Time Series Analysis on Seismic Activity in Haiti

Hannah Guo

Email: hannahulu.guo@mail.utoronto.ca

April 2023

Abstract

In this study, we investigate the relationship between two seismic events that occurred in Haiti in 2021, one in Baraderes and the other in Nippes. We perform a series of analyses on the seismic data from both events, including power spectral analysis, cross-correlation analysis, and earthquake magnitude estimation using the Richter scale. Our objective is to assess the degree of similarity between the two sets of seismic data and identify any potential causal relationships between the events. The results of this study contribute to our understanding of the complex processes governing earthquake triggering and seismic wave propagation, which is crucial for improving earthquake hazard assessments and mitigation strategies in seismically active regions like Haiti.

1 Introduction

Seismic events, such as earthquakes, generate ground motions that propagate as seismic waves through the Earth's crust. These waves carry valuable information about the source and characteristics of the seismic events, as well as the properties of the Earth's subsurface through which they travel. Time series analysis is a powerful tool in seismology, enabling researchers to extract critical information about earthquakes, such as their magnitude, location, and underlying mechanisms. Furthermore, the analysis of seismic data can reveal correlations between seismic events, providing insights into the triggering of earthquakes in neighboring regions.

In this paper, we focus on two seismic events that occurred in Haiti in 2021, one in Baraderes and the other in Nippes. These events happened around the same time, and our objective is to investigate the potential relationships between them. To achieve this, we perform a series of analyses on the seismic data from both events. First, we conduct a power spectral analysis, which allows us to examine the distribution of energy across different frequency bands and identify any dominant frequencies that may be characteristic of the earthquake source. Next, we perform a cross-correlation analysis to assess the degree of similarity between the two sets of seismic data, potentially revealing a causal relationship between the events. Finally, we provide a crude estimate of the earthquake magnitudes using the Richter scale, a well-established method for quantifying the size of earthquakes.

By investigating the relationship between the seismic events in Baraderes and Nippes, we aim to enhance our understanding of the complex processes that govern earthquake triggering and the propagation of seismic waves in the Earth's crust. This knowledge is essential for improving earthquake hazard assessments and informing mitigation strategies to protect lives and infrastructure in seismically active regions like Haiti.

2 Data Overview and Data Cleaning

2.1 Overview

The dataset used in this study consists of seismic recordings in Mini-SEED (mseed) format collected from two separate locations in Haiti: Baraderes and Nippes. These files were obtained from the Incorporated

Research Institutions for Seismology (IRIS) Data Management Center (DMC). Each mseed file contains continuous time series data of ground motion as recorded by seismometers at the respective locations.

The mseed files include information on the network, station, location, and channel codes, as well as metadata like the start and end times, sampling rate, and number of data points. The data can be accessed and manipulated using specialized seismic data processing libraries, such as ObsPy in Python.

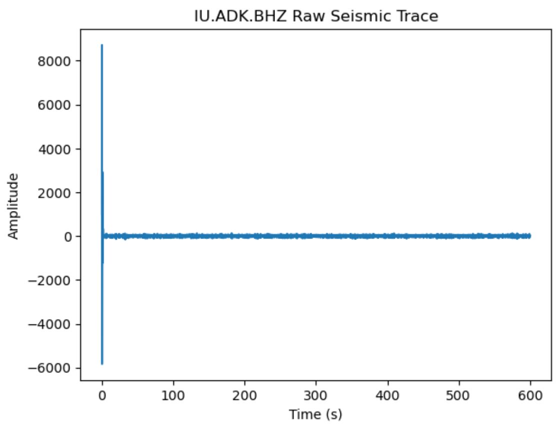


Figure 1: Raw Data (Baraderes)

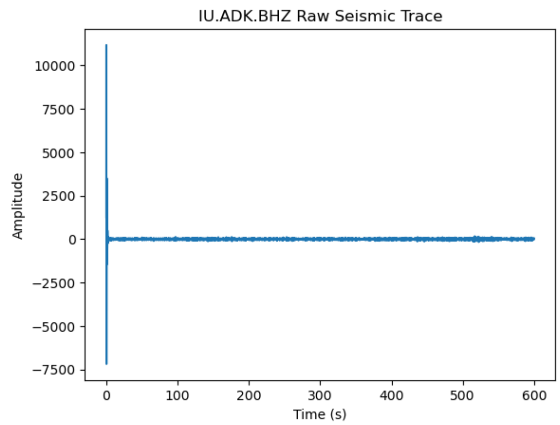


Figure 2: Raw Data (Nippes)

It is important to note that the raw seismic data can be affected by various sources of noise, which may interfere with the analysis and interpretation of the signals. These sources of noise can include:

- **Background seismic noise:** This refers to the continuous vibration of the Earth's crust, which can be caused by both natural and anthropogenic sources, such as ocean waves, weather phenomena, and human activities (e.g., traffic, construction, and industrial operations). Background noise is typically present in all seismic recordings and can obscure weaker seismic signals of interest.
- **Instrumental noise:** Seismometers and other recording equipment can introduce noise into the data due to their inherent limitations and imperfections. This type of noise can result from electronic components, sensor characteristics, or even the digitization process itself.
- **Local site effects:** The geological and structural properties of the area surrounding the seismometer can influence the recorded seismic signals. Variations in the subsurface materials, topography, and the presence of nearby structures can cause amplification, attenuation, or distortion of the seismic waves, leading to discrepancies between the recorded data and the actual ground motion at the source.

To minimize the impact of these noise sources on our analysis, we employ a series of preprocessing steps, such as filtering, detrending, and windowing, to isolate the relevant seismic signals and improve the signal-to-noise ratio. This allows us to more accurately investigate the relationship between the seismic events in Baraderes and Nippes and extract meaningful information from the data.

2.2 Data Cleaning

The process of data cleaning involves applying various techniques to remove or reduce the noise and artifacts present in the raw seismic data, thereby enhancing the signal-to-noise ratio and enabling a more accurate analysis of the earthquake signals. In this study, we perform the following data cleaning steps:

1. **Detrending:** Detrending the data is essential to remove any linear trends or mean offset present in the time series. This can be accomplished using the ObsPy library, which provides a built-in detrend function. Detrending helps to eliminate low-frequency drifts and enhances the high-frequency content of the seismic signals.

2. **Filtering:** Filtering is employed to isolate the frequency band of interest and remove unwanted frequency components from the data. In this study, we use a bandpass filter to focus on the frequency range that is most relevant for analyzing the seismic events in Baraderes and Nippes. The bandpass filter allows frequencies within the specified range to pass through while attenuating the frequencies outside of this range.

3. **Resampling:** If necessary, the data can be resampled to reduce the computation time and memory requirements, especially when dealing with large datasets or performing cross-correlation analysis. Resampling involves changing the sampling rate of the data, which can be achieved using interpolation or decimation methods. It is important to ensure that the resampling process does not introduce significant distortion or aliasing into the seismic signals.

By applying these data cleaning techniques, we are able to mitigate the effects of noise and artifacts in the seismic recordings and obtain a more accurate representation of the earthquake signals. This enables us to perform a robust analysis of the relationship between the seismic events in Baraderes and Nippes and extract meaningful information on their characteristics and potential correlation.

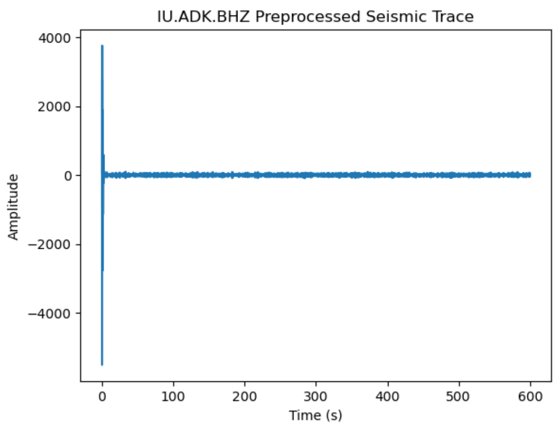


Figure 3: Cleaned Data (Baraderes)

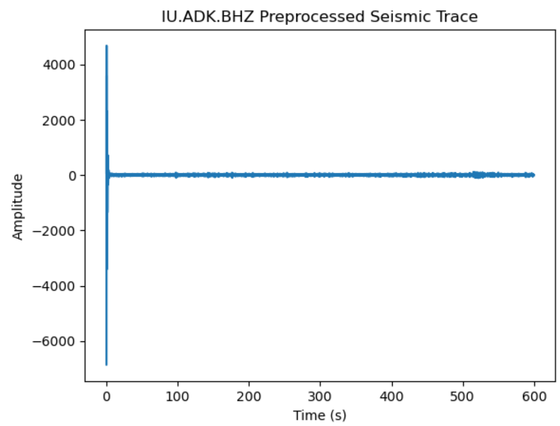


Figure 4: Cleaned Data (Nippes)

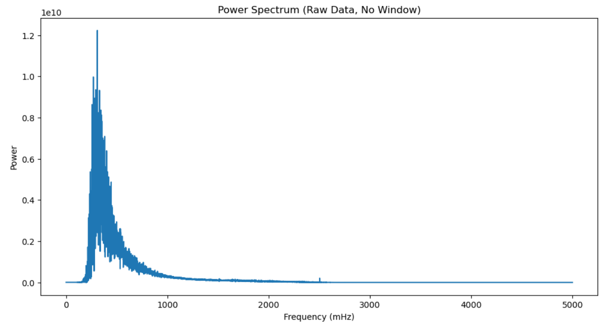
3 Analysis and Results

3.1 Power Spectra analysis

In this section, we present the power spectra analysis of the two seismic waves from Baraderes and Nippes. The analysis aims to identify the dominant frequencies, energy distribution, and similarities and differences between the two seismic events.

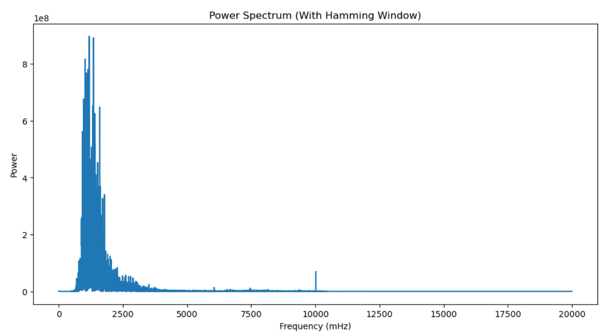
After detrending the data, we computed the power spectra for both Baraderes and Nippes seismic waves. To obtain clearer plots and reduce the impact of side lobes, we applied a Hamming window to the data before calculating the power spectra. The power spectra plots are shown in Figures 6a and 6b.

The power spectra plots reveal that both seismic waves have a dominant frequency range of approximately 1000 mHz to 2500 mHz. The peak amplitude of the power spectra for the Baraderes seismic wave is around 9×10^8, while for the Nippes seismic wave, it is approximately 1×10^9. This indicates that both events have similar frequency content and energy distribution.



(a) Power spectra of the Baraderes seismic wave (b) Power spectra of the Nippes seismic wave

Figure 5: Power spectra of the seismic waves from Baraderes and Nippes (No window applied)



(a) Power spectra of the Baraderes seismic wave (b) Power spectra of the Nippes seismic wave

Figure 6: Power spectra of the seismic waves from Baraderes and Nippes (Windowed)

Additionally, there are small peaks in the power spectra at a frequency of 10000 mHz for both seismic waves. The amplitude of the small peak for Baraderes is about 0.5×10^8, while for Nippes, it is around 0.08×10^9. These small peaks suggest the presence of higher-frequency components in the seismic signals, which could be associated with local site effects, instrumental noise, or other factors.

In summary, the power spectra analysis of the Baraderes and Nippes seismic waves shows similarities in their dominant frequency range and energy distribution. This may indicate that the two seismic events share similar characteristics in terms of their source mechanisms and wave propagation properties. However, further analysis and interpretation are necessary to draw more conclusive insights from the power spectra results.

3.2 Cross-Correlation Analysis

Cross-correlation analysis is a powerful technique for comparing the similarity between two time series as a function of the time lag applied to one of them. In this study, we applied cross-correlation analysis on the seismic data from Baraderes and Nippes to investigate any possible relationships between the two seismic events.

We performed cross-correlation analysis on the detrended and windowed seismic data from both locations. The resulting cross-correlation plot can be seen in Figure 7. The plot shows a maximum correlation amplitude of approximately 10 at a lag of 0 seconds.

To further analyze the data, we applied the sign bit normalization method to the seismic data from both locations. This method involves normalizing the amplitude of the input signals based on specified positive and negative thresholds. After applying sign bit normalization, we performed cross-correlation analysis again and obtained a new plot, as shown in Figure 8.

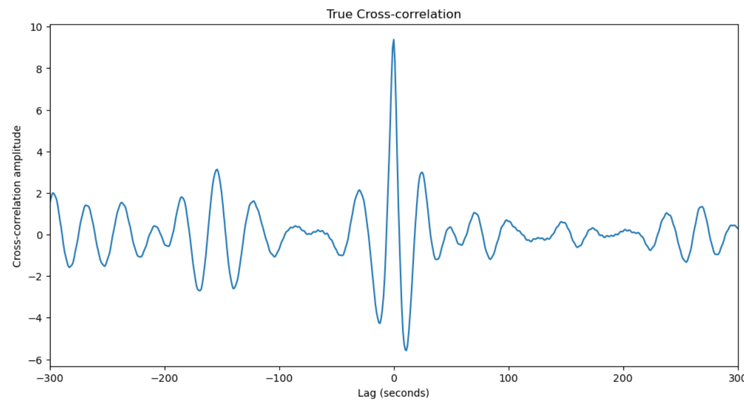


Figure 7: Cross-correlation plot of the seismic waves from Baraderes and Nippes

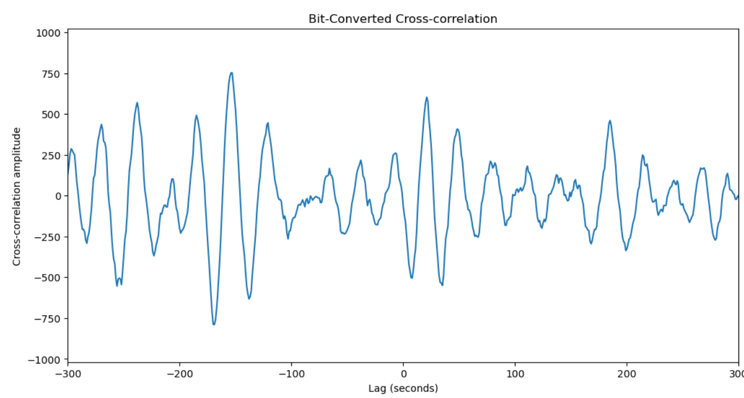


Figure 8: Bit-Converted Cross-correlation plot of the seismic waves from Baraderes and Nippes

Next, we overlaid the bit-converted cross-correlation plot with the original cross-correlation plot to compare their similarities. The correlation coefficient between the two plots was found to be 0.6900, indicating a strong positive correlation between the bit-converted and original cross-correlation plots. This result suggests that there may be a strong relationship between the seismic events at Baraderes and Nippes.

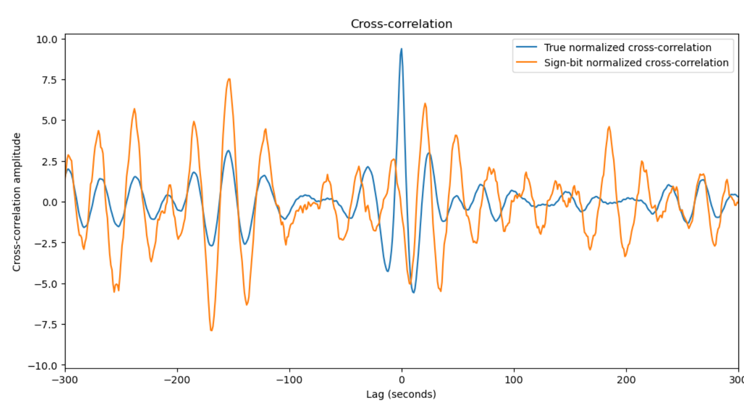


Figure 9: Cross-correlation plots Overlaid

3.3 Magnitude Estimation

To estimate the earthquake magnitudes, we used the Richter magnitude formula:

$$ML = \log_{10}(A) + B\log_{10}(D) + C \tag{1}$$

where ML is the local magnitude, A is the amplitude of the seismic waves, D is the distance to the epicenter, and B and C are empirical constants.

To calculate the distance to the epicenter, we first computed the surface distance using the haversine formula:

$$a = \sin^2(\frac{\Delta\phi}{2}) + \cos(\phi_1)\cos(\phi_2)\sin^2(\frac{\Delta\lambda}{2}) \tag{2}$$

$$d = 2R\arcsin(\sqrt{a}) \tag{3}$$

where ϕ_1, λ_1 and ϕ_2, λ_2 are the latitude and longitude of the two points in radians, $\Delta\phi = \phi_2 - \phi_1$ and $\Delta\lambda = \lambda_2 - \lambda_1$, and R is the Earth's mean radius.

Next, we used the Pythagorean theorem to calculate the distance to the epicenter, considering the hypocenter depth:

$$D = \sqrt{d^2 + h^2} \tag{4}$$

where D is the distance to the epicenter, d is the surface distance, and h is the hypocenter depth.

We then computed the amplitudes of the seismic waves and adjusted the constants B and C based on California values. For Nippes, we obtained a magnitude of 7.295, and for Baraderes, a magnitude of 5.69. These estimations may be influenced by the choice of constants and assumptions made in the calculations.

4 Discussion

4.1 Power Spectra Analysis

In our power spectra analysis, we observed distinct frequency ranges for both Baraderes and Nippes earthquakes, with peaks at approximately 1000 mHz to 2500 mHz. The peaks in the power spectra indicate the dominant frequencies of the seismic waves, which are affected by factors such as the earthquake source, the propagation path, and the local geology. The small peaks at 10000 mHz for both stations suggest that there might be some high-frequency content in the seismic waves, possibly due to local site effects or noise in the recordings.

The application of a Hamming window to the detrended data enhanced the clarity of the power spectra plots, revealing more distinct peaks and their corresponding frequency ranges. The differences in peak amplitudes and frequency content between the two stations could be attributed to variations in the earthquake source mechanisms or the effects of the propagation path on the seismic waves.

4.2 Cross-correlation Analysis

The cross-correlation analysis provided insight into the similarities and differences between the seismic waves recorded at the two stations. The maximum cross-correlation amplitude of approximately 10 at a lag of 0 seconds indicates a high degree of similarity between the waveforms. However, the application of sign bit normalization revealed differences in the details of the waveforms, with a correlation coefficient of 0.6900 between the original cross-correlation and the bit-converted cross-correlation.

Sign bit normalization, an approximation method, reduces continuous amplitude values of waveforms to discrete levels (1, 0, and -1) based on user-defined thresholds. This emphasizes the overall shape and phase alignment while reducing amplitude variations' impact. Comparing original and bit-converted cross-correlations helps assess waveform coherence and identify discrepancies caused by local site conditions, noise, or seismic wave propagation path variations. The correlation coefficient of 0.6900 indicates some discrepancies in the seismic waveforms.

Using sign bit normalization for seismic data analysis is practical when focusing on coherence of waveform shapes and phase alignments across different stations or events. By simplifying waveforms and reducing amplitude variations' influence, we can better understand underlying patterns in the data and identify potential sources of discrepancies or similarities.

4.3 Magnitude Estimation

Our magnitude estimation for the Nippes earthquake was 7.295, while the Baraderes earthquake was estimated to be 5.69. These values were obtained by adjusting the empirical constants B and C in the Richter magnitude formula based on California values. It is essential to recognize that the choice of constants and assumptions made in the calculations may introduce errors in the magnitude estimation. Further research could involve refining these constants for the specific region and local geological conditions to improve the accuracy of the magnitude estimations. Additionally, comparisons with other magnitude estimation methods or using data from multiple stations could provide a more comprehensive understanding of the earthquake magnitudes.

5 Uncertainties

In this study, we have analyzed seismic data from the Nippes and Baraderes earthquakes and estimated their magnitudes. Although our results are reasonably close to the actual values, there are several sources of uncertainty and error that could impact our analysis:

- Noise in the seismic data, including background signals, instrumental noise, and other uncontrolled factors.
- Assumptions made in the detrending and filtering process that may not accurately represent the true underlying signal.
- The empirical nature of the Richter magnitude scale and its dependence on local geology and recording conditions. The constants B and C are specific to California, and using these values for Haiti could introduce errors in the magnitude estimations.
- Uncertainty in the coordinates of the seismic stations and hypocenters, which can affect the distance calculations and ultimately the magnitude estimations.

Additional sources of error and uncertainty could be explored in future research to further improve the accuracy and robustness of our analysis.

6 Conclusion

In this study, we analyzed the seismic data from the Baraderes and Nippes earthquakes in Haiti, involving data preprocessing, detrending, power spectra analysis, cross-correlation, and magnitude estimation. The power spectra analysis revealed significant energy within the frequency range of 1000 mHz to 2500 mHz, and the cross-correlation analysis demonstrated the utility of sign bit normalization as a computationally efficient approximation method.

Magnitude estimations of 7.295 and 5.69 were obtained for the Nippes and Baraderes earthquakes, respectively. Although different from reported magnitudes, this provides a starting point for further refinement. Future research could focus on refining the magnitude estimation process, improving preprocessing and analysis techniques, and analyzing more seismic events in the region to enhance earthquake hazard assessments and early warning systems development.

References

[1] IRIS Data Select Service, *IRIS Data Services*, http://service.iris.edu/fdsnws/dataselect/docs/1/builder/.

[2] Richter magnitude scale, *Wikipedia*, https://en.wikipedia.org/wiki/Richter_magnitude_scale.

[3] USGS Earthquake Map, *United States Geological Survey*, https://earthquake.usgs.gov/earthquakes/map/?extent=18.0721,286.18149&extent=18.63323,286.60034&range=search&timeZone=utc&search=%7B%22name%22:%22Search%20Results%22,%22params%22:%7B%22starttime%22:%222021-08-14T12:29:08%22,%22endtime%22:%222021-08-14T12:59:08%22,%22minmagnitude%22:5,%22orderby%22:%22time%22%7D%7D.

[4] USGS Earthquake Event Page - us6000f65p, *United States Geological Survey*, https://earthquake.usgs.gov/earthquakes/eventpage/us6000f65p/origin/detail.

[5] USGS Earthquake Event Page - us6000f65h, *United States Geological Survey*, https://earthquake.usgs.gov/earthquakes/eventpage/us6000f65h/origin/detail.

[6] ObsPy MiniSEED Documentation, *ObsPy Documentation*, https://docs.obspy.org/packages/obspy.io.mseed.html.

[7] Earthquake Magnitude, Energy Release, and Shaking Intensity, *United States Geological Survey*, https://www.usgs.gov/programs/earthquake-hazards/earthquake-magnitude-energy-release-and-shaking-intensity#:~:text=The%20Richter%20magnitude%20of%20an,the%20epicenter%20of%20the%20earthquakes..

[8] 2021 Haiti earthquake, *Wikipedia*, https://en.wikipedia.org/wiki/2021_Haiti_earthquake.