COMPLUTENSE UNIVERSITY OF MADRID
FACULTY OF PHYSICAL SCIENCES

INTERNSHIP REPORT

EXTRACTING ATTRIBUTES FROM A SEISMIC RESGITER

NATIONAL GEOGRAPHIC INSTITUTE

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ORDINARY Call

Contents

1 Introduction

Historically, the study of seismic phenomena has raised numerous debates and questions within scientific circles, not only for the motivation of preserving the existence of human beings on our planet, but also for the knowledge about the nature of these events. Thanks to the advancement of science and consequently of technology, the implementation of sensors, e.g., seismographs, has become possible. Thanks to them, it has been possible to detect a large number of seismic events, which are subsequently analyzed in order to better understand their nature and thus be able to differentiate them from artificial explosions.

At that time, the questions of the time were exclusively related to the understanding of seismic phenomena and the placement of sensors. Today, a second focus is on the development of data analysis and processing techniques, among other things, thanks to the great scientific work of the past and present. Some of these tools have shown great potential in performing iterative tasks, such as machine learning. Thanks to *machine learning*, natural events can be discriminated from those intentionally triggered, based on the attributes of each seismic event. However, the discrimination of seismic events is complicated due to the low incidence rate. [AKL+22]

In order to be able to introduce data in a *machine learning* model, it is necessary to know the attributes to be introduced in the model, and for this, each event has to be processed in order to extract its most relevant characteristics. The work done during the two months of the internship, among other things, has consisted of signal processing, to try to discriminate earthquakes from blasting, in order to extract the attributes that characterize them and analyze them, so that in the future, a model of *machine learning* can differentiate them.

2 The NGI as an institution

This internship has been carried out during February and March at the National Seismic Network within the National Geographic Institute, located at Calle del General Ibáñez de Ibero, 3, Madrid.

Within the conglomerate of tasks performed by the NGI, there is a wide variety of projects and activities ranging from seismic studies to research work in the field of radio astronomy. The Seismic Network is in charge of planning and managing the systems for detecting and communicating seismic movements that occur within the country and their possible impact on the coast, in addition to carrying out work and research on seismic activity and coordinating the regulations associated with these phenomena. It is important to highlight the cooperation that exists at a national and international level, since the progress of science depends on it.

Currently, the discrimination of events is carried out by a group of workers within the Seismic Network, this group is known as the 24-hour group. These people monitor in real time the relevant events occurring in the Iberian Peninsula or in places within the scope of the technical capabilities of the entity.

3 Objectives and Motivation

The work carried out during the internship at the NGI, was to analyze and study aspects of a seismic record by implementing codes in `Python` with the help of libraries such as `numpy, pandas` and `obspy`. All this, in order to understand the attributes of a seismic record in order to relate them to other artificial (non-seismic) events, which present similarities in the waveform in the time domain, similarities in the frequency domain or share values with the seismic record. The latter pursues a main objective, to exploit software techniques that contribute to differentiate better and faster, blasting from earthquakes.

4 Development

This section explains the tools used, as well as the dynamics followed during the two months of practice. It is important to mention, that the techniques explained throughout this report, have been applied to multiple seismological records, but due to lack of space, it has only been documented for a series of examples. However, at the end of the report a link to the repository where you can see many of the images that have been generated throughout the internship period, as well as all the records that have been studied, is attached.

4.1 Work environment

The analysis work at the beginning of the internship was carried out with the software: *Swarm*. This software provides an intuitive interface that allows the analysis of waveforms in *.mseed* format.[1]. As an example, figure 1 shows three graphs generated with this program, corresponding to the Granada earthquake of 2021, both in the time and frequency domains. It is important to mention that the deeper analysis, after the use of *Swarm*, was carried out with the help of `Python` and libraries such as:

- `NumPy.` This is a `Python`library that provides multidimensional *arrays*, Fourier transforms and algebraic operations, among many other functions. (see link).
- `Pandas.` Pandas is a `Python` package that provides fast, flexible and expressive data structures designed to make working with tagged data an easy and intuitive task. (see link).
- `Obspy.` ObsPy is an open source project dedicated to providing a `Python` framework for seismological data processing. It provides parsers for common file formats, clients for accessing data centers, and seismological signal processing routines that allow manipulation of time series. The goal of the ObsPy project is to facilitate the rapid development of applications for seismology. (ver link).

As we can see in figure 1, there is indeed an earthquake at the stated time, this can also be seen in the frequency spectrum of the signal where the range of colors changes drastically at

[1] `.seed` ("Standard for the Exchange of Earthquake Data") is the international standard format for the exchange of raw seismological data between different institutions and agencies. [GFZ]

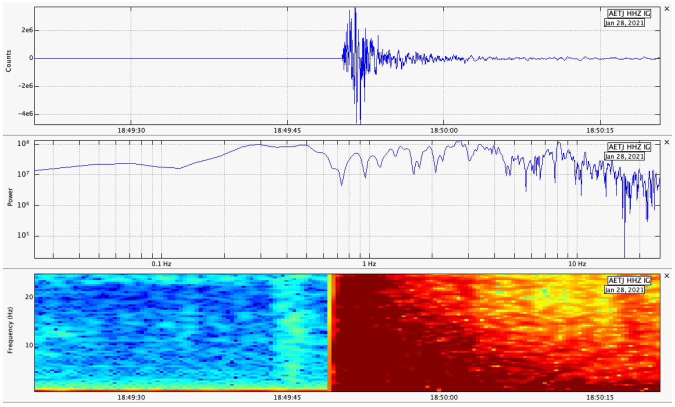


Figure 1: Granada earthquake on 28/10/2021 at 18:49:49 of magnitude 4.4

that instant of time. It is also observed how the maximum power is given for $f = 2.76$ Hz. [2]. In some cases, when the presence of an earthquake was in doubt, bandpass filters were applied, with $f \in \{f_1, f_2\}$ [Hz], where $f_1 \approx 2$ Hz and $f_2 \approx 8$ Hz. The use of filters allows a clearer view of the spectrum, in order to emphasize an area of the spectrum or simply to want to eliminate a band of frequencies. It is important to note the unity of the vertical axis, because as can be seen in the figure above, in the time domain, the **y** axis measures the *counts*. Each *count* equals 10 nm of ground displacement, which equals 10^{-9} meters.

4.2 Data

The data analyzed were provided by the person who guided us during the two-month internship, Resurrección Antón.

Thanks to the `Obspy` library, it has been possible to import seismic records in `seed` format, allowing the study and understanding of the functionalities that this library written in Python offers. Although multiple events have been studied in different logs, this report focuses on the study of two data sources;

- `EMLI.mseed`. This file contains data with several earthquakes in the southern Alboran Sea at an NGI station in Melilla[3].
- `CART.mseed`. This other `.mseed`, contains underwater bursts at a station in Cartagena, which is part of a consortium between the Complutense and the Real Observatorio de la Armada. The NGI welcomes the sharing of this data for research purposes.

The study focused on these two records, because the first one has submarine earthquakes, and in the second one, there is a set of recorded explosions, and it is believed that among them there is an earthquake.

[2]Earthquakes that generate tsunamis generally rupture relatively slowly, producing more energy over longer periods (lower frequencies) than those generally used to measure magnitude. Most frequencies in earthquakes are around [Hz]. [Wik23a]

[3]Spanish autonomous city in North Africa.

4.3 Procedure

The work dynamics followed for the study and analysis of the two aforementioned records and the rest are explained in detail in the following paragraphs.

The first step is to identify a real earthquake, this will only be done for the `EMLI.mseed` file, since the `CART.mseed` only has recorded blasts, with the exception of the mentioned event. To identify the earthquake, it is necessary to know the day it occurred, for this a small research task has been carried out on the NGI web site (see: `earthquake-catalog`) and through all the resources cited in this document, in order to know the earthquakes that occurred in the Alboran Sea. After the search, 114 earthquakes were found (most of them in the Alboran Sea) recorded by the NGI station in Melilla, on October 28, 2021. As a summary, the list of the most outstanding earthquakes is shown below, as a table:

Place	**Date**	**Time**	**Depth** (km)	**Intensity**	**Magnitude**
ALBORÁN SOUTH	28/08/2021	02:03:20	18.0	-	2.3
ALBORÁN SOUTH	28/08/2021	02:29:15	14.0	-	2.2
ALBORÁN SOUTH	28/08/2021	03:31:31	30.0	-	2.4
ALBORÁN SOUTH	28/08/2021	03:37:35	27.0	-	2.2
ALBORÁN SOUTH	28/08/2021	06:17:12	7.0	-	2.2
ALBORÁN SOUTH	28/08/2021	11:20:50	0.0	IV	5.1
ALBORÁN SOUTH	28/08/2021	11:24:11	14.0	II	3.2
ALBORÁN SOUTH	28/08/2021	11:27:34	0.0	II	3.1
ALBORÁN SOUTH	28/08/2021	11:30:01	5.0	II	3.3
ALBORÁN SOUTH	28/08/2021	11:31:26	0.0	-	2.6
ALBORÁN SOUTH	28/08/2021	11:32:32	9.0	-	2.5
ALBORÁN SOUTH	28/08/2021	11:33:34	16.0	-	2.4
ALBORÁN SOUTH	28/08/2021	11:39:21	2.0	-	2.5
ALBORÁN SOUTH	28/08/2021	11:40:19	0.0	-	2.4
ALBORÁN SOUTH	28/08/2021	11:41:36	9.0	-	2.4

Table 1: Some of the earthquakes recorded in the Alboran Sea.

The earthquake with intensity[4] = IV, is the one selected to study the attributes. Once the earthquake is selected, the associated signal interval is plotted, with the help of the *Swarm*, to confirm the presence of the earthquake in the `EMLI.mseed` and to study its main characteristics. The `EMLI.mseed` earthquake and a set of explosions recorded in the `CART.mseed` and in two other files corresponding to two other stations are shown below: `ATIN.mseed` and `APOR.mseed`.

The following are the explosions[5];

In the images 3 and 4 the explosions recorded in the Alboran Sea are observed, in the time and frequency domain respectively. As can be seen, the other two records mentioned above

[4]The **intensity**, defines how much and how the earthquake has been felt by the people and the environment. IGN et al [IGN], definitions and assignments can be found on the page `4/6` of the following document written by the NGI: `SIS-Escala-intensidad-Macrosismica.pdf`

[5]In this internship report, the terms "flare-ups" and "explosions" are synonymous.

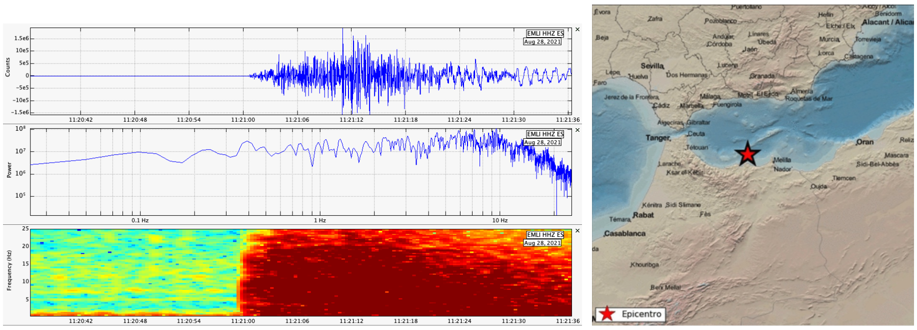


Figure 2: Earthquake of magnitude 5.1, in the Alboran Sea on 28/08/2021 at 11:20:50. On the right you can see the geographical location of the place where it occurred.

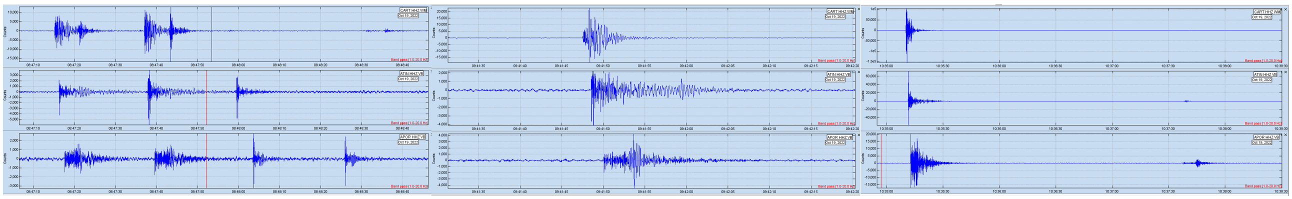


Figure 3: Possible explosions in the time domain.

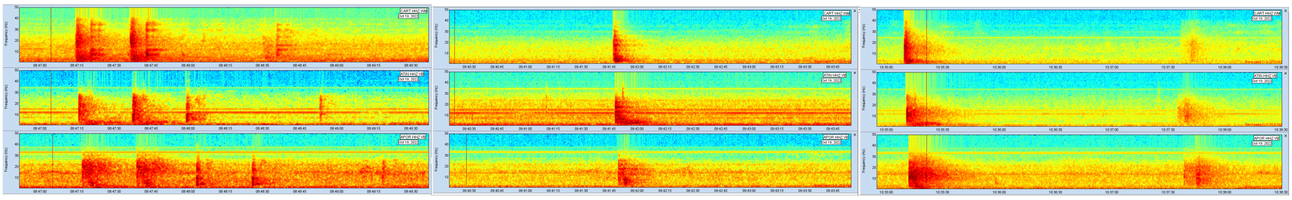


Figure 4: Possible explosions in the frequency domain.

have been included, in order to discriminate at a glance whether it can be an earthquake or an explosion.

Studying figures 3 and 4, one can realize how the station of `APOR` is farther away, with respect to the station of `ATIN`, since the wave appears moments later. In addition, at `APOR`, the received wave arrives more attenuated than the one obtained at the station corresponding to the `ATIN` register.

Finally, focusing on the 10:37 event, it can be seen how it has slightly lower frequency values with respect to the 10:35 event and the rest of the events in the figure, but a slight difference is also appreciated. While in the events at 8:47:15 and 9:41:45 abrupt frequency increases are observed, typical of explosions, at 10:37 this behavior is not observed, since the maximum frequency between 10:37:30 and 10:38:00 is reached almost halfway through the interval. From here arises the doubt about the real nature of this event.

4.3.1 Spectral method

Once the earthquake in the `EMLI.mseed` has been chosen and the possible earthquake in the `CART.mseed` has been identified, it is passed to `Python`, to process the signals and compare their spectra. Figure ?? shows the `EMLI.mseed` earthquake in the time domain. When comparing the

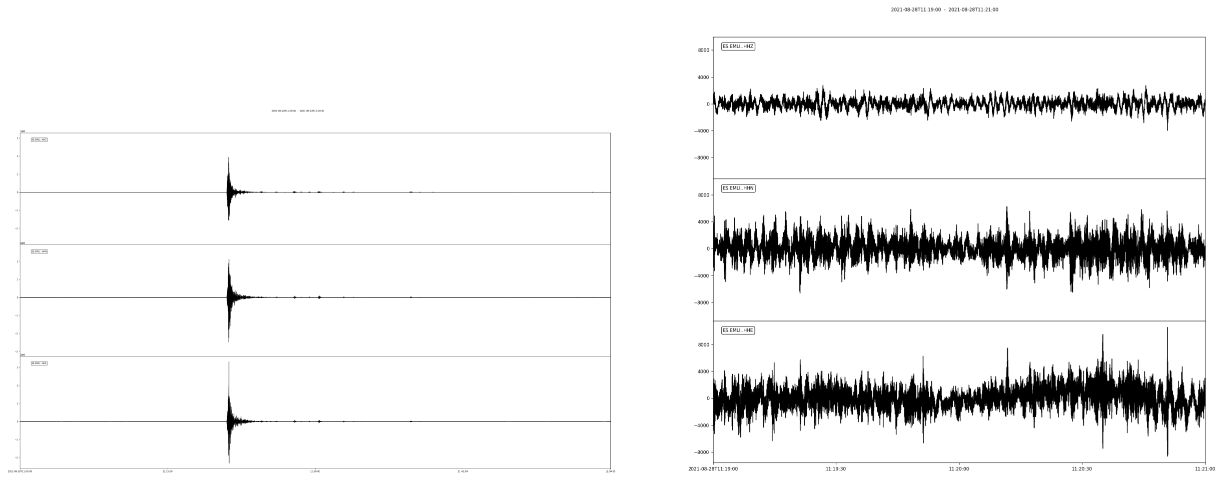


Figure 5: Earthquake of magnitude 5.1, in the Alboran Sea on 28/08/2021 at 11:20:50, full signal (left) and earthquake (right).

two signals, the only part of the signal that matters is the part corresponding to the earthquake, so the signal is trimmed with the function `trim(start_time,end_time)`. This function is specific to `Obspy` and allows to trim signals by specifying the start and end time in seconds. To represent this signal, a sampling frequency of $f_s = 100$ Hz has been chosen, which means that the signal to be processed has 360001 samples. Depending on the recording, an earthquake may have been recorded with one orientation of the seismograph, or with all three (`HHZ`, `HHN` and `HHE`). The two images in Figure 5 show three signals, corresponding to each of the three traditional seismograph orientations with which the event was recorded:

- `ES.EMLI..HHZ` ⇒(`H`:“High Broad Band”,`H`:“High Gain Seismometer” y `Z`:“Vertical”)
- `ES.EMLI..HHN` ⇒(`H`:“High Broad Band”,`H`:“High Gain Seismometer” y `N`:“North-South”)
- `ES.EMLI..HHE` ⇒(`H`:“High Broad Band”,`H`:“High Gain Seismometer” y `E`: “East-West”)

Each of these three letters has a meaning, which can be seen in more detail in the following document written by IRIS[6]: `SEED_Format_definitions.pdf`. Meanings of above;

- `H`. This letter determines the sampling frequency and as it is High Broad Band, then $f_s \geq 80$ Hz[7].
- `H`. This letter specifies the type of seismometer, in this case, it is a high gain seismometer.
- `Z`, `N`, `E`. Determines the orientation of the seismometer; vertical orientation, north-south orientation and east-west orientation, respectively.

[6]IRIS is a university research consortium dedicated to exploring the Earth's interior through the collection and distribution of seismographic data. Wikipedia et al [Wik23b]

[7]That is why the sampling frequency in Python is 100 Hz.

By studying the images in Figure 5, no binding conclusions can be drawn, as the signal must be filtered and its frequency spectrum calculated to learn more about it. Attached below is the spectrum of the original filtered and unfiltered signal, and the spectrum of the unfiltered and then filtered earthquake.

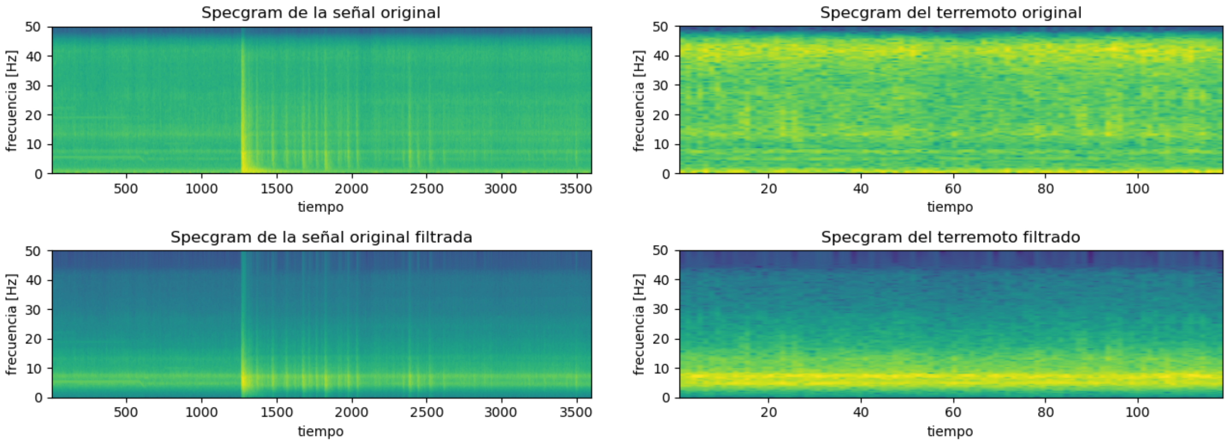


Figure 6: Whole-signal spectrogram (left) and earthquake spectrogram (right)

It can be seen how the energy is concentrated in the lower frequencies. Having the spectrum, one could compare the signals more easily. This process is repeated for the signal from the `CART.mseed`.

Studying the image on the right in figure 7, similarities between the two signal pairs are observed. Since in the two pairs of signals a first explosion can be seen and moments later, another one of much smaller magnitude.

Figure 8 shows the two spectrograms of the two images in figure 7. Comparing the spectrograms of the lower right image in figure 8, with respect to the spectrogram in the lower right image in figure 6, it is clearly seen how in the case of the earthquake, the frequencies remain constant over time, while in figure 8 there are abrupt frequency changes, typical of an explosion. If we compare the spectrogram in figure 8 with the 10:37 event in figure 4, we can see clear differences, while the first one shows a behavior typical of a blast, the second one is more similar to an earthquake.

Although the visualization of the spectrogram of figures 8 and 6 has not given much more information than what was already known, it has allowed to corroborate the clear difference between the spectrograms of an earthquake and that of a blast.

It should be noted that both the selected Melilla earthquake and the 8 a.m. blast in Cartagena have been filtered with a bandpass filter with $f \in \{4 - 16\}$ Hz. The vertical axis frequencies shown in the figures 6 and 8 do not clearly represent the real frequencies, this is because the figures were obtained with the Python library `matplotlib`, and this library only works well when *arrays* created with `numpy` are passed to it, but in this case, the data being represented are data obtained with `Obspy`, hence the problem when representing this type of data.

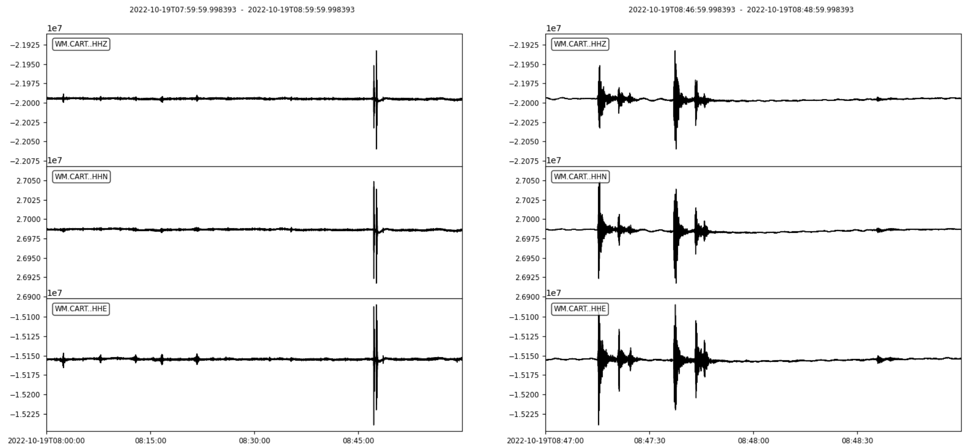


Figure 7: Full signal (left) and blast signal (right)

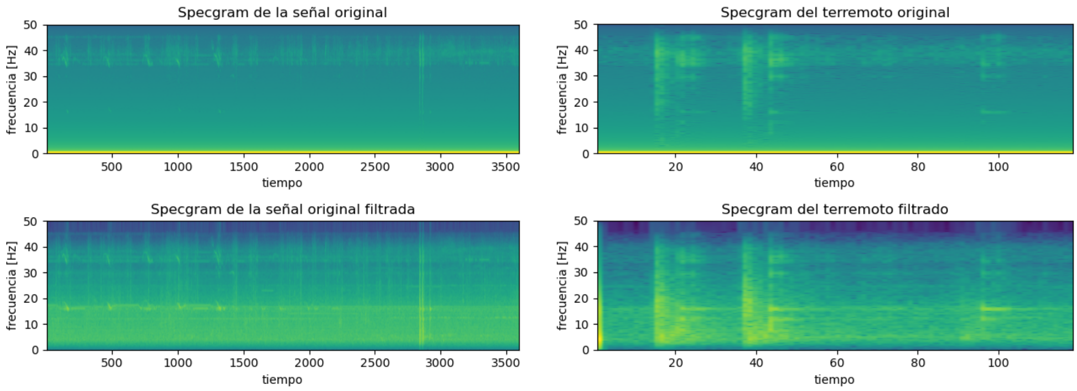


Figure 8: Full spectrogram (left) and blast spectrogram (right)

However, `Obspy` offers a function to represent the spectrogram of the signals of a seismic record.

In Figure 9 the two spectrograms corresponding to the `EMLI.mseed` earthquake and the `CART.mseed` underwater blast are attached. The difference between the two images is clear and also verifies a concept that has been mentioned before, which is that, earthquakes have lower frequencies, while explosions, reach higher frequency values. While the maximum frequency of an earthquake is 1 Hz, blasting reaches a maximum frequency of 40 Hz. Another aspect that has already been commented before, is that, in the case of earthquakes, the bands adjacent to the frequencies that occur with greater intensity, usually fade with time, while in explosions, the frequency of greater intensity (on the time axis) is reached abruptly. See the two points of high intensity, concentrated in the upper part of the blast spectrogram.
Now attached is the 10:37 event, which is believed to be an earthquake. As can be seen in the image on the left in figure 10, there is an amplitude peak, this peak does not correspond to the mentioned event, but to a strong explosion at 10:35 (this is confirmed in figure 4). Therefore, on the right is shown the 10:37 event, in this case, the `trim(...)` function has proved to be of great utility and importance, as the mentioned event could have been overshadowed by the blast at 10:35. The spectrogram of the 10:37 event together with the Melilla earthquake and the 8:47 blast is attached below.

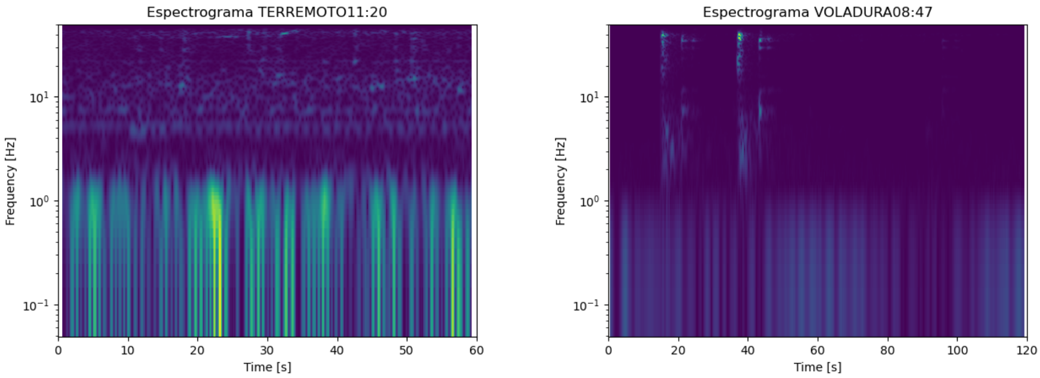


Figure 9: Spectrogram of earthquake (left) and spectrogram of blasting (right)

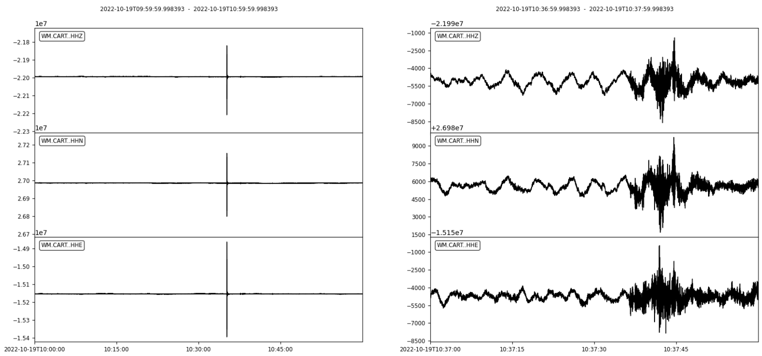


Figure 10: Full signal (left) and earthquake (right).

In figure 11, one can quickly notice the great similarity between the first two images, even though they come from different seismic records and belong to unrelated events. The third image, on the other hand, does not resemble the first one at all. The maximum frequencies in the first two images are very similar, being slightly lower in the first one. Therefore, it can be concluded that the 10:37 event is not a small magnitude earthquake, but it is far from the station and corresponds to an earthquake and not to a blast. As we have seen, the study of

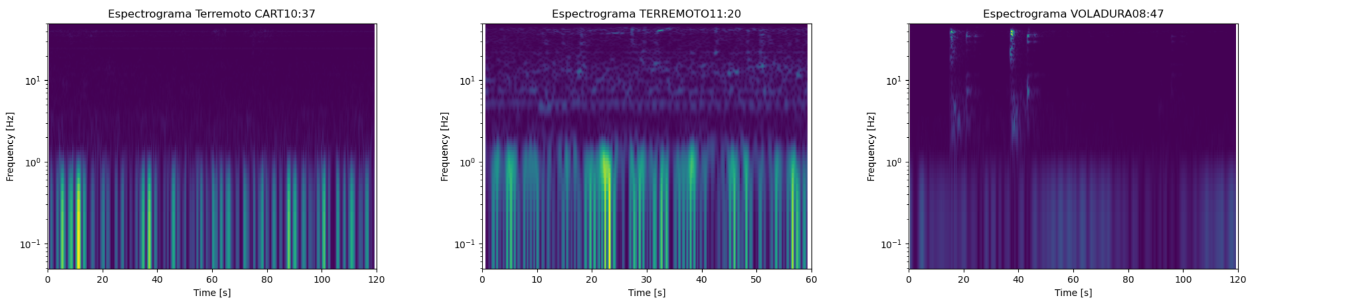


Figure 11: Spectrograms of the supposed earthquake, of the Melilla earthquake, and of the Cartagena voldaura.

spectra resolves many doubts and corroborates assumptions, but more information is needed to find more differences between blasts and explosions.

4.3.2 Correlation method

What is sought with this method are the possible similarities that may exist, correlating the two signals. The library of `Obspy`, called `obspy.signal.cross_correlation`, offers multiple functions that allow to carry out the correlation of signals.

The dynamics to follow is simple, first the signal is extracted from the seismic record and then the signal is sliced to extract the interval to be correlated against another complete signal. In this case, the complete signal is called *stream*, and the slice to be correlated is called *template*. It should be noted that a bandpass filter with $f \in \{0'5 - 2\}$ Hz has been implemented for the filtering of the two signals.

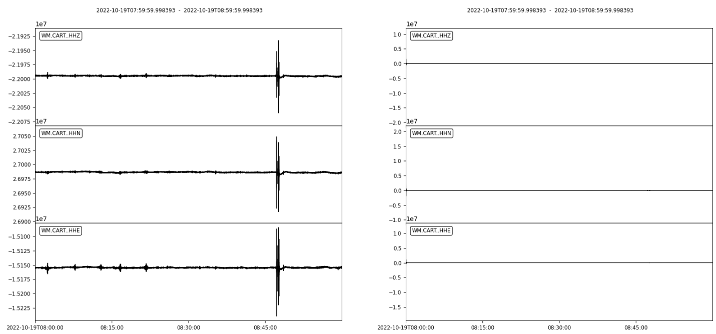


Figure 12: Explosions 08:00-09:00 unfiltered (left), filtered explosions (right)

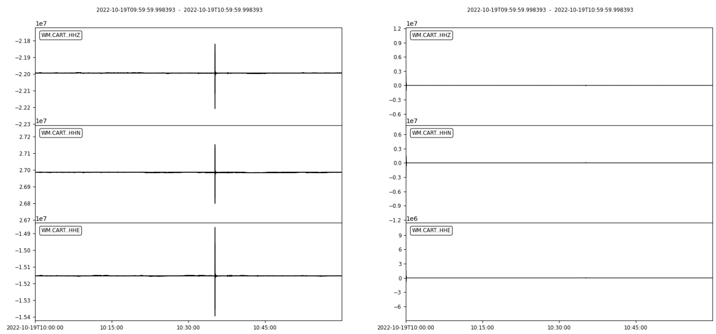


Figure 13: Earthquake 10:37 unfiltered (left), filtered explosions (right)

The first correlation carried out was between the earthquake corresponding to the 10:37 event and the blasts occurring between 08:00 and 09:00 hours, in order to rule out any major coincidence. The results obtained for thresholds of 0.15, 0.20 and 0.25, are shown in figure 14. As can be seen from the results, above a threshold of 0.25, there are almost no matches. Normally the threshold is 0.4 and as it decreases, the coincidences increase. For a threshold of 0.3 there is no correlation between signals, therefore, this shows us a clear difference between the 10:37 earthquake and the rest of the blasts that follow. Now we repeat the same process as before, but correlating the earthquake at 10:37 with the earthquakes that occur in the `EMLI.mseed`, the results after correlating these two signals are as follows;
In this case, no similarity could be found between the 10:37 earthquake in `CART.mseed` and the

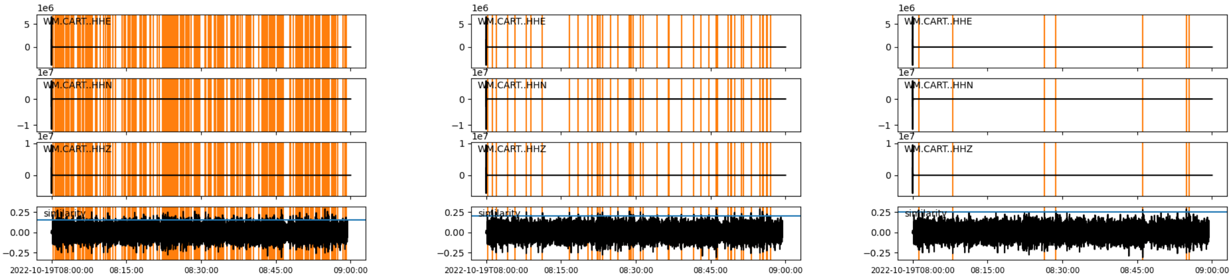


Figure 14: Correlation result, 0.15 (left), 0.20 (center), 0.25 (right)

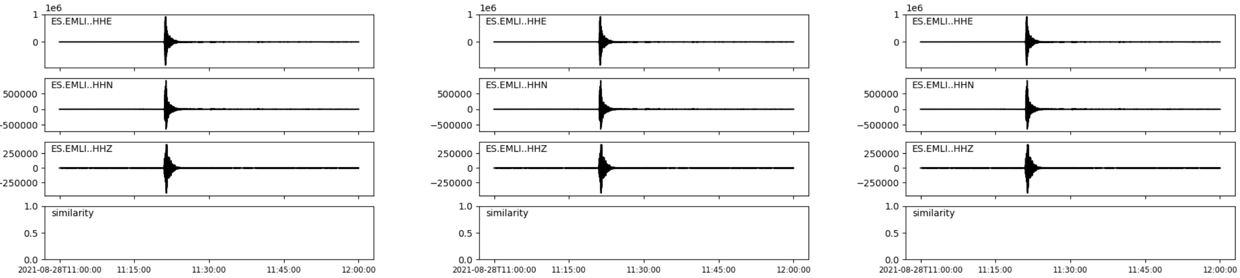


Figure 15: Correlation result, 0.15 (left), 0.20 (center), 0.25 (right)

other earthquakes in `EMLI.mseed`. This may be due to several reasons: not having filtered out [8] well the signal, or to have put a wrong distance between detections. It may also be due to the fact that the 10:37 earthquake has negative amplitudes in the `HHZ` and `HHE` orientation, while in the `HHN` component there are only positive components. If one compares these amplitudes with the `EMLI.mseed` amplitudes in the figure above, one can see how in all three `EMLI.mseed` components there are positive and negative amplitudes, in each of the `HHE, HHZ` and `HHN` orientations. This could reduce the degree of correlation between signals, as similar patterns would not be found due to the amplitude of the events. It should be noted that we tried to correlate the signals with other Python functions, but the data type was not compatible.

4.3.3 Attribute method

The purpose of this discrimination method is to extract the attributes corresponding to each of the seismic records studied, in order to relate and compare them, to know if they have any similarity between them. The result of comparing the attributes of each record gives us information about the characteristics that the events of those records may have in common. To better understand what the attributes of a seismic record represent, the following has been studied this document written by Turner et al. [TLR21].

This process consists of extracting the attributes of an event (in the case of this report, the 10:37 earthquake has been chosen) and the attributes of the earthquakes recorded in the `EMLI.mseed`. Once the attributes have been extracted, they have been represented graphically, in this way,

[8] Before designing the bandpass filter, the spectra of the signals were analyzed to study the frequencies of interest. Once this was done, many frequencies were tested, and none of them gave good results.

by representing the values in a graph, it is possible to see which attributes of the EMLI.mseed are closer to the attribute values corresponding to the earthquake of the CART.mseed.

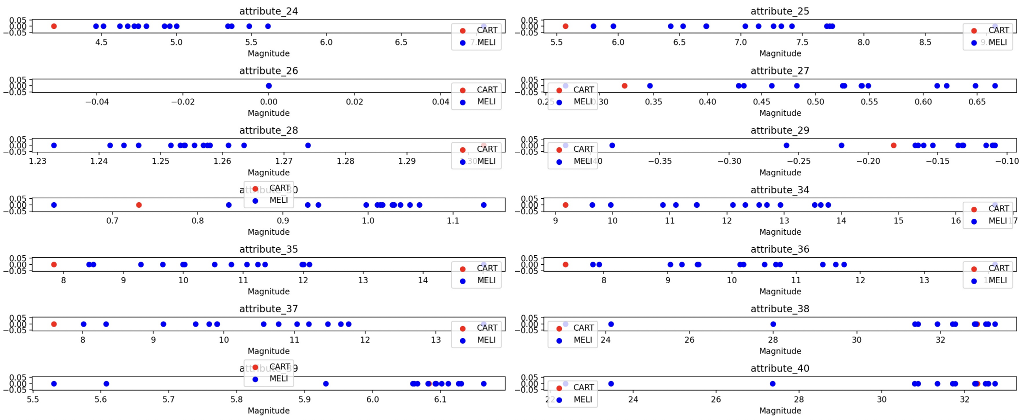


Figure 16: In red, the values of the attributes of the CART.mseed and in blue those of the EMLI.mseed.

As can be seen in the figure above (16), the attributes that are closest to each other are attributes: 26, 29, 38 , 39 and 40, while attributes 34, 35 and 36 only share a downward trend. Attributes 26, 29, 38, 39 and 40 represent the frequency at the maximum value, the median of the normalized DFT, the spectral centroid[9], the turning radius[10], and the width of the spectral centroid[11] respectively. Considering the attributes that share similarities, one can notice how two of them correspond to attributes that represent spectral characteristics, validating the spectral study carried out at the beginning. The attributes related to the spectral centroid, the radius of gyration and the width of the spectral centroid, also confirm that the 10:37 event is an earthquake, since they are key characteristics when describing an earthquake.

5 Results and conclusions

As we have seen, the discrimination between earthquakes and blasting is not an easy task, since it requires an exhaustive data analysis and different signal processing techniques, such as applying filters or clipping signals, in order to purify the information that will later be interpreted. The three techniques that have been seen, are techniques that complement each other, in order to reach a binding conclusion.

Although the main objective of these practices was the extraction of attributes, the whole process documented in this report was necessary. This is very important, because in order to know what attributes to extract, you have to know the corresponding event, and to know the event you have to analyze the signal meticulously, in much the same way that has been documented.

[9] Provost et al. [PHM17], defines this term as $\gamma_1 = \frac{m_2}{m_1}$ where m_1 y m_2 are the first and second moment. Wang et al. [WYW13] relates the concept of moment to the product of fault slip and rupture zones, among others.

[10] Provost et al. [PHM17], defines this term as $\gamma_2 = \sqrt{\frac{m_3}{m_2}}$, where m_3 denotes the third moment.

[11] Provost et al. [PHM17], defines this term as $\sqrt{\gamma_1^2 - \gamma_2^2}$

Finally, I would like to thank Resu for her time, his dedication to us and for hosting us in his office every Wednesday.

6 Learning and some reflections

These internships have been very fruitful and enriching, not only for the amount of new things I have learned, but also for the amount of concepts that I have been able to put into practice to solve the problems that have arisen throughout this internship period.

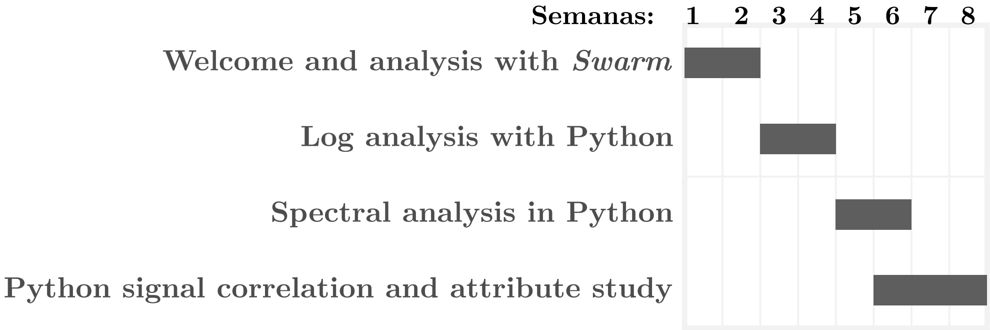
All the tools and solutions that I have applied are the result of 4 years of career, in which I have learned many things, and believe it or not, all the subjects I have studied, have contributed directly or indirectly to the development of these practices, and have allowed me to face them with confidence and motivation. In these practices I have learned curiosities about the dynamics of the plates and the impact of the mantle on the frequency of earthquakes. In addition, I have greatly improved my Python programming skills, as I have had to write code by myself, to represent and manage data correctly and efficiently. I have finally managed to understand the use of `pandas`, developing codes to read the attributes of the records and relate them to others. I have also learned to use the `Obspy` library with which I have become familiar, and I have to say, its potential is still blowing my mind.

These practices have been possible thanks to the knowledge of subjects such as, Linear Systems, Computer Science, Operating Systems, and above all, Signal Processing, because working with seismological files requires knowledge about any type of signal and its properties, such as spectra, probability and filters. Indirectly, this experience has also contributed to the development of my bachelor's thesis, because like much of these practices, I have developed it in Python and in it, signal processing along with *Deep Learning* play a leading role.

7 Link to the codes

The following link redirects to the `GitHub` page where you can find the repository with all the codes developed in Python, as well as all the images that could not be included in this report due to lack of space. https://github.com/pablosreyero/IGN-codes

8 Gantt Chart



References

[AKL+22] Hyeongki Ahn, Sangkyeum Kim, Kyunghyun Lee, Ahyeong Choi, and Kwanho You. Imbalanced seismic event discrimination using supervised machine learning. *Sensors*, 22, 2022.

[GFZ] GFZ. Data format. GFZ, Data Format.

[IGN] IGN. Descripción del tipo de magnitud. `https://www.ign.es/web/resources/docs/IGNCnig/SIS-Tipo-Magnitud.pdf`.

[PHM17] F. Provost, C. Hibert, and J.-P. Malet. Automatic classification of endogenous landslide seismicity using the random forest supervised classifier. *Geophysical Research Letters*, 44(1):113–120, 2017.

[TLR21] Ross J. Turner, Rebecca B. Latto, and Anya M. Reading. An obspy library for event detection and seismic attribute calculation: Preparing waveforms for automated analysis. *Journal of Open Research Software*, Oct 2021.

[Wik23a] Wikipedia. Escalas de magnitud sísmica — wikipedia, la enciclopedia libre, 2023. [Internet; descargado 14-abril-2023].

[Wik23b] Wikipedia contributors. Iris consortium — Wikipedia, the free encyclopedia, 2023. [Online; accessed 11-May-2023].

[WYW13] J. P. Wang, X. Yun, and Y.-M. Wu. A first-order second-moment calculation for seismic hazard assessment with the consideration of uncertain magnitude conversion. *Natural Hazards and Earth System Sciences*, 13(10):2649–2657, 2013.