Characterization of Seismic Signals from Air Filtration Systems in a Nuclear Facility.

Omar Marcillo[1], Monica Maceira[1], James O. Thomas[2], Joshua Cunningham[2], and Chengping Chai[1]
[1] Oak Ridge National Laboratory
[2] Consolidated Nuclear Security LLC

Air filtration systems are used in industrial facilities to prevent the release of contaminants and are indicative of ongoing operations. We are investigating the potential of using seismic measurements to identify and characterize the operational state of filtration systems in a nuclear facility. We are using seismic data collected at a nuclear facility in Texas (US) that uses multiple air filtration systems for routine operations. The data were collected at distances of few hundred meters and different azimuths from the units. The seismic data were recorded with three-component sensors with a sampling rate of 1000 samples per second. We are evaluating the use of cross-coherence and bi-spectral analysis to identify the spectral regions excited by the operation of the scrubbers. Initial results show a mixture of spectral lines with frequencies below 50 Hz and broadband signals between 200 and 400 Hz. We are also using frequency dependent polarization and cross-bearing analyses to distinguish between multiple machines distributed in the facility and operating asynchronously. The use of specific machines in industrial environments can provide information about the types of operations and level of activity of a facility. Our approach can provide a low-profile and low maintenance tool to identify and characterize operations in facilities with limited access.

1 INTRODUCTION

Climate control, air conditioning units, and air purifiers are ubiquitous in industrial environments and can be indicative of ongoing operations. These systems produce mechanical signals that can be captured remotely on the ground as seismic energy or in the air as acoustic waves. These units operate simultaneously with other machines, such as power generators or pumps, with potentially similar spectral features and other operations (movement of vehicles or personnel)(Guenaga et al., 2021; Marcillo O. et al., 2021). In these conditions, identifying seismic or acoustic signatures emanating from specific machines at specific buildings or areas requires methodologies to identify and isolate signals of interest from the background. Besides the challenges related to a cluttered or signal-rich environment, these signals can provide a tool to remotely assess the operational status of machines (e.g., frequency of operations) in areas with limited access. Here, we describe data collected at the nuclear facility in Texas to identify seismic signals related to the operations of multiple air conditioning systems and filtration systems and analysis for source characterization and spatial location. Our work includes data collected by several seismic sensors deployed in the facility for several days and analysis to identify spectral features in seismic signals and their characterization. Our analysis includes station-level analysis for feature identification and extraction of parameters of the polarization field and network level analysis to associate those parameters for geospatial localization.

2 DATA ANALYSIS

Figure 1 shows the sensor distribution and the footprint of some buildings in the facility. Magenta dots show the location of the stations. Each station includes a 4.5 Hz three-component geophone and a GPS-synchronized high-resolution digitizer (Geospace Inc.). The digitizers were configured with a 1000 samples per second sampling rate. The sensors were installed near roads, and in most cases noise from commuter vehicles traffic is clear in the recordings. The separation between sensors and nearby buildings ranges from several tens of meters to few hundreds of meters.

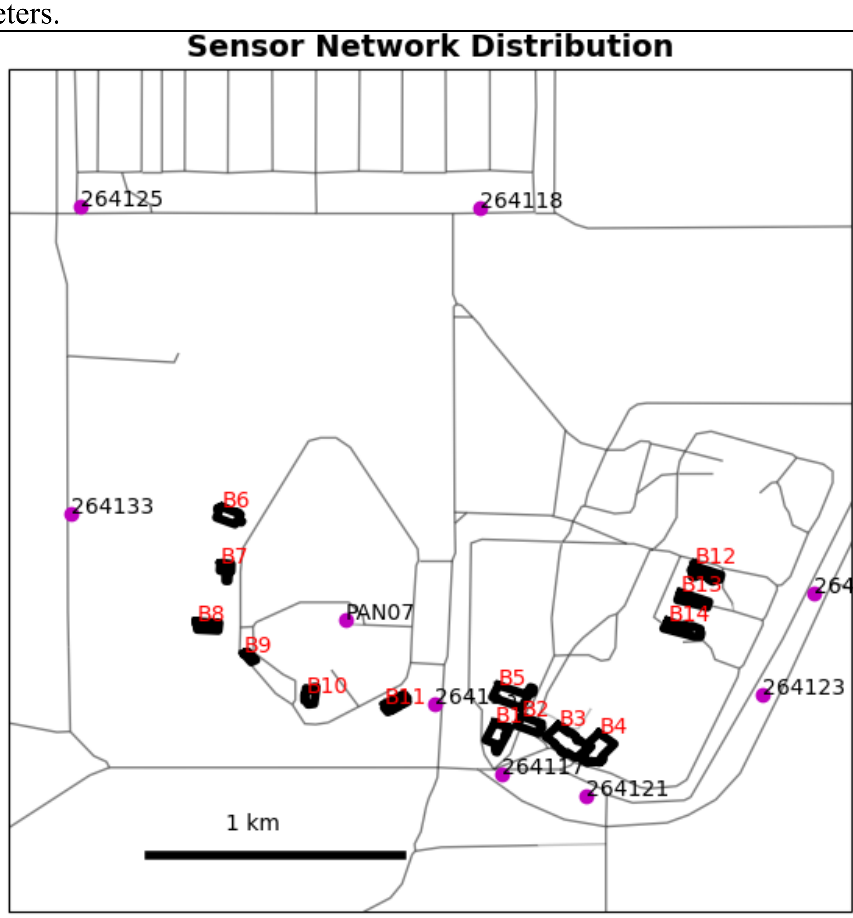

Figure 1: Sensor distribution. The map shows the stations used in this analysis (magenta dots) and the footprint of the buildings with potential machines labeled B1-B14.

Figure 2 and Figure 3 show waveforms and corresponding spectrograms for seven stations (station 264125 show noise and seem to have a malfunctioning station) for 24 hours during a workday. These waveforms correspond to the vertical component of the seismometer and are normalized to the maximum amplitude of all waveforms. The data show diurnal distribution of signal intensity with higher levels of overall amplitude during the day hours and reduced levels at night hours. The presence of pulses in the waveforms are likely related to vehicular traffic.

This behavior is clear for station 264133. The diurnal pattern is characterized by high noise levels starting few hours before 6 am (local time) that continue throughout the day and start decreasing after hour 17 (local time). This broadband increase in noise seems to correspond to normal work-day behaviors. Note that the stations were deployed near facility roads and exposed to traffic noise. The spectrograms show that this increase in noise is localized in middle frequencies between around 10 and 150 Hz. In this region, several harmonic sequences are present for machines using AC motors with two or four poles, which correspond to 3600 and 1800 rpm (30 or 60 Hz), such as fans or pumps.

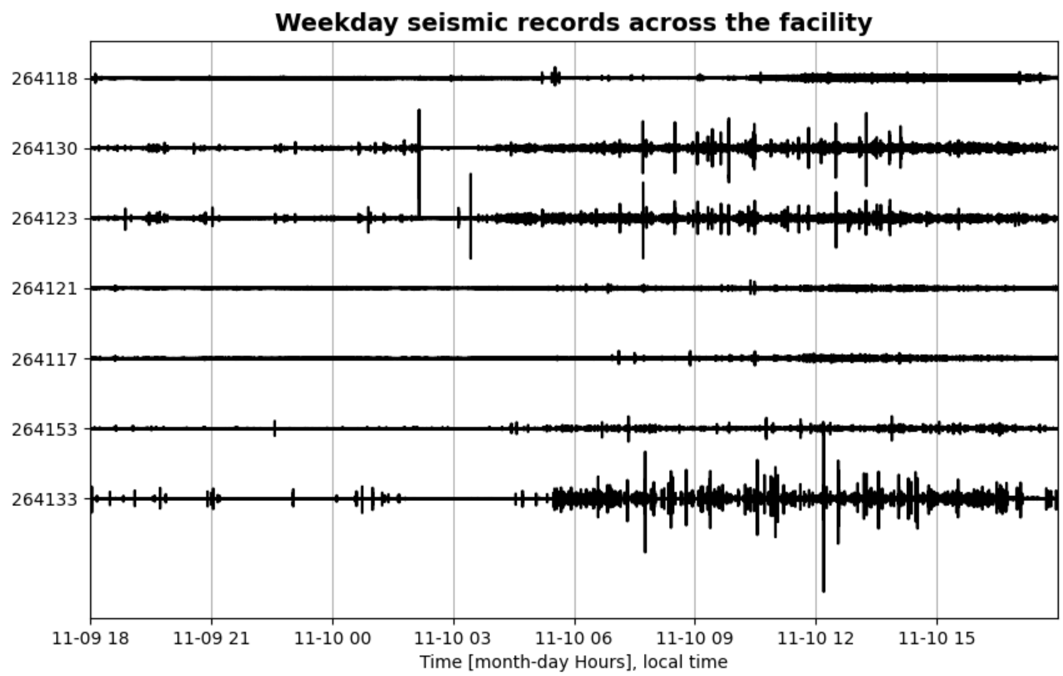

Figure 2: One day of waveform data. These waveforms correspond to a normal weekday. The waveforms are normalized to a global maximum value.

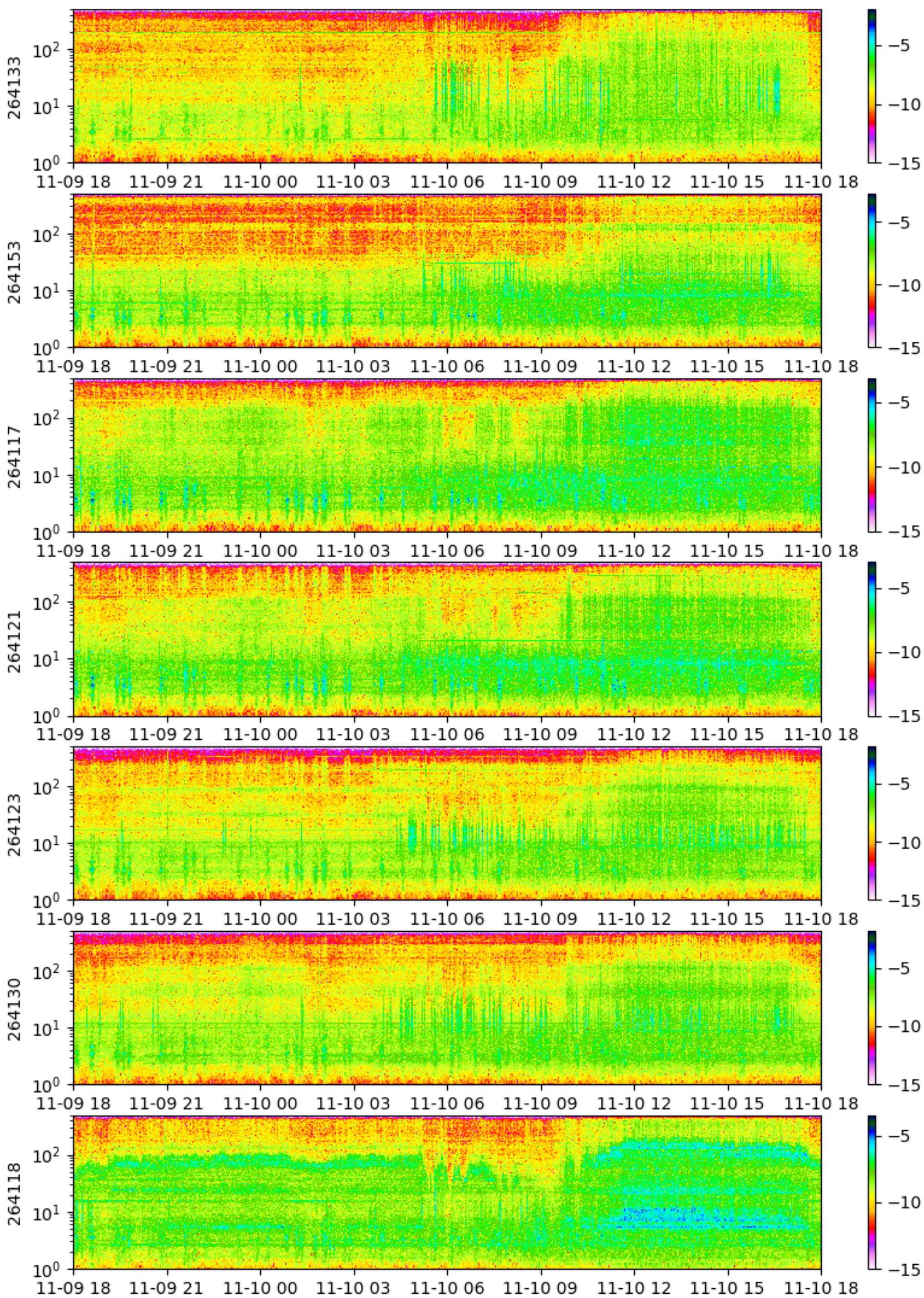

Figure 3: One-day spectrograms.

Spectrograms can provide information about the evolution of the overall energy, but details of specific spectral lines observed at network level can be missed. To detect spectral lines and associate them at network-level we select a period with very low noise and group stations with lines detected. On this period of low noise, we estimate the power spectral density using multitappers (to maximize frequency resolution) and detect spectral lines using f-statistic detector under a probability threshold. In our case we select find spectral lines with more than 70% probability of detection. Figure 4 shows a binary map with specific frequencies that are detected by the different stations. A specific frequency detected by a station is color-coded with a blue pixel in the map. This map shows that some we cannot identify a single frequency that is detected by all stations, which may be related to a more localized propagation. The 199 Hz labels correspond to two frequencies that were rounded to the closest integer. The 199 Hz placed at the right is detected by five of the seven stations. These stations are located at the southeast part of the plant and concentrated near building B1. Frequency 193 and its potential first harmonic (387) is not detected by stations near building B1.

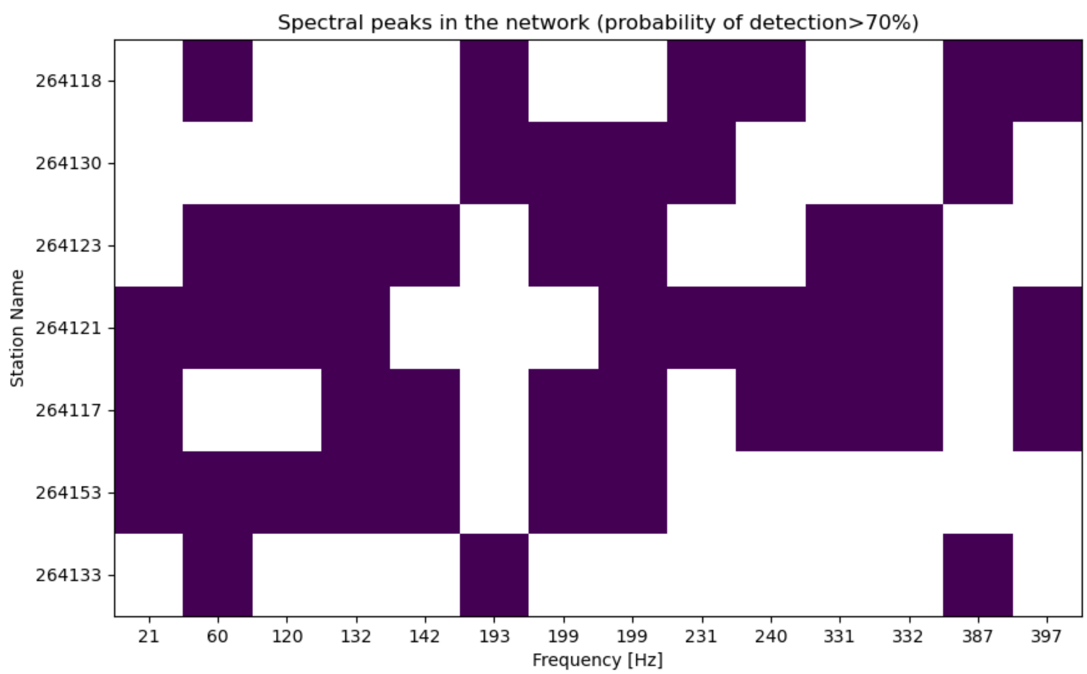

Figure 4: Summary of spectral peaks detected by multiple stations. A frequency detected by a specific station with more than 70% of detection in the network is marked with a dark pixel in the map.

Spectral estimation was used to identify regions with coherent noise. We further analyzed these regions to identify the source of the signal. We analyze the polarization field to find coherent noise across sensors and localize potential sources of noise by cross-bearing polarization orientation. In the following section, we briefly describe the analysis workflow for polarization estimation and cross bearing.

2.1 Extracting polarization parameters from three-component seismic data

We follow Koper and Hawley (2010) to estimate frequency dependent polarization features based on Park et al. (1987). The polarization analysis is based on the estimation of a polarization vector z, which is the eigenvector with the largest eigen value of the single value decomposition (SVD) of $\hat{S}(f)$, which is the estimate of the spectral density matrix, $S(f)$. A well-resolved polarization vector is found if the largest eigenvalue of the SVD is significantly larger than the others. Another approach to measure the degree of polarization is to estimate β^2 (Samson, 1983), which is defined as

$$\beta^2 = \frac{nTr(S^2) - Tr(S)^2}{(n-1)Tr(S)^2}, \qquad \text{Equation 1}$$

where Tr is trace of $S(f)$, z can be used to estimate spatial features of the ellipse that define the particle motion, Θ_H is the azimuth of the major axis, and Θ_V is the vertical angle of the ellipse's plane. As these quantities are estimated for each frequency, maps with these parameters as function of time and frequency (f-t pixels) can be estimated with 3C data. In our analysis, waveform data are first detrended and then a minimum distortion 2-pole 10 to 450 Hz band pass filter is applied. Twenty-second windows are split in 2-second subwindows with 50% overlap. A Blackman-Harris window is applied to the sub-window and the Fourier transform is applied to estimate $S(f)$.

3 RESULTS AND DISCUSSION

Figure 5 shows a frequency-azimuth map that summarized the results for 1 hour of polarization analysis. The axes correspond to frequency and azimuth, horizontal, and vertical (respectively). Regions with high density correspond to the direction of coherent polarized energy. Each pixel in the map corresponds to the logarithmic value of the number of times coherent energy (beta>0.6) was found on the one-hour segment. In the 1-hour segment, spectral regions with high number of detections indicate signals that repeat consistently in the polarization space and similar azimuth estimates. Two spectral regions one between 100 and 150 Hz and the second one between 200 and 350 Hz display consistent energy for each station these regions have different azimuths as the potential sources have different relative azimuths. As similar machines can be deployed in different buildings the presence of signals with specific spectral features in multiple stations can correspond to multiple machines. We can filter out the multiple machines by geolocalizing using the cross-bearing with the relative azimuths from the polarization preprocessing. Figure 6 shows an example of using cross-bearing to highlight areas where noise is likely to originate. Cross-bearing can include two or more stations, where two or more ray-paths intersect in a point (plus a small tolerance). Using the intersection method with more than three ray-paths is restrictive. Given the sparsity of our network, we use cross-bearing with a single pair. Using this approach, we found that building B2 is more likely to be the source of energy between 250 and 300 Hz.

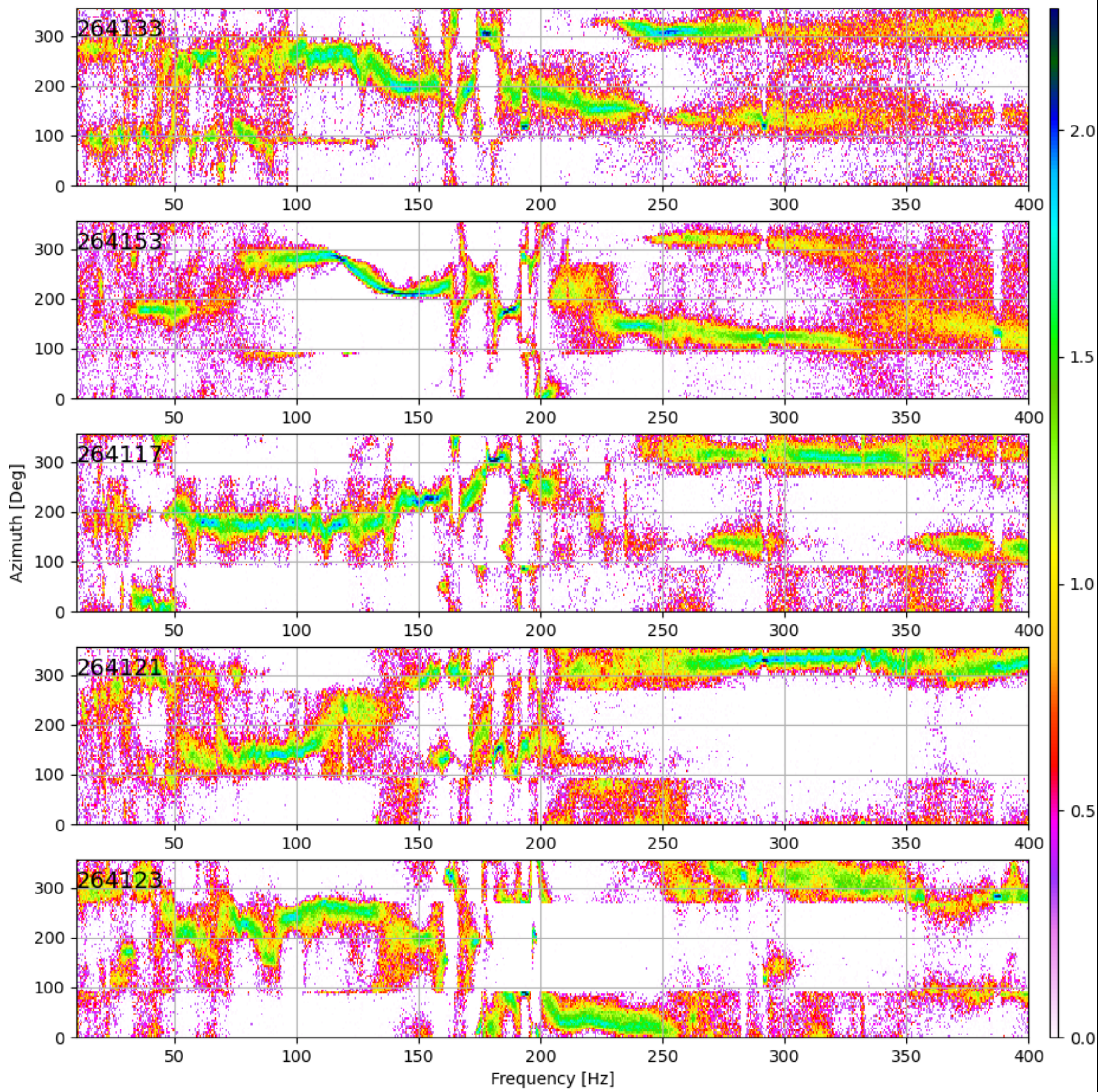

Figure 5: Frequency-azimuth signal polarization map. Regions with high density correspond to the azimuth of coherent polarized energy. Each pixel in the map corresponds to the logarithmic value of the number of times coherent energy (beta>0.6) was found on the 1-hour segment

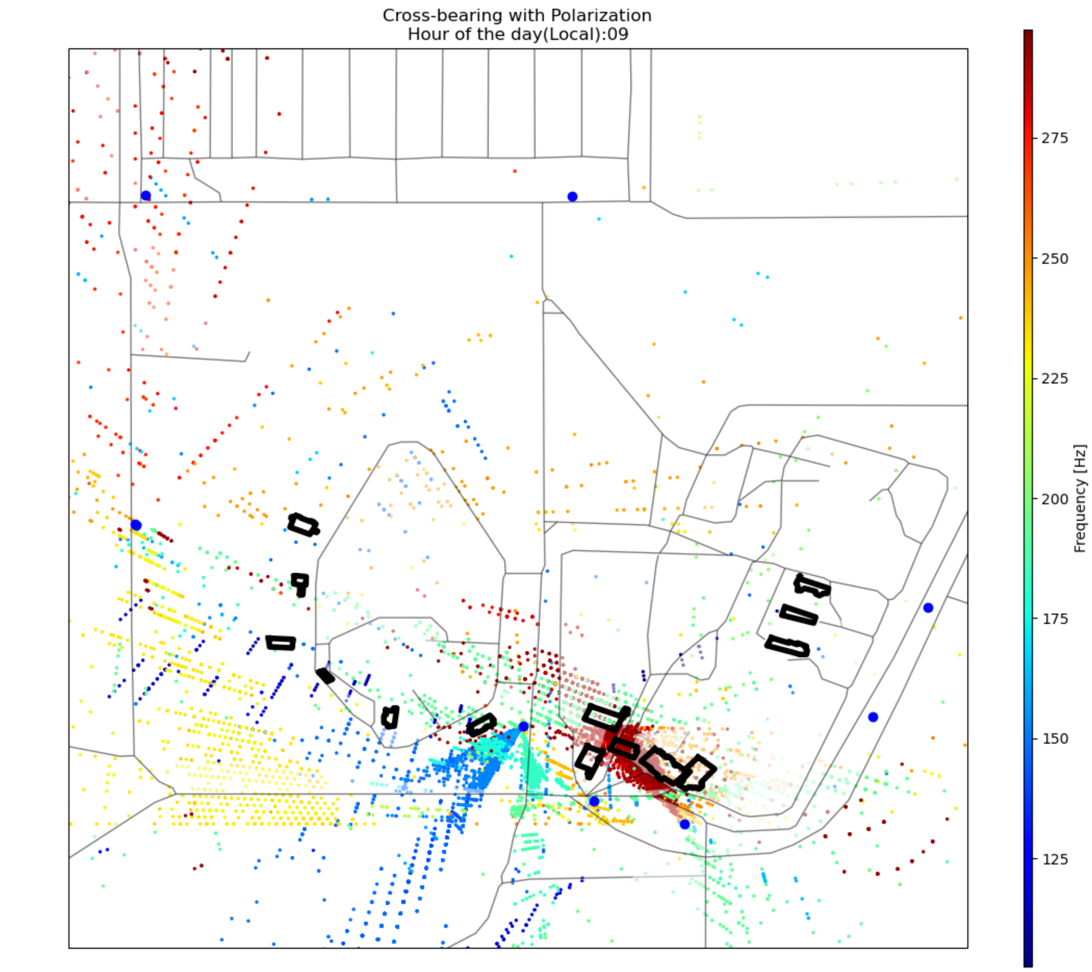

Figure 6: Example of cross-bearing for frequencies between 100 and 300 Hz.

4 CONCLUSIONS

Industrial settings are cluttered with broadband and spectrally discrete signals from machines distributed in small areas and potentially operating at similar configurations. We show that seismic data collected outdoors but inside an industrial facility can capture mechanical noise that can provide information to constrain the spatial location of sources. Our results show that seismic data contains information that can be extracted to identify spectral regions of both discrete and broadband signals related to the operation of machines detected by multiple stations. Also, we show that polarization analysis can be applied to these signal-rich regions to recover directionality that can be further use to identify the location of machines.

REFERENCES

Guenaga, D. L., Chai, C., Maceira, M., Marcillo, O. E., & Velasco, A. A. (2021). Seismically Detecting Nuclear Reactor Operations Using a Power Spectral Density Misfit Detector. *Bulletin of the Seismological Society of America, 111*(3), 1378–1391.

Koper, K. D., & Hawley, V. L. (2010). Frequency dependent polarization analysis of ambient seismic noise recorded at a broadband seismometer in the central United States. *Earthquake Science, 23*(5), 439-447. https://doi.org/10.1007/s11589-010-0743-5

Marcillo O., M. Maceira, C. Chai, & Krebs, J. (2021, August 23-26 & August 30-September 1). *Material transfers detection with seismic observations.* Paper presented at the INMM & ESARDA Joint Annual Meeting.

Park, J., Vernon III, F. L., & Lindberg, C. R. (1987). Frequency dependent polarization analysis of high-frequency seismograms. *Journal of Geophysical Research: Solid Earth, 92*(B12), 12664-12674.

Samson, J. C. (1983). Pure states, polarized waves, and principal components in the spectra of multiple, geophysical time-series. *Geophysical Journal International, 72*(3), 647-664. https://doi.org/10.1111/j.1365-246X.1983.tb02825.x