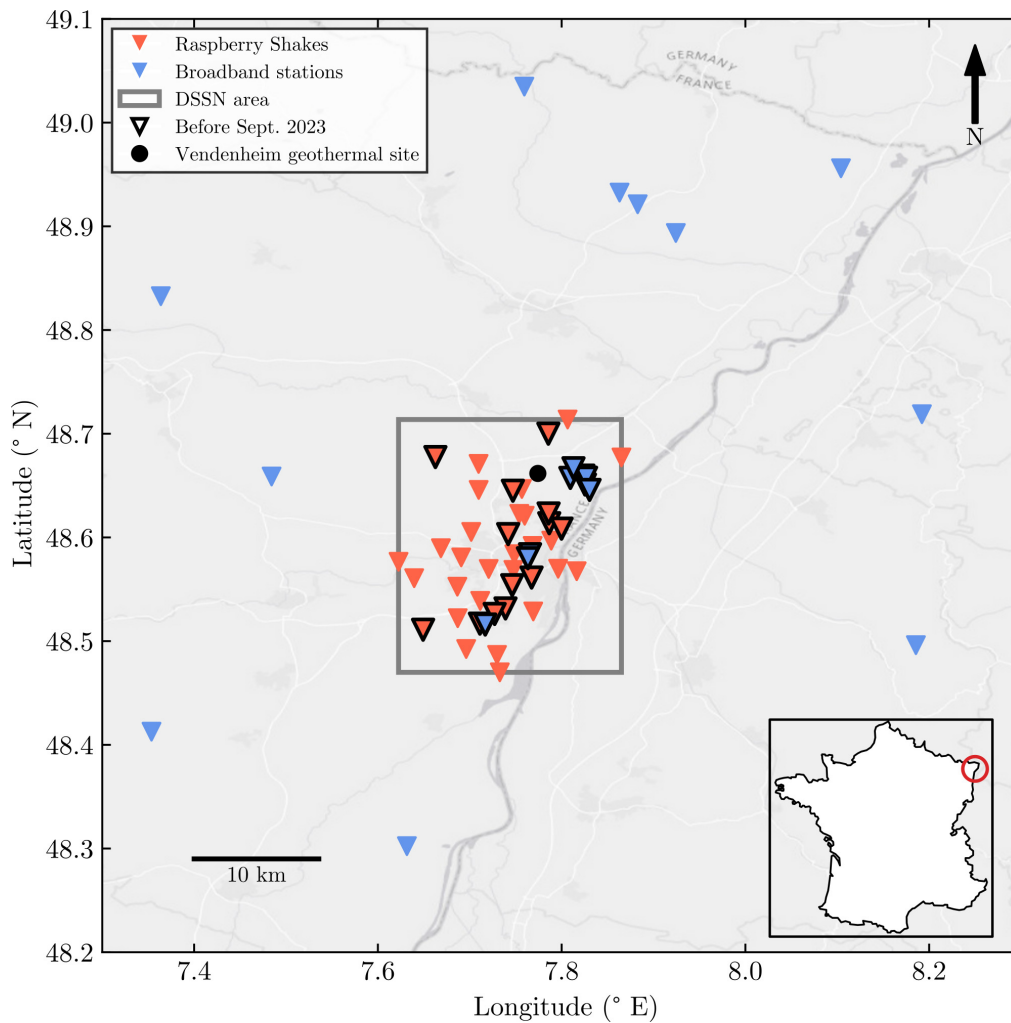


Figure 4: Location of the stations used in the study. The red inverted triangles represent the Raspberry Shake stations, while the blue inverted triangles represent the traditional (broadband or short-period) stations. The gray rectangle marks the area covered by the stations part of the Strasbourg DSSN. The DSSN stations with a thicker outline are the stations active during the Vendenheim sequence.

3.1 Method

To derive M_c , we used the Wideband Spectral Ratio (WSR) ([Schultz et al., 2015](#)). The WSR is defined as

$$WSR = \frac{\sqrt{P_S}}{\sqrt{P_N}}$$

where P_N is the noise power and P_S is the signal power. At a given station, P_N is defined as the integral of the modal noise Power Spectral Density (PSD) N_m , which is derived from the Probabilistic Power Spectral Density (PPSD) calculated over a specified time period:

$$P_N = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} N_m df$$

where f_1 and f_2 are the lower and upper frequencies that define the integration interval. For this study, we computed the noise PPSPD of all available components using the recordings between January 2018 and December 2024. We estimated the PPSPDs for each hour of the day to precisely evaluate how noise levels change over the 24 hours of the day and, in turn, to what degree M_c can change at different times of the day (Figure 5). frequency band used to compute PN ranges from 5 to 23 Hz.

P_S is estimated from the theoretical PSD of an earthquake $|S_s|$:

$$P_S = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} |S_s| df$$

where S_s is the theoretical amplitude spectrum derived from the Brune source model. We refer to [Schultz et al. 2015](#) for the complete formulation of S_s .

We placed the theoretical earthquake sources on a 25 x 30 km grid that covers the DSSN area. The grid points have a spacing of 0.1 km and are located at a depth of 4 km. We calculated the theoretical earthquake PSDs at each point of the grid assuming that the modeled waves are P waves.

When computing the theoretical PSD, we assumed a stress drop of 4 MPa, a rock density of 2900 kg/m³, a source-receiver average P-wave velocity of 3800 m/s, and a S-wave velocity at the source of 3450 m/s. The stress drop corresponds to the average stress drop calculated for the largest events in the catalog, while the wave velocities are taken from a 1D velocity model derived from a 3D model inferred at the location of the Geoven wells ([Lengliné et al., 2023](#)). We determine the quality factor Q for each station by finding the Q value that minimizes the difference between the theoretical spectra and the observed P wave spectra (averaged over the available components) of the Vendenheim earthquakes.

For a given station, the M_c at a grid point is defined as the minimum magnitude required to reach a WSR of 6. We choose this threshold because it corresponds to the WSR value above which the majority (>90 %) of the earthquake waveforms recorded by the DSSN stations have a P-wave pick in the BCSF-Rénass catalog. When evaluating the detection capabilities of the network, M_c at a given point is the fourth-lowest M_c at that location. In other words, an event must be recorded by at least four stations. This criterion reflects the fact that in real earthquake catalogs, detections from multiple stations are typically used to confirm an event.

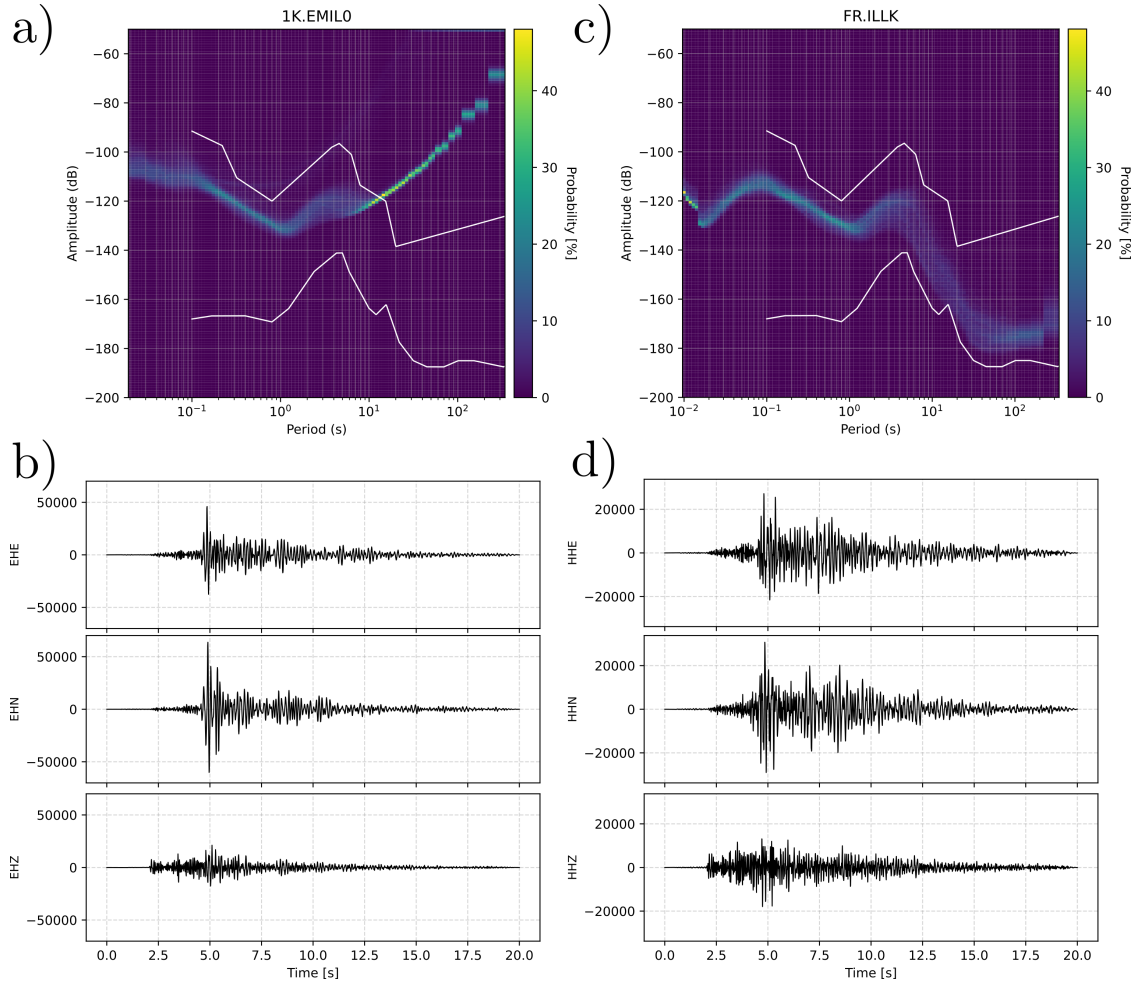


Figure 5: Comparison between data recorded by a Raspberry Shake (EMIL0) station and a nearby broadband station (ILLK). a) PPSD of the Raspberry Shake station. The two white lines represent the high and low noise models from Peterson (1993). b) M2.2 event recorded by the three components of the Raspberry Shake station. c) Same as (a), but using the broadband station data. d) Same as (b), but using the recordings of the broadband station.

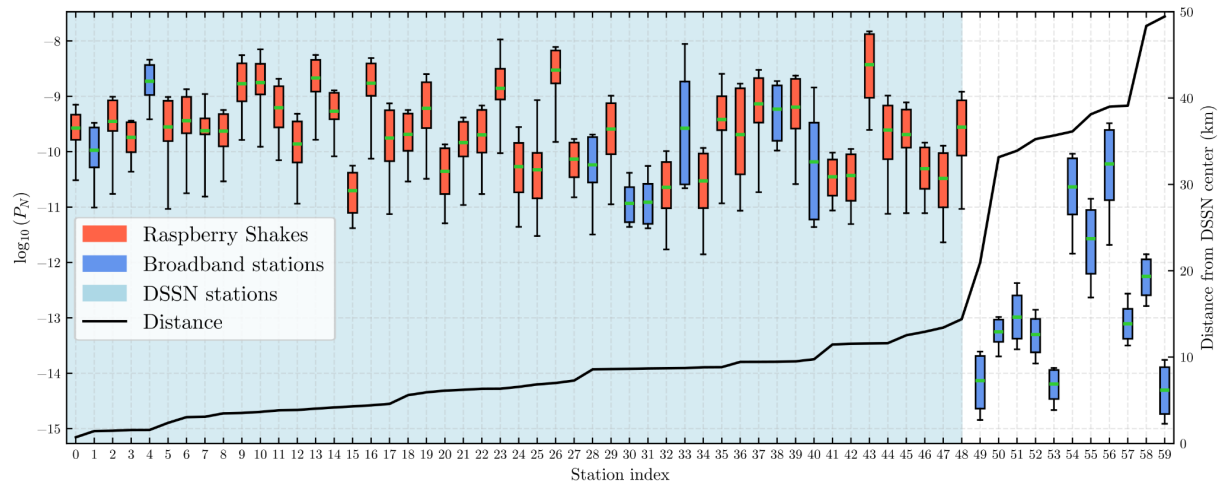


Figure 6: Diurnal variation of noise power (P_N) at different stations. The boxes indicate the interval between the first and third quartiles, while the whiskers extend from the minimum to the maximum value of P_N . The black tick in the box indicates the average $\log_{10}P_N$ value. The stations are ordered by distance from the center of the DSSN, with the black line indicating their exact distance. The light blue area highlights the DSSN stations. Boxes with a thicker outline are part of the old DSSN (i.e., installed before 2023).

3.2 Noise level variations

At a given station, P_N levels can vary by up to two orders of magnitude over 24 hours (Figure 6), with the noisiest hour being 08:00–09:00 and the least noisy hour being 03:00–04:00 local time. The least noisy hour is defined as the hour with the lowest P_N at most of the DSSN stations. Similarly, the noisiest hour is defined as the hour with the highest P_N at most of the DSSN stations.

For a given hour, P_N can vary by more than one order of magnitude between stations (Figure 5). We point out that the broadband stations part of the DSSN, which are hosted in public institutions' buildings or by private entities' buildings, have noise levels comparable to those of the Raspberry Shake stations, which are hosted in private homes (Figure 6). However, at the stations outside the DSSN, noise levels can be several orders of magnitude lower than those observed at the DSSN stations. In addition, the change in noise level between day and night is often limited to less than one order of magnitude (Figure 6).

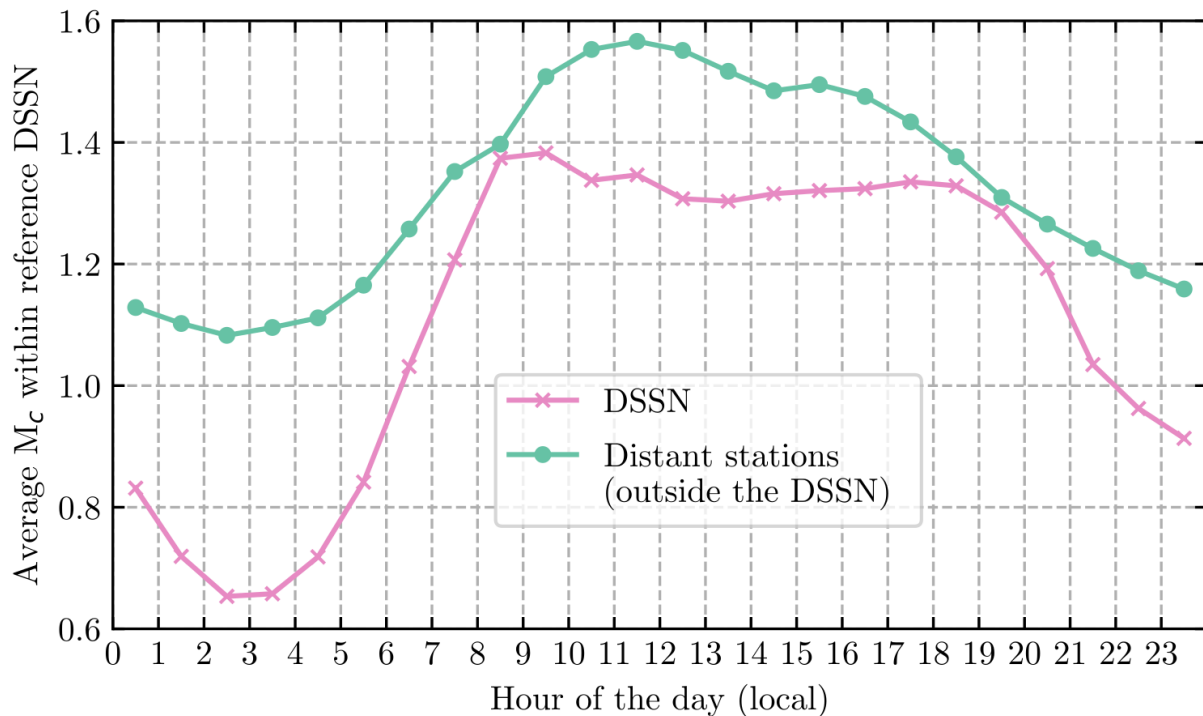


Figure 7: Diurnal variation of M_c , computed as the average of the M_c values estimated within the area covered by the DSSN (rectangle in Figure 4), for two station configurations: the DSSN and the network of broadband stations surrounding the DSSN (Figure 4).

3.3 Impact of the DSSN on magnitude of completeness

The diurnal noise fluctuations are also reflected in the network M_c , as the average M_c within the DSSN increases by approximately 0.7 magnitude units from the least noisy to the noisiest hour (Figure 7). However, when using the network of distant stations, the average M_c remains more stable throughout the day, varying less than 0.4 magnitude units (Figure 7).

The difference observed during the least noisy and noisiest hours can be generalized to the time intervals 20:00–08:00 and 08:00–20:00, respectively, since the average M_c in the area remains relatively stable within these periods for the different networks (Figure 7).

Given the large fluctuations in noise levels throughout the day and the generally higher noise levels within the DSSN, particularly during daytime, some DSSN stations are outperformed by, or perform

similarly to, stations located more than 30 km away. This is evident when analyzing the spatial variation of the difference in M_c between DSSN and the network of distant stations surrounding it, which are well shielded from anthropogenic noise.

During the least noisy hour, the DSSN reduces the M_c achieved by the network of distant stations across most of the network coverage area by up to 0.6 magnitude units (Figure 8a). However, during the noisiest hour, this improvement is more limited (up to 0.2 magnitude units) and largely restricted to regions with the highest station density (Figure 8b). In areas with sparse station coverage, the distant station network achieves M_c values comparable to or even lower than those of the DSSN (Figure 8b).

The addition of more than 20 stations between 2023 and 2024 brings modest (< 0.2) improvements in M_c within the area both at night and during the day (Figure 8c and 7d). The reduction in M_c is limited to small areas of low station density.

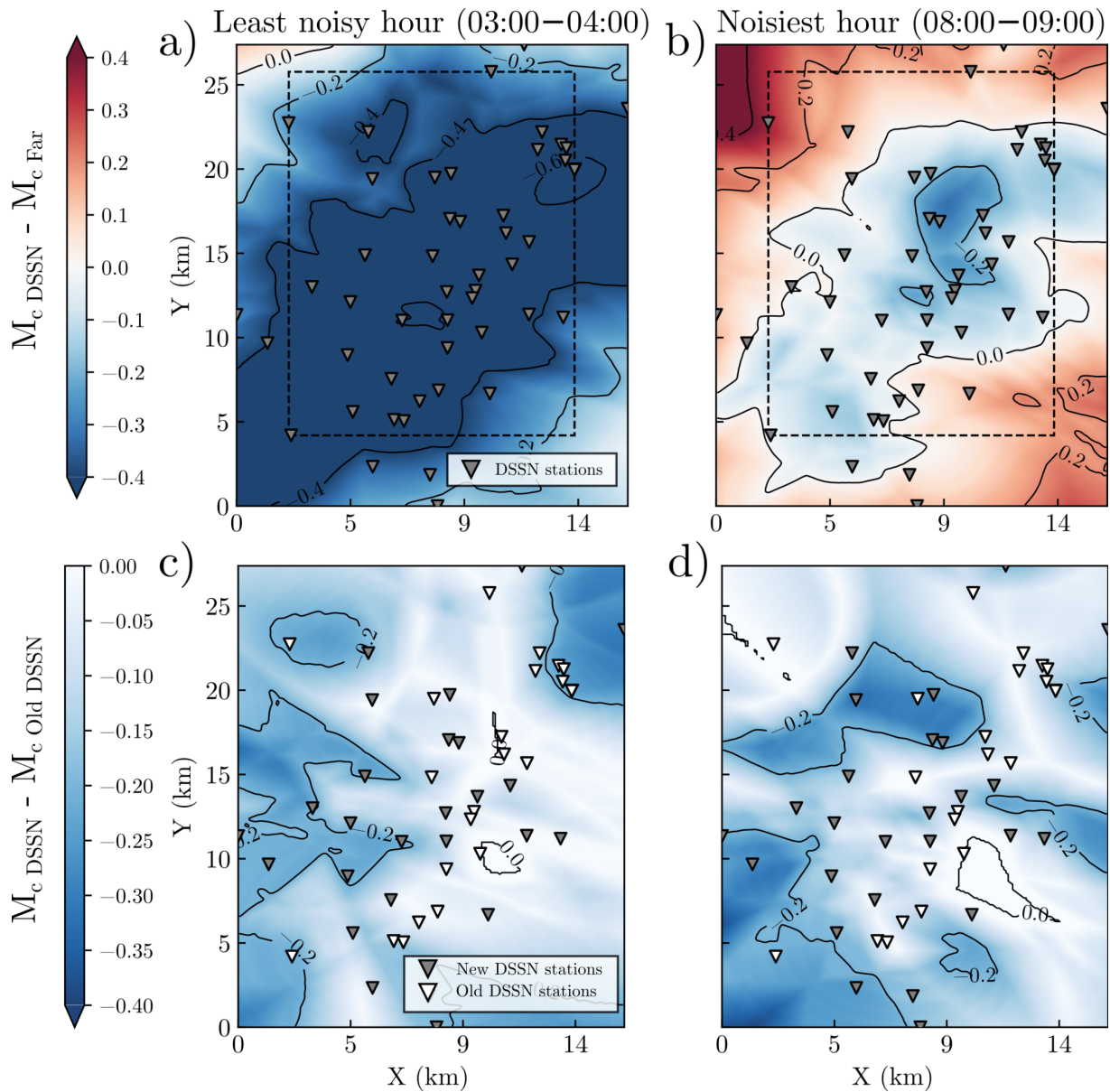


Figure 8: Maps showing the difference between the M_c calculated using different network configurations and at different times of the day, assuming earthquakes located at 4 km depth: a-b) Between DSSN and distant stations c-d) Between the full and old (before 2023) DSSN. The inverted white triangles represent the DSSN stations. Coordinates are given in a local Cartesian reference system.

3.4 Impact of network density on earthquake location uncertainty

We tested whether the addition of new DSSN stations can still improve seismic monitoring, such as by reducing location uncertainty, particularly in depth. Knowing the location of the events, we first calculated the theoretical arrival times using a 3D velocity model, and, to simulate pick uncertainty, we added to the P- and S-wave arrivals a random Gaussian error with a variance of 0.02 and 0.05 s, respectively. We then located the events with NonLinLoc (Lomax et al., 2020). Finally, we took the square root of the diagonal elements of the covariance matrix to derive the uncertainty in the three directions.

Figure 9 shows the change in depth uncertainty within the DSSN for $M_L 1.5$ earthquakes after the addition of the new DSSN stations. During the least noisy hour, events within the network are detected and located by the majority of the available stations. In these conditions, uncertainty decreases primarily in low-coverage areas (up to 0.7 km), but also to a lesser extent (by up to 0.2 km) in well-covered areas (Figure 9a) where no improvement in M_c was observed (Figure 8c). Similar considerations can be made for the noisiest hour (Figure 9b).

We note that, to derive the location uncertainty and M_c , we assumed that all stations are active simultaneously. In practice, even if no new stations are removed or added from the network, stations are not active at all times. The number of available stations is therefore lower and fluctuates over time. For example, the DSSN stations have an average uptime of about 85%. Assuming that all stations share the same uptime and that station downtimes are independent, a binomial model predicts that maintaining for example at least 15 active stations with probability >95% would require 21 stations, corresponding to a 40% increase. Increasing the number of stations can therefore still be beneficial for the network, as it mitigates the impact of temporary station unavailability.

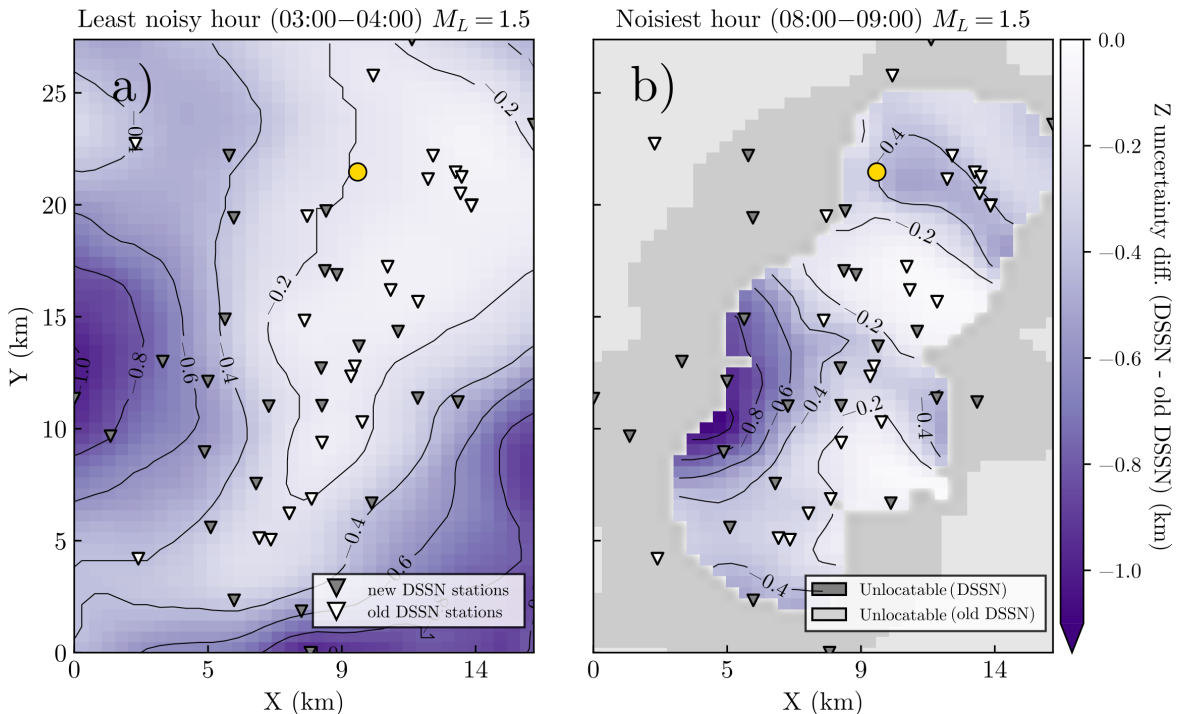


Figure 9: Maps showing the difference between the vertical location uncertainty estimated using current and old DSSN, assuming at each grid point earthquakes of magnitude 1.5 located at 4 km depth; a) Uncertainty differences calculated using noise levels from the least noisy hour; b) Uncertainty differences calculated using noise levels from the noisiest hour. The inverted triangles represent the DSSN stations, the yellow point marks the Vendenheim site. Regions where conditions needed for locating the earthquake are not met are represented in gray for the old DSSN and in light gray for the current DSSN. Coordinates are given in a local Cartesian reference system.

4. Conclusions and perspectives

Anthropogenic noise severely affects the recordings of the DSSN stations, where power noise levels are orders of magnitude higher than those found at some of the permanent stations located in less populated areas and are better protected from noise sources. In addition, noise levels at the DSSN stations vary drastically between night (low noise conditions) and day (high noise conditions). As a result, the average M_c within the network can vary by up to 0.7 units between day and night. Under such conditions, the use of permanent stations located at greater distances from the area of interest, but less affected by anthropogenic noise, can help mitigate the loss of detectability experienced by the local network during the day. In particular, complementing the existing network with these quieter, more distant stations may be more effective in reducing M_c than adding an equal number of stations locally.

Even when increasing the number of local stations has a limited impact on M_c , it can still improve the determination of seismological parameters, such as location uncertainty, and help to maintain coverage in case stations are removed or are temporarily unavailable.

The findings on M_c and location uncertainty show the importance of evaluating both noise levels, network geometry, and target depth when designing or expanding a seismic network. Failure to do so could lead to either having a large network to maintain with little added benefit in characterizing seismicity compared to a much smaller network or to a small network whose performance could be significantly improved with few additional stations.

We have also shown that noise levels can vary significantly between stations, regardless of their location or station type. This variation is likely influenced by the differing levels of human activity between neighborhoods, buildings, and residences. Since Raspberry Shake stations are installed in private homes, our results thus indicate that residential environments do not necessarily exhibit higher noise levels than those found in public or commercial buildings, where DSSN broadband stations are installed.

Given the lack of seismicity since the completion of the Strasbourg DSSN, it was not possible to test its performance directly on observed earthquakes. Future work will focus on the Rittershoffen area, which is currently experiencing ongoing induced seismicity and where a DSSN of similar size is in operation.

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