DEEP

Innovation for:
De-Risking Enhanced
Geothermal Energy Projects

Deliverable

D1.2 Lessons learnt from DSSN deployment: Benefits and Drawbacks.

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Table of contents

Introduction

Through the DEEP project and its French support, the PrESENCE ANR[1] project (2022-2025), is a test of a new paradigm of collaborative monitoring of geohazards in urban environments. It relies on seismological observations obtained using a large number of low-cost internet-connected equipment, together with strong involvement of local public authorities and citizens. **The breakthrough strategy at the heart of the project relies on the deployment of Dense Semi-permanent Seismic Networks (DSSN) using low-cost seismic stations (Raspberry Shake) installed in internet-connected buildings and operated by non-seismologists.** We based our approach on our rich experience from the recent seismic crisis in Strasbourg, which culminated in the paroxysmal Dec 4, 2020 M3.6 earthquake that led to the closure of the deep geothermal energy Geoven site (Fonroche-Geothermie company). The new seismic network concept goes beyond the historical choice between sparse permanent networks and very dense but temporary networks that cannot facilitate long-term monitoring. DSSNs represent an opportunity for traditional seismic network operators (public research institutes or private companies) to benefit from a vast amount of complementary data. The deliverable characterizes the impacts of this new network concept on operational seismic monitoring.

1. Raspberry Shake stations

The stations used are **Raspberry Shake seismic stations**. Raspberry Shake stations are **low-cost internet-connected equipment**. Several of these stations were already used by us in the framework of previous projects (in Alsace and at Mayotte, France). They have proven their usefulness, notably during the seismic crisis near Strasbourg. Raspberry Shake stations were indeed able to strongly improve our monitoring of the seismic events induced by the Geoven deep geothermal project at Vendenheim, in spite of their deployment in urban and noisy environments.

A total of 72 Raspberry Shake were acquired for the project. All are 3D models (i.e. 3-Component model), with 3 orthogonal velocimetric components. **The advantages of these stations include their low cost and their ease of deployment.** It only needs to be electrically connected, internet connected (via a RJ45 cable), leveled and oriented. However, the models we have are only designed for an **indoor installation**.

Technical specifications of Raspberry Shake stations can be found online here:
https://manual.raspberryshake.org/specifications.html

[1] This project is funded by the French National Research Agency (ANR).

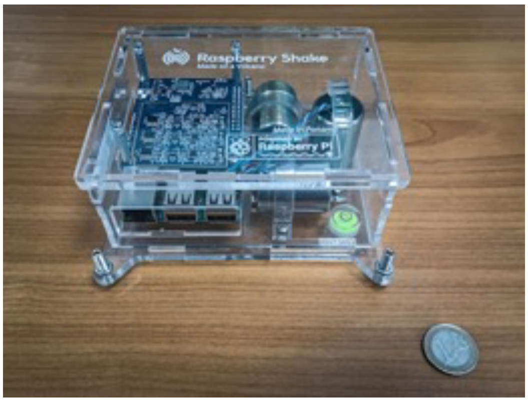

Figure 1: A Raspberry Shake 3D station.

1.1 Calibration test

Before deployment, all stations were controlled with a calibration test. Raspberry Shake stations were successively installed on the test platform of EOST[2], a pillar decoupled from the EOST building (*Figure 2*). A Trillium Compact broadband sensor is used as a reference station. Instrumental responses were computed for all tested stations using the reference station, and then compared with the theoretical instrumental responses given by Raspberry Shake (*Figure 3*). **All the measured instrumental responses were in adequation with the theoretical instrumental response** announced by Raspberry Shake in the interest frequency range (0.2 - 10 Hz).

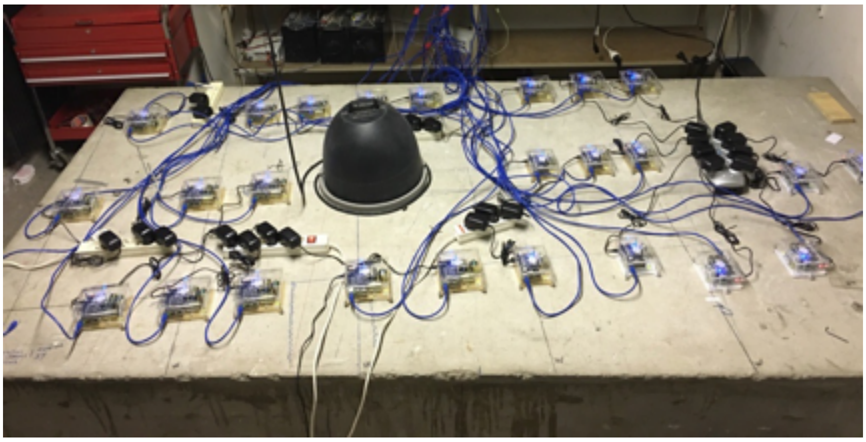

Figure 2: Raspberry Shake stations deployed on the test platform of EOST. The broadband reference station is located at the center of the pillar under the thermal insulating cover.

[2] EOST: Ecole et Observatoire des Sciences de la Terre, Université de Strasbourg, France

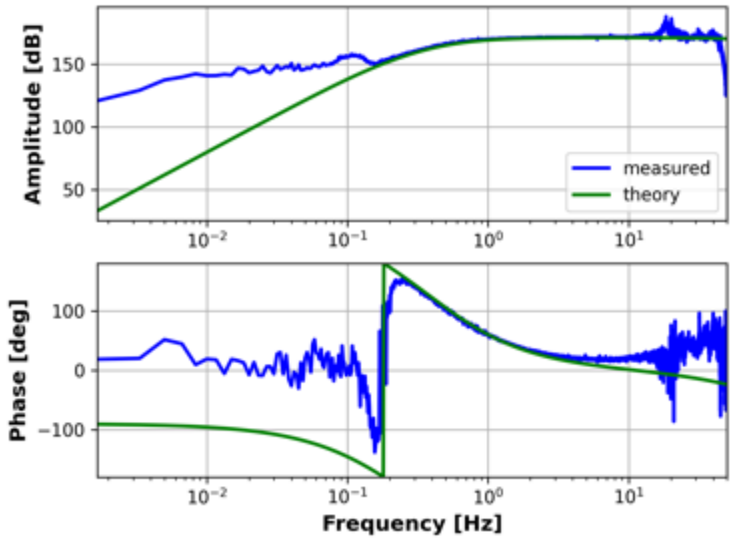

Figure 3: Measured instrumental response of a Raspberry Shake station (blue curve) compared to the theoretical response (green curve).

1.2 Dephasing at high frequencies

During cross-calibrations tests, **a dephasing between the measured and the theoretical instrumental responses from 2 Hz and above was observed for most of the stations** (*Figure 3*). This dephasing can be explained by a difference in the dating of data between the broadband reference station and the Raspberry Shake stations.

A first hypothesis was that the dephasing was due to the inaccuracy of the NTP timing protocol used by Raspberry Shake stations. The NTP protocol is a networking protocol for clock synchronization. The internal NTP server on each station maintains accurate timing by continually correcting for the timing offsets with a distant reference NTP server. However, the NTP protocol is less accurate than GPS timing, used to date data from our Trilllium compact reference station. The relative inaccuracy of the Raspberry Shake stations compared to the reference station would result in the observed dephasing.

A few preliminary tests were performed to observe the eventual influence of the NTP timing protocol on the dephasing. The NTP protocol uses an algorithm to select accurate time servers. By default, Raspberry Shake stations are configured to select time servers from the 'pool.ntp.org' pool, which contains about 1000 servers around the world. The main drawback of this configuration is that the selected server can be geographically distant from the station. For a better timing accuracy, it is preferable for the chosen timing server to be close to the station location. In our preliminary tests, we tried several configurations of the Raspberry Shake stations to force them to synchronize with one of our local servers in the region, or to synchronize with one server of the French pool network.

The initial results did not reveal any influence of the change in configuration of the NTP protocol. However, the following observations were made:

- the dephasing is different between stations tested together during the same period,
- the dephasing is not constant in time for a given station (*Figure 4*), even if the latter seems to be synchronized to the same time server.

Further tests need to be performed to confirm or not the influence of the NTP timing protocol on the dephasing at high frequencies (above 10 Hz) of the Raspberry Shake stations and assess the magnitude of the dephasing and its stability over time.

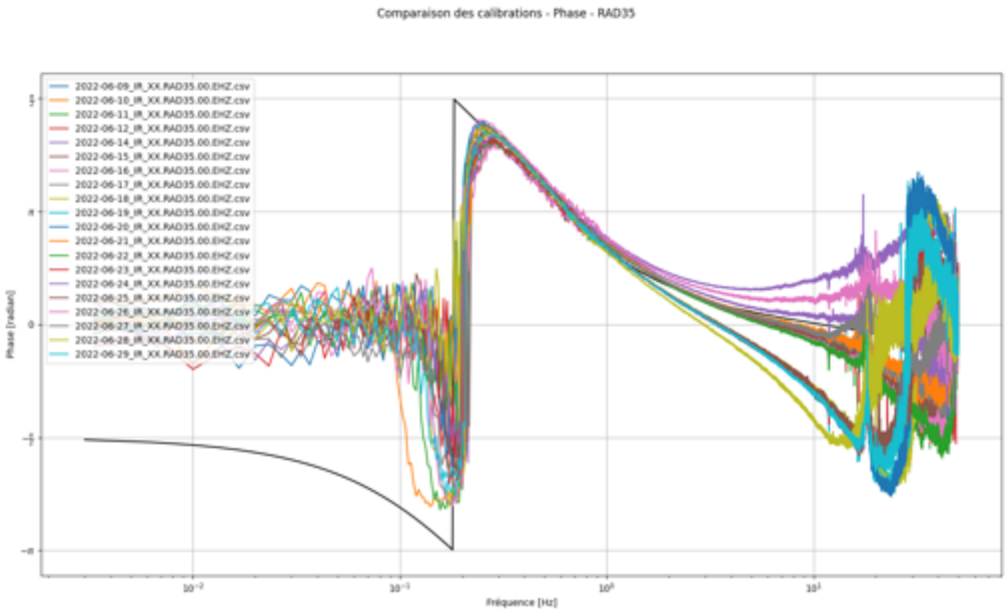

Figure 4: Evolution of the measured instrumental response of a Raspberry Shake station. Each coloured curve represents the measured instrumental response computed for one day. The black curve represents the theoretical instrumental response.

1.3 Defective Raspberry Shake stations

Quickly during the calibration tests, and after the first deployments, we observed issues with some of our Raspberry Shake stations. Some of the stations freeze after a certain amount of time that can vary widely between stations**.** Some stopped functioning after several days, some after 1-2 hours, some even after a few minutes. The latter were unusable. About 15 of the 72 stations of the PrESENCE project were seriously jeopardized by this issue. It was the first time such a problem was observed on some of our Raspberry Shake stations. Other Raspberry Shake stations that we have from previous projects never faced a similar issue.

The symptoms of the crashes are the following:

- the station is unreachable via the rs.local webpage, nor via ssh,
- the station does not respond to the keyboard when one is plugged into the station,
- when the station is connected to a screen, the latter is frozen, sometimes (not always) with an error message (*Figure 5*). The error message often reads “*end Kernel panic - not syncing: Fatal exception in interrupt*”.
- the Raspberry Pi red LED is on, the green one is off (sometimes on but fixed instead of blinking),
- the Raspberry orange LED under the RJ45 connection is blinking.

Several tests were performed on some of the defective stations:

- changing the alimentation cable gave no results,
- formatting and reinstalling the distribution on SD cards gave no results,
- updating the Raspberry PI OS distribution gave no results,
- trying new SD cards (industrial grade) gave no results,

- crashes do not seem related to the use of seedlink protocol[3] as they were observed on stations with the protocol deactivated,
- removing the acquisition card (hat) from the Raspberry PI gave no result.

SD cards from the defective stations and new SD cards were tested on the older Raspberry Shake model we have and work properly. Giving this and the previous tests listed, we deduced that the crashes came from the Raspberry PI. The Raspberry Shake stations purchased with the support of the PrESENCE project were all 3Dv8 versions, all equipped with 3 model B+ Raspberry PI (instead of 3 model B for our other Raspberry Shake stations). It is possible that we received a defective batch of Raspberry PI 3 model B+.

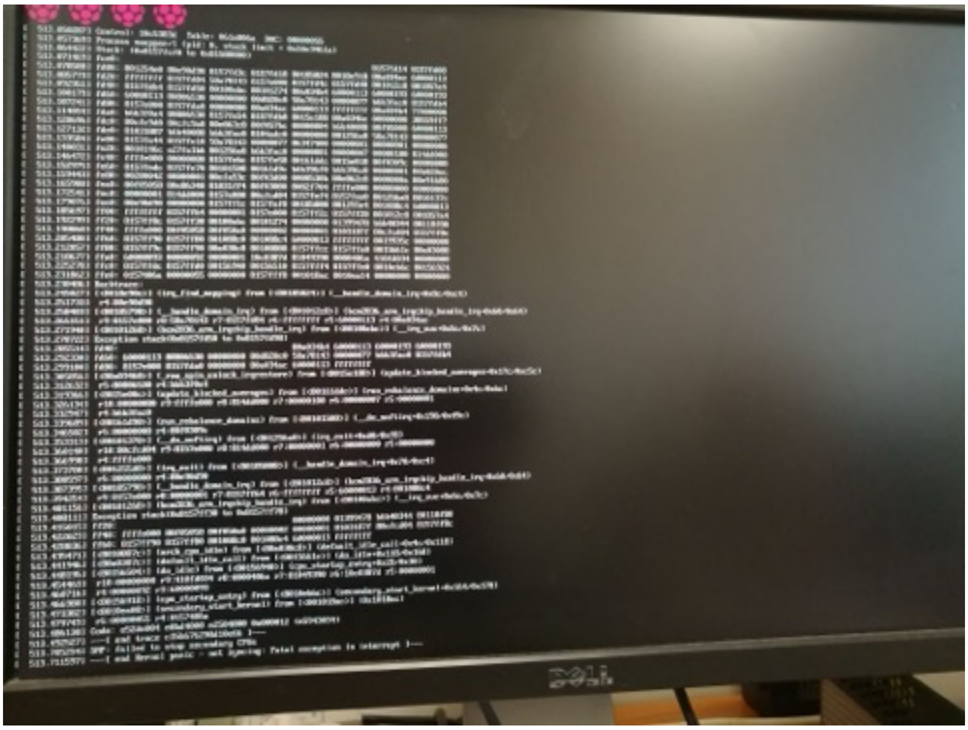

Figure 5: Error message on the screen of a frozen station.

Following these problems, we contacted Raspberry Shake who supplied us with 15 new Raspberry PIs. **The problem has now been globally solved.** Raspberry PI of the most problematic and unusable stations were replaced, and we configured the hardware watchdog of all stations to reboot them in case of freezing (see Part 3).

2. Deployment

2.1 Deployment context

The project is a participatory science project: stations are mostly deployed in residences of non-seismologist voluntary citizens, or in a few cases in administrative buildings (town hall, school). A total of 72 low-cost Raspberry Shake seismic stations were purchased with the aim of deploying them in **two different areas: one corresponding to the Eurometropole of Strasbourg, one corresponding to the "Outre-Forêt" region**, 40 km north of Strasbourg.

[3] We used seedlink protocol to recover waveforms data from the stations via a VPN, not natively installed on the stations. For more details, consult Part 3.

These two areas were targeted because they include **deep geothermal projects**. Two deep geothermal sites are in operation in the Outre-Forêt area at Soultz-sous-Forêts and Rittershoffen. Two deep geothermal sites are actually stopped in the Eurometropole area at Vendenheim and Illkirch. Theoretical maps of the network in the two areas were established, with a denser mesh near the deep geothermal sites (*Figure 6* and *Figure 7*).

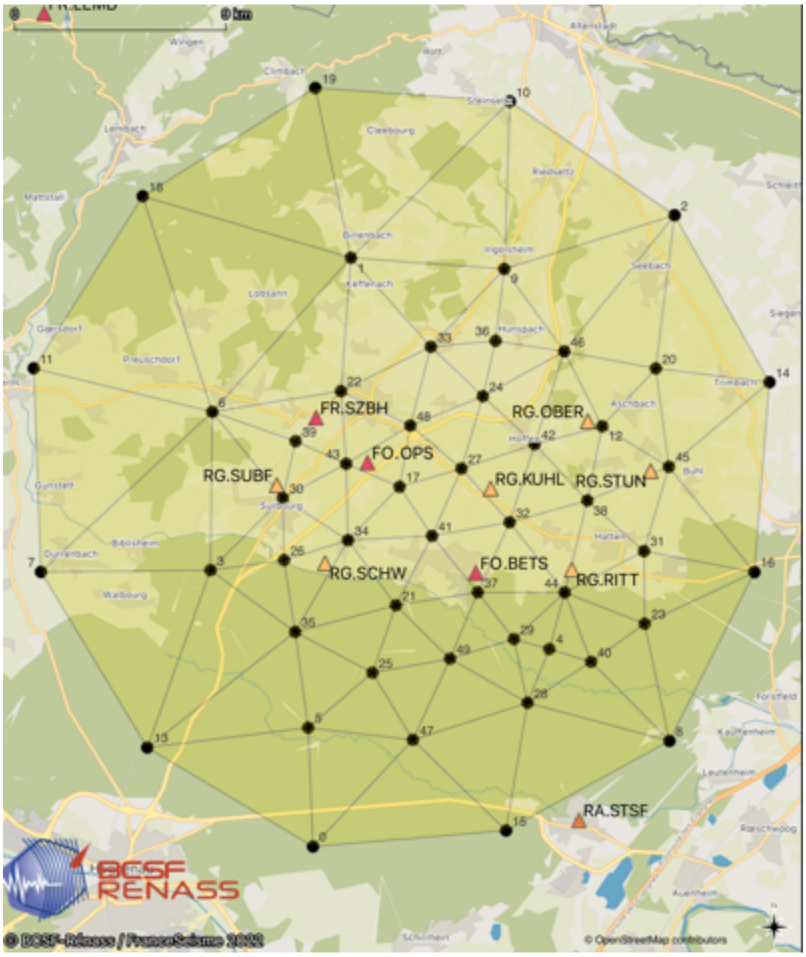

Figure 6: Initial deployment plan map of the network in the Outre-Forêt area. **Black nodes**: Raspberry Shake stations theoretical emplacements. **Red triangles**: Epos-France permanent stations. **Orange triangles**: geothermal operators stations.

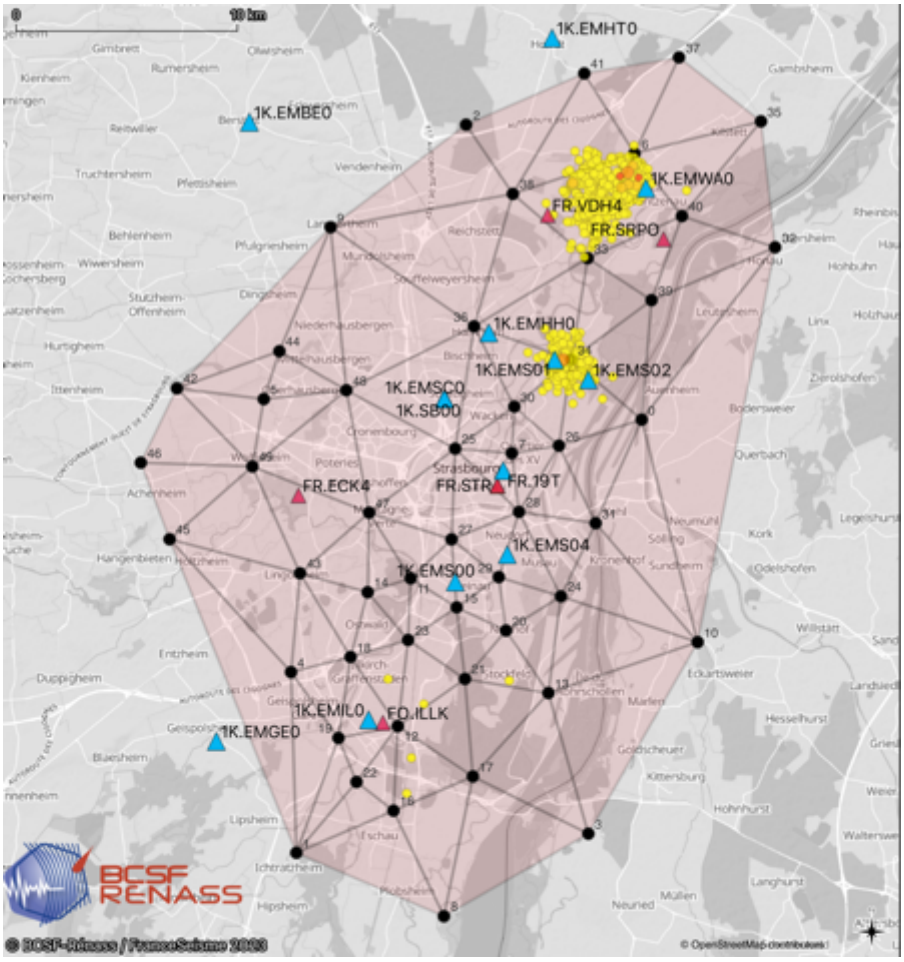

Figure 7: Theoretical map of the network in the Eurometropole of Strasbourg area. **Black nodes**: Raspberry Shake stations theoretical emplacements. **Blue triangles**: Raspberry Shake stations of previous project. **Red triangles**: Epos-France permanent stations. The seismicity from 2019-2022 is represented.

2.2 Search of volunteers

One of the first stages of the project was therefore to find in the two areas voluntary citizens agreeing to host a seismic station for a duration of three years minimum. **To find station hosts, a call for volunteers was circulated** using different means: newspaper, social network, relay of the information by town halls and local associations, flyers in letterboxes, etc.

The search of candidates does not cause difficulties in the area of the Eurometropole of Strasbourg. A base of more than 200 volunteers was quickly established. However, **it was much more difficult to find candidates in the Outre-Forêt area.** After 2 months, only 20 volunteers applied for the project, which did not leave us much possibilities of station locations. We hardly reached about 35 volunteers after 5 months next to the beginning of the call for volunteers. Thanks to a contact in the region and by word of mouth, we have been able to install a dozen stations before the call for volunteers.

One of the hypotheses we have about the lack of volunteers for the Outre-Forêt region is that there is **no federating media with the capacity to relay the information to a lot of people like for the Eurometropole**. In fact, a significant number of volunteers from the Eurometropole area learned about the project thanks to the publication on the official Facebook page of the Eurometropole of Strasbourg, which has about 120k followers. In the Rittershoffen area, controversy has also arisen over the development of a methanation unit, which has limited the population's involvement in renewable energy projects and may have had an impact on the population's propensity to welcome the installation of seismological stations. Hosting seismological stations became a politically committed act.

2.3 Selection of volunteers and deployment

In the framework of the project, some of the candidates were selected to take part in a sociological survey to estimate the impact of the project on their perception of science. **Candidates were primarily chosen according to the seismic interest of their location**, and then for some of them to represent the social variability of the population for the sociological survey.

From a "seismic" point of view, candidates were selected according to the following factors:

- location of EPOS-France permanent seismic stations,
- location of already deployed Raspberry Shake stations from previous projects,
- location of deep geothermal power plants,
- theoretical location of Raspberry Shake stations for the project,
- non-presence of high noisy sources: highways, railways, etc,
- possibility of installation on first floor maximum.

27 candidates for the Eurometropole area and 30 for the Outre-Forêt area were selected to host a station. 15 of them in each area were selected to participate in the sociological survey too.

Stations were deployed in two phases. 14 stations were deployed in the Outre-Forêt area from October 2022 to May 2023. These stations correspond to the candidates we had by word of mouth thanks to our contact in the region. The rest of the stations were progressively installed in the Eurometropole and then in Outre-Forêt from September 2023 to March 2024.

Figure 8: Evolution of the number of installed stations in the area of Strasbourg and Outre-Forêt.

71 Raspberry Shake stations are currently deployed in the two scheduled zones of the project:

- 27 stations were added to the previously 14 installed stations in the area of Strasbourg,
- 30 stations were installed in the area of Outre-Forêt.

Figure 9: 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.

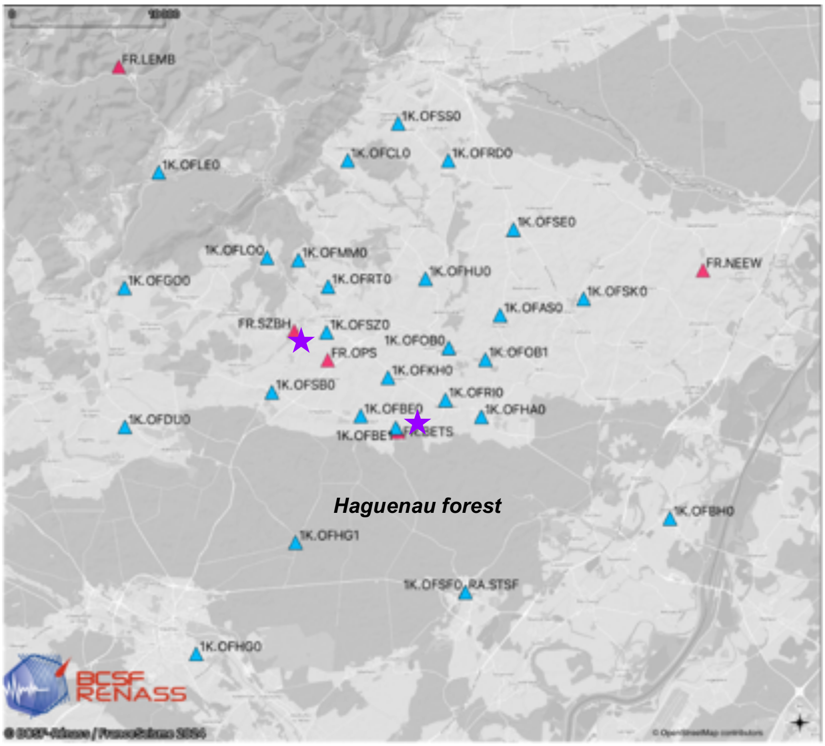

Figure 10: Map of the stations in Outre-Forêt. **Blue triangles:** Raspberry Shake stations. **Red triangles**: Epos-France permanent stations. **Purple stars**: deep geothermal sites in operation.

Deployment review:

- **The deployment in the Eurometropole is quite homogeneous.** We were able to choose desired locations for the stations thanks to the numerous candidates in the area.
- **The deployment in Outre-Forêt is satisfactory, even if we would have liked to have more stations in two zones.** The first one is the central zone of the area, north to the two geothermal deep projects (around the OFHU0 station on *Figure 10*). It is not dense in stations due to the lack of volunteers in the concerned villages. The second zone is the forest of Haguenau, south to the two geothermal projects. Due to the requirements for installation (internet connection, electricity, indoor installation), we were not able to cover that zone with the exception of one station.
- **Raspberry Shake stations are easy and quick to install**: only 20-30 minutes per station are needed.
- **The need for Raspberry Shake stations to be connected by cable to the internet box of hosts can be restrictive for the deployment.** Raspberry Shake stations are almost all the time installed next to the internet box, which is not always the ideal location in the house (first floor, noisy room with domestic appliances like washing machine, etc).
- **The time to deploy such a DSSN network in the framework of a science participative project is quite long.** The call for volunteers can take several months to have a sufficient number of candidates. Then the process of selection, and the time to obtain an appointment with all selected candidates lengthens deployment times.

3. Network consolidation

During our previous projects with Raspberry Shake stations, real time waveforms data were recovered through Raspberry Shake server (https://raspberryshake.org/data-center/). Stations were configured to transmit data to Raspberry Shake using CAPS protocol (**native operating mode**), and we paid for Raspberry Shake to send us data in real time on a selection of stations.

The main drawbacks of this operating mode are the following:

- no direct connection access to the stations: impossibility to know the origin of the problem when the transmission of data stops,
- cost of the real time transmission : 1€ per month per channel,
- questionable reliability of the process: numerous gaps in data (*Figure 12*),
- Raspberry Shake data center services issues[4].

To overcome these shortcomings, **we decided to change the process of data acquisition**. It was decided to use a **VPN** (WireGuard) to directly transfer waveforms data to our servers without passing by Raspberry Shake. The seedlink protocol is now used to collect waveforms data directly from the station instead of the CAPS protocol, facilitating integration into BCSF-Rénass monitoring activities. The VPN also gives us **direct connection access to the stations** and permits us to use Ansible, an open source IT automation platform. With Ansible, **we can perform configuration and management tasks and deploy them simultaneously on all stations**.

Two major updates were performed on all stations to improve the network reliability:

[4] Raspberry Shake has experienced serious data center services issues from February to April 2024 (https://community.raspberryshake.org/t/live-data-issues/4322). Live data stream stopped functioning for several days and could have seriously affected our activities if we had not changed our operating mode for data acquisition before.

- a **hardware watchdog** was configured to reboot the station in case of freezing. It permits to reboot the station in the vast majority of the problem encountered (see Part 1),
- a **crontab routine** was installed to automatically and daily check the VPN connection and to restart the VPN in case of failure.

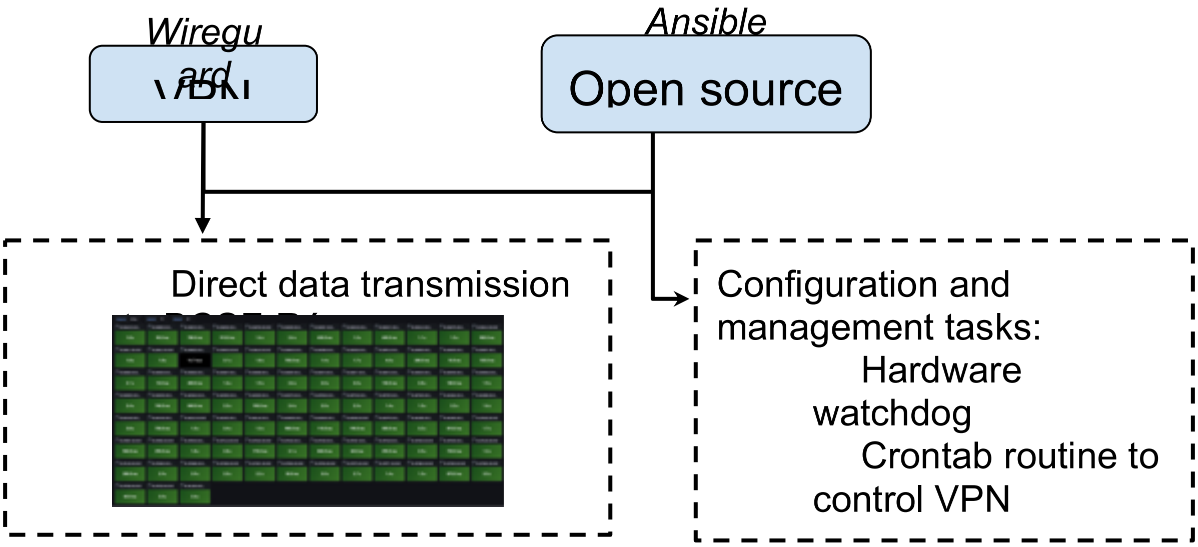

Figure 11: Impact of wireguard and ansible to the network consolidation.

With these tools, **the data acquisition is more reliable. We observed an improvement of data completeness** compared to our previous operating mode using the official Raspberry Shake live data transmission (*Figure 12*). We can also benefit from rapid and consistent production deployment solutions.

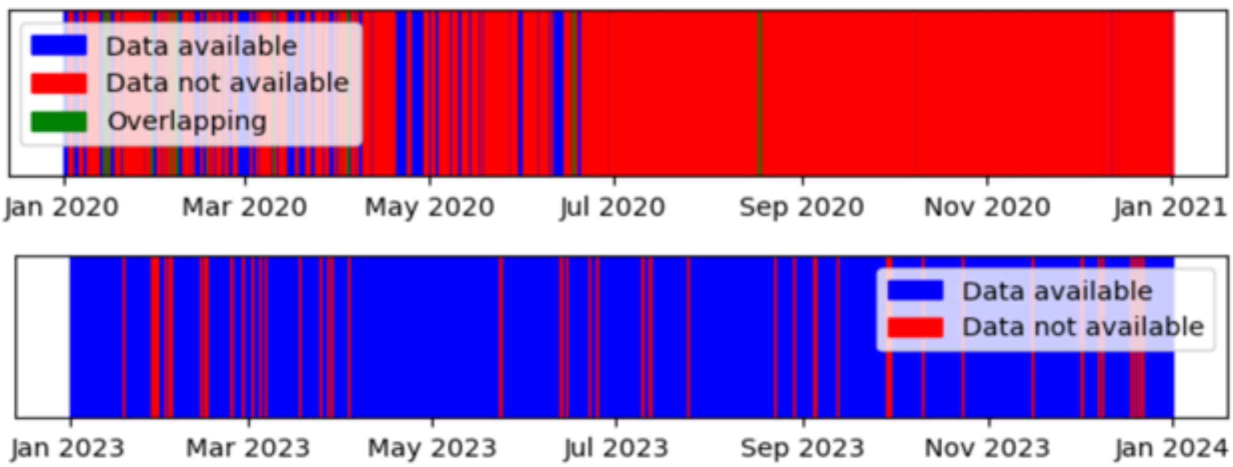

Figure 12: Data availability of station R3374 at BCSF-Rénass before (top) and after (bottom) the change of method of acquisition. Days in red does not mean that no data at all were recovered, but that some gaps are present.

4. Quality control after deployment

The quality control of our deployed stations will represent a major part of our work in the next few months. This work will consist of **analyzing the signal-to-noise ratio** or its proxy using the number of automatic PhaseNet picks produced by each station to understand why some stations are much noisier, and if it is possible to improve the installation of the stations to get a better signal-to-noise ratio. Some preliminary observations are given here.

The representation of the automatic PhaseNet picks mean count per working day by stations (*Figure 13* and *Figure 14*) can be seen as a first order analysis of the noise level of the stations. We can see from the figures the following observations:

- Raspberry Shake stations count most of the time and logically more picks per day than the permanent high-quality stations due in part to their generally noisier environment.
- The number of picks per day varies widely between Raspberry Shake stations. There is more than a factor 3 of the number of picks between some stations.
- The number of picks decreases during night generally (like anthropogenic activity), but not for all stations.
- For some stations, the number of picks is surprisingly low. For example, the EMS09 station (*Figure 14*) is deployed in a school in the city center of Strasbourg. We could expect a high pick count, but it is not the case.

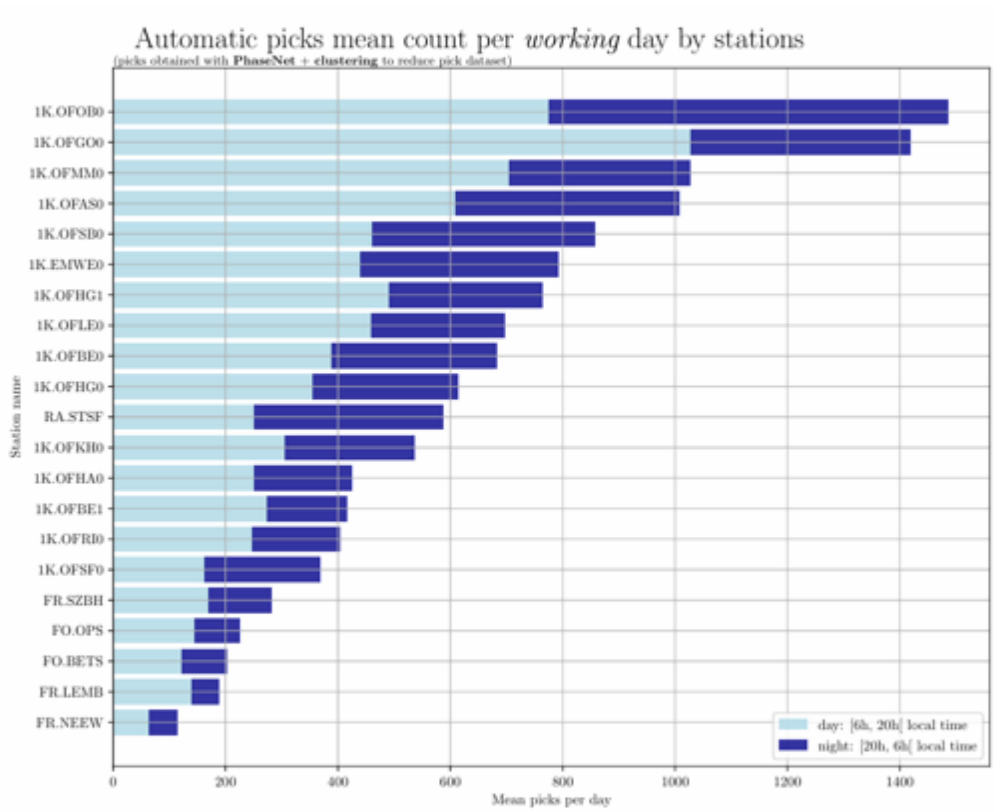

Figure 13: Automatic picks mean count per working day by stations of the Outre-Forêt area. “1K” stations are Raspberry Shake stations, “FR” stations are permanent EPOS-France stations, “FO” stations are geothermal operators stations.

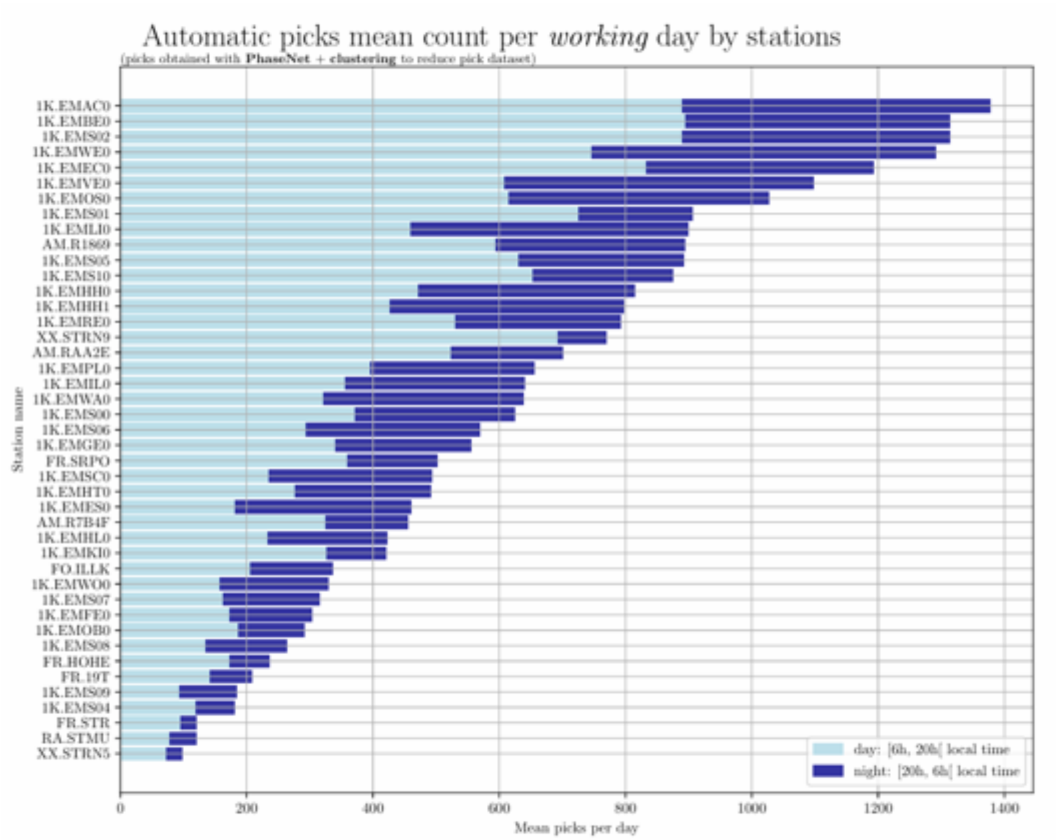

Figure 14: Automatic picks mean count per working day by stations of the Eurometropole of Strasbourg area. “1K” and “AM” stations are Raspberry Shake stations, “FR” stations are permanent EPOS-France stations, “RA” stations are accelerometric stations, “XX” stations are temporary EOST stations, “FO” stations are the geothermal operator’s stations.

Probabilistic power spectral densities (PPSD) were computed regularly for all stations, with other charts such as the level of amplitude over time according to the frequency range, the number of detections over time, etc. An example of the summary sheet obtained is given in *Figure 15*.

We were able to observe some strange features for some of the stations. For example, in *Figure 16*, the PSD function is given for the vertical component of three stations. We can observe that the microseismic pick is not visible for the OFBE1 Raspberry Shake station. It can be observed on the east and north components of the station. Maybe the vertical component is defective in particular on the release v8 of the 3D Raspberry stations. This problem was observed on three stations. Further analysis needs to be performed to check if this is related to the VPN protocol or to the version of the hardware.

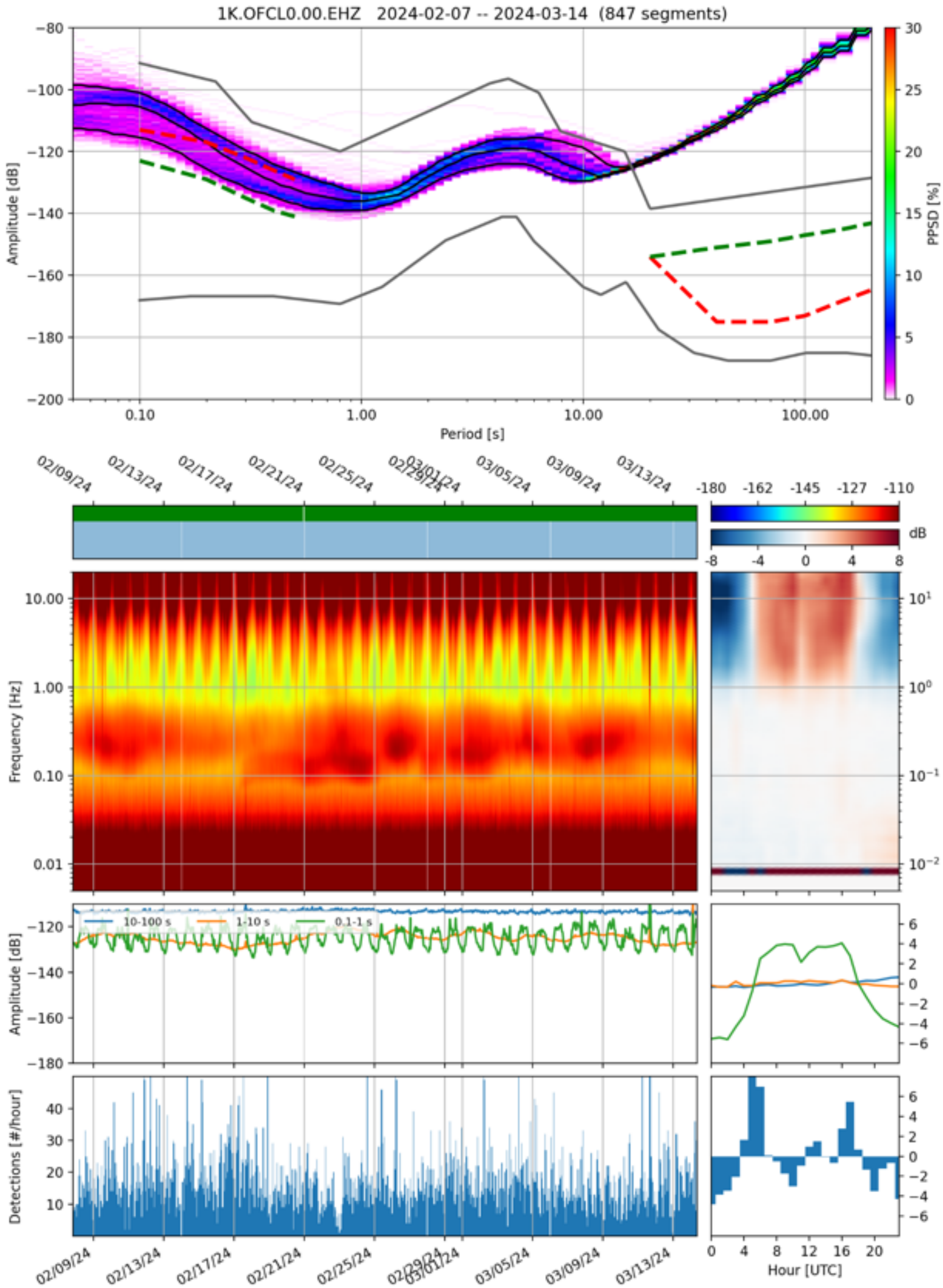

Figure 15: Signal analysis summary sheet of OFCL0 Raspberry Shake stations.

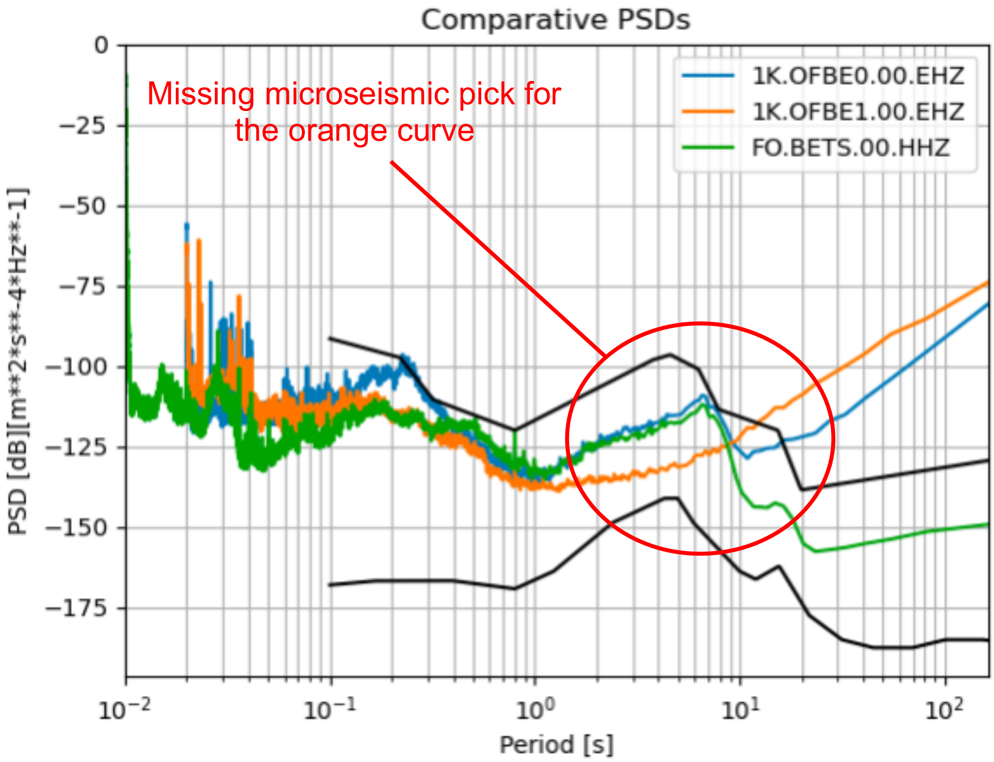

Figure 16: PSD functions of the vertical component of three stations: two Raspberry Shake stations (OFBE0 and OFBE1) and one permanent EPOS-France station (BETS). The three stations are located 1-2 kilometers from each other.

5. Seismicity analysis

The seismicity of the two regions (Eurometropole of Strasbourg and Rittershoffen area in Outre-Forêt) is analyzed using a workflow derived from the one used by BCSF-Renass_to review the seismicity of metropolitan France. It uses all waveforms from Epos-France (FR, RA network) and RaspberryShake (1K network) stations described above. The obtained catalog benefits from our advances in the use of new artificial intelligence tools, such as PhaseNet, a deep learning automatic picking method, as well as in the development of a deep learning method, SpectroCNN, for discrimination between earthquakes, quarry blasts and explosions. Indeed recordings of quarry blasts are numerous in this region.

Briefly, the process workflow includes several steps. The first one is to obtain from each station's waveforms the set of PhaseNet (Zhu et al, 2019) picks (P and S) and their associated probabilities. The second one is the association of seismic phases to create events, by combining the HDBSCAN (McInnes et al, 2017) algorithm (to gather picks close in time and space) with the PyOcto (Münchmeyer, 2023) one (to discard picks that did not follow typical travel-time curves). The third step consists in event location using NonLinLoc (Lomax et al, 2000) algorithm with several regional models chosen based on the prior location obtained from PyOcto. At the last step, a moment magnitude Mw is computed (when possible) from waveform spectral fitting using a modified version of SourceSpec (Satriano, 2023). To compute robust magnitudes in particular for low magnitude events, we include magnitude station corrections computed from statistics on magnitude differences between event and stations. Finally, event information (picks, origins, magnitudes) is integrated into the catalog in accordance with the QuakeML standard, so that it can be integrated into Seiscomp for later review and also made accessible via our web services.

Preliminary results obtained on data from 2023 to March 2024 are shown in Figures 17 to 19 for the Rittershoffen area. No seismic activity was observed in the Eurometropole of Strasbourg during this period, although low-magnitude induced seismic activity (cf. figure 19) did occur in the Rittershoffen area in Outre-Forêt as shown in Figures 17 and 18. Several hundred events have been detected and localized (of which around 350 were well constrained), while no more than ten were detected by the national seismic monitoring network (BCSF-Rénass), given their low magnitudes and the fact that RaspberryShake stations were not used for real-time detection.

We will continue to develop our workflow to improve event detection and localization, in particular how the use of deep learning denoising filters on stations impacts the number and quality of picks.

Figure 17: Number of daily events automatically detected for the 2023.01-2024.03 period in the Rittershoffen area. Given the low magnitudes of the events, fewer than ten events were detected by the seismic national agency BCSF-Renass.

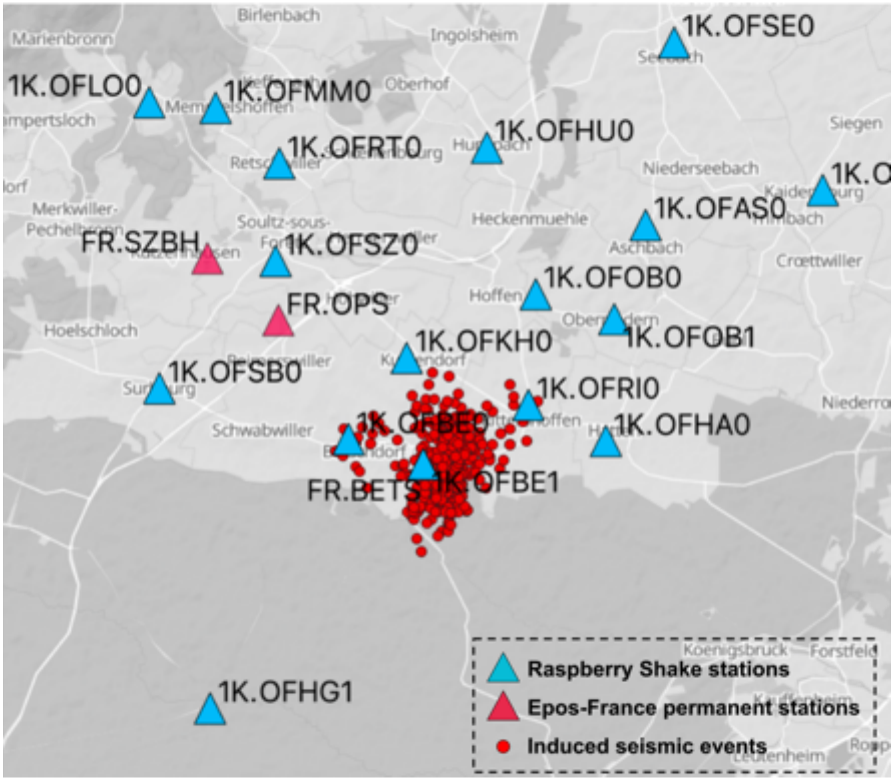

Figure 18: Maps of the seismic events of the 2023.01-2024.03 period obtained by our workflow in the Rittershoffen area.

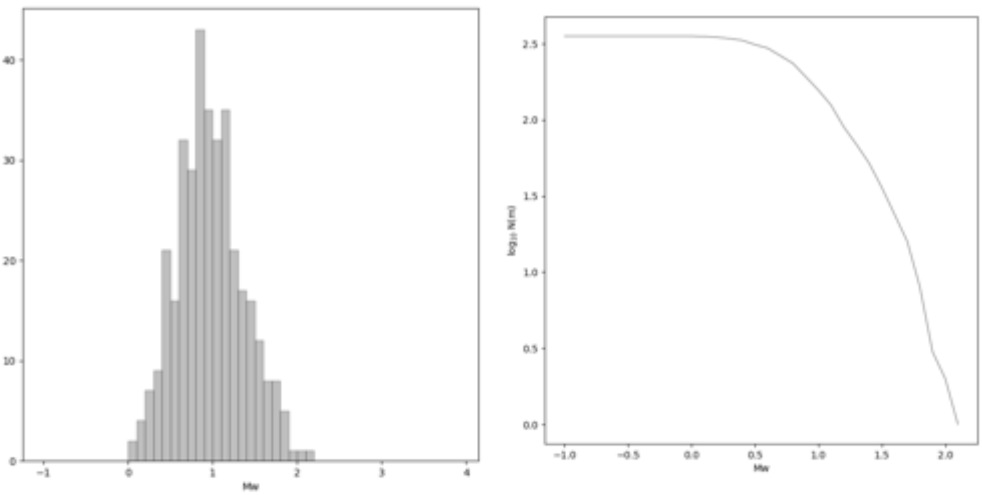

Figure 19: Magnitude (Mw) distribution (left hand side) and cumulative magnitude-frequency diagram (right hand side) for the automatically detected events for the 2023.01-2024.03 period in the Rittershoffen area.

6. Evaluation of the performance of the Strasbourg DSSN

6.1 Estimation of the magnitude of completeness

We tested the performance of the Strasbourg DSSN during the Vendenheim induced seismic sequence (i.e., between 2018 and 2021) with the aim of evaluating the capability of the Raspberry Shakes in monitoring seismicity. We assessed the DSSN performance by comparing the magnitude of completeness (M_c) and location uncertainty calculated using the DSSN stations with those calculated using a network of permanent stations surrounding the DSSN (*Figure 20*). 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. P_N is calculated from the modal Power Spectral Density (PSD) N_m, which is derived from the Probabilistic Power Spectral Density (PPSD) of the ambient noise at a given station:

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

where f_1 and f_2 are the lower and upper frequencies that define the integration interval. For this study, we computed the modal PSD of each hour of the day to precisely evaluate how noise levels change over the 24 hours. Moreover, we calculated the PSDs only using the vertical component, as about 1/3 of the available stations record only on this component.

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 PSDs, we assumed a stress drop of 4 MPa, a density of 2900 kg/m^3, a source-receiver average P-wave velocity of 3800 m/s, and a S-wave velocity at the source of 3450 m/s. Due to the large variability in epicentral distance between stations, we used more than one frequency-independent quality factor to account for attenuation: 200 for the stations that are part of the DSSN network (*Figure 20b*), 180 for HOHE and BABA, and 250 for all remaining stations (values are coming from visual inspections of the spectra). To ensure that the magnitude *M* used in the modeling could be compared to the one in the Rénass catalog, we used the following relation to determine the seismic moment M_0: $M_0 = 10^{1.143M + 9.86}$. This relation was obtained by fitting the observed seismic moment values with the corresponding local magnitude found in the Rénass catalog, which was calculated on the vertical component.

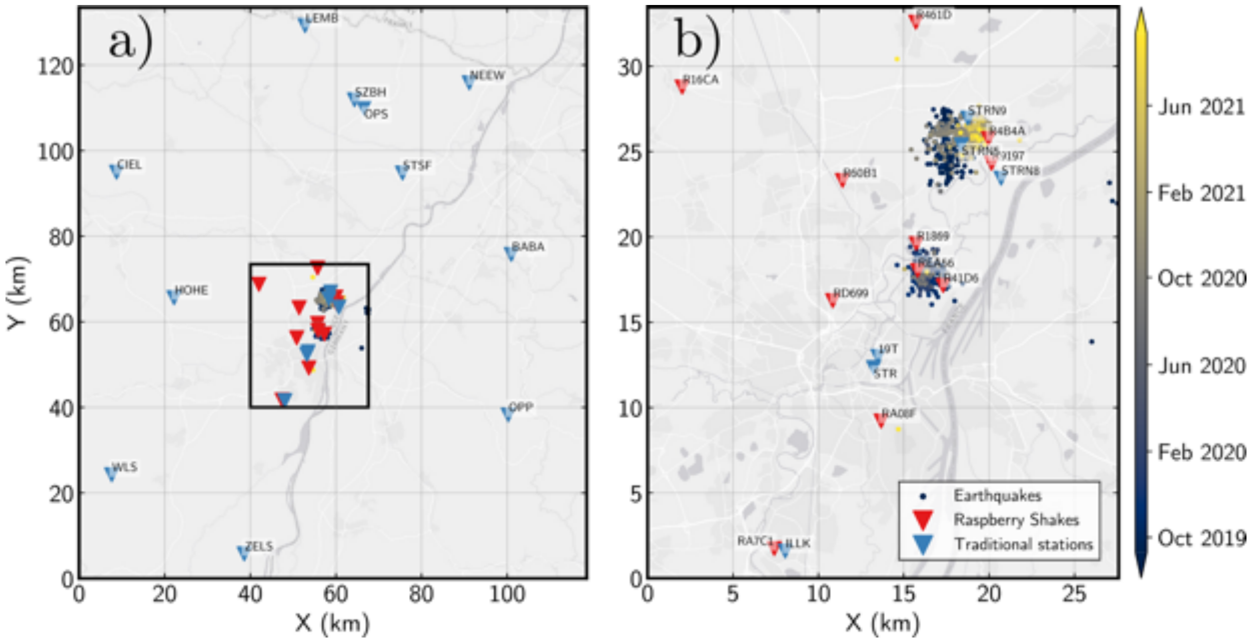

Figure 20: Location of the stations used in the study. a) Map showing the Strasbourg DSSN (within the black rectangle) and the surrounding permanent stations. b) Map of the stations part of the Strasbourg DSSN. The red inverted triangles represent the Raspberry Shakes, while the blue inverted triangles represent the traditional (broadband, short-period, or accelerometric) stations. The circles are the epicenters of the events of the Vendenheim sequence that occurred between 2018 and 2021.

The frequency band used for integration (i.e., f_1 and f_2) is between 5-30 Hz for stations with a sampling frequency of 100 Hz or 200 Hz, and 5-22 Hz for stations with a sampling frequency of 50 Hz. Finally, we assumed that the M_c at a given point is the magnitude needed to reach a WSR of 6 at 3 stations at least. Actually, for location, we suppose that both P and S wave can be picked. Accordingly, we use at least 6 observations to locate an event. To improve this, we plan to recalculate everything with 4 stations to see how much this can change the final result.

We point out that small changes to the WSR threshold and to the minimum number of required stations can significantly change the estimate of M_c. To avoid relying on absolute values, our analysis is therefore based on M_c differences between two network configurations: local stations only (stations part of the DSSN, located less than 20 km from the Vendenheim seismicity) and distant stations only (station outside the DSSN located more than 20 km from the Vendenheim seismicity) (*Figure 20*).

6.2 Estimation of the location uncertainties

Similarly, to what was done for the M_c maps, we placed the earthquake sources on a 25 x 30 km grid covering the DSSN, with grid points spaced 0.1 km apart and located at a depth of 4 km. To locate an event, we selected only the stations that were able to detect it (i.e., where WSR > 6). If a station is able to detect an event, we assume that both P and S waves can be picked. The magnitude of the events corresponds to the average magnitude observed in the area during the noisiest hour (9:00-10:00 local time).

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 (values are coming from the picking errors), respectively. We then located the events with NonLinLoc using the same 3D velocity model. Finally, we took the square root of the diagonal elements of the covariance matrix to derive the uncertainty in the three directions.

6.3 Noise level variations

The noise PSDs indicate that, at a given site, noise levels at the DSSN stations can vary by up to two orders of magnitude over a 24-hour period (*Figure 21a*). Since noise increases during the day and the stations are located in a heavily urbanized area, the origin of the noise is likely anthropic. It should also be noted that the noise levels can vary considerably from station to station (*Figure 21b*), likely due to different levels of human activity in the neighborhood and in the building. Such changes in the noise level can also be observed between stations that are less than 1 km apart. This means that the selection of the installation site plays a crucial role in urban environment. When investigating why some Raspberry Shakes show strong amplifications in the vertical component, we observed that likely these amplifications are due to the installation site (e.g, how the stations are installed in the house). If we manage to prove this and find the precise cause, we will provide indications on how to properly install the Raspberry Shakes and avoid unwanted amplifications.. In situations where it is not feasible or practical to investigate the noise conditions at the candidate sites, increasing the station density in the area may help to reduce the impact of noise variability on the detection capability of the network.

Traditional stations part of the DSSN are hosted in public institutions buildings or by private entities buildings. These stations have noise levels similar to those of the Raspberry Shakes. This means that the home environment does not necessarily degrade the quality of the recordings compared to other possible installation sites that can be found in an urban area.

At distant stations, the change in noise levels between day and night is often limited to less than one order of magnitude (*Figure 21c*). In addition, noise levels can be several orders of magnitude lower than those observed at the DSSN stations (Figures 21a and 21c), especially at high frequency (> 10 Hz). This is because distant stations are typically installed in sparsely populated areas and are well shielded from noise sources above ground.

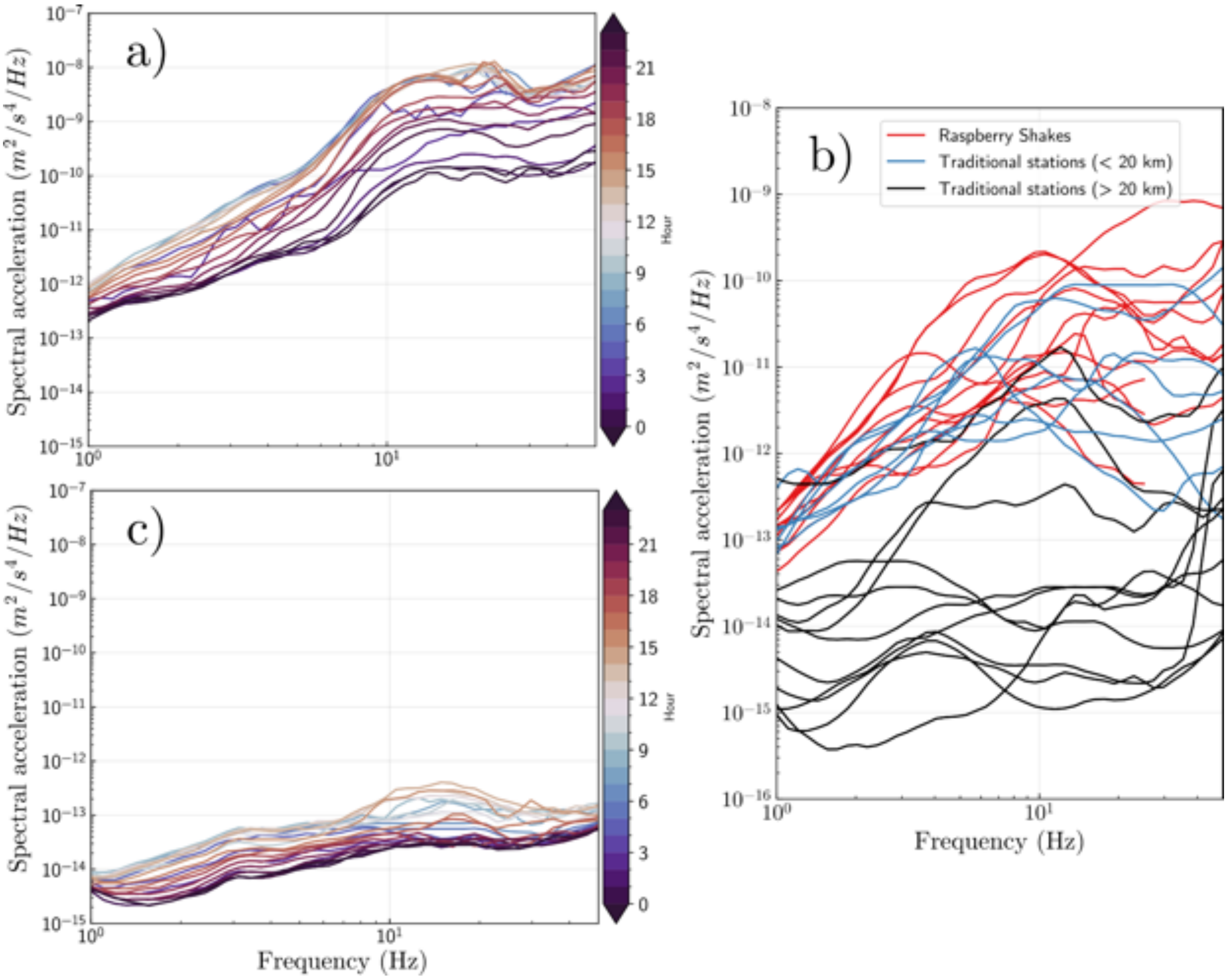

Figure 21: Noise levels variations between stations and during the 24 hours of the day. a) Modal PSD of each hour of the day at a Raspberry Shake station. b) Modal PSD of each station used in this study, averaged over the 24 hours of the day. c) Same as a), but for a permanent broadband station located outside the DSSN.

6.5 Impact of the DSSN on magnitude of completeness

To evaluate the performance of the DSSN network in detecting earthquakes, we used maps where each point indicates the difference between the M_c calculated using only distant stations and the M_c calculated using only DSSN stations (*Figure 22*). During the least noisy hour (2:00-3:00, local time), the DSSN can produce notable improvements in M_c (up to 0.85 magnitude units) in most of the region within the network (*Figure 22a*). During the noisiest hour (9:00-10:00, local time), the improvement is more limited (up to 0.45 magnitude units) and restricted to the areas with the highest station density (*Figure 22b*). In areas with low station density, the network of distant stations can offer similar or lower M_c. The considerations made for the least noisy and noisiest hour can be generalized for the hours between 21:00 and 7:00 and between 7:00 and 21:00, respectively. In fact, M_c tends to remain stable during these two-time intervals (*Figure 22c*).

By combining the distant network with the DSSN network, it is possible to reduce M_c to levels lower than what can be achieved with either network configuration alone (*Figure 22c*). This is especially true during the noisiest hours. This means that stations that are well shielded from noise sources, even if they are at a considerable distance from the area of interest, can help mitigate the loss of detectability that the local network experiences during the day.

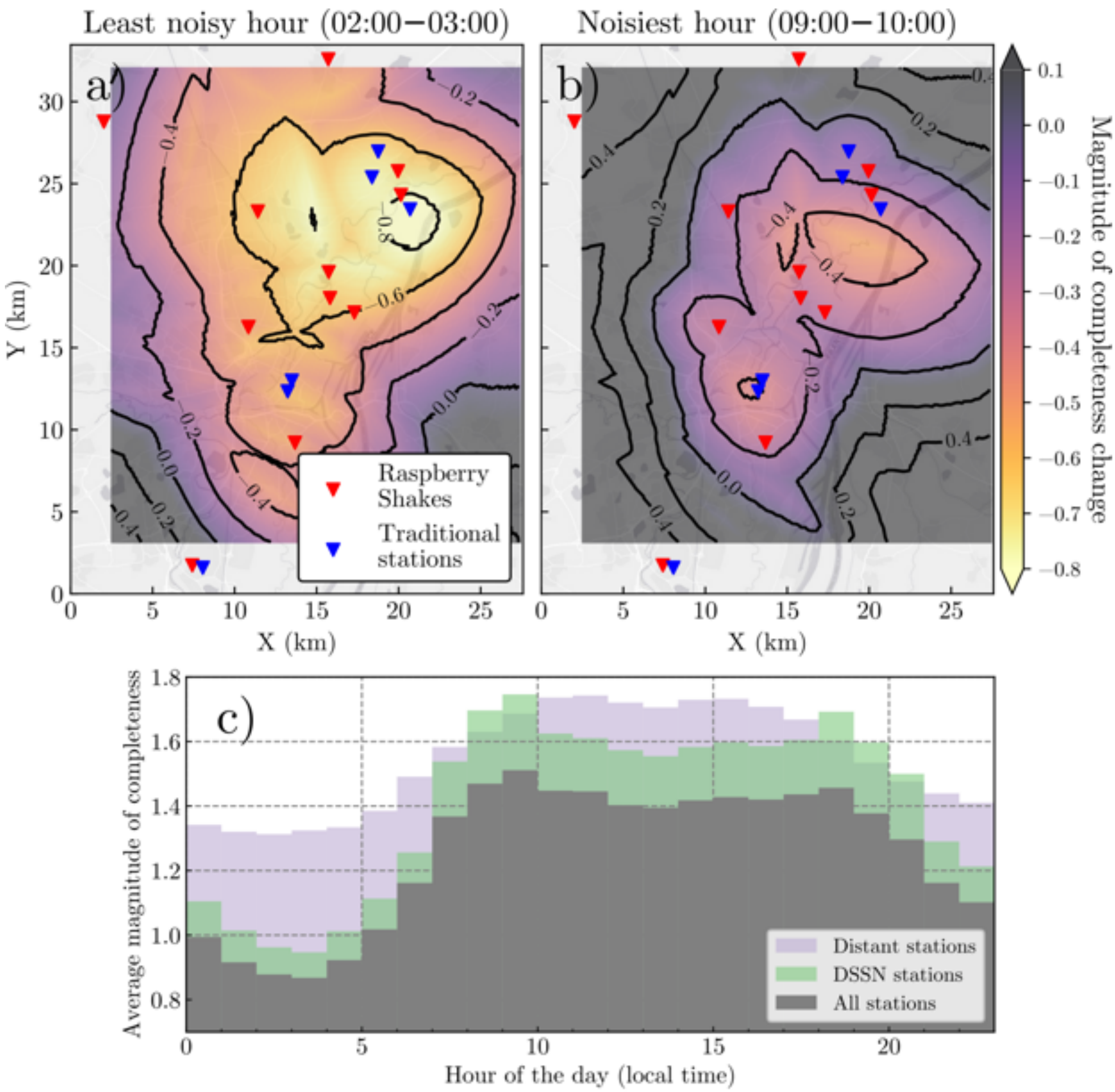

Figure 22: Maps showing the difference between the M_c calculated using only the permanent stations outside the DSSN (*Figure 20a*) and the M_c calculated using only the DSSN stations. a) M_c is calculated using the noise PSDs of the least noisy hour. b) M_c is calculated using the noise PSDs of the noisiest hour. c) Variation of the average M_c of the area over the 24 hours of the day for different station configurations.

6.5 Impact of the DSSN on location uncertainty

The drastic difference in noise levels between night and day affects not only M_c, but also location accuracy, as it is dependent on the number of available stations and their position. Similarly, to Figure 22, we calculated for each grid point the difference between the location uncertainty (easting, northing, depth) obtained by using only the distant stations, and the location uncertainty obtained using only the DSSN stations (*Figure 23*). The magnitude of the theoretical events was set to 1.7, which corresponds to the maximum M_c during the day (*Figure 22c*).

During the least noisy hour, the DSSN depth uncertainty is significantly lower than that of the distant network (up to 1.5 km) in most of the DSSN area (Figure 23a). The large improvement is

due to the presence of stations close to the epicenters, which helps to better constrain the location at depth.
During the noisiest hour, only the events occurring in areas with the highest station density can be detected by enough stations and thus located (Figure 23b). In these cases, the improvement is comparable to that found during the least noisy hour (about 1.5 km). This indicates that only a few stations are needed to significantly reduce location uncertainty if they are close to the epicenters.

Similar considerations can be made for the horizontal uncertainties, although the improvement provided by the DSSN is more limited than that found for the depth uncertainty. This is likely due to the geometry of the DSSN network (elongated NS) and the already good spatial coverage provided by the distant network.

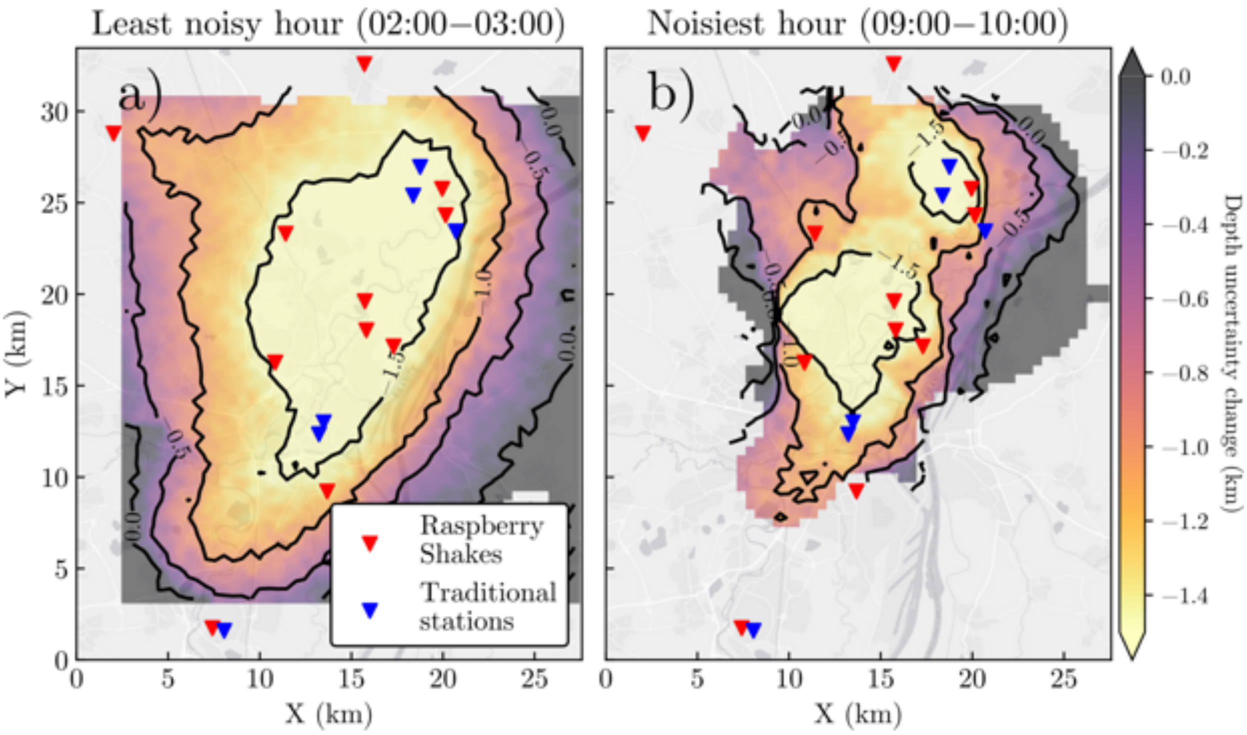

Figure 23: Maps showing the difference between the depth uncertainty calculated using only the permanent stations outside the DSSN (*Figure 20a*) and the depth uncertainty calculated using only the DSSN stations. a) Uncertainties are determined using the noise PSDs of the least noisy hour b) Uncertainties are determined using the noise PSDs of the noisiest hour.

7. Conclusion

In the current deliverable we have presented an innovative approach of monitoring geohazards in urban environments. **The project relies on the deployment of Dense Semi-permanent Seismic Networks (DSSN) using low-cost seismic stations deployed in residences of voluntary non-seismologist citizens.** This science participative approach permits us to cover quite homogeneously our **two targeted areas with 71 stations**, even if the search of volunteers was difficult in the Outre-Forêt area. It should be noted that the deployment of such a DSSN network in the framework of a participative science project with a social study is quite long: the call for volunteers on its own can take several months to have a sufficient number of candidates.

Raspberry Shake stations were chosen for the project. These stations have the advantages to be low-cost and to be easy and quick to deploy. They have proven their usefulness, notably during the seismic crisis near Strasbourg. The native Raspberry Shake operating mode to transmit data, used during our previous project with Raspberry Shake stations, is no longer suited us for reasons of reliability and costs. **We decided to change the process of data acquisition by using a VPN to directly transfer data to our server**. The data acquisition is now more reliable and the VPN facilitates the monitoring of the stations and the deployment of configuration and management tasks.

Raspberry Shake stations were integrated in a new process for earthquake detection and location using deep learning methods. **On preliminary results obtained on data from 2023 to March 2024, several hundred events have been detected and localized (of which around 350 were well constrained) in the Outre-Forêt region, while only ten events were localized by the standard procedure of the BCSF-Rénass**.

We have shown that, within a DSSN operating in urban environment, **noise levels can vary widely from station to station and they show no clear dependence on the type of station**. As Raspberry Shakes are installed in private homes, this means that the **home environment does not necessarily lead to higher noise levels** than those found in public or private entity buildings.

Noise levels can also **change drastically between nighttime (low noise conditions) and daytime (high noise conditions)**, leading to **large differences in M_c and location uncertainty** between different hours of the day. During nighttime, DSSNs can lead to lower M_c and location uncertainty compared to using distant stations that are less affected by anthropic noise. However, during daytime, improvements are only possible where station density is high (i.e., stations immediately close to the epicenters). Therefore, stations installed in urban environment, including Raspberry Shakes, have the potential to help create more complete catalogs, but **a high station density or a selection of high-quality sites may be required to maintain a more consistent network performance throughout the 24-hour period**. Alternatively, distant stations that are less affected by noise are needed to compensate for the loss of detectability of the local stations.

Perspectives:
The quality control of our deployed stations will represent a major part of our work in the next few months, with the analysis of the signal-to noise ratio. Preliminary observations seem to show that the noise level can widely vary between stations. Some stations present abnormally an absence of microseismic pick on some of their components on PSDs. These two points in particular will be interesting to work on, in order to eventually improve the signal-to-noise ratio on our stations, and to identify the defective ones.

References

Detection Threshold and Location Resolution of the Alberta Geological Survey Earthquake Catalogue
Schultz, R., Stern, V., Gu, Y. J., and Eaton, D. (2015). Detection Threshold and Location Resolution of the Alberta Geological Survey Earthquake Catalogue. Seismological Research Letters, 86(2A):385–397.

Induced and triggered seismicity below the city of Strasbourg, France from November 2019 to January 2021
Schmittbuhl, J., Lambotte, S., Lenglin´e, O., Grunberg, M., Jund, H., Vergne, J., Cornet, F., Doubre, C., and Masson, F. (2021). Induced and triggered seismicity below the city of Strasbourg, France from November 2019 to January 2021. Comptes Rendus. G´eoscience, 353(S1):561–584.

PrESENCE: a participative citizen seismic network
Turlure, M., Grunberg, M., Jund, H., Engels, F., Schlupp, A., Chavot, P. and Schmittbuhl, J.: PrESENCE : a participative citizen seismic network, EGU General Assembly 2023, Vienna, Austria, 23–28 Apr 2023, EGU23-7615, https://doi.org/10.5194/egusphere-egu23-7615, 2023.

Contribution of SeismoCitizen Raspberry Shake dense network in monitoring induced seismicity in northern Alsace (France)
Turlure, M., Grunberg, Engels, F., Jund, H., Schlupp, A. and Schmittbuhl, J.: Contribution of SeismoCitizen Raspberry Shake dense network in monitoring induced seismicity in northern Alsace (France), EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-10651, https://doi.org/10.5194/egusphere-egu24-10651, 2024.

BCSF-Rénass
BCSF-Rénass, Bureau central sismologique français - Réseau national de surveillance sismique, https://renass.unistra.fr

BCSF-Rénass workflow
Grunberg, M. and Lambotte, S.: A new workflow for revising the seismicity catalog for mainland France, covering the period 2010-2018, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-5100, https://doi.org/10.5194/egusphere-egu24-5100, 2024.

PhaseNet
Weiqiang Zhu, Gregory C Beroza, PhaseNet: a deep-neural-network-based seismic arrival-time picking method, Geophysical Journal International, Volume 216, Issue 1, January 2019, Pages 261–273, https://doi.org/10.1093/gji/ggy423

HBDSCAN
L. McInnes, J. Healy, S. Astels, hdbscan: Hierarchical density based clustering In: Journal of Open Source Software, The Open Journal, volume 2, number 11. 2017

PyOcto
Münchmeyer, J. (2023). PyOcto: A high-throughput seismic phase associator. Preprint at arxiv.org/abs/2310.11157.

NonLinLoc

Lomax A., Virieux J., Volant P., Berge-Thierry C. (2000) Probabilistic Earthquake Location in 3D and Layered Models. In: Thurber C.H., Rabinowitz N. (eds) Advances in Seismic Event Location. Modern Approaches in Geophysics, vol 18. Springer, Dordrecht. https://doi.org/10.1007/978-94-015-9536-0_5

SpectroCNN

Grunberg, M., Lambotte, S., Dretzen, R. (2023): A new deep learning tool to discriminate earthquakes and quarry blasts in Mainland France, XXVIII General Assembly of the International Union of Geodesy and Geophysics (IUGG) (Berlin 2023). https://doi.org/10.57757/IUGG23-1872

Epos-France

RESIF; (1995): RESIF-RLBP French Broad-band network, RESIF-RAP strong motion network and other seismic stations in metropolitan France. RESIF - Réseau Sismologique et géodésique Français. doi:10.15778/resif.fr

SourceSpec

Satriano, C. (2023). SourceSpec – Earthquake source parameters from P- or S-wave displacement spectra (X.Y). doi: 10.5281/ZENODO.3688587