Seismic Background Noise Levels in Italian Strong Motion Network

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Abstract. Italian strong motion network monitors the seismic activity of Italy and its surrounding with more than 700 stations. Thanks to the upgrade of the stations with continuous data acquisition, it is possible to measure the noise level of the strong motion network. In this study, we used the background noise to estimate the variations in the noise levels of the network. Data recorded in 2019 and in the first quarter of 2022 are used to understand the noise level of the stations and data from the COVID-19 lockdown period are used to study the effect of the anthropogenic sources on the background noise. To do that, power spectrum density is calculated for the continuous stations. It is found that more than half of the stations exceed the background noise model designed for strong motion stations by Cauzzi and Clinton (2013) in at least one of the calculated periods. Considering the characteristics of the instrumentation at the stations and their deployment often near urban areas, we focused on relatively short periods ($\leq$5s), as they are affected by anthropogenic noises. Stations can be noisier during the day, up to 14 decibels and during the weekday, up to 5 decibels in short periods. Noise level differences between day - night decrease with an increasing period as the human-related high - frequency effects of humans are attenuated. As expected, the noisiest stations are located in densely populated areas such as the center of Naples, whereas the quietest stations are located far away from cities. The swell, sea, and wind effects, on the other hand, are not observed at RAN stations. During the COVID-19 lockdown, noise levels dropped by 6.5 decibels in the daytime and 12.5 decibels on weekdays. Noise levels are reduced by around 2 decibels in 0.1s, in which cultural noise is predominant. Furthermore, we found that the vehicles have significant effects on noise levels.

1 Introduction

Seismic stations record the vibration of the ground that is given by the superposition of multiple sources. The definition of seismic noise varies based on the target of each specific study. Since most of the seismic networks are established to detect seismic events (i.e., earthquakes, volcanic activities, quarry blasts, and nuclear explosions) all other vibrations are referred to as (ambient) noise. On the other hand, ambient noise itself has been object of specific studies (e.g., for the characterization of layers of the earth (Shapiro et al., 2005), Moon (Larose et al., 2005), and Mars (Schimmel et al., 2021)). Noises can also be subcategorized based on their source such as; i) seismic recorder (Ringler and Hutt, 2010), ii) temperature changes (Stutzmann et al., 2000; Doody et al., 2018), iii) ocean and sea waves (Webb, 1998; McNamara and Buland, 2004; Bonnefoy-Claudet et al., 2006; Cauzzi and Clinton, 2013; D'Alessandro et al., 2021; Anthony et al., 2022), iv) gravity-gradient noise (Harms et al., 2009), v) wind (Mucciarelli et al., 2005; Bonnefoy-Claudet et al., 2006; D'Alessandro et al., 2021; Anthony et al., 2022),

vi) human activities (McNamara and Buland, 2004; Bonnefoy-Claudet et al., 2006; Cauzzi and Clinton, 2013; Vassallo et al., 2019; D'Alessandro et al., 2021; Anthony et al., 2022) (Figure 1). This work is focused on the study of the background seismic noise levels.

The level of noise affects the quality of the seismic signals, hence the ability to detect seismic events. To be able to monitor the seismic sources, seismic networks require knowledge about the noise content of the networks. To characterize the noise at a given station, the frequency content of the noise is calculated via power spectrum density (PSD). The above-mentioned noise sources can be seen in different frequency bands of the PSD (D'Alessandro et al., 2021). Various models have been created to interpret the noise levels. The model of Peterson (1993) is widely used to define the lower (New Low Noise Model, NLNM) and upper (New High Noise Model, NHNM) bounds of the recorded noise as a baseline, developed using a worldwide catalogue from a wide variety of seismic stations. Cauzzi and Clinton (2013) developed the accelerometer low-noise (ALNM) and high-noise (AHNM) models using accelerometric data from the Swiss Seismological Service (Clinton et al., 2011) and very broad-band along with accelerometric data from Southern California Seismic Network (California Institute of Technology and United States Geological Survey Pasadena, 1926). The AHNM is computed as the lower boundary of 5-percentile PSD amplitudes observed on rock sites while the ALNM is computed as a particular combination of accelerometric sensors with a given gain and response with dataloggers. In ALNM, instrument and data logger noise are dominant at all frequencies, whereas in AHNM, urban noise, microseismic activities, and data logger systems dominate the short periods, mid-range periods, and long periods, respectively. This model is widely used as the baseline model for strong motion sensors (Ringler et al., 2015, 2020).

Even though to optimize the quality of the recordings seismic stations should be installed away from any source of noise (e.g., roads, major cities, and factories), the selection of the "optimal" location to install a seismic station weights multiple parameters depending on the purpose of the specific network. The National Accelerometric Network (RAN), owned and managed by the Italian Civil Protection Department (DPC) (Presidency of Counsil of Ministers - Civil Protection Department , 1972; Gorini et al., 2010; Zambonelli et al., 2011; Costa et al., 2022), is established to monitor strong motions at a national level. The integrated RAN is the combination of RAN with the following networks; i) the Friuli Venezia Giulia Accelerometric Network (RAF, Rete Accelerometrica Friuli Venezia Giulia in Italian, University of Trieste 1993; Costa et al. 2010) in the North-East Italy, owned and managed by the University of Trieste (UniTS) ii) Irpinia Seismic Network (ISNet, Weber et al. 2007) in the South of Italy, owned and managed by Analysis and Monitoring of Environmental Risk Society (AMRA). Thereinafter, RAN will refer to the integrated RAN.

In this paper, we focus on the background noise in RAN by analyzing the data coming from 532 continuous stations between 2019 and 2022. To do that we focused, in general, on the short periods (≤ 5 s) since they carry more relevant information related to parameters useful for civil defence purposes (e.g., PGA, PSA0.3, PSA1.0, and PSA3.0). The progressive conversion of data acquisition from triggered to continuous recording starting from the end of 2020 increased the number of stations available to study noise levels on a national scale. In Section 2, we explain the properties of RAN and the time coverage of the data. In Section 3, the data preprocessing and PSD processing workflow are explained. Background noise levels are presented in Section 4 and the possible noise sources are discussed in Section 5. To see the effect of the COVID-19 pandemic on the anthropogenic noise, we compare the 2019 and 2022 noise data with the one from the Italian nationwide lockdown. Numerous studies showed that during the pandemic, background noise levels are decreased due to the lockdown measures forced on a national scale all around the globe (Lecocq et al., 2020; Poli et al., 2020; Piccinini et al., 2020). During the COVID-19 lockdown the opportunity is raised to see the noise level changes due to human activity and how 'silent' the stations can be. Variations in the noise levels during the COVID-19 and non-COVID-19 time periods, along with several noise sources that we can clearly identify, are interpreted, and the overall background noise of RAN is presented in Section 6.

2 Data

RAN consists of more than 700 stations of which 532 provided continuous data in the time range that we are interested in. RAN stations have generally a standardized installation near urban areas (see Table 1) in free-field conditions, with instruments placed on an isolated pillar anchored on rock or put inside of the sediments.

Data from 2019 are used to characterise background noise information from RAN along with seasonal, daily, and hourly changes. Data collected during the lockdown (9 March - 4 May 2020) provide information about the noise levels when the anthropogenic sources nationwide were reduced in many places. Data from 2022 (1 January - 30 April 2022) are used to study the post-lockdown noise level and, thanks to the great increase in the number of continuous stations, provide better coverage of the Italian territory.

Thereinafter the combined data from 2019 and 2022 will be referred to as non-lockdown data, as opposed to the data from 9 March - 4 May 2020 which will be addressed as lockdown data. The location and data availability for each station is presented in Figure 2.

3 Method

The method introduced by McNamara and Buland (2004) represents the de facto standard for the evaluation of PSDs. This method was originally developed as a tool for monitoring the status of seismic stations: as such, the original parameters used for the computation of the PSDs and the use of smoothing and averaging provide a way to reduce the storage and computation costs involved, but can be limiting when the method is extended to scientific uses, as shown by Anthony et al. (2020).

The method implemented to compute the PSDs partially mirrors the one by Anthony et al. (2022), which in turn is an adaptation of McNamara and Buland (2004). Each daily recording is divided into $90\,\mathrm{min}$ windows with $50\,\%$ overlap, each one subsequently divided into $15\,\mathrm{min}$ subwindows with $75\,\%$ overlap: as pointed out by Anthony et al. (2020), the window length becomes less relevant for higher frequencies and noisier stations, which are the conditions of the present study. Data completeness above $90\,\%$ is required for each $90\,\mathrm{min}$ window. Transient signal, consisting also of earthquakes, are not removed from the seismic traces since they are low-probability occurrences with respect to ambient seismic noise (McNamara and Buland, 2004): Anthony et al. (2020) showed that while the presence of earthquakes in the recordings can skew the median ambient-noise estimates for longer periods ($10\,\mathrm{s}$-$50\,\mathrm{s}$), no significant effects have been observed for short periods. During preprocessing, data are linearly detrended, the gaps are linearly interpolated, and a Hann window is applied to limit spectral leakage (Peterson, 1993; Anthony et al., 2022). For each 15 min subwindow the PSD is computed using Welch's method (Welch, 1967), the results for all the subwindows within each 90 min window are averaged, and the instrument response is then removed from the PSD. No binning and smoothing are performed during the PSDs computation. Similar to Anthony et al. (2022), we performed a one-third octave average over the PSDs: the averaging bandwidth can be assumed as a reasonable trade-off between the obtained spectral resolution and the accuracy in the broadband noise sources characterization in each band. The parameters used for the evaluation of the PSDs in our study, along with the ones used in McNamara and Buland (2004), D'Alessandro et al. (2021), and Anthony et al. (2022) are reported in Table 2.

To study specific patterns in the noise levels over time, the PSDs are studied by grouping them over different time ranges. To study the effects of anthropogenic noise it is a common practice to consider the variations between day (08:00 - 18:00) and night (20:00 - 07:00) and between weekday (Monday - Friday) and weekend (Saturday - Sunday). Similarly, the variations between summer and winter are analysed to check seasonal variations of the noise levels. To study seasonal variations we limited our analysis to 2019 being the only year-long dataset analysed in this study with continuous recordings unaffected by lockdown measures. Stations with more than 50 % of data for both summer and winter time periods are selected to analyze seasonal effects. The statistics related to these variations are computed over the daily difference of the medians of each group.

4 Results

The results obtained for 20 randomly selected stations applying the method described in Section 3 are shown in Figure 3 for the periods of interest, namely 0.1 s, 0.25 s, 0.5 s, 1 s, 2 s, and 5 s: this provide an overview of the behaviour of the noise at different timescales for different periods, as described in details afterwards (see Figure 1). The overall background noise levels for all stations in RAN are presented in Figure 4. The period-wise median of the PSDs for each station is computed and interpreted as the representative noise level. Since RAN is a strong motion network, we are mainly interested in periods less than 5 s. Anthropogenic sources can have a major role in the noise content of short periods (Table 1) which also are essential information for seismic parameters estimation, seismic engineering and building monitoring. Noise level statistics of RAN stations for each period of interest are reported in Table S1 with the related noise level and the station placement.

RAN has relatively high noise levels in short periods. Numerous stations exceed the levels defined by Cauzzi and Clinton (2013). The median noise at each station, presented in Figure 4, and the AHNM have been compared and the results are reported in Table 3. 1 s is the period for which we have the highest rate of exceedance of the AHNM level with 34.4 % of the stations. The probability density function calculated over the median PSD of all stations can be seen in Figure 5. The median values for 0.1 s, 0.25 s, 0.5 s, 1 s, 2 s, and 5 s are -112.59 dB, -119.09 dB, -120.35 dB, -119.98 dB, -118.07 dB, and -115.98 dB, respectively. The median values are always below the AHNM model for the period range of interest. Between 0.1 s and 2 s, stations located in the Po valley and the area from Ischia Island to Naples have relatively high noise levels. Stations around Naples and Ischia Island have the same trend in higher periods.

Under the common assumption that the anthropogenic noise decreases during the night hours and during the weekend, we characterised the contribution of human activities to the ambient noise levels. Considering the data from 2019 and 2022, at

$98.2\,\%$ of the stations there is a reduction in noise levels at nighttime with respect to the average noise during daytime (Figure 6). Daytime-nighttime noise level change reduces with increasing periods at $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1\,\mathrm{s}$, and $2\,\mathrm{s}$ with median values of $6.14\,\mathrm{dB}$, $1.37\,\mathrm{dB}$, $0.30\,\mathrm{dB}$, $0.8\,\mathrm{dB}$, and $0.8\,\mathrm{dB}$, respectively. Among these periods 529, 512, 498, 433, 405, and 485 stations are noisier during the daytime.

We also studied the changes in the noise levels between weekdays and weekends and the general trend of noisier weekdays are observed (Figure 7), consistently with the assumption of a reduction in human activities during the weekends. Median changes between weekdays and weekends are smaller with respect to the daytime-nighttime changes with the same trend of decreasing differences with increasing periods. Weekday-weekend median differences are $0.95\,\mathrm{dB}$, $0.38\,\mathrm{dB}$, $0.11\,\mathrm{dB}$, $0.02\,\mathrm{dB}$, $0\,\mathrm{dB}$, and $-0.07\,\mathrm{dB}$ for $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1\,\mathrm{s}$, $2\,\mathrm{s}$, and $5\,\mathrm{s}$, respectively. General trend of noisier weekdays can be followed between $0.1\,\mathrm{s}$ to $1\,\mathrm{s}$ with 487, 484, 457, and 353 stations in the periods of interest.

Data from 2019 are further used to study the seasonal variation of very long period noises ($\geq 5\,\mathrm{s}$), as shown in Figure 8. The results show that winters are noisier than summers as suggested by previous studies (Stutzmann et al., 2000; McNamara and Buland, 2004; Anthony et al., 2022; D'Alessandro et al., 2021) with the number of stations that are noisier during winters with respect to summer can go up to 121 in $16\,\mathrm{s}$ with median noise level change up to $1.55\,\mathrm{dB}$. Despite the difference in noise sources potentially contributing in the long periods (Figure 1), no significant variations have been noticed among different periods and no particular effect related to any specific source has been found.

4.1 COVID-19 Lockdown

In the early periods of the COVID-19 pandemic, Italy introduced a full lockdown in the whole country which limited the daily activity of the general public as well as a wide range of industrial activities. Lockdown started on the 9th of March 2020 (8th of March in Northern Italy) and ended on the 4th of May 2020. Following the nationwide lockdown, different containment measures were set on a more local scale and at different times.

To observe the noise level changes during the lockdown, 309 stations that were continuously recording during both the lockdown and the non-lockdown periods are selected. For short periods general trend of quieter stations during the lockdown than the non-lockdown dates can be noticed (Figure 9), with 303, 277, 255, 237, 280, and 259 stations being quieter at periods of $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1.0\,\mathrm{s}$, $2.0\,\mathrm{s}$, and $5.0\,\mathrm{s}$ for the common stations, respectively. In all of the periods lockdown dates are quieter than the non-lockdown dates. During the lockdown 303, 277, 255, 237, 280, and 259 stations are quieter. Furthermore, hour and day specific results are also presented in daytime - nighttime (Figure 10). During the both daytime and nighttime of lockdown dates stations are quieter with respect to non-lockdown dates. Median daytime changes vary between $2.27\,\mathrm{dB}$ and $0.13\,\mathrm{dB}$ whereas nighttime changes are between $1.19\,\mathrm{dB}$ and $0.12\,\mathrm{dB}$. Weekday-weekend differences results, not presented in the paper for the sake of simplicity, but reported Figure S2. Median weekday noise level changes goes up to $4.12\,\mathrm{dB}$ and weekend changes goes up to $0.39\,\mathrm{dB}$ in $0.1\,\mathrm{s}$. Majority of the stations are noisier in weekday ($\geq 75\,\%$) and weekends ($\geq 60\,\%$) of non lockdown period.

5 Discussion

Table 1 shows the distribution of the stations according to the classification proposed by Istituto Superiore per la Protezione e la Ricerca Ambientale (2022). Even though most of the stations are located in urban areas and potentially subjected to high levels of anthropogenic noise, this classification is too reductive (e.g., not considering the population density and the presence or making a distinction between residential and industrial areas) to be associated to specific noise levels.

The interpretation of the background noise in Italian strong motion network can be done in three different ranges that are low periods (<1 s), medium range periods (between 1 s and 5 s), and long periods, (>5 s). As mentioned before, in the lower periods, human activities are the main source of background noise. 273 of 532stations have noise levels exceeding the AHNM developed by Cauzzi and Clinton 2013, as reported in Table 3 considering the results for different periods. In Table 3 the highest percentage number of stations exceeds the AHNM is at 1 s. This can be due to the specific datalogger systems used by RAN, as discussed by Cauzzi and Clinton (2013), that shift the background noise levels up and cause network-wide high level noise (Figure 4) at this specific period.

As shown in Table 3, 51.3 % of all stations exceed the AHNM for at least one period. However, by comparing with the P-wave corner frequencies by Brune (1970), even the 10 noisiest stations theoretically detect the P wave arrival of magnitude 2.7 event starting from 1 km epicentral distance (Figure S3). Since the purpose of RAN is to record peak amplitudes, those stations are useful even for earthquakes with smaller magnitudes and longer epicentral distances.

The effect of human activity on noise levels can be seen by comparing daytime noise to nighttime noise, for which human activity is reduced. As seen in Figure 6, the majority of the stations are noisier during the day for periods less than 1 s. The noise difference between day and night decreases with increasing periods, but the nationwide trend of days being noisier is valid for 0.1 s, 0.25 s, and 0.5 s. The same pattern can be seen in broadband stations located in Italy (D'Alessandro et al., 2021).

In the weekday - weekend variations, the same pattern can be followed in short periods. Figure 7 shows that weekdays were noisier with respect to weekends in almost all stations. The noise level changes are consistent with the changes in weekly human activities.

In the medium range periods, there are multiple noise sources that have been identified by previous studies (Figure 1). Cauzzi and Clinton (2013) stretches the cultural noise up to 3 s whereas D'Alessandro et al. (2021) indicates that wind and swell related noises are dominant between 1 s to 10 s. Consequently, variations in the noise sources in 2 s and 5 s can be found by analyzing the daily, weekly and seasonal changes.

Day and night differences follow the trend that is seen in shorter periods in most of the network. However, in 1 s the day and night differences are nulled at most stations with the notable exception of the stations located in the Po valley, on Ischia island, and in Naples which remain noisier during the day. The majority of the stations exceed the AHNM threshold in 1 s, and the noise levels do not change during the night, which means that the anthropogenic effects are not the dominant source. Even though in 2 s and 5 s there is a general trend of having higher noise levels during the daytime, the power change is very small (0.11 dB and 0.22 dB, respectively). Moreover, the effects of sea, swell, and/or wind at our stations have not been identified and thus, do not have a significant role on the noise levels. There is no clear correlation between the noise level at RAN stations and their distance to the coastline, as also shown in Figure 4.

Considering weekly variations, stations become noisier on weekends with decreasing power change with increasing periods. In the Po valley, the general trend of a high noise level diminishes starting from $2\,\mathrm{s}$ in average and in the same periods, unlike the day and night difference, weekends follow the same trend.

In long periods, the effects of wind, swell, sea, pressure, and instrumental noises are addressed in literature as the main sources of the noise (Figure 1). The difference between the noise levels in the winter and summer periods of 2019 can be seen in Figure 8. Unlike in the study of D'Alessandro et al. (2021) in which it is stated that in periods between $0.83\,\mathrm{s}$ and $8.33\,\mathrm{s}$ noises are higher in coastal areas with respect to the inland, we found no evidence of such a pattern for RAN stations. This is consistent with the instrumental noise of the stations being the main source of long period noise associated with accelerometric recordings, as indicated by Cauzzi and Clinton (2013).

In Figure 4, there are some areas that follow the pattern found by D'Alessandro et al. (2021), such as in Naples, noise levels are higher than in the stations that are East of Naples inland. In $1\,\mathrm{s}$ only the stations in Naples are in agreement with D'Alessandro et al. (2021) and in our study noise levels are much higher in other parts of Italy. The same trend can be seen in longer periods ($>5\,\mathrm{s}$). There are numerous stations located in the Po valley with high noise levels even though they are far away from the sea, and several stations located in the Alps in North West Italy. In $0.1\,\mathrm{s}$, we have noisy stations in Po valley, Puglia, and the eastern part of Sicily, where our stations are noisier than the ones analyzed in D'Alessandro et al. (2021). However, in short periods our results are in agreement with the study of D'Alessandro et al. (2021) in other parts of Italy. We can conclude that human-made activities dominate the low periods of the noise content and high noise levels can be linked to the activities that are occurring in the area where anthropogenic sources are present. Reduction in human activity can be seen in Figure 6 in which almost all stations have lower noise levels at night with respect to their daytime counterparts.

5.1 COVID-19 Lockdown

Previous studies showed that during the COVID-19 lockdown there was decrease in noise levels due to the reduction of human-related activities, and as recorded by both broadband (Poli et al., 2020; Xiao et al., 2020; Lecocq et al., 2020; Somala, 2020; Dias et al., 2020; Roy et al., 2021; Grecu et al., 2021; Cannata et al., 2021) and strong motion (Yabe et al., 2020; Łukasz Ścisło et al., 2021) stations. Yabe et al. (2020) found a clear noise level drop in Tokyo metropolitan area in Japan in periods between $0.05\,\mathrm{s}$ and $1\,\mathrm{s}$. Cannata et al. (2021) found that in Sicily (Italy) $0.1\,\mathrm{s}$ and lower periods have the most noise level reduction in COVID-19 pandemic. Lecocq et al. (2020) found that background noise levels of numerous seismic stations all around the globe reduced up $50\,\%$ during COVID-19 lockdown with respect to the average background noise of the previous weeks before the lockdown. It affected not only the densely populated cities such as London and Paris but also relatively less populated areas such as Barbados and Faroe Islands.

Human-related activities affect RAN stations significantly since several of them are located inside or near public buildings. These activities were reduced during the lockdown period of the COVID-19 pandemic, since individuals were only allowed to move within $500\,\mathrm{m}$ from their homes and only essential workers were exempt from the distance restrictions. Many public institutes worked remotely in most of their units, which also reduced human activity in public buildings. This led to the reduction in noise levels shown in Table 4. In the $0.1\,\mathrm{s}$, there is almost $2\,\mathrm{dB}$ noise reduction between the median noise difference between lockdown and no - lockdown time periods at the stations (Figure 9a). The difference has the lowest reduction in $1\,\mathrm{s}$ but the noise levels are higher during this period with respect to AHNM (Figure 4). In Apennines there are numerous stations whose noise levels between $0.5\,\mathrm{s}$ to $2\,\mathrm{s}$ have not been affected by the lockdown (Figure 9c-e). Since for periods greater than $5\,\mathrm{s}$ the instrument self-noise is the dominant source, as previously described, we limited our analysis of the effect of the lockdown to periods up to $5\,\mathrm{s}$. For all the periods considered, the lockdown period is on average quieter during daytime than the 2019 - 2022, with an average noise level reduction of $1.0\,\mathrm{dB}$.

The change between daytime and nighttime are visible especially on shorter periods ($\leq 0.5\,\mathrm{s}$, Figure 10a,c,e). Changes in the daytime are more significant than the changes in the nighttime between the lockdown and no-lockdown time span. All stations are noisier both during the daytime and nighttime in periods shorter than $0.5\,\mathrm{s}$, whereas, in periods of $1\,\mathrm{s}$ and $2\,\mathrm{s}$, stations in the Apennines have similar power change in both daytime and nighttime. There is a clear trend of noisier day and night in Southern Italy in $2\,\mathrm{s}$ and it can be partially traced in $5\,\mathrm{s}$. Even though numerous stations have relatively high noise levels in $2\,\mathrm{s}$ (Figure 4e), there is no particular pattern in this period with respect to other parts of Italy.

5.2 Case Study: Stations Located in Trieste

To show the significant effects that the nearby surrounding of a station can have on its noise level we considered two RAF stations, CARC (latitude: 45.652, longitude: 13.770) and DST2 (latitude: 45.658, longitude: 13.801), located in Trieste (in North-East Italy), that despite their proximity (<$3\,\mathrm{km}$) show significant differences. The selection of these two particular stations is further supported by the extensive knowledge of their spatial and administrative information.

DST2 station is located in the basement of one of the Mathematics and Geosciences Department buildings of the UniTS that sits on a deep Flysh deposits (Figure 11). CARC station is located on the ground floor of the Palazzo Carciotti which is located in the city center of Trieste and was built in the early 19th century. It crosses with one of the main major roads in the city center and the building is surrounded by multistory residential buildings. Historically, this area was a salina (Figure 12) and the area is filled with a $27\,\mathrm{m}$ depth material layer (Fitzko et al., 2007) to cover up the salina to expand the city in the 18th century.

In Figure 13, median of lockdown and no-lockdown periods are presented. In order to see the hourly changes in noise levels, $90\,\mathrm{min}$ PSDs are plotted, separately. In the lower periods ($<1\,\mathrm{s}$) where anthropogenic noises prevail, CARC station is noisier in both time ranges. In the daytime noise levels exceed the upper limit of Cauzzi and Clinton (2013) model, whereas in nighttime they are close to the upper limit. During the lockdown, both stations have lower amplitudes in low periods that can be associated with the reduction in the human activities. At CARC station, there is significant decrease in noise between 20:00 and midnight. Between $0.08\,\mathrm{s}$ and $1\,\mathrm{s}$, median noise levels are decreased $8.68\,\mathrm{dB}$ and $2.36\,\mathrm{dB}$ for DST2 and CARC stations, respectively.

It is worth to consider that San Giovanni campus of the UniTS, where DST2 is located, is an isolated area within the city where almost all human activities ceased during the lockdown. On the other hand, being located near one of the city road artery, CARC was still affected by the limited human activity present during the lockdown, hence the minor reduction in the noise levels.

5.3 Vehicle Noise

As mentioned before in Section 1 some of the seismic stations are positioned in public buildings, located in urban areas and connected by convenient transportation infrastructure. Consequently, these stations provide relatively noisy recordings with cars being one of the main noise sources.

To demonstrate the effect of the cars in seismic noise measures, PLTA (latitude: 41.886, longitude: 14.789) station is chosen (Figure 14). The station is located next to the municipality building of Palata in Central Italy, which has 2 intersections within $50\,\mathrm{m}$. Cars are detected in seismic trace in 13 days of 2019 by visually analyzing the data. In total, 7289 car-related signals with time duration between $5\,\mathrm{s}$ and $20\,\mathrm{s}$ are chosen for further analysis in which Fast Fourier transforms (FFTs) are calculated (Figure 14). In Figure 15, it can be seen that the frequency content of the analyzed car-related signals and peaks in PSD overlap which means that in the period range between $0.95\,\mathrm{s}$ and $0.06\,\mathrm{s}$, cars can be considered as the main source of the noise.

6 Conclusions

The recent modernization of RAN stations allowed us to study their noise levels on a nationwide scale. The analysis is performed by computing PSDs over $90\,\mathrm{min}$ windows of signals using continuous recordings acquired between 2019 and 2022. The results of this study improve the overall seismic background noise information of Italy, complementing the previous work by D'Alessandro et al. (2021) for the Italian broadband network. It is found that a significant number of stations (up to $51.3\,\%$ of all stations) have higher noise levels than the AHNM that is defined for accelerometers in Switzerland and California by Cauzzi and Clinton (2013).

As presented in Section 4, RAN has several very noisy stations located within cities. We must stress that the fundamental duty of RAN is to provide ground motions of the locations where civil defence may need to provide assistance in post-disaster (e.g., strong earthquake) situations. Even though some of these stations are noisy (e.g., CSA7), they are well capable of providing the true nature of the ground motion if there is a strong earthquake nearby, hence they are able to serve their purpose (Costa et al., 2022). Depending on the nature of the future station installations and studies, noise levels of RAN (Figure 4) may give an insight into the capabilities of the stations.

The surrounding conditions for RAN stations within settlements are variable and have noticeable effects on the noise levels. The comparison of CARC and DST2 stations, located less than $3\,\mathrm{km}$ apart, clearly describes this situation. It also highlights another common problem for stations installed in settled areas which is the presence of vehicle noise that is dominant in the short period range (Figure 15). From the comparison we can conclude that by carefully considering the surrounding conditions for the station placement is possible to record high quality data without compromising the coverage of the area of interest.

The daily variations of the noise levels of the station, obtained comparing the daytime (08:00 - 18:00) and nighttime (20:00 - 07:00) results, show that in short periods where human - made activities dominate the seismic records daytime is noisier than nighttime. This trend can be seen in some stations also in longer periods, but it cannot be generalized to the whole network.

In the longer periods ($\geq 1\,\mathrm{s}$), unlike various previous studies, our analysis has not found any evidence of the swell and sea effect on noise levels (between $1\,\mathrm{s}$ and $40\,\mathrm{s}$) with no clear pattern arising considering stations at different distance to the coastline (Figure 4). Additionally, no seasonal pattern has been found in very long periods ($\geq 5\,\mathrm{s}$, Figure 8). In periods between $2\,\mathrm{s}$ to $5\,\mathrm{s}$ winter is noisier as expected from previous studies (D'Alessandro et al., 2021) but in longer periods it is reversed and the median noise differences between winter and summer are generally constant network-wise with values increasing with periods. These results are consistent with the instrumental noise being the main noise source at long periods, as indicated by Cauzzi and Clinton (2013).

During the COVID-19 lockdown in Italy (from March to May 2020) noise levels are reduced due to several measures that limited the human activity. Its effect can be seen for all the considered periods with an average reduction in the noise level of $1.0\,\mathrm{dB}$ (and up to $2.9\,\mathrm{dB}$ at $0.0625\,\mathrm{s}$) during the daytime. The effect of the lockdown also affected the weekday and weekend variations of the noise levels.

Thanks to the continuous data acquisition in RAN, further studies related with background noise can be carried out in future. The high density of RAN stations can be leveraged to perform local and regional studies of noise level variations. Moreover, national level background noise models can be developed similar to D'Alessandro et al. (2021).

Code and data availability. The analysis has been performed using the data and metadata from the Italian Strong Motion Network (RAN, Gorini et al. 2010; Costa et al. 2022). Data and materials along with the developed models can be found in a dedicated GitHub repository.

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Competing interests. The contact author has declared that none of the authors has any competing interests.

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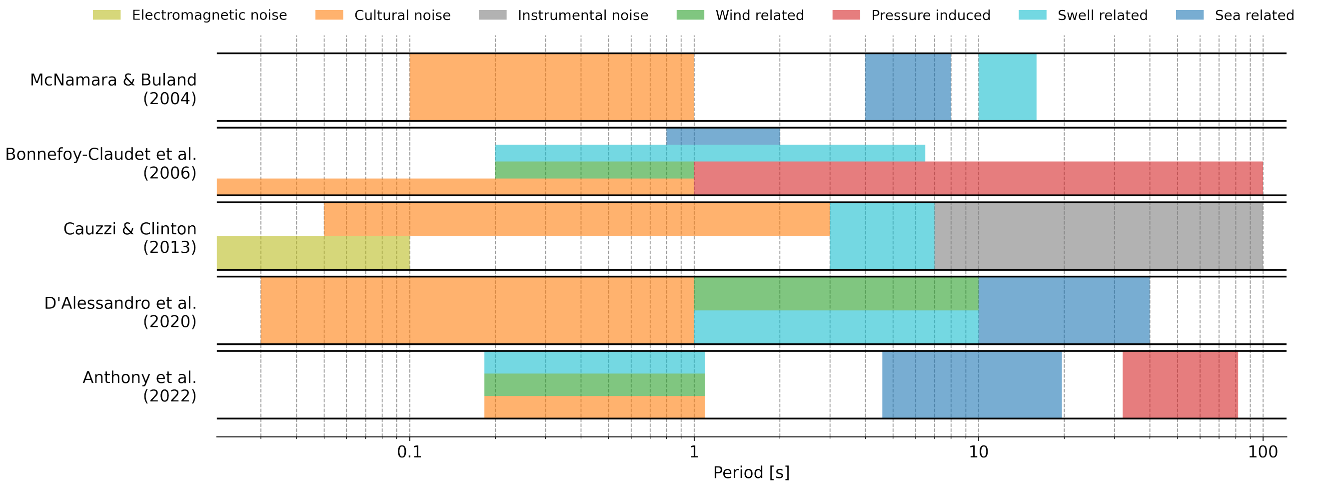

Figure 1. Main noise sources for different period bands from the studies of McNamara and Buland (2004); Bonnefoy-Claudet et al. (2006); Cauzzi and Clinton (2013); D'Alessandro et al. (2021); Anthony et al. (2022)

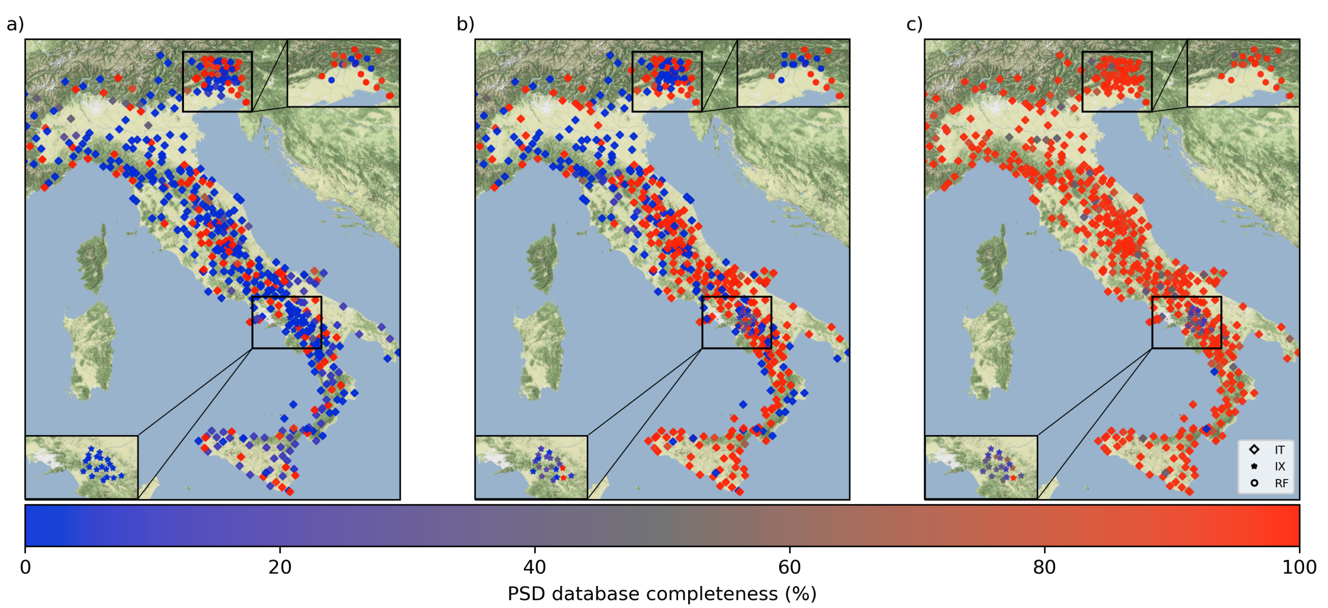

Figure 2. Data availability of the stations in a) 2019, b) lockdown period, and c) 2022. The close up boxes in lower left and upper right highlight ISNet (IX) and RAF (RF), respectively. Basemap data are retrieved from © Stamen Design.

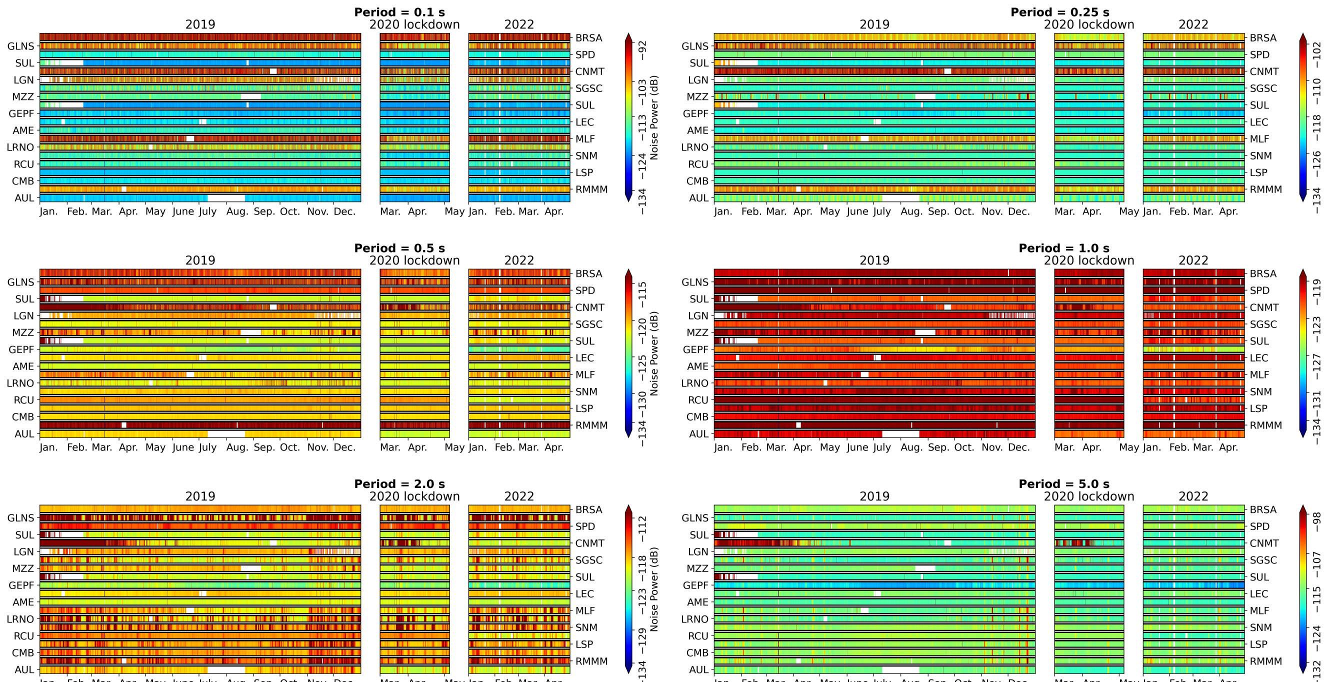

Figure 3. PSD timeseries for randomly selected 20 stations in periods of 0.1 s, 0.25 s, 0.5 s, 1 s, 2 s, and 5 s. The limits of the color scale are based on the models by Cauzzi and Clinton (2013).

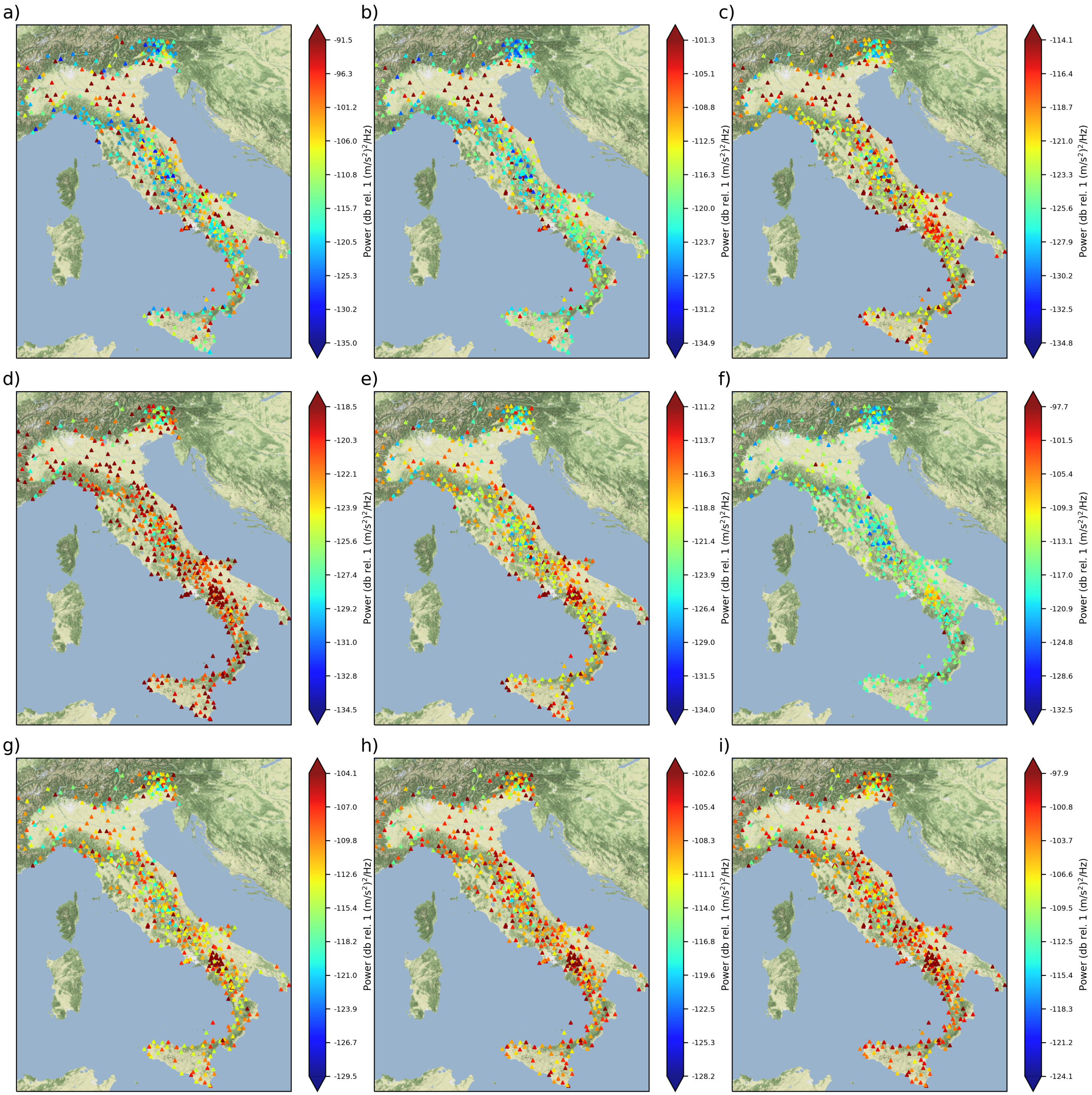

Figure 4. Median vertical component noise maps in one-third octave bands around a-g) $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1\,\mathrm{s}$, $2\,\mathrm{s}$, $5\,\mathrm{s}$, $16\,\mathrm{s}$, $32\,\mathrm{s}$, and $80.6\,\mathrm{s}$. Upper and lower limits of the color bar are defined by the model developed by Cauzzi and Clinton (2013). Vertical components are presented in the following figures and Electronic Supplement. Background noise levels of all calculated periods can be found in Figure S1. Basemap data are retrieved from © Stamen Design.

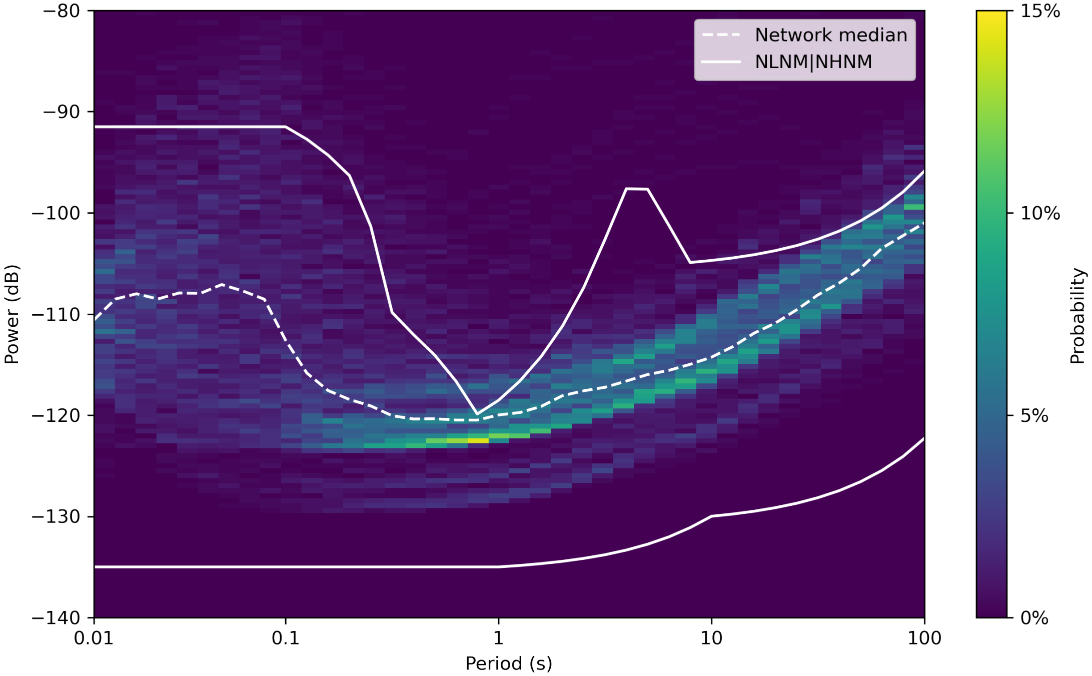

Figure 5. Probability density function of medians of PSDs of all stations. Dashed white line represent the median of the network and solid white lines represent NLNM and NHNM defined by Cauzzi and Clinton (2013).

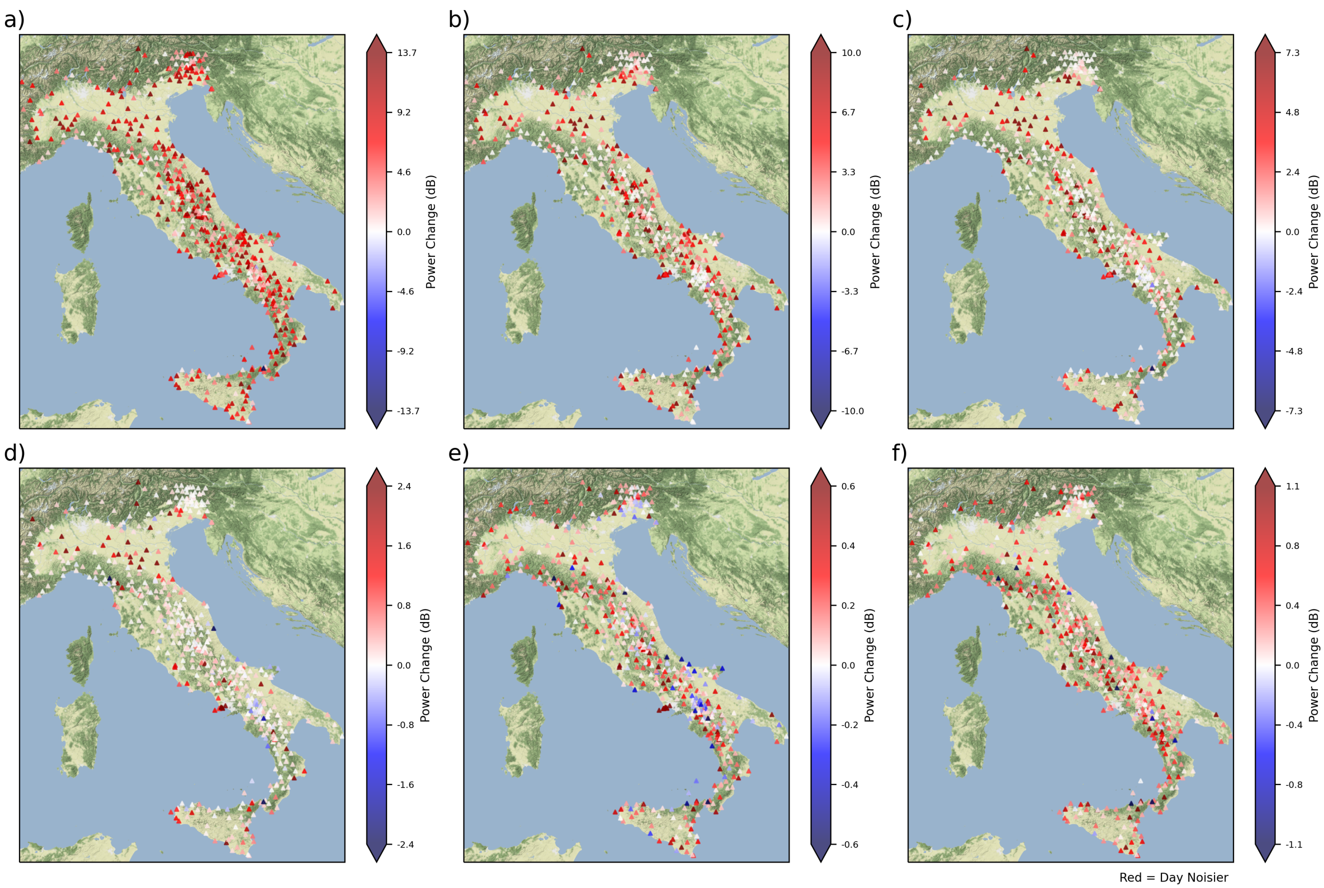

Figure 6. Median noise levels in dB for daytime and nighttime for the periods of $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1.0\,\mathrm{s}$, $2.0\,\mathrm{s}$, and $5.0\,\mathrm{s}$. Red color means day is noisier than night. Basemap data are retrieved from © Stamen Design.

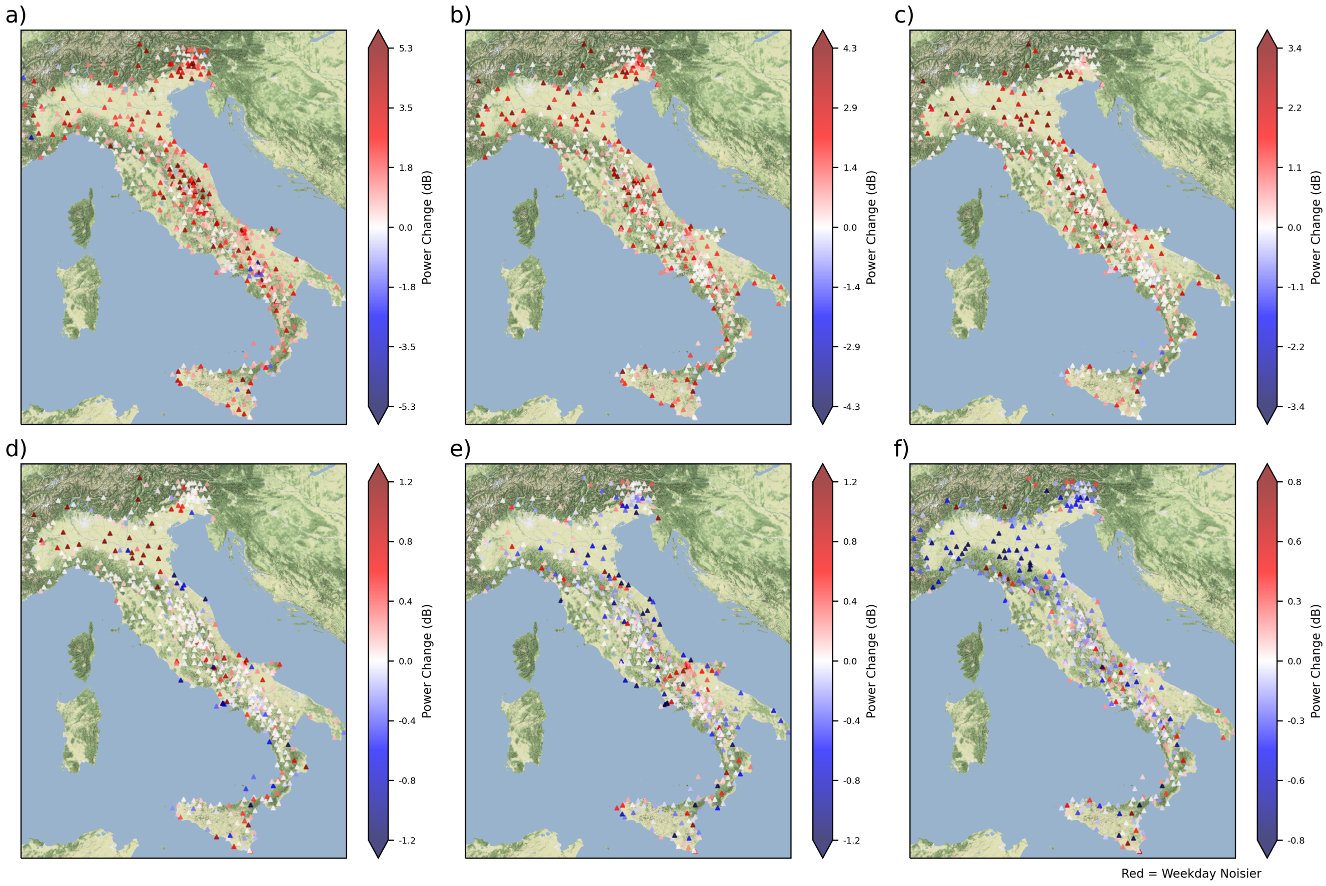

Figure 7. Median noise levels in dB for weekday and weekend time for the periods of $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1.0\,\mathrm{s}$, $2.0\,\mathrm{s}$, and $5.0\,\mathrm{s}$. Red color means weekday is noisier than weekend. Basemap data are retrieved from © Stamen Design.

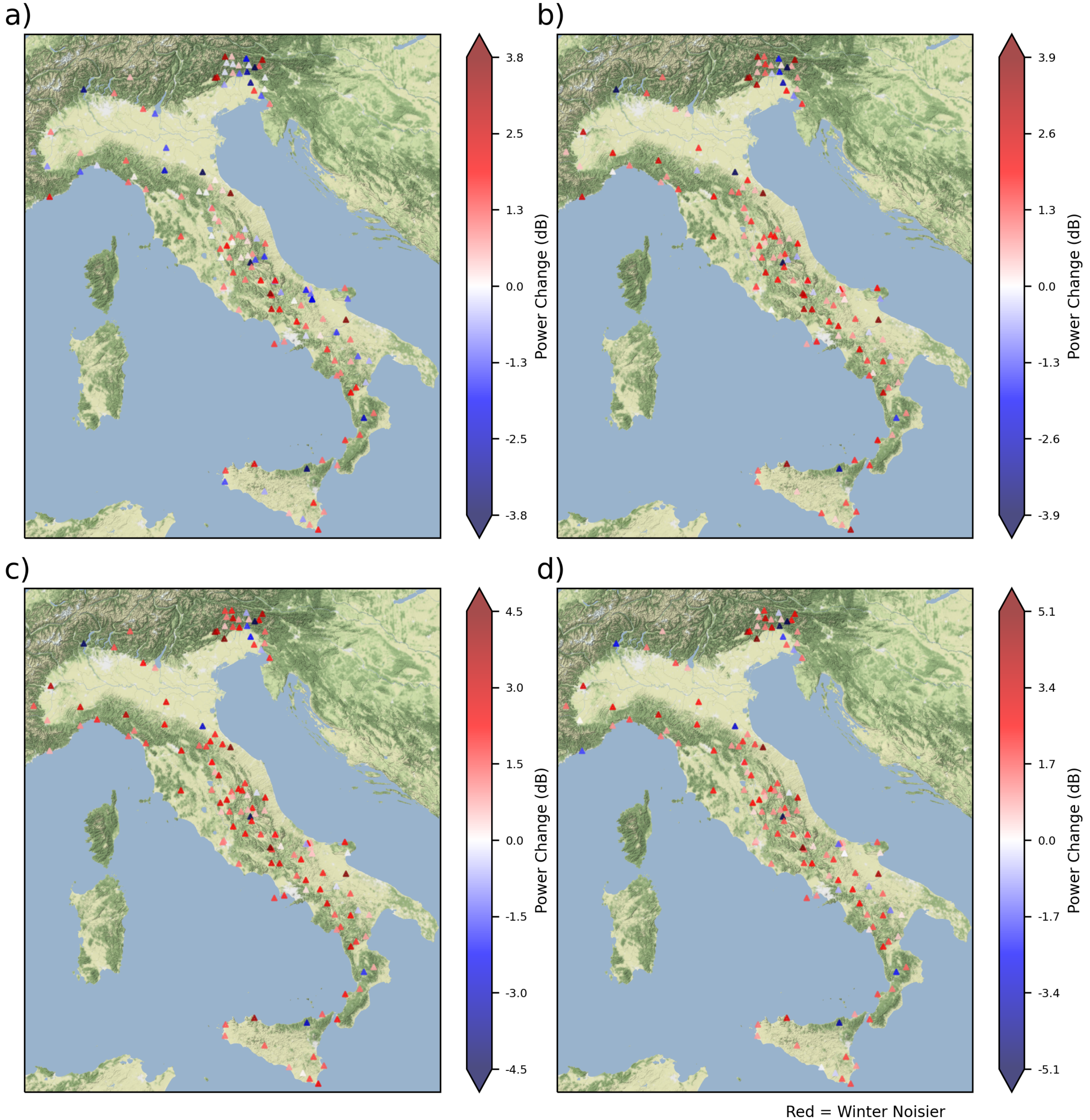

Figure 8. Difference between noise levels in 5 s, 8 s, 16 s, and 32 s between the winter and summer of 2019. Red color means summers are noisier than winters. Basemap data are retrieved from © Stamen Design.

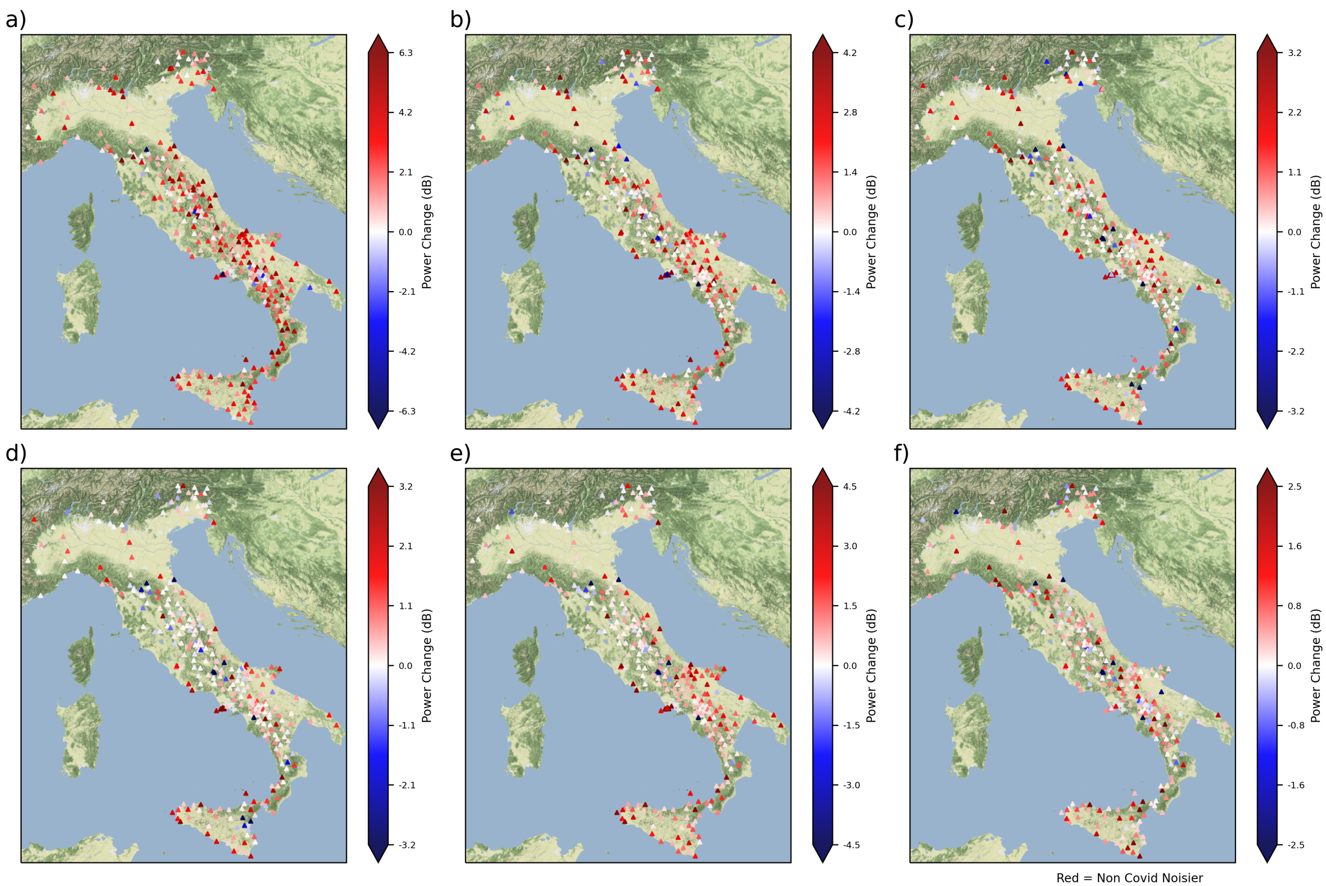

Figure 9. Difference between noise levels in 0.1 s, 0.25 s, 0.5 s, 1.0 s, 2.0 s, and 5.0 s between 2019 - 2022 and lockdown. Red color means 2019 and 2022 are noisier than lockdown period. Basemap data are retrieved from © Stamen Design.

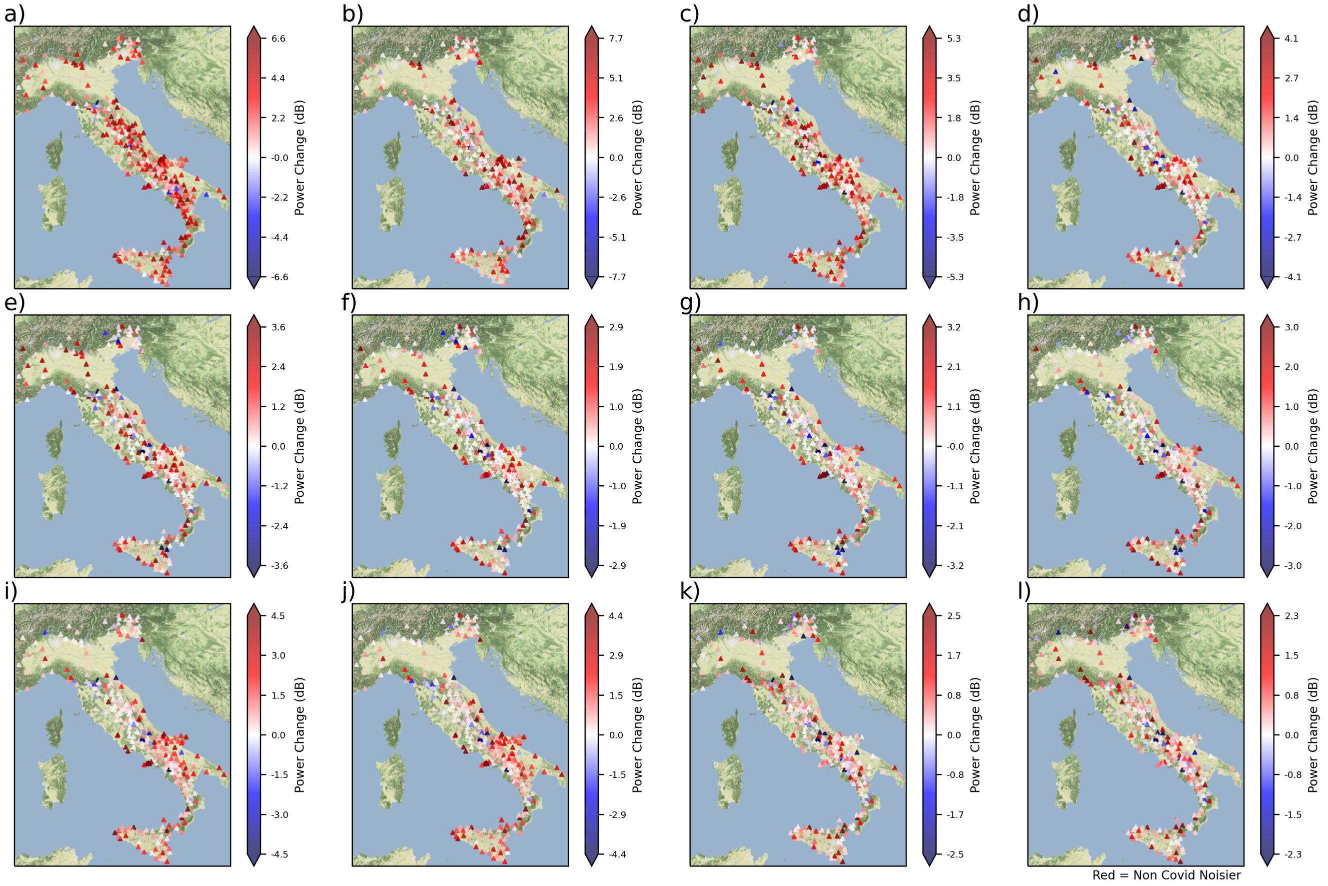

Figure 10. Difference between noise levels in 0.1 s, 0.25 s, 0.5 s, 1.0 s, 2.0 s, and 5.0 s between 2019 - 2022 and lockdown in a, c, e ,g, i, k) daytime, b, d, f, h, j,l) nighttime. Basemap data are retrieved from © Stamen Design.

Figure 11. Geological Map of Trieste (grey, orange, and yellow colors indicate anthropic, ubiquitous deposit units, and flysh of Trieste, respectively), modified from Cucchi et al. (2013).

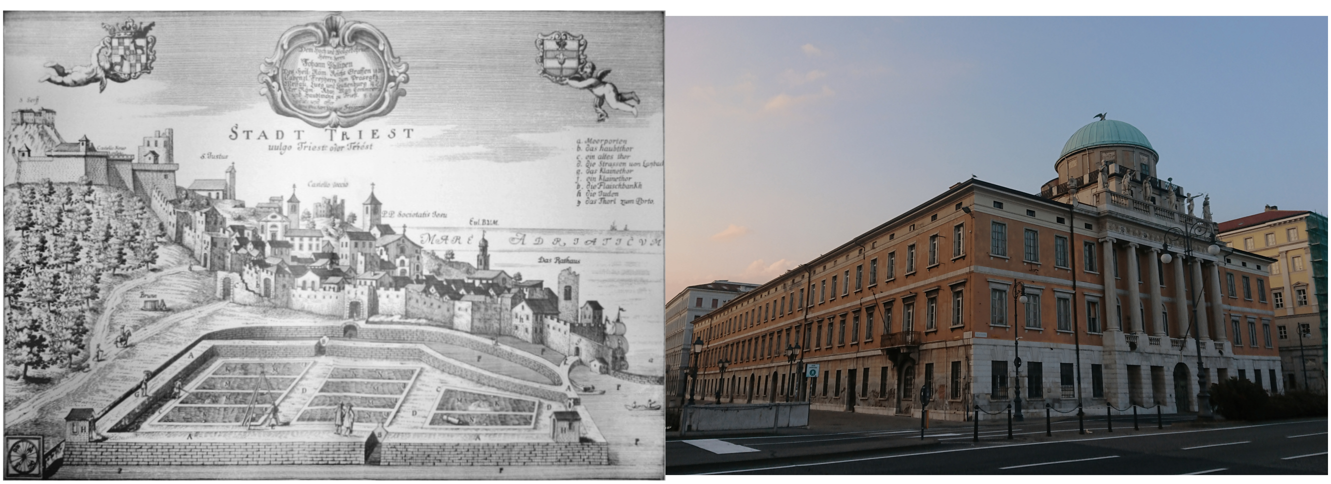

Figure 12. left) Drawing of the salina part of the city of Trieste by Johann Weikhard von Valvasor in 1689 taken from © Wikipedia (https://upload.wikimedia.org/wikipedia/commons/6/67/Mesto_Trst-Valvasor-2.jpg, last access: 7 November 2022), right) Palazzo Carciotti.

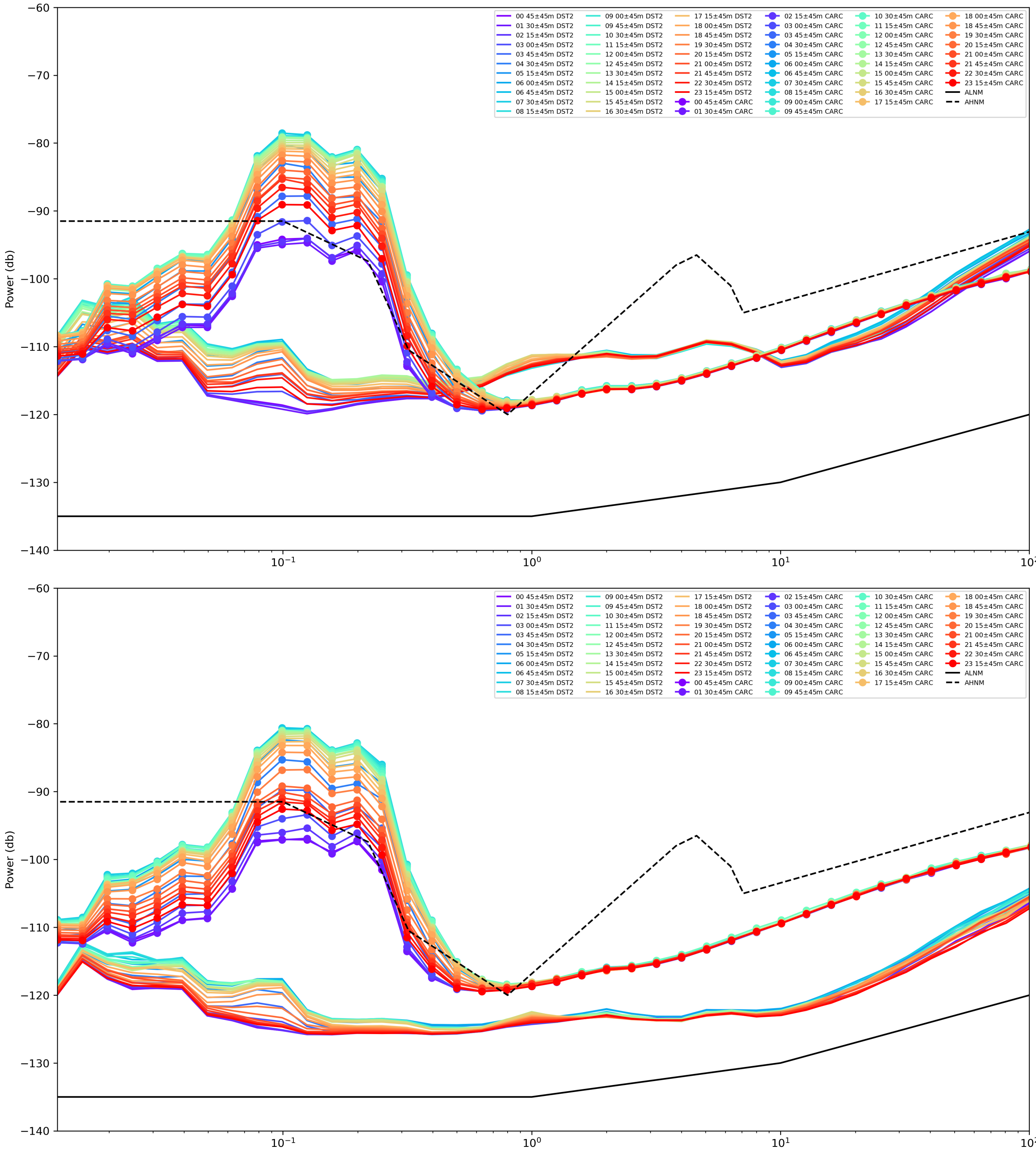

Figure 13. Hourly average plots of noise levels of DST2 (line) and CARC (line with dots) for no-lockdown (top) and lockdown (bottom) dates. ALNM and AHNM introduced by Cauzzi and Clinton (2013) are black line and dashed line, respectively.

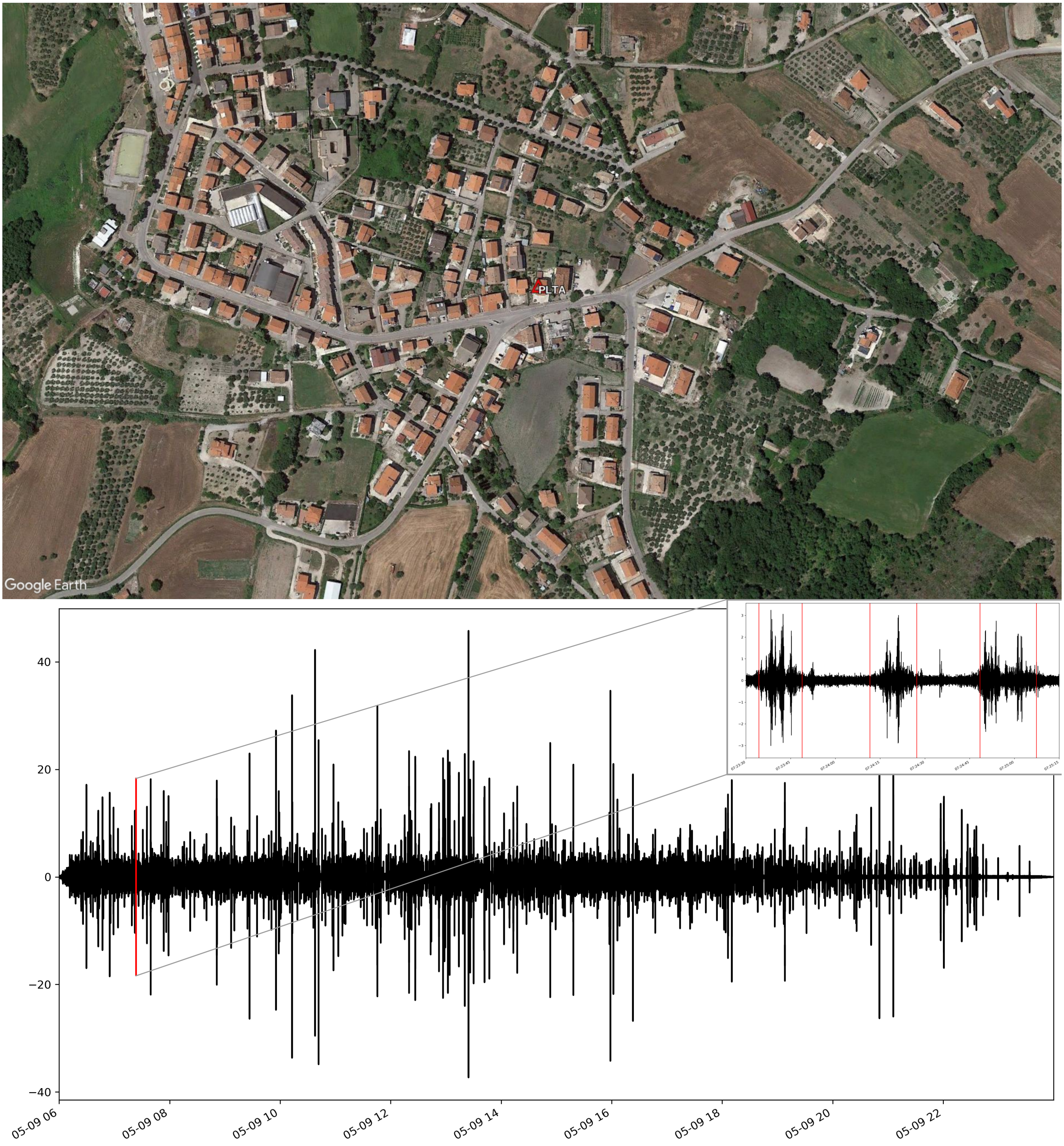

Figure 14. top) Satellite image of the Palata. PLTA (red triangle, latitude: 41.88, longitude: 14.78) station which is located in Palata municipality building in Central Italy (the image is generated by © Google Earth). bottom). Seismic record registered on 9th of May 2019. Three detected cars are presented in the upper right with red vertical lines presenting the initiation and termination position of the car signals.

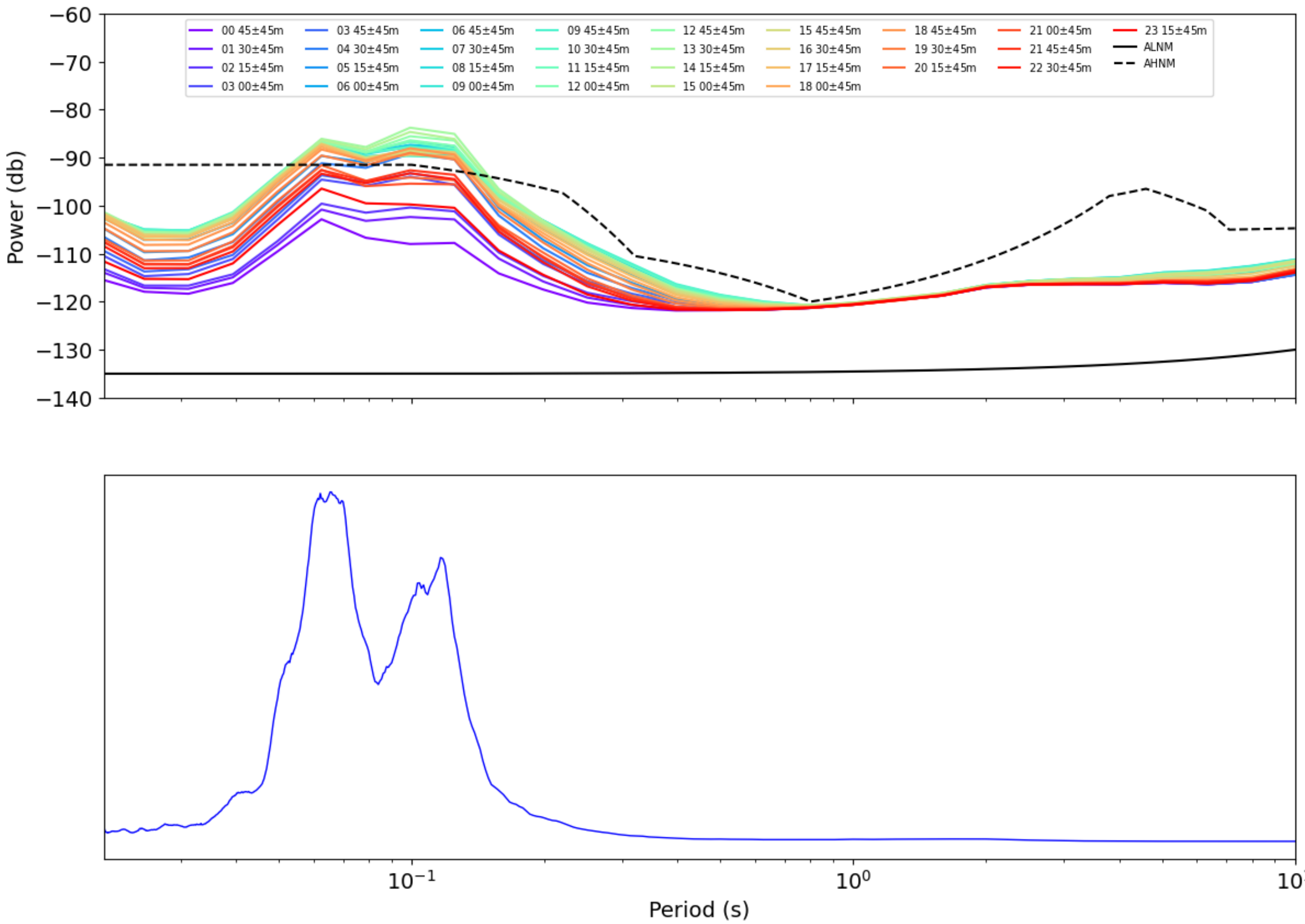

Figure 15. top) Hourly average plot of noise levels of PLTA, and bottom) Average of FFT of the detected cars in PLTA in 2019.

Land Usage	Code	Stations
Settlements	SL	388
Annual Cropland	ACL	48
Permanent Cropland	PCL	12
Grassland	GL	39
Forest	FL	38
Other land	OL	7
Wetland	WL	0
Water	WT	0

Table 1. Land usage at RAN stations (Istituto Superiore per la Protezione e la Ricerca Ambientale, 2022).

Parameter	McNamara and Buland (2004) D'Alessandro et al. (2021)	Anthony et al. (2022)	Present work
Window	60min	60min	90min
Window overlap	50%	50%	50%
Completeness	-	>90%	>90%
Sub-window	900s	819.2s	900s
Sub-window overlap	75%	75%	75%
Detrend	Linear	Linear	Linear
Gaps	Removed	Zero-pad	Linear interpolation
Window type	10% cosine	Hann	Hann
Binning/smoothing	Yes	None	None
Average	Overlapped 1 octave	1/3 octave	1/3 octave

Table 2. Data processing parameters for the evaluation of the PSDs of our study along with the studies of McNamara and Buland (2004), D'Alessandro et al. (2021), and Anthony et al. (2022).

Period (s)	AHNM Threshold	Exceeding stations	Percentage of network (%)
0.10	-91.50	58	10.90
0.25	-101.34	43	8.08
0.50	-114.06	88	16.54
1.00	-118.53	183	34.40
2.00	-111.20	41	7.71
5.04	-97.66	8	1.50
8.00	-104.91	12	2.26
16.00	-104.14	40	7.52
32.00	-102.60	51	9.59
64.00	-99.53	67	12.59
80.60	-97.93	64	12.03
Any	-	273	51.32

Table 3. Stations with higher than AHNM in the network.

	Period (s)					
	0.1	0.25	0.5	1	2	5
db	1.937	0.515	0.210	0.155	0.490	0.300

Table 4. Median noise level changes between $0.1\,\mathrm{s}$ and $5\,\mathrm{s}$ seconds. Positive values mean noise levels are higher during no - lockdown time span.