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Application of Probabilistic Power Spectral Density Technique to Monitoring the Long-Term Vibrational Behaviour of CERN Seismic Network Stations

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Abstract

In this paper, a statistical method called Probabilistic Power Spectral Density based on the standard spectral density plots is presented and utilized. The practical application and utility of this method are shown based on the seismic data collected over a long period from three seismic stations connected within the so-called CERN Seismic Network. The analysis was used to observe and monitor the increase in ambient vibration levels over a long period during the heightened heavy machinery work close to LHC Point 1 (ATLAS detector).

Keywords: ground motion, power spectral density, seismic network

1. Introduction

Large Hadron Collider (LHC) situated inside the underground tunnels beneath the border between France and Switzerland, a few kilometres from the city of Geneva is the world largest and highest-energy particle accelerator in the world. The underground placement of the accelerator was chosen to diminish the influence of undesirable vibrations and disturbances on the operation of this extremely precise scientific apparatus. The cultural noise related to human activity on the surface is typically not strong enough to disturb the measurements performed by LHC.

However, one might expect that strong ground motion caused by a nearby earthquake or a long-term heavy machinery work performed in the close vicinity of the accelerator might impact the operation of the detector and in the worst-case scenario invalidate the data collected during its run. Considering that such a machinery work was planned to commence at the site of LHC Point 1 in mid-2018 in relation to the High Luminosity Project upgrade [1], the team from CERN Mechanical Measurement Lab which was tasked with monitoring the vibrations at the worksite have decided to observe and analyse the changing data both in the short- and long-time frame. In the latter case the Probabilistic Power Spectral Density analysis, as presented in the paper by McNamara and Buland [2] has been utilized. In their paper, they have proposed an unique idea of combining two parameters: power spectral density function (PSD) and probabilistic density function to obtain a graph corresponding to the long-term seismic noise of the stations they have analysed. The method took into account the remarks given in Peterson's report [3] regarding the ambient noise spectra, new high and low noise models and the general approach to presenting unified station data. The in-depth description of the method with defined functions and detailed procedure for the calculations of Probabilistic Power Spectral Density graphs has been presented in the paper published by McNamara and Boaz in 2006 [4].

In recent years PPSD analysis has been successfully utilized to assess the ambient seismic noise levels at different regions of the world e.g., in India to obtain the seismic background noise at newly constructed sites of the Eastern Ghat Mobile Belts (EGMB), Orissa [5], in Bulgaria using PDFSA software to evaluate the ambient seismic noise for five digital broadband National Operative Telemetric System for Seismic Information stations [6], in southern Italy to study induced seismic activity in the region of High Agri Valley [7] or in Austria to determine the noise conditions in selected sites before establishing a countrywide seismic network [8].

2. Probabilistic Power Spectral Density

When analysing the data using Power Spectral Density primary the aim of the analysis must be considered and the limitation imposed upon this technique – that the collected data has to stationary. We can make this assumption for short-term measurements (typically 5-20 minutes) when no sudden excitation is present, but if the aim is to analyse the data over a long period it is necessary to undertake a different approach. One such possible option is to utilize the Probabilistic Power Spectral Density method, which combines the information from multiple PSD graphs to describe the long-term vibration behaviour of the observed area. This method and its application to the fore-mentioned seismic stations operating within CERN Seismic Network is presented in this paper. All the calculations, results and graphs shown in this paper have been calculated and plotted using Python3 with the standard scientific packages (*NumPy, SciPy, matplotlib*) and a specialized package ObsPy for the retrieval, post-processing and analysis of seismic data [9].

The detailed procedure for calculating and plotting Probabilistic Power Spectral Density is specified in the paper published by McNamara and Buland [2]. The processing begins with the partitioning of the data obtained from the long-term measurement into short-time (several minutes) segments. For each of these segments, a separate Power Spectral Density function is calculated using a Fast Fourier Transform and stored for further processing. The standard approach is that the values of full-octave averages in 1/8 octave intervals are calculated for each of the acquired PSD functions. This step makes it possible to greatly reduce the further computation time, as instead of considering the value at each available frequency (related to the sampling frequency and the bandwidth of analysis) the number of values under consideration is reduced to the total number of the octave bands used. The acquired values are afterwards converted from units of power $m^2/s^4/Hz$ (acceleration derived from measured velocity) to dB range, under the assumption that the reference acceleration $a_0 = 1$ m/s^2.

The next step of the assembly of the Probabilistic Power Spectral Density graph from the acquired data is accomplished by discretizing the amplitude graphs by value (usually with discretization step of 1 dB) and counting the number of times the value of amplitude falls within a specified range bin (e.g., between -99 and -100 dB). This procedure is repeated for every amplitude of every frequency octave range of every PSD graph. When finished, the percentages are calculated based on the tallied data vs the total amount, and these percentages are plotted to form the actual PPSD graph. The three steps of the data processing procedure presented above are described and defined by McNamara [1] as: binning periods in 1/8 octave intervals, binning power in 1 dB intervals and normalization by the total power of PSDs, respectively.

3. CERN seismic network

To monitor the ground vibration activity in the areas close to the accelerator, a CERN Seismic Network has been established as a collaboration between CERN (EN-MME, EN-STI groups) and Swiss Seismological Service SED [10]. It consists of three separate seismic stations (vaults) as shown in Fig. 1: two underground stations, placed in the tunnels at Point 1 (near ATLAS detector) and Point5 (near CMS detector) and a third surface station located approximately in the central placement of the accelerator ring.

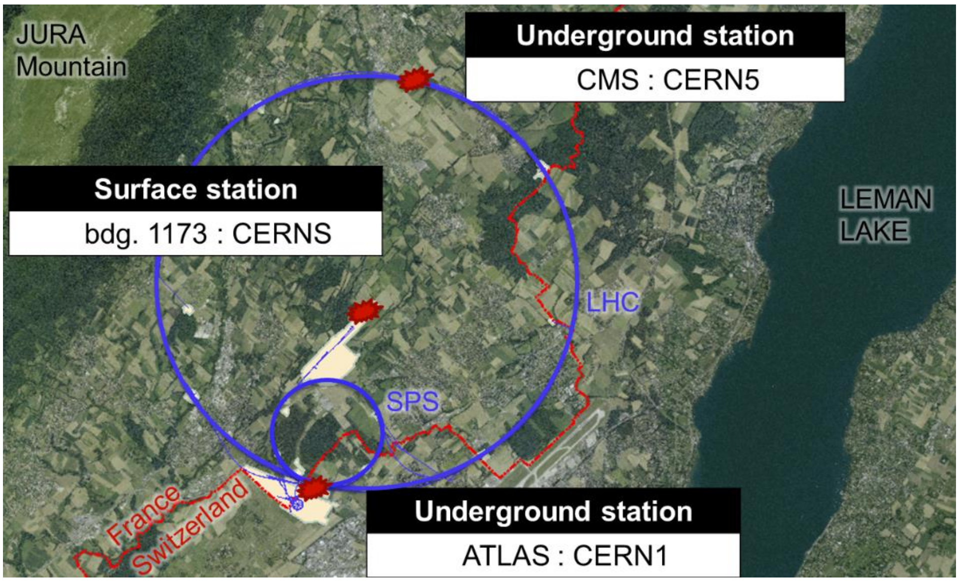

Figure 1. Map of CERN Seismic Network with specified locations of separate seismic stations.

Each station has been equipped with two precise seismic vibrometers – a strong motion accelerometer (to detect high amplitude excitations such as an earthquake) and a broadband sensor (to record vibration in wide frequency range). The network has been in continuous operation since March 2017 (with only a few brief maintenance breaks), constantly recording the vibration measurement data and feeding it directly to international servers provided by SED. This data is stored using standard seismic format miniSEED and publicly accessible for download and further processing.

Still, even providing the large amount of data that is stored and easily accessible it is equally important to decide on a way to process this data is such a way as to acquire useful insight into the vibrational behaviour of the station. A typical approach when analysing vibration is to transform the time-domain quantitative data into frequency-domain qualitative data, such as Power Spectral Density. By analysing the data in the frequency domain in becomes readily visible which frequencies (if any) are dominant in the area of the station and it can be deduced how they are related to the nearby activities.

4. Results of ground measurements and their interpretation

As mentioned above, the data obtained for the analysis and calculation of the Probabilistic Power Spectral Density has been downloaded directly from the publicly available servers set up by Swiss Seismological Service SED. The designated code for the CERN Seismic Network is C4 [11], and the station names are CERN1 (at Point1), CERN5 (at Point5) and CERNS (on the surface). This data has been collected and processed using a Python/ObsPy script.

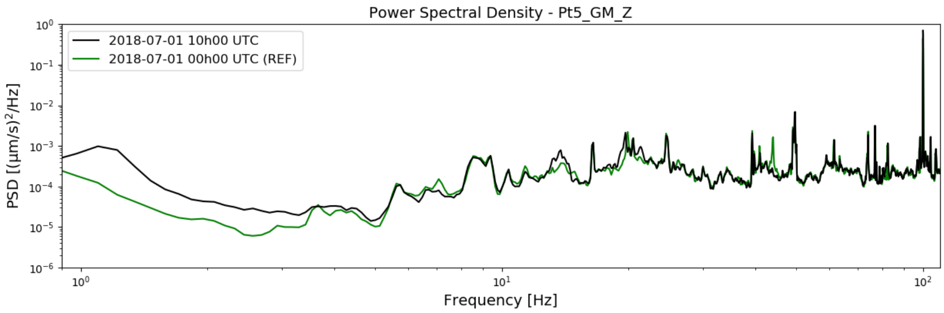

Figure 2. Exemplary PSD graphs of acceleration for the vertical direction of station CERN5.

Figure 2 shows an exemplary PSD acceleration graph for the vertical direction at CERN5 calculated from a 20-minute measurement, while figure 3 presents some exemplary PPSD graphs obtained from ground motion data (vertical direction) that was collected at CERN5 (Point5) seismic station. The left graph has been assembled from 55 separate segments collected over one day, while the one the right shows a PPSD that corresponds to the vibrational behaviour of the station over 5 months (6936 segments). The thick black lines on the graph correspond to the so-called New-High Noise Model (upper line) and New-Line Noise Model (lower line) as defined by Peterson in his report [3]. These lines represent the highest and lowest measured levels of ambient Earth noise sources.

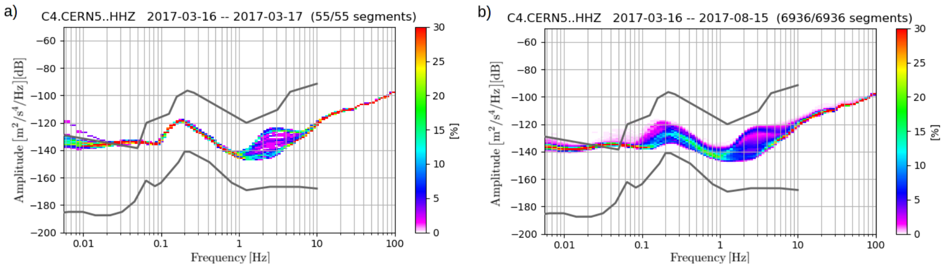

Figure 3. Probabilistic Power Spectral Density of CERN Seismic Station at Point 5 (CMS) calculated over one day (left graph) and 5 months of operation (right graph).

It is noticeable that a great deal of information regarding the characteristics of ground motion near the location of the station can be already deduced based on the PPSD graph plotted from the data collected over one day. With the increase in the number of segments used for plotting the data, additional details can be exposed and investigated. This is especially crucial when attempting to compare the vibratory levels near the station between the typical periods of operation and periods of increased activity (due to e.g., construction works).

When considering the graphs shown in figure 3, notably, they can be split into three approximate frequency regions. The first one located within the frequency range between 0.1 and 1 Hz, shows an amplitude maximum at 0.15-0.2 Hz and a sudden drop afterwards. This behaviour is consistent over 5 months, albeit with an amplitude shift. It shifts and peak amplitude is to be expected though as this range corresponds to the so-called micro-seismic vibration caused by the movement Earth’s oceans.

When regarding figure 3 (both left and right graph), two amplitude curves are readily visible within the frequency range from 1Hz to 10Hz. Those can be interpreted as the vibration caused by human activity, known also as “cultural noise” (operating machines, manufactures, public transport etc.), with the upper line corresponding to the peak-level of human activity during the day and the lower one to the nightly hours. Everything in between these amplitude curves corresponds to the complete range of increasing and decreasing human activity levels over a whole period of 24 hours.

Finally, within the last frequency range in-between 10 and 100 Hz a mostly stable amplitude curve can be seen. As the CERN5 station is located in an underground tunnel, the influence of the vibration sources operating within this range on the surface is most part diminished and thus negligible over a long period of this. This means that the curve represents the actual ambient noise level inside the tunnel. It should be noted, that with continuous construction work in the vicinity of the station, this level is expected to increase and the curve is expected to shift towards higher amplitude values.

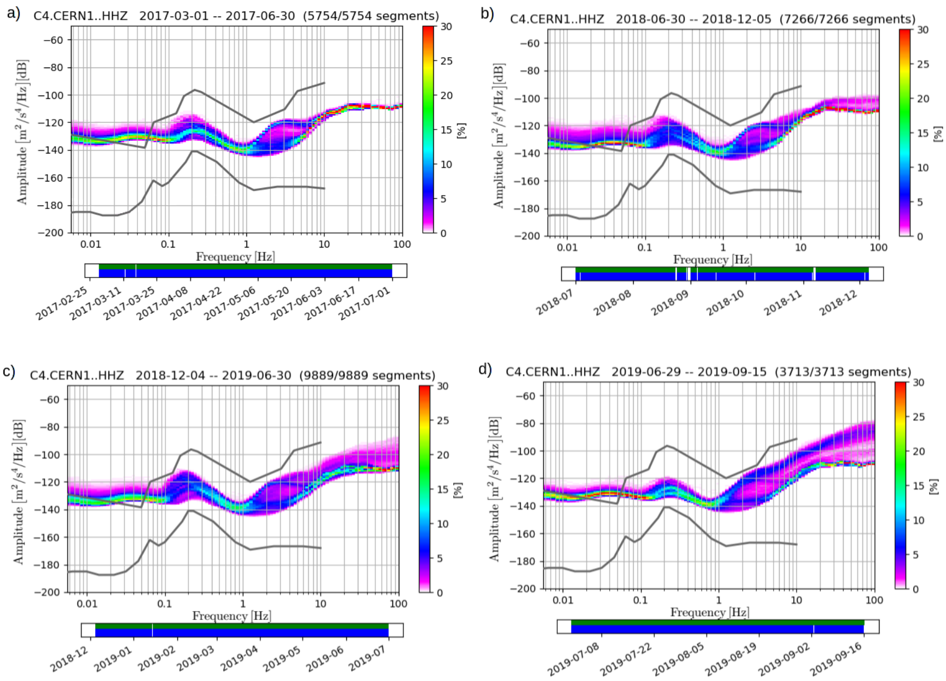

Figure 4. Probabilistic Power Spectral Density of CERN Seismic Station at Point 1 (ATLAS detector): (a) during standard operation (March 2017 – June 2017), (b) during surface machinery work (June – December 2018), (c) during Point 1 shaft excavation (December 2018 – July 2019) (d) during Point 1 cavern excavation (July – September 2019).

Such a situation is presented with the PPSD graphs in figure 4, which shows the shift in the amplitudes after the heavy machinery work has begun at Point 1 in early 2018. As can be seen from these graphs, the amplitudes within the frequency range between 0.1 and 10 Hz are very similar to the ones presented for Point 1 in figure 3, and also correspond to the micro-seismic vibration and cultural noise. The amplitude of vibration in the frequency range 10-100 Hz was mostly stable during the period of standard operation in the vicinity of the station as seen in figure 4 (a), but it started to increase when the construction works began in April 2018. As expected, the levels of vibrations were getting higher, the closer the distance between the excavation location and the placement of the seismic station as seen in figure 4 (b, c, d) respectively.

5. Conclusions

The Probabilistic Power Spectral Density method presented in this paper has proven useful in determining the long-term vibration behaviour of seismic stations included in CERN Seismic Network. The main purpose of the method in the presented case was to provide a tool for the people monitoring the construction site at LHC Point 1 to observe the evolution and increase in ambient vibrations levels close to the established seismic stations over a long period, specifically during the times of increased excavation works.

As such, the method has made it possible to determine the levels and most possible causes of the experienced vibrations. As one of the reasons for the stations' construction and operation was to monitor the vibration caused by nearby excavation works, the method made it possible to determine the affected frequency range (expected in the range 10-100 Hz) and the amplitude increase over the periods of heightened industrial activity. (around 40dB difference between the standard activity and during the time of cavern excavation work).

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