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~~ in the region with more than ~~700 stations. Thanks to the upgrade of the~~ 585 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~~ determine the background seismic noise characteristics 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~~ by using the data collected in 2022. We analyze the spatial and temporal characteristics of the background noise. ~~To do that, power spectrum density is calculated for the continuous stations.~~ It is found that ~~more than half~~ most 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 (≤5s), as they are affected by anthropogenic noises~~suffer from anthropogenic noises since the strong motion network is designed to capture the peak ground motions in populated areas. Hence human activities enrich the low periods of noise. Therefore, land usage of the area where the stations are located affects the background noise levels. Stations can be noisier during the day, up to ~~14 decibels~~12 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~~In long periods (≥5 s), accelerometric stations converge to similar noise levels and there are no significant daily or weekly changes. It is found that more than half of the stations exceed the background noise model designed for strong motion stations in Switzerland by Cauzzi and Clinton (2013) in at least one of the calculated periods. We also develop an accelerometric seismic background noise model for periods between 0.0124 s to 100 s for Italy by using the power spectral densities of the network. The model is in agreement with the background noise model developed by D'Alessandro et al. (2021) using broadband data for Italy in short periods but in long periods there is no correlation among studies.

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 the object of specific studies (e.g., for the characterization of layers of the ~~Earth~~ earth (Shapiro et al., 2005), Moon (Larose et al., 2005), and Mars (Schimmel et al., 2021)). Noises can also be sub-categorized based on their source such as; i) ~~seismic recorder~~ recorders (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~~recorded waveforms, 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)~~(Figure 1). 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,~~ in which urban noise, microseismic activities, and data logger systems dominate the short periods, mid-range periods, and long periods, respectively. The ALNM is computed as a particular combination of accelerometric sensors with a given gain and response with dataloggers. 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 and Veneto 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. Being the RAN main goal to provide information valuable for Civil Protection duties, the selection criteria of the "optimal" location to install seismic stations weighs multiple parameters and the quality of the recordings in terms of noise generated by nearby sources could play a secondary role.

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,~~ recorded by 585 continuous stations during 2022 and developed the Italian accelerometric noise models. We focused our analysis mainly on the short periods ($\leq 5\,\mathrm{s}$) 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~~, PSD evaluation workflow, and development of the Italian accelerometric noise models are explained. Background noise levels and the noise models 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 noisedata 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 (???). 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~~ , temporal and spatial variations of noise, 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~~ comparison between previous background noise models with the developed model are discussed in Section ~~6~~5.

2 Data

~~RAN consists of more than 700 stations of which 532 provided continuous data in the time range that we are interested in .~~

In this study, data from the vertical component of 585 stations of the RAN collected in 2022 have been analyzed (Figure 2). 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. On average, 383 of these stations were operational in continuous recording for more than 90 % of the year. We set a threshold of 50 % of completeness of PSD time series for data selection to calculate the background noise model for the RAN which makes 494 out of 585 stations (84.6 % of stations) eligible for the further steps: the remaining stations operated either in triggered mode throughout the year or converted into continuous data recording later in the year.

~~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~~ Seismic instruments of the network consist mostly of Kinemetrics and Syscom sensors (Table 2) with 24 bit acquisition. Data transfer from the station to the data centre in Rome, Italy is carried out mainly by an Access Point Name (APN) dedicated to RAN and a copy of the data is sent to Trieste (Italy) via a Virtual Private Network (VPN).

The evolution of the RAN is not only about the combination of several networks but also the installation of new stations across the Italian territory ~~.~~

~~Thereinafter the combined data from 2019~~ over time. Moreover, the data acquisition systems of the network have changed over time. After 2020, a large number of triggered stations have been replaced with continuous data acquisition. The purpose of the RAN is to determine the ground motion parameters recorded in the areas where there is considerable human activity. RAN provides valuable information to the Italian civil defence (DPC) to help in decision-making after seismic events. Because of that, factors that affect the quality of the seismic waveforms recorded (i.e., background noise levels and soil conditions) may not be the main priority for DPC in deciding where a new station is going to be deployed. Most of the RAN stations (Table 3) sit on top of a B 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~~C class soil (Aucun et al., 2012) and many of the stations are located in the settlements (Table 1).

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~~ Considering only the vertical components at the stations, each daily recording in acceleration 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~~signals, 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 4.

To study specific patterns in the noise levels over time, the PSDs are ~~grouped~~ 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 ?? for the periods of interest, namely~~ method explained in the previous section is applied to all the stations in RAN to create the Italian accelerometric high (IAHNM) and low (IALNM) noise models (Figure 3). Amplitudes for each period are given in Table S1 for IAHNM and IALNM. In low periods ($\lesssim$0.1 s) median of the RAN is closer to the higher end of the noise model developed by Cauzzi and Clinton (2013). Between ($\lesssim$0.02 s) to ($\lesssim$0.1 s) IAHNM exceeds the AHNM and between the periods IAHNM and IALNM cover a large range between -124 dB to -84 dB. IAHNM is in a downtrend between ($\lesssim$0.08 s) to around 1 s and it goes upward in the longer periods whereas IALNM is in general upward trend. Around 1 s median of the RAN exceeds the AHNM and IAHNM is greater than AHNM between 0.5 s to 3.5 s. The upwards trend of background noise can be seen in both models but in our study such trend is smoother than the model of Cauzzi and Clinton (2013).

The lower limit of the noise model, IALNM, is, on average, 15 dB higher than the ALNM of Cauzzi and Clinton (2013) which is defined as the theoretical lower boundary of the station noise. Figure 4 shows that only a small amount of stations goes below the IALNM and even these stations cannot reach the ALNM model. PSD values are concentrated in a barrow band in long periods ($\gtrsim$5 s) and in short periods they cover a wide range of values. Station locations play an important role in noise characterization (Figure 5). Most of the stations that are located in settlements have high levels of noise, hence increasing the upper boundary of the IAHNM. Even though land usage influences short periods, its effect on long periods shows no clear pattern.

Being RAN a strong motion network, we are mainly interested in periods less than 5 s: afterwards we focus on the specific period bands centred around 0.1 s, 0.25 s, 0.5 s, 1 s, 2 s, and 5 s~~: this~~. We would like to provide an overview of the behaviour of the noise at different timescales for different periods, as described in ~~details~~ detail afterwards (see Figure 1). The overall background noise levels for all stations in RAN are presented in Figure 6. 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~~Figure 1) which ~~also are~~ provide 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~~ S2 with the related noise level and the station placement.

RAN has relatively high noise levels in short periods ~~. Numerous stations exceed~~ with numerous stations exceeding the levels defined by Cauzzi and Clinton (2013). The median noise at each station, presented in Figure 6, and the AHNM have been compared and the results are reported in Table 5. $1\,\mathrm{s}$ 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 3. The median values for $0.1\,\mathrm{s}$, $0.25\,\mathrm{s}$, $0.5\,\mathrm{s}$, $1\,\mathrm{s}$, $2\,\mathrm{s}$, and $5\,\mathrm{s}$ are $-112.59\,\mathrm{dB}$, $-119.09\,\mathrm{dB}$, $-120.35\,\mathrm{dB}$, $-119.98\,\mathrm{dB}$, $-118.07\,\mathrm{dB}$, and $-115.98\,\mathrm{dB}$, respectively. The median values are always below the AHNM model for the period range of interest. Between $0.1\,\mathrm{s}$ and $2\,\mathrm{s}$, 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~~ In 2022, at ~~98.2 % of the~~ 493 stations there is a reduction in noise levels at nighttime with respect to the average noise during daytime (Figure 7). 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 dB, 1.37 dB~~6.00 dB, 1.45 dB, 0.30 dB, ~~0.8 dB, and 0.8 dB~~0.11 dB, and 0.14 dB, respectively. Among these periods ~~529, 512, 498, 433, 405, and 485~~ 491, 489, 480, 447, and 439, and 475 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 **??**), 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~~ Weekday - weekend median differences are ~~0.95 dB , 0.38 dB, 0.11 dB, 0.02 dB, 0 dB, and −0.07 dB~~ 0.88 dB, 0.36 dB, 0.08 dB, −0.01 dB, −0.10 dB, and −0.02 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~~ The general trend of noisier weekdays can be followed between $0.1\,\mathrm{s}$ to ~~1 s with 487, 484, 457, and 353~~ 0.5 s with 453, 453, and 414 stations in the periods of interest. In the periods between 1 s to 5 s only 215, 52, and 190 stations are noisier in the weekends.

~~Data from 2019 are further used to study the seasonal variation of very long period noises (≥ 5 s), as shown in Figure **??**. The results show that winters are noisier than summers as suggested by previous studies (Stutzmann et al., 2000; McNamara and Buland, 2004; with the number of stations that are noisier during winters with respect to summer can go up to 121 in 16 s with median noise level change up to 1.55 dB. Despite the difference in noise sources potentially contributing~~ To see the seasonal changes in the long periods which can be affected by the marine and atmospheric sources we analyzed the stations in their median summer and winter (McNamara and Buland, 2004) noise level changes (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 stationsthat 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 **??**), with 303, 277, 255, 237, 280, and 259 stations being quieter at periods of 0.1 s, 0.25 s, 0.5 s, 1.0 s, 2.0 s, and 5.0 s for the common stations~~9) by defining 21st of June to 21st of September as summer and 21st of December to 21st of March as winter. Surprisingly in long periods summer time is noisier than the winter time in 5 s, 8 s, 16 s, and 30 s. These periods are chosen to visualize the effect of the long period background noise at network level. Previous studies (eg. McNamara and Buland (2004); Anthony et al. (2022)) have found the opposite behaviour in the stations. In total the median difference between summer and winter are 0.19 dB, 0.97 dB, 1 dB, and 0.75 dB, for 5 s, 8 s, 16 s, and 30 s , 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 **??**) . 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 dB and 0.13 dB whereas nighttime changes arebetween 1.19 dB and 0.12 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 dB and weekend changes goes up to 0.39 dB in 0.1 s. Majority of the stations are noisier in weekday (≥ 75 %) and weekends (≥ 60 %) of non lockdown period~~The purpose of the accelerometric network is to detect the peak ground parameters in destructive earthquakes. Parameters such as peak ground acceleration (PGA) and peak spectral acceleration (PSA) in short periods provide meaningful information about the possible damage in a site of interest and these parameters are, in general, arrive to the station in the high frequencies of its spectrum. Hence, high background noise levels in long periods do not affect the capabilities of the RAN.

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~~ with specific noise levels.

The interpretation of the background noise in ~~Italian strong motion network~~ the RAN 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~~ low periods, human activities are the main source of background noise. ~~273 of 532~~291 of 493 stations have noise levels exceeding the AHNM developed by Cauzzi and Clinton 2013, as reported in Table 5 considering the results for different periods. In Table 5 the highest percentage ~~number of stations exceeds~~ of stations exceeding 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~~ noise level (Figure 6) at this specific period. Furthermore, both the geological and anthropogenic settings of Switzerland present some differences from the Italian ones. Different geodynamic forces act on Italy which creates diverse geological structures in the territory whereas in Switzerland the geology is more homogeneous. The cultural noise is also different between the two countries: the stations used in Cauzzi and Clinton (2013) are, with the exception of the ones in Basel, mainly located in the countryside or in small settlements, with respect to the RAN stations.

~~As shown in Table 5, 51.3 % of all stationsexceed the AHNM for at least one period~~The potential relation between the geological settings and the background noise characteristics in low periods is also investigated. Stations located in Po valley, having large alluvial deposits, have relatively high noise levels (Figure S2, Cocco et al. 2001). 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 (FigureS3). Since the purpose of RAN is to record peak amplitudes, those stations are useful even for earthquakes with smaller magnitudes and longer epicentral distances~~there are other noisy stations that are located in completely different geological settings such as the ones in Naples (local geology is dominated by intrusive rocks). Hence, high background noise cannot be directly linked to the local geology but the anthropogenic activities. Marzorati and Bindi (20 analyzed the station in and around the Po valley in terms of background noise by linking the high noise levels to industrial activities and comparing the considerable noise level changes with respect to the stations in the North of Po Valley. A similar trend can be seen in our results as well (Figure S2). Stations located in the North-East of Po Valley (where local geology is dominated by carbonate rocks) are some of the quietest stations in the RAN network due to the lack of human activity.

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 7, 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). During the daytime anthropogenic sources (e.g. factories, offices, public buildings, vehicles) may enrich the low period portion of the background noise. During nighttime, most of these activities are either reduced or completely stopped. In North-East Italy, there are several stations with relatively low daytime-nighttime difference. These stations are located far away from all settlements and located on mountainous parts of Italy. A similar trend can be seen in central Italy in 0.25 s and 0.5 s. Le Gonidec et al. (2021) showed that vehicle noise enrich the periods between 0.067 s and 0.1 s in seismic signals. In 0.1 s nationwide daytime - nighttime difference can be linked to vehicles whereas in periods 0.25 s and 0.5 s other anthropogenic noises (eg. movement of individuals) can be active. In both North-East and central Italy, these noises can be minimal. Hence in daytime - nighttime power change there is no significant difference.

In the weekday - weekend variations, the same pattern can be followed in short periods. Figure **??** 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. Most of the banks, public buildings, and offices are not working on weekends and on Sundays commercial activities are reduced which may limit human activities. Hence, in short periods, the background noise of weekdays is dominated by labour-related activities. As in daytime - nighttime differences, in both North-East and central Italy, there are minimal power change differences and the same interpretation can be done for the weekday - weekend differences.

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 in medium range periods follow the trend that is seen in shorter periods ~~in most of the network. However, in~~ except in 1 s. 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~~ : analyzing the trend of median and variability of noise levels at the stations as a function of the distance to the coastline (Figure S3), no evident pattern emerges, as also shown in Figure 6. Almost starting from 1 s background noise levels do not vary too much over the network (Figure 4) and the effect of sea, swell and/or wind effect should not significantly alter by these forces.

Considering weekly variations, stations become noisier on weekends ≥ 1 s with decreasing power change~~with increasing periods~~. In the Po valley, the general trend of a high noise level diminishes starting from 2 s in average and in the same periods, unlike the day and night difference, weekends follow the same trend.

~~In long periods,~~ In 1 s central Italy has almost the same noise levels between weekdays and weekends and in both 1 s and 2 s several stations in Central Italy and Sicily coastlines become noisier during the weekend. Previous studies suggest the effects of ~~wind, swell, sea, pressure,~~ anthropogenic sources, wind and ~~instrumental noises are addressed in literature as the main sources of the noise~~ sea-related activities to be dominant in those periods. As seen in lower periods, human activity increases the weekday noise levels which makes it irrelevant from the observation. Sea and wind might be the source of the observation if they could be in Figure 6 since neither wind nor sea-related noises should be changed between weekdays and weekends. Hence, we do not have a reasonable explanation about the phenomena.

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). Despite their proximity (<3 km), they have different noise characteristics. The selection of these two particular stations is further supported by the extensive knowledge of their spatial and administrative information. DST2 station sits on deep Flysh deposits (Figure ~~1). The difference between the noise levels in the winter and summer periods of 2019 can be seen in Figure ??. Unlike in the study of D'Alessandro et al. (2021) in which it is stated that in periods between 0.83 s and 8.33 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~~ 10). CARC station is located on the ground floor of the Palazzo Carciotti which is located in the city centre of Trieste and was built in the early 19th century. It crosses with one of the main major roads in the city centre and the building is surrounded by multistory residential buildings. Historically, this area was a salina and the area is filled with a 27 m depth material layer (Fitzko et al., 2007) to cover up the salina to expand the city in the ~~stations being the main source of long period noise associated with accelerometric recordings, as indicated by Cauzzi and Clinton (2013).~~ 18th century (Figure S4).

To see the hourly changes in noise levels, 90 min PSDs are plotted, separately (Figure 11). In the lower periods (<1 s) where anthropogenic noises prevail, CARC station is noisier almost in all time ranges. In very short periods (≤ 0.025 s) they converge but in such low periods electromagnetic noises can be the dominant noise source, hence it is expected to have a converged background noise. In the daytime noise levels of CARC station converge to the AHNM between 0.2 s and 1 s. For periods above 0.5 s, day and night differences are similar which may suggest that anthropogenic sources do not have a major role. On the other hand, in shorter periods there are clear day-night patterns at both stations. DST2 station is located in the basement of a small two-story university building (accommodating just a library, a few offices, and a study room) where human activity is rather limited both inside and outside. Moreover, the building is not located near any major road. Different environmental factors may play a role with changing period of the background noise. Both of the stations are located inside buildings, hence wind effect should be minimal. For periods longer than 10 s, both stations have similar background noise levels and the same trend with increasing periods.

As shown in Table 5, 308 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 S5). Since the purpose of RAN is to record peak amplitudes, those stations are useful even for earthquakes with smaller magnitudes and longer epicentral distances.

Measuring the background noise levels of the RAN allows us to understand the earthquake detection capability. As presented in Figure 4 detection of $M \approx 3$ earthquakes is possible by near-fault stations in raw signals with the stations near the IAHNM. In median noise level it is possible to detect $M \approx 2$ in near fault. DPC publish $M \gtrsim 2.5$ earthquakes in quasi real time (https://ran.protezionecivile.it/EN/, last access: 02/08/2023). Data filtering algorithm of Gallo et al. (2014) allows us to reduce the background noise to detect ground motion parameters up to 100 km away from the epicenter for $M = 2.5$ earthquakes (Figure S6). Even though earthquakes with small magnitudes are located by the network, they are not published to the public (Costa et al., 2022).

In Figure 6, 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 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 s) in which wind and swell are the dominant noise sources. 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 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 7 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, andas recorded by both broadband (????????)~~ The model by D'Alessandro et al. (2021) has a notable relevance with our study since, first, it covers the same area of interest and, second, spatial variability of their model has been developed by means of the inverse distance weighted method (Lu and Wong, 2008). H_{INM} of the D'Alessandro et al. (2021) is almost identical with the IAHNM between 0.05 s and 0.3 s which are higher than the AHNM and NHNM of Cauzzi and Clinton (2013); Pet . The agreement between IAHNM in low periods indicates that both broadband and strong motion ~~(??) stations. ? found a clear noise level drop in Tokyo metropolitan area in Japan~~ networks in Italy get affected by the anthropogenic noises in the same order of magnitude and in periods between 0.05 s and ~~1 s. ? found that in Sicily (Italy) 0.1 s and lower periods have the most noise level reduction in COVID-19 pandemic. ? found that background noise levels of numerous seismic stations all around the globe reduced up 50 % during COVID-19 lockdown~~ 0.1 s anthropogenic noises have larger effects on the seismic networks 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 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 ??. In the 0.1 s, there is almost 2 dB noise reduction between the median noise difference between lockdown and no - lockdown time periods at the stations (Figure ??a). The difference has the lowest reduction in 1 s but the noise levels are higher during this period~~ Swiss and the US seismic networks. Around 1 s the most significant divergence among higher limit of the models is observed. AHNM and NHNM are close to the median of our network and the IAHNM is about 10 dB higher than them. Interestingly, H_{INM} has even higher noise levels with respect to ~~AHNM (Figure 6). In Apennines there are numerous stations whose noise levels between 0.5 s to 2 s have not been affected by the lockdown (Figure ??c-e). Since for periods greater than 5 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 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 dB~~our model. Between 5 s and 10 s other models converge whereas our model has a completely different trend. As we discussed before our model is not susceptible to any long-period trends. AHNM and IAHNM have similar trends for periods above 10 s as AHNM developed by using strong motion stations.

~~The change between daytime and nighttime are visible especially on shorter periods (≤0.5 s, Figure ??a,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 s, whereas, in periods of 1 s and 2 s, stationsin 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 s and it can be partially traced in 5 s. Even though numerous stations have relatively high noise levels in 2 s (Figure 6e), there is no particular pattern in this period with respect to other parts of Italy.~~

5.1 ~~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 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 10). 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 ??) and the area is filled with a 27 m depth material layer (Fitzko et al., 2007) to cover up the salina to expand the city in the 18th century.~~

~~In Figure 11, median of lockdown and no-lockdown periods are presented. In order to see the hourly changes in noise levels, 90 min PSDs are plotted, separately. In the lower periods (<1 s) where anthropogenic noises prevail, CARC station is noisier in both time ranges. In~~

The second important outcome of the D'Alessandro et al. (2021) is to model the spatial variance of the noise of the Italian broadband network for 4 different band period bands. This allows us to calculate the predicted noise levels for most of our stations. To compare our noise levels with 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 s and 1 s, median noise levels are decreased 8.68 dB and 2.36 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.~~

5.1 ~~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 **??**). The station is located next to the municipality building of Palata~~ predictions of D'Alessandro et al. (2021) we calculate the median of periods that reside in the limits of the bands. The difference between the noise levels in RAN stations and the model developed by D'Alessandro et al. (2021) can be seen in Figure **??**. In Band IV ($0.033\,\mathrm{s} \geq \mathrm{T} > 0.1\,\mathrm{s}$) of D'Alessandro et al. (2021) anthropogenic sources are the dominant source type and the major cities of Italy (e.g. Milan, Rome, and Naples) have higher noise levels. In this band difference between the background noise of RAN and the model prediction has greater values in the regions where the model prediction is relatively low such as North-East Italy and several parts of South Italy. There are numerous stations with almost no difference between the prediction and observation but there is no overall trend in any geographical location. Since sources of the low period noises are very local, the difference is mostly dominated by local effects. Hence, there are numerous stations with almost zero dB difference located near to stations with larger differences in Central Italy~~, which has 2 intersections within 50 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 s and 20 s are chosen for further analysis in which Fast Fourier transforms (FFTs) are calculated (Figure **??**). In Figure **??**, 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 s and 0.06 s, cars can be considered as the main source of the noise~~. In Band III both natural and anthropogenic sources are in action and the difference between the noise levels in major cities and relatively rural areas of Italy is can be seen easily in the model of D'Alessandro et al. (2021).

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~~ in 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 ~~noise levels higher than~~ 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~~Table 5), 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 6) 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 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 **??**). 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.~~ The difference is relatively low in the stations located on the mountainous parts of North-East Italy.

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 6). ~~Additionally, no seasonal pattern has been found in very long periods ($\geq 5\,\mathrm{s}$, Figure **??**).~~ 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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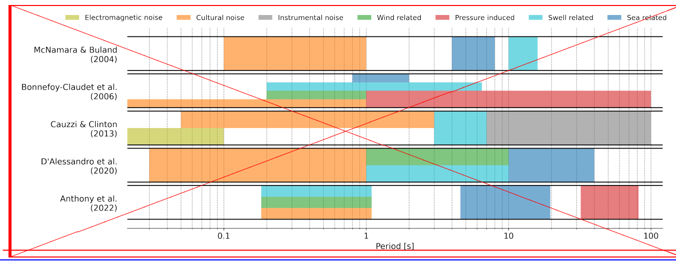


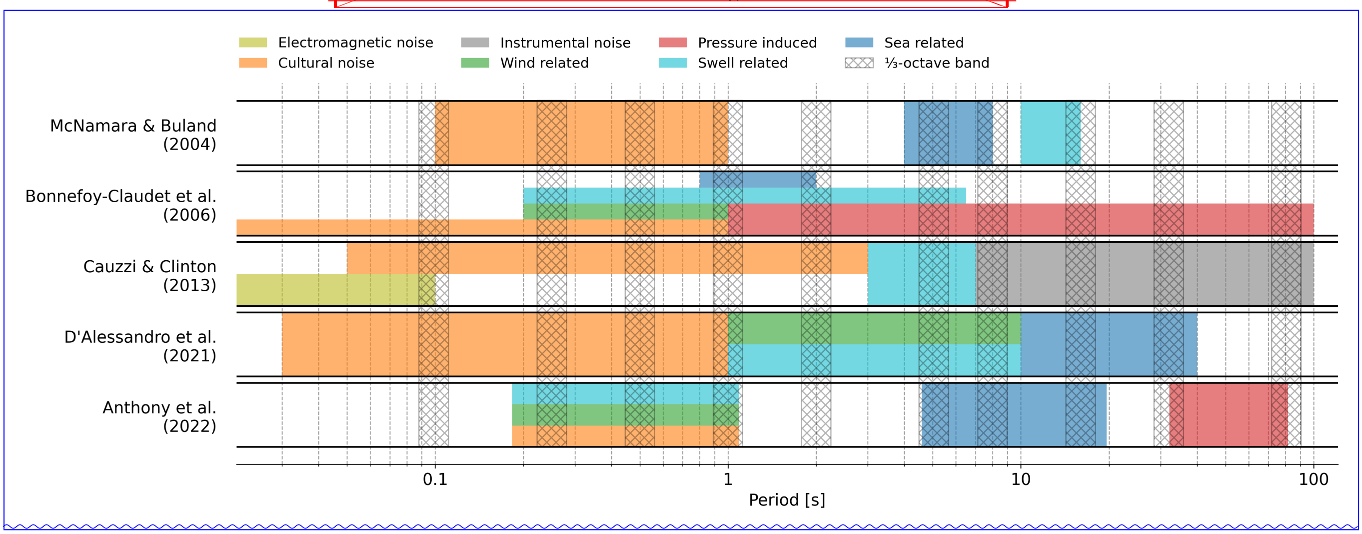


Figure 1. Main noise sources ~~for~~ at different ~~period bands~~ periods from the studies of McNamara and Buland (2004); Bonnefoy-Claudet et al. (2006); Cauzzi and Clinton (2013); D'Alessandro et al. (2021); Anthony et al. (2022). The hatched bands represent the one-third-octave bands used for the analysis.

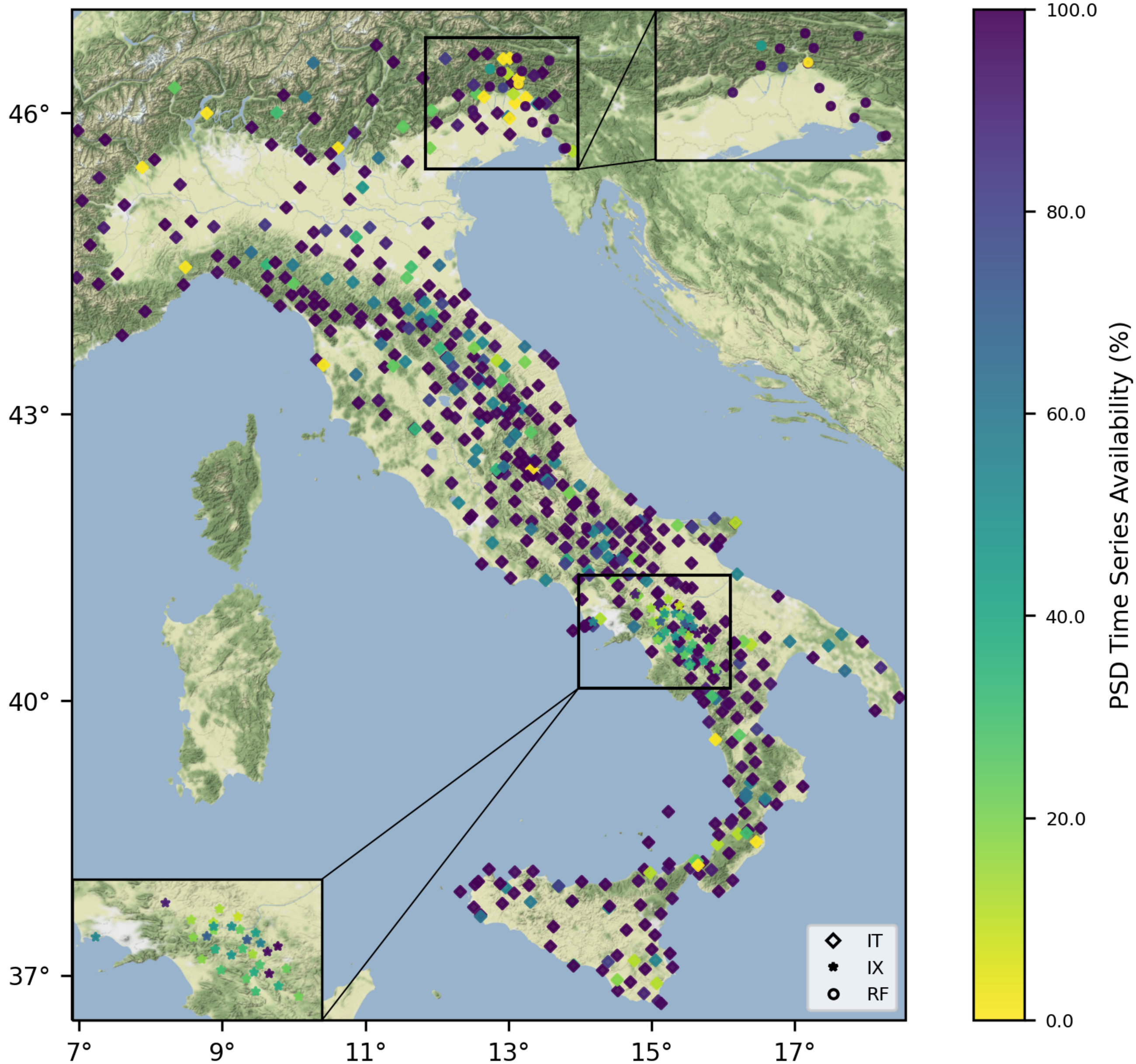
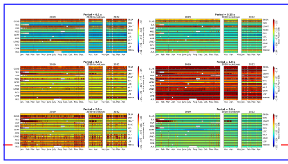
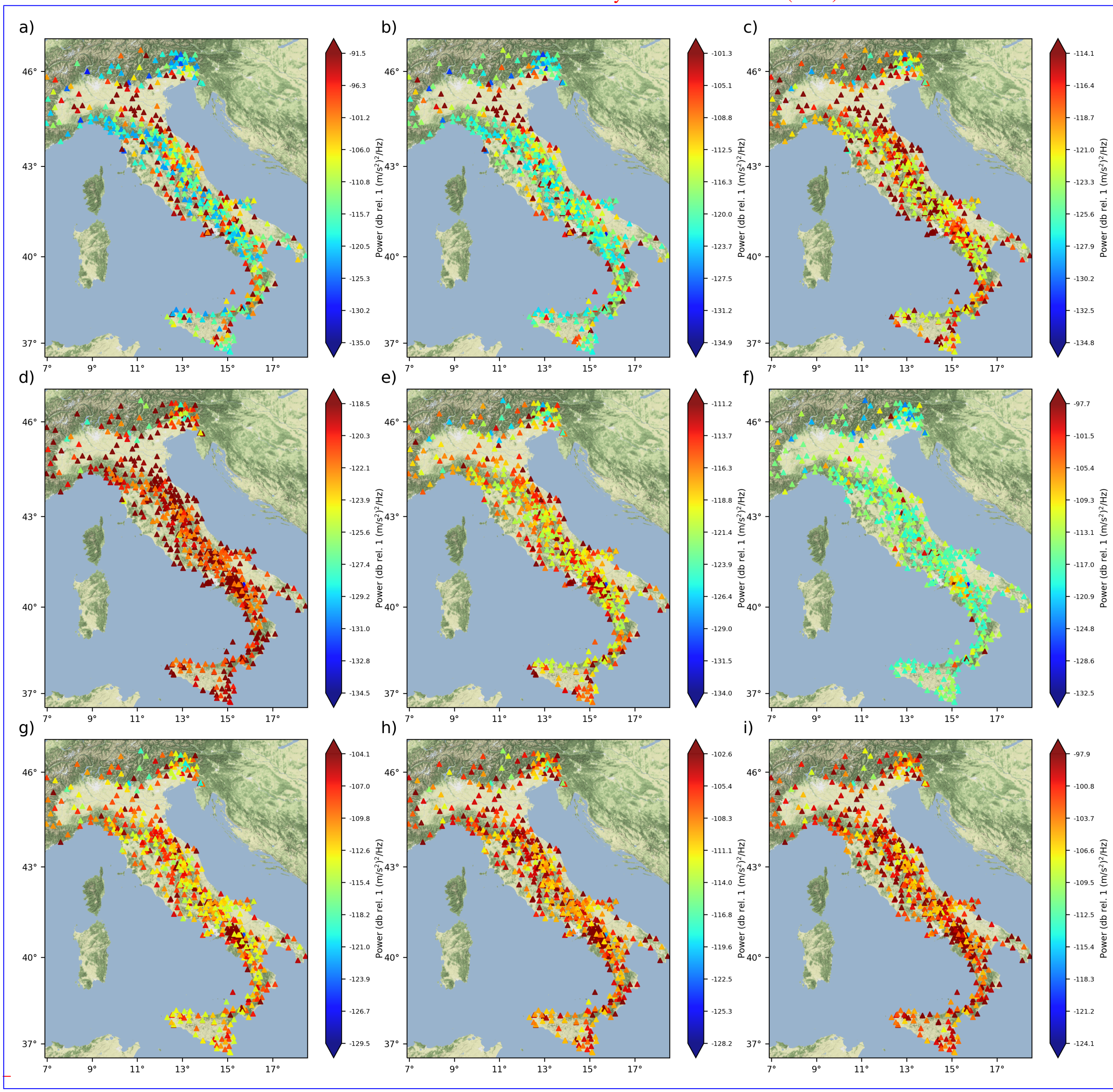


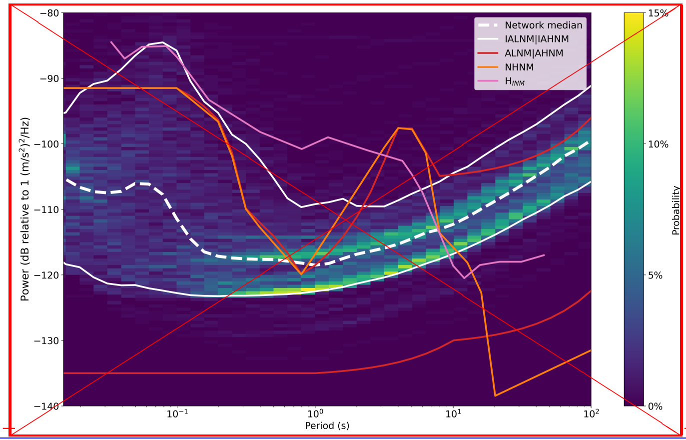
Figure 2. ~~Data~~ PSD time series availability of the ~~stations~~ RAN in ~~a) 2019, b) lockdown period, and c)~~ 2022. The ~~close up~~ close-up boxes in the lower left and upper right highlight ISNet (IX) and RAF (RF), respectively. Basemap data are retrieved from © Stamen Design.



~~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).~~



~~Median vertical component noise maps in one-third octave bands around a-g) 0.1 s, 0.25 s, 0.5 s, 1 s, 2 s, 5 s, 16 s, 32 s, and 80.6 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.~~



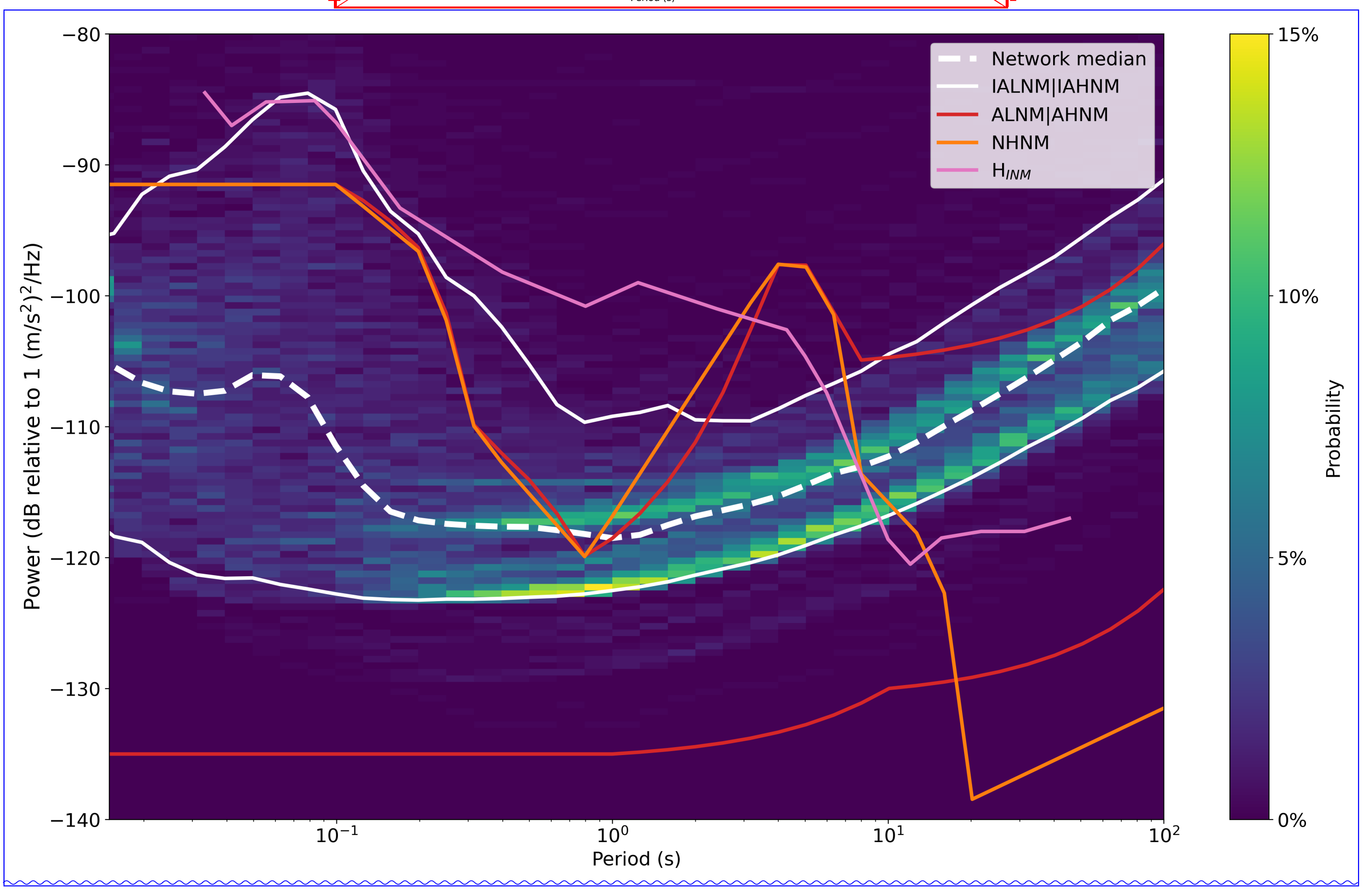
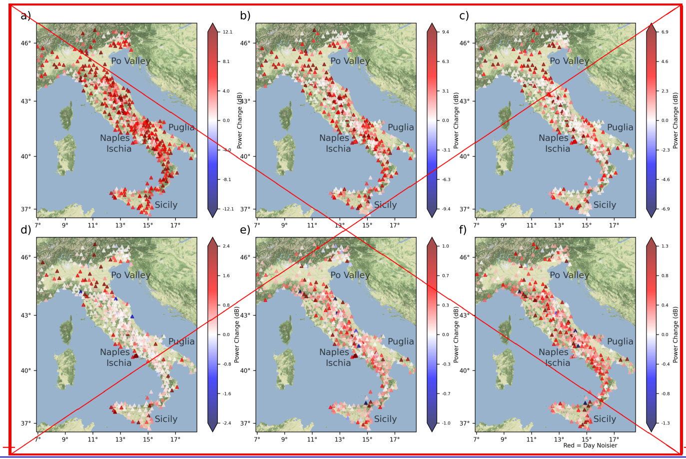


Figure 3. ~~Probability~~ PSD probability density function of ~~medians of PSDs of all stations~~RAN. Dashed white line ~~represent~~ represents the median of the network and ~~solid white~~ dotted lines are the 5 % and 95 % limits of the network. Solid green lines represent ~~NLNM~~ the ALNM and ~~NHNM~~ AHNM defined by Cauzzi and Clinton (2013). Red, and purple lines are NHNM and H_{INM} defined by Peterson (1993) and D'Alessandro et al. (2021), respectively.



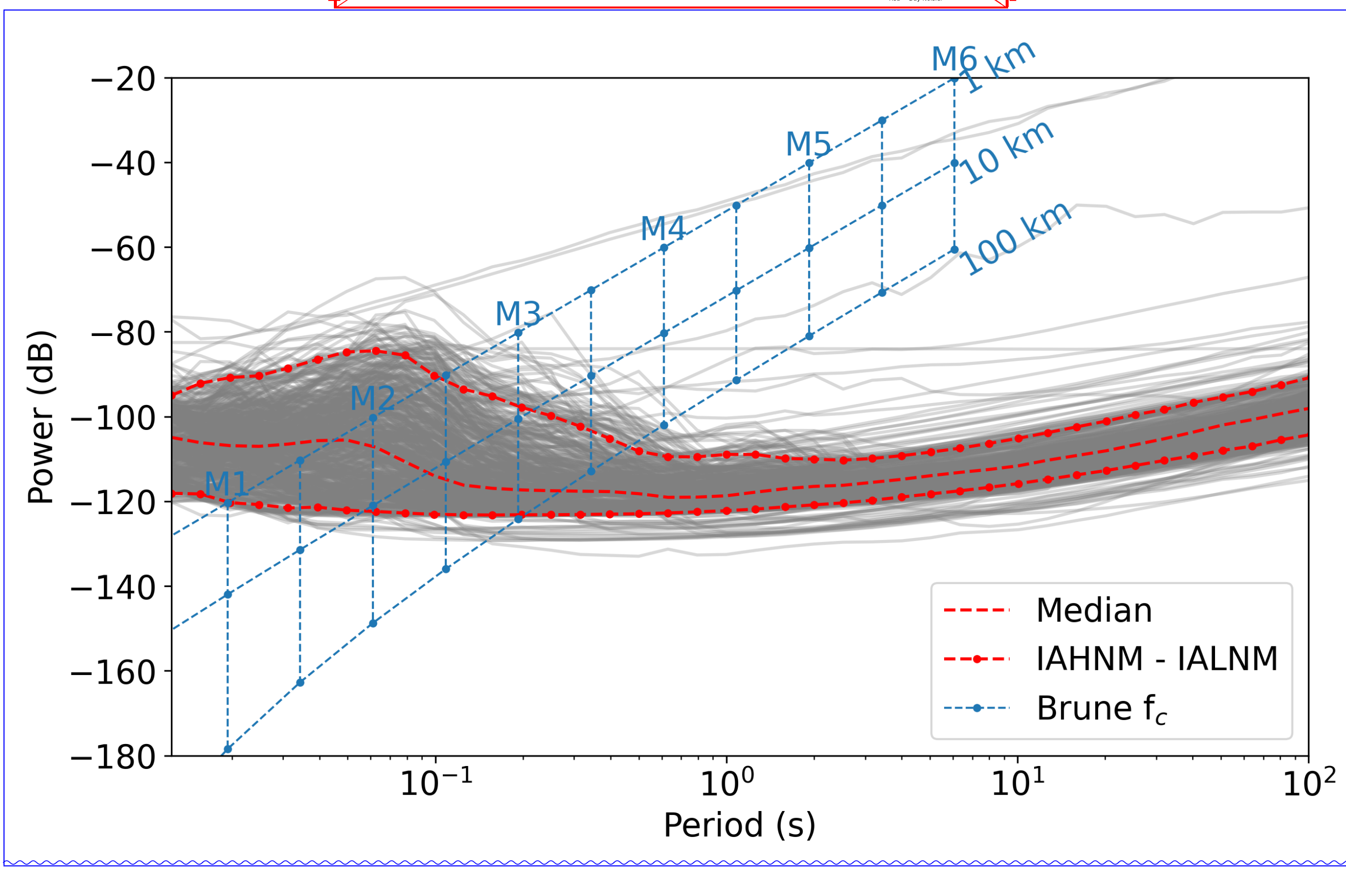


Figure 4. Median ~~noise levels in dB for daytime~~ PSD of RAN stations (grey lines). Red dashed line and ~~nighttime for~~ dots represent the ~~periods~~ median and IAHNM&IAHNM, respectively.

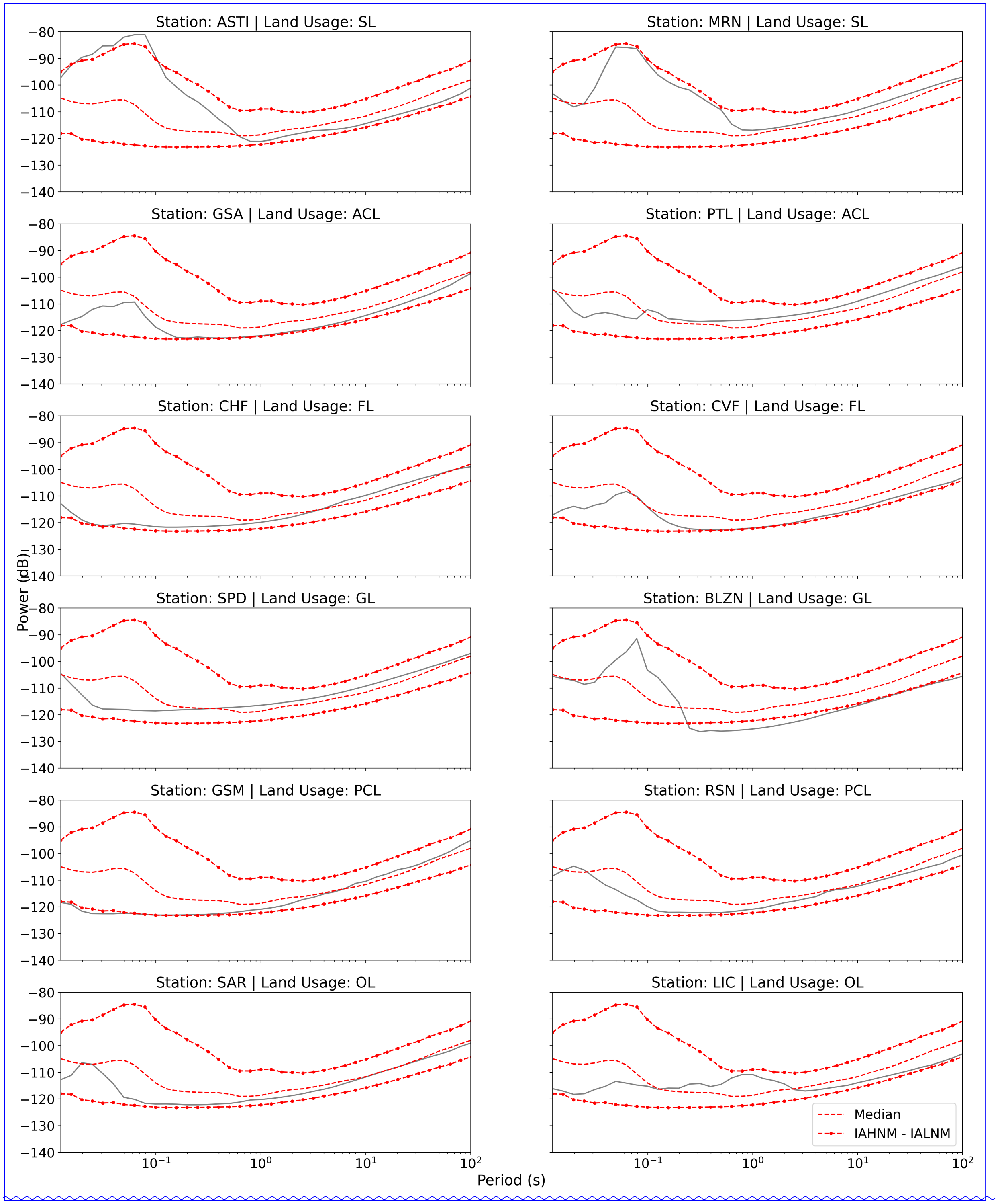


Figure 5. Median PSD of 2 randomly selected stations from each land usage type defined in Table 1. Red dashed line and dots represent the median and IAHNM&IAHNM, respectively.

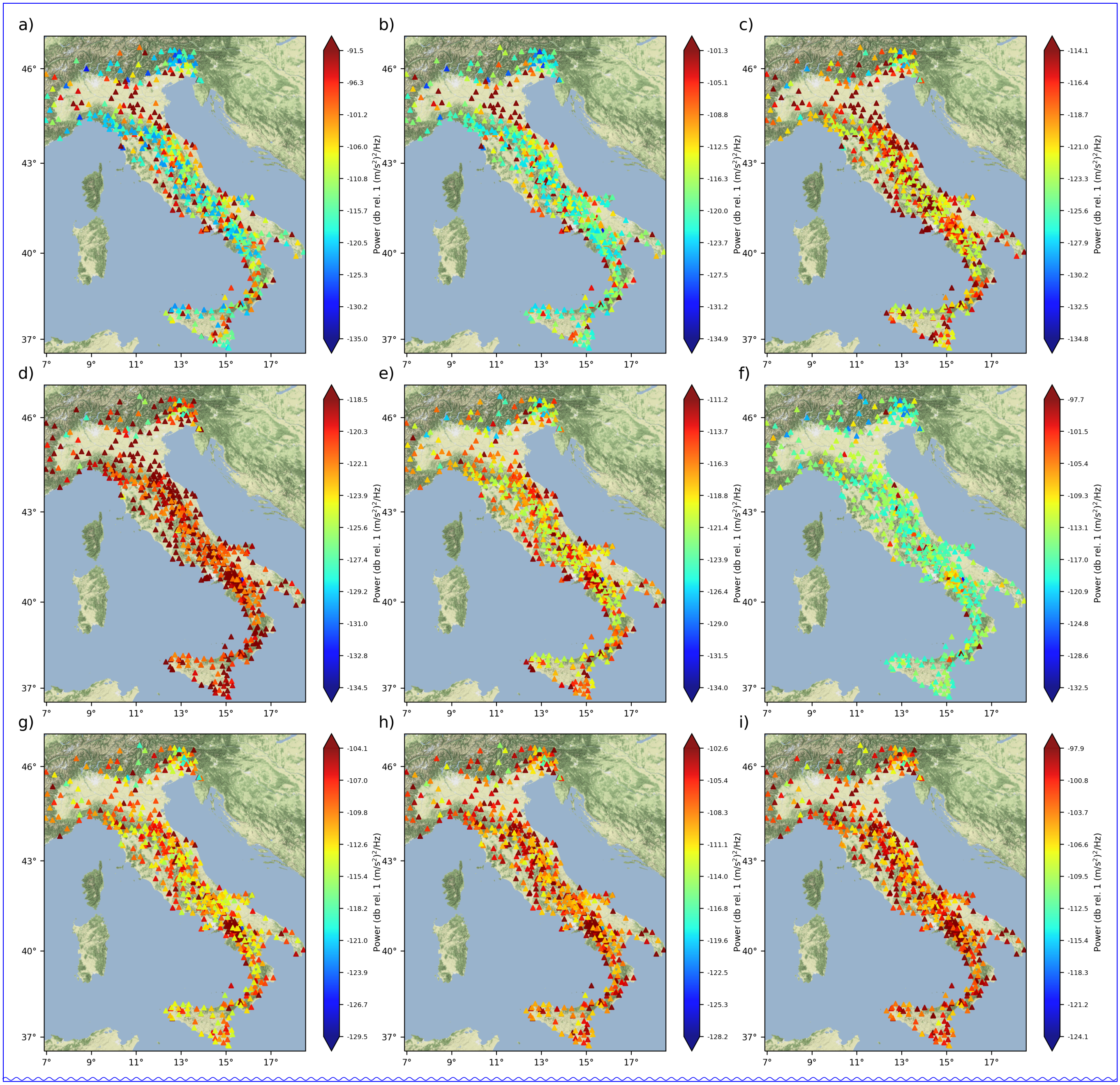
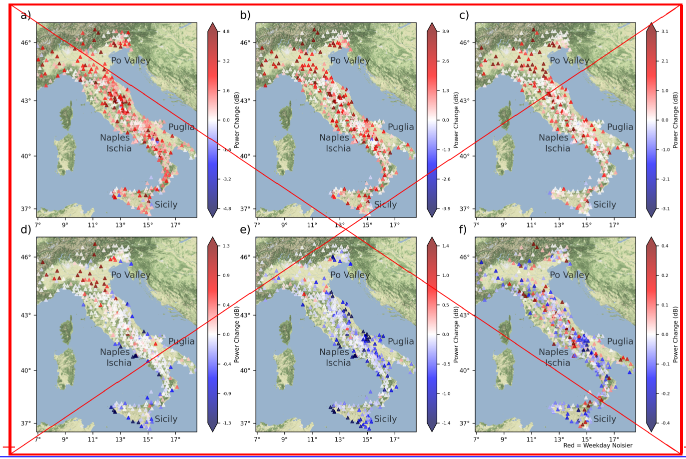


Figure 6. Median vertical component noise maps in one-third octave bands around a-i) 0.1 s, 0.25 s, 0.5 s, ~~1.0 s~~1 s, ~~2.0 s~~2 s, 5 s, 16 s, 32 s , and ~~5.0 s~~80.6 s. ~~Red~~ Upper and lower limits of the color ~~means day is noisier than night~~bar are defined by the model developed by Cauzzi and Clinton (2013). Background noise levels of all calculated periods can be found in Figure S1. Basemap data are retrieved from © Stamen Design.



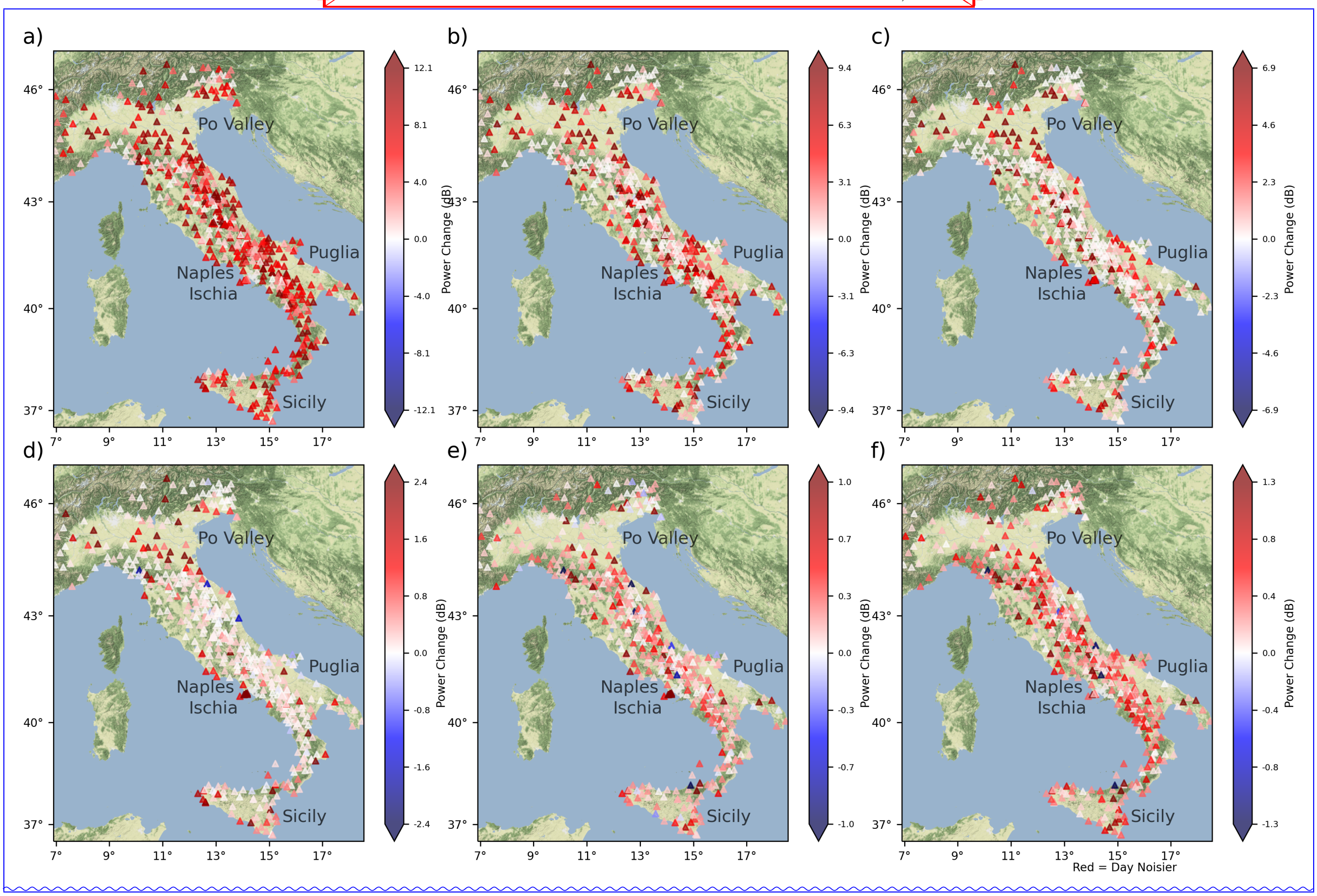
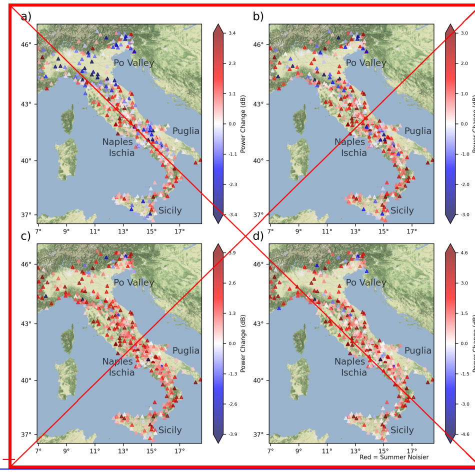


Figure 7. ~~Median noise levels in dB for weekday~~ Difference between daytime and ~~weekend time~~ nighttime for the periods of a) 0.1 s, b) 0.25 s, c) 0.5 s, d) 1.0 s, e) 2.0 s, and f) 5.0 s in dB. Red color means ~~weekday~~ day is noisier than ~~weekend~~night. Basemap data are retrieved from © Stamen Design.



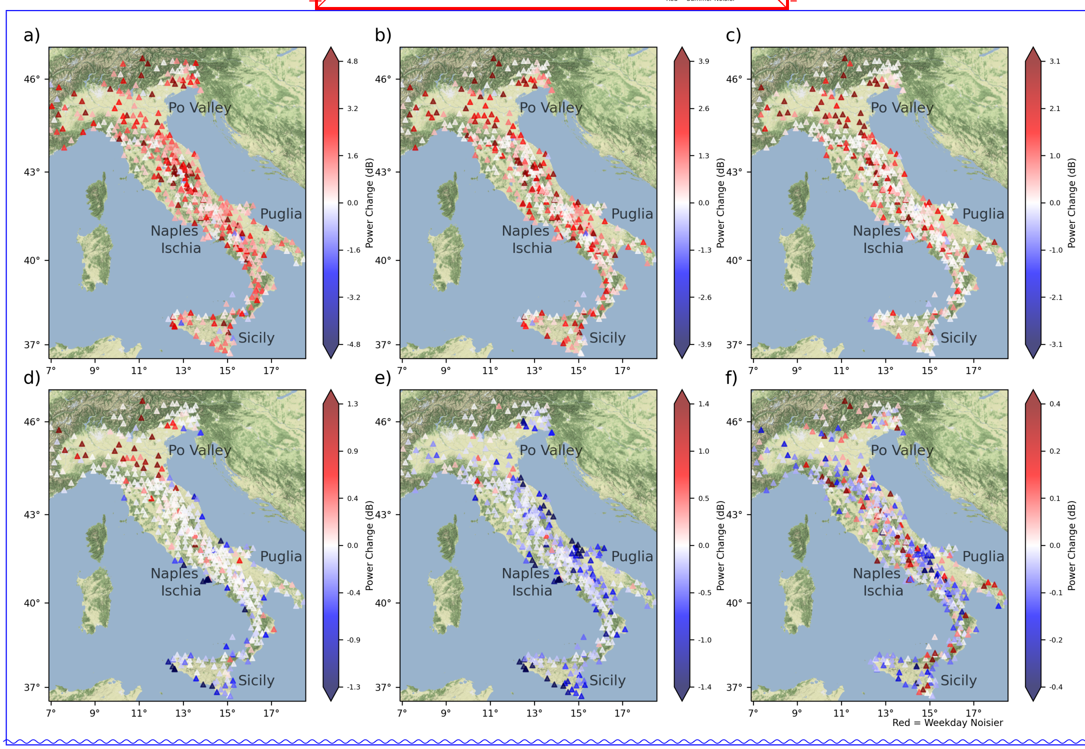
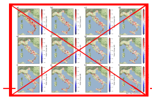


Figure 8. Difference between ~~noise levels in 5 s, 8 s, 16 s,~~ weekday and ~~32 s between~~ weekend time for the ~~winter and summer~~ periods of ~~2019. Red color means summers are noisier than winters. Basemap data are retrieved from Stamen Design.~~



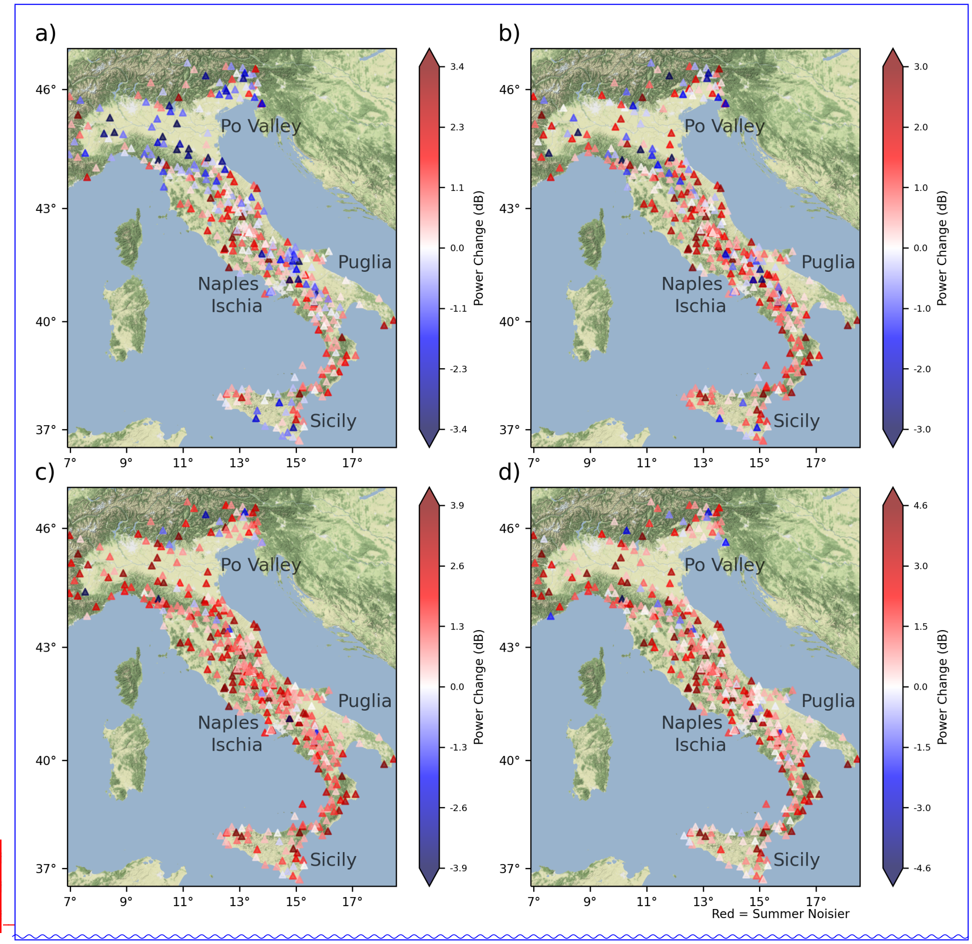


Figure 9. ~~Difference between~~ Seasonal median noise ~~levels in 0.1 s, 0.25 s, 0.5 s, 1.0 s, 2.0 s, and 5.0 s between 2019 - 2022 and lockdown~~ level change in dB for a~~, c, e ,g, i, k~~) ~~daytime~~5 s, b) 8 s, ~~d, f, h, j~~c) 16 s, ~~l~~and d) ~~nighttime~~32 s. ~~Basemap data are retrieved from Stamen Design~~Red color means summer is noisier than winter.

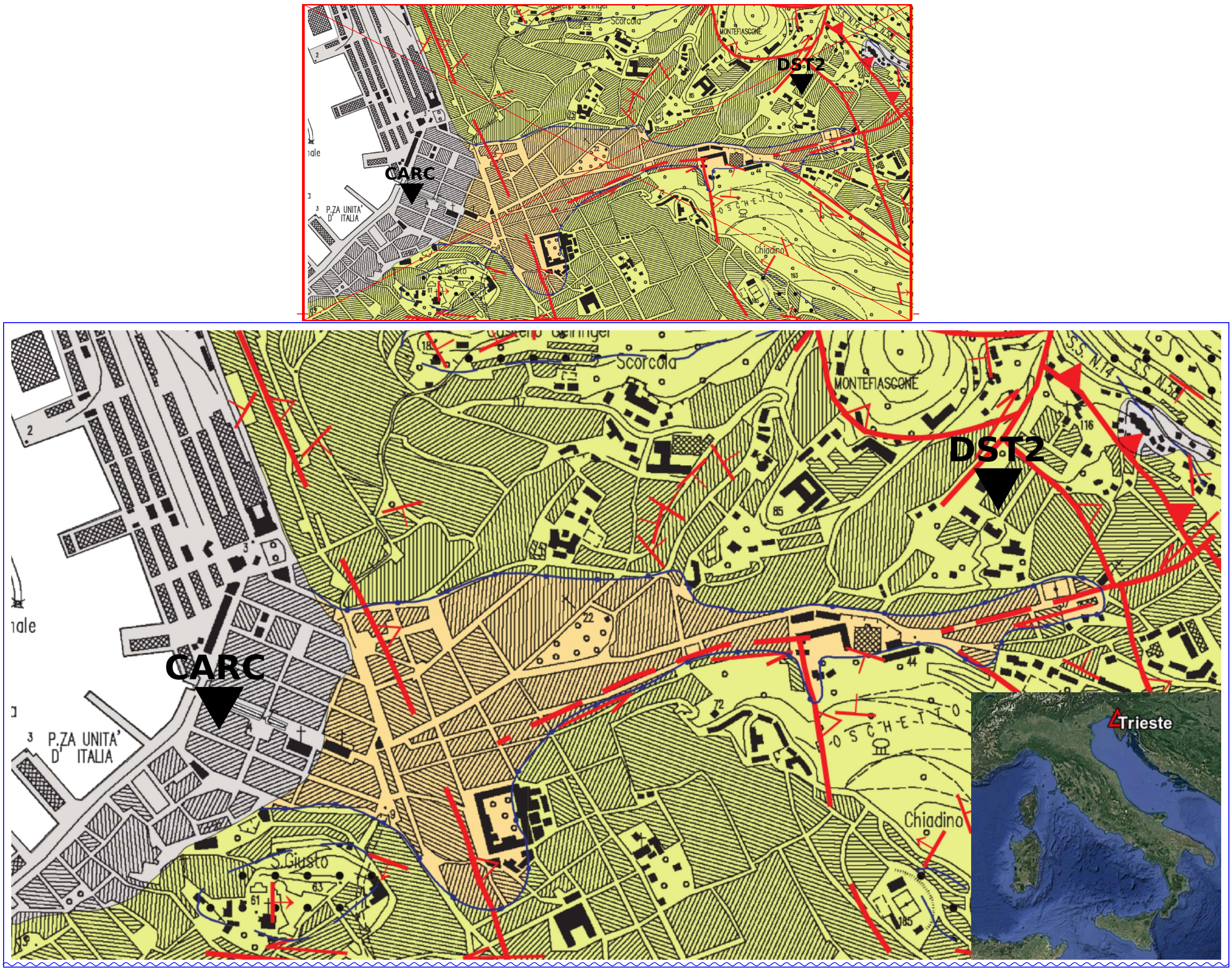
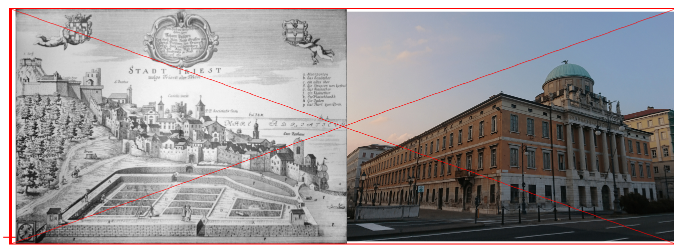
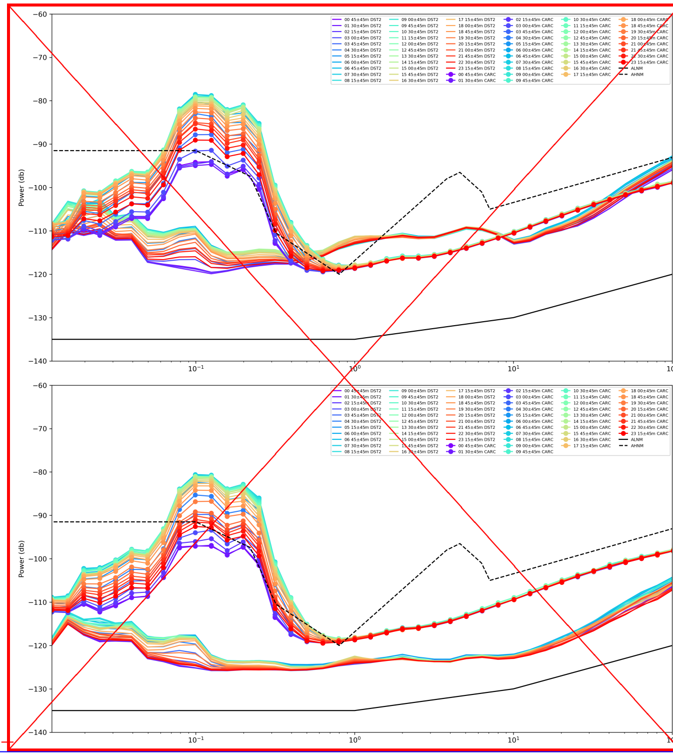


Figure 10. Geological Map of Trieste (grey, orange, and yellow colors indicate anthropic, ubiquitous deposit units, and flysh of Trieste, respectively), modified from Cucchi et al. (2013). Map on the lower right is created by using © Google Earth with satellite information from Landsat/Copernicus.



~~left) Drawing of the salina part of the city of Trieste by Johann Weikhard von Valvasor in 1689 taken from Wikipedia (, last access: 7 November 2022), right) Palazzo Carciotti.~~



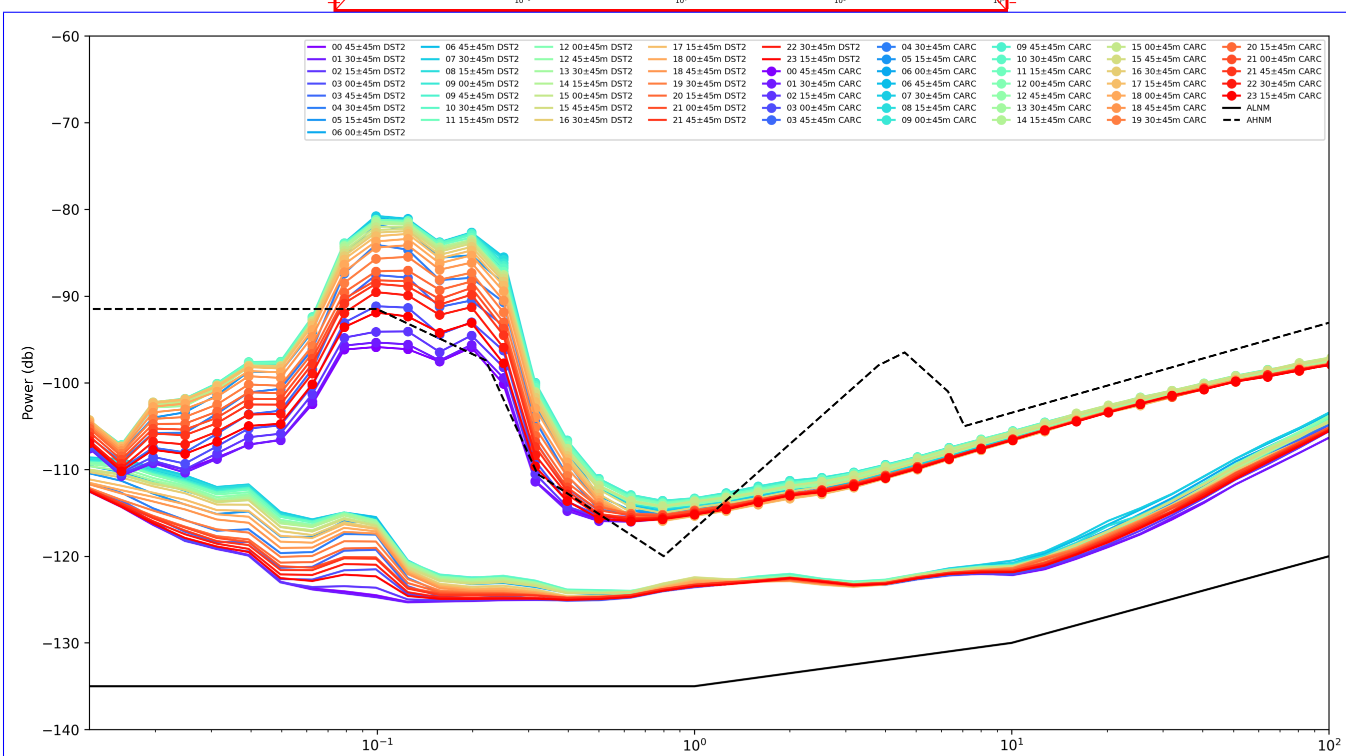


Figure 11. Hourly average plots of noise levels of DST2 (line) and CARC (line with dots)~~for no-lockdown (top) and lockdown (bottom) dates~~. ALNM and AHNM introduced by Cauzzi and Clinton (2013) are black line and dashed line, respectively.

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

Land Usage	Code	Stations
Settlements	SL	~~388~~ 424
Annual Cropland	ACL	~~48~~ 56
~~Permanent Cropland~~ Forest	~~PCL~~ FL	~~12~~ 43
Grassland	GL	~~39~~ 41
~~Forest~~ Permanent Cropland	~~FL~~ PCL	~~38~~ 14
Other land	OL	7
~~Wetland~~		

Table 2. Sensors at integrated RAN stations.

Sensors[a]	~~WL~~ # Stations [b]	~~0~~ Sampling rate [Hz]
~~Water~~ heightKinematics EpiSensor	~~WT~~ 355	~~0~~ 200
Syscom ms2007	180	200
Guralp CMG-5T	28	100
Reftek 147A	18	200
CFX US4H	3	200
Lunitek FB	1	250

[a] Equipped with 24bit recorders

[b] Status at 1st January 2022

~~0.1 0.25 0.5 1 2 5 db 1.937 0.515 0.210 0.155 0.490 0.300 Median noise level changes between 0.1 s and 5 s seconds. Positive values mean noise levels are higher during no - lockdown time span.~~

Table 3. Soil conditions of integrated RAN stations (Felicetta et al., 2023).

EC8	# Stations
A	112
B	297
C	140
D	15
E	9
Unknown	12

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

Table 4. 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).

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

~~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 5. ~~Stations with higher than AHNM~~ Number of stations in the network with median noise level exceeding AHNM for different periods.

Period (s)	AHNM Threshold	Exceeding stations	Percentage of network (%)	Land Usage					
				SL	ACL	FL	GL	PCL	OL
0.10	-91.50	57	11.54	49	5	1	0	1	0
0.25	-101.34	41	8.30	36	4	1	0	0	0
0.50	-114.06	92	18.62	81	7	1	1	1	1
1.00	-118.53	219	44.33	169	18	10	11	8	3
2.00	-111.20	34	6.88	27	1	1	4	0	1
5.04	-97.66	5	1.01	4	0	1	0	0	0
8.00	-104.91	15	3.04	10	1	1	2	0	1
16.00	-104.14	28	5.67	18	2	3	3	1	1
32.00	-102.60	57	11.54	42	0	3	5	1	2
64.00	-99.53	97	19.64	73	5	6	5	6	2
80.60	-97.93	79	16.00	59	4	6	5	3	2
Any	-	308	62.35	244	25	14	14	8	3