University of Auckland

Department of Physics

Bachelor of Physics and Chemistry

Monitoring the Auckland Volcanic Field using Ambient Seismic Noise

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Abstract

We aim to investigate the use of ambient noise tomography to monitor the Auckland Volcanic Field. The vertical velocity time-series from 11 seismic stations across the Auckland region are retrieved. Using the python package MSNoise they are cross correlated allowing an impulse response between stations to be obtained. From this, the surface velocity is calculated, and due to the continuous nature of ambient seismic noise data, the speed between stations can be monitored. Changes in the surface velocity may precede a volcanic event or infer changes in the ground water level. Auto-correlations, created by correlating a stations waveform with itself, are used to create a zero distance impulse response. This technique is used to identify local sources of seismic noise and may be used to study anthropogenic events.

Contents

1 Introduction

1.1 Career Development

This summer research project has allowed to apply my knowledge of physics to the landscapes of the world around me. I have done a few earth science courses but saw them as more of an interest topic on the side from my physics and chemistry degree. Through this research I have been able to combine earth science with physics to explore the realm of geophysics, seismology and volcanology. I have come to realize I am very interested in these fields, and will investigate doing geophysics papers and research in the future.

The skills gained from my research will be invaluable and I will be able to use and develop them further in the future. I built on my previous Python skills using the packages Obspy and MSNoise to gather and analyze my data, as well as using a Linux OS for the first time. In developing skills in these areas, I have also become more resourceful and know where to find help for any technical issues. This research has given me a chance to write about science instead of just learning about it. I have done far more academic reading over this summer than I had ever done in my life and have felt the challenge of undertaking a piece of formal writing and gained a new-found appreciation for how carefully thought out it is.

1.2 Summary

Using seismic data gathered from 11 seismic stations around the Auckland region, ocean generated ambient seismic noise is cross-correlated between station pairs to create an impulse response for surface seismic waves between stations. The seismic wave velocity can be determined and monitored allowing for any changes to be detected. These may be attributed to changes in the material properties of the earth between stations and/or the source of our ambient seismic noise, be it the ocean or large anthropogenic events such as the Rugby World Cup.

This research can be furthered to create a tool to monitor seismic velocities in Auckland which could be used to monitor change in groundwater level, as a result of precipitation or a rising magma batch preceding a volcanic eruption. The landscape of Auckland is evidence that Auckland has been and, is still prone to a volcanic event. With a large population, economy and associated infrastructure, a tool to help the prediction, location and monitoring of volcanic events in Auckland is incredibly valuable. With further developments, ambient seismic noise could be one of the key pieces of evidence used by organizations such as DEVORA and council to manage this hazard. This research can also be furthered to create a tool for the likes of Watercare to use ambient seismic noise to monitor the groundwater level beneath Auckland.

Individual station data can be correlated with itself to create an Auto Correlation (AC). The Eden park station was of interest with the influence of anthropogenic events such as the Rugby World Cup in 2011. Changes in the AC at a range of frequency windows can show the influence of these events on the seismic noise profile at these stations. The AC technique can be extended to determine the depth of impedance boundaries in the earth beneath and allow us to infer structures in the subsurface.

2 The Auckland Volcanic Field

Comprised of 53 volcanoes, the Auckland Volcanic doesn't follow the trend of other volcanoes in the North Island. Central North Island volcanism is the result of the plate subduction between the Australian and Pacific plate, resulting in viscous felsic eruptions [8].Another type of volcanism is associated with hotspots, as seen in the Hawaiian Islands. Auckland doesn't fit the hotspot profile and is not located near the middle of a tectonic plate, so the cause of Auckland's volcanism is a bit of a mystery.

Auckland's volcanoes are typically small basaltic cones, less than 150 m in height. As the crust deep below the city melts, it accumulates into what is known as a "batch" before rising to the surface [8]. This results in monogenic volcanoes as each volcano and its subsequent eruptions is the result of a single batch of magma rising. The monogenic nature is also curious, suggesting that once the magma has been expelled from its batch, it cools down and effectively returns to solid crust again, so there is no preference for the magma to erupt from the same chamber twice. The consequence of this is that it we can't predict where the next eruption will come from, nor can we focus our monitoring on one specific region.

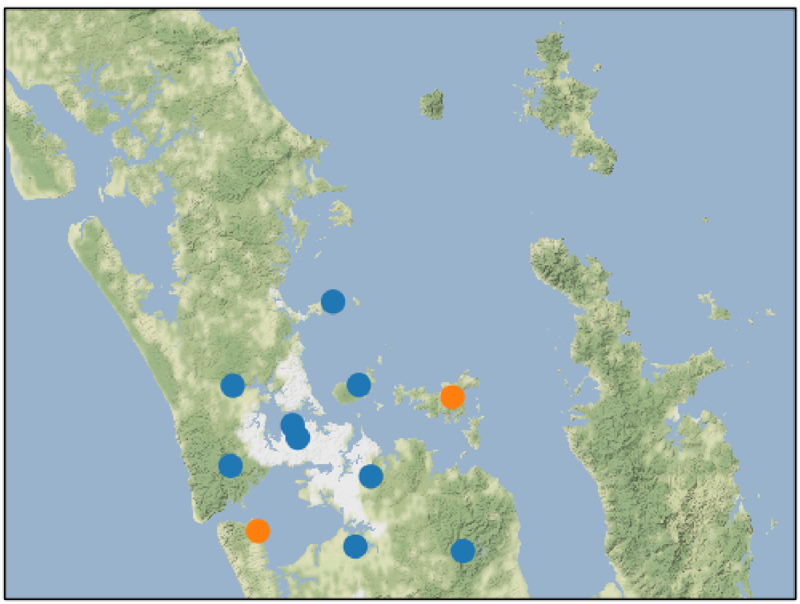

Figure 1: Seismic station map, with the orange dots representing AWAZ (Awhitu) and WIAZ (Waiheke Island), which will be the example station pair for this report

3 Ambient Noise Tomography

Ambient noise tomography uses seismic noise (energy travelling through the earth that is not the result of a ballistic event such as an earthquake) to infer the internal structure of the earth. The prominent source of energy used in ambient noise tomography originates from the oceans.

More traditional seismological methods take data from quake events and used these signals to work out the epicenter and magnitude. This data not only contained the ballistic impulse from the earthquake, it also contained noise from the ocean, which needed to be filtered out to get a clear signal. With the epicenter determined, the speed that the seismic waves travelled from the source to the receivers could be calculated. Typically these studies were undertaken in seismically active areas where small ballistic quake events were plentiful, so there was constant opportunity to monitor the velocity of energy propagation from quakes.

In Auckland however, there are very few earthquakes due to its location away from any significant active faults. As a result there are few opportunities to use ballistic data to observe how energy travels through the earth of Auckland. Instead, the ocean noise that was polluting ballistic seismographs is the data we want to obtain to perform ambient noise tomography[4]

Using weak motions sensors from the 11 seismic stations of the Auckland Seismic Station Network, continuous velocity-time data is collected and downloaded from GeoNet FDSN (International Federation of Data Science Networks) database, using the python package, Obspy [1]. In this investigation only the vertical component (ZZ) is used. The prefilter process has three stages. The first is a frequency filter, then instrument response is removed, followed by cosine tapering and the addition of a water level so there are no 'zero' values, so that any calculations requiring inversion do not result in an infinite value. These wave forms are then exported in the MSEED format for processing.

The data is then cross-correlated using the python package MSNoise [5]. The process involves taking slices of the seismic data for two stations at a time and measuring their similarity, or correlation, as one is moved or shifted in time against the other. The amount shifted is referred to as the lag time. This results in a cross correlation [9]. To get a usable cross correlation function (CCF) each of these slices is summed over a length of time to create a stack. It is typical to create stacks with length anywhere between 1 day and 1 month [5].

The resulting CCF is also known as a Green's function and serves as the impulse response function for surface seismic waves between station pairs in the Auckland Volcanic field [4] . The impulse response is as if one of the stations is the source of continuous seismic energy and the other is the receiver, and vice verse. These two combinations are shown as the positive and negative sides of the CCF. The magnitude of these virtual earthquakes should in theory be even, however some stations will have a higher magnitude if they are closer to the noise source, which in Auckland is the ocean.

Ambient Noise tomography is suited to study the Auckland Volcanic field due to the region being surrounded by ocean on both sides, creating a diffuse wave field. The ocean is the primary reliable source of ambient seismic noise in this study, hence our data is filtered to look at frequencies by filtering between 0.03-0.35Hz [11]. There are two frequency bands associated with ocean noise. The first is called the single frequency (SF) and is located around 0.7 Hz and is the result of energy from the wind being transferred to the ocean [3]. The second band is called the double frequency (DF) band with the dominant frequency at 0.15 Hz. It is the result of interactions between SF waves. We observe the DF band in this study as it contains the most seismic energy, outside of earthquakes [3]. Being surrounded by ocean ensures that Auckland's wave-field is pseudo isotropic, meaning there is almost equal energy travelling in every direction. This ensure that the impulse response for each of the station-pair's paths can be calculated.

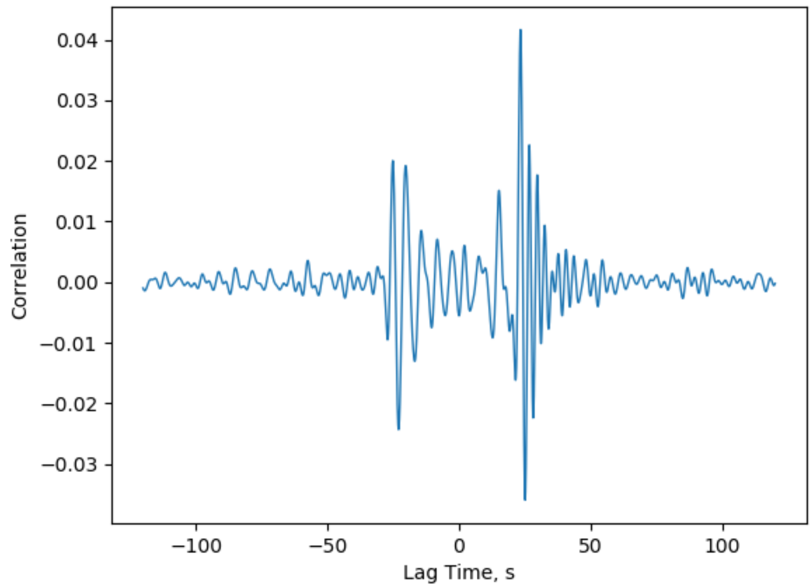

Figure 2: Green's function derived from the reference correlation between AWAZ and WIAZ station

From the impulse response, the arrival time for waves between stations and the surface wave speed can be calculated. As the data from these stations are continuous this process can be performed routinely with recent data, to compute the temporal variations in lag time between stations, with any variations potentially indicating changes in the subsurface beneath the Auckland Volcanic Field.

4 Surface Seismic Response Function

Figure 2 presents an example of an impulse response for the stations AWAZ (Awhitu, the head of the Manukau Harbour) and WIAZ (Waiheke Island in the Hauraki Gulf). These two stations are represented by the orange dots in Figure 1. The positive lag times correspond to energy travelling from the Awhitu station on the West Coast to Waiheke in the east.

There is an imbalance between the of ocean noise on either side of lag time = 0. This is a result of the uneven distribution of noise. The impulse from the Awhitu station is stronger as this station is near the West Coast. New Zealand's west coast is notorious for big surf and strong waves due to the large fetch distance across the Tasman Sea. A station that is closer to the prominent source of seismic noise (Awhitu) will appear to be sending stronger "virtual earthquakes" to the receiver station (Waiheke) than the other way around.

Dispersion of waves is observed in this impulse response, seen clearly in the positive lag time side. The depth at which these surfaces waves penetrate is proportional to their wavelength [9]. As a result, long period, high amplitude waves arrive first as they travel at greater depth, where wave speed is faster. High frequency, short period waves arrive after [4].
The peaks occur at the same time either side of t=0. Asymmetry about the t=0 axis could indicate a clock error as the time for a wave to go from station A to B should be the same as a wave from B to A. This is called the reciprocity of the wave equation [9].

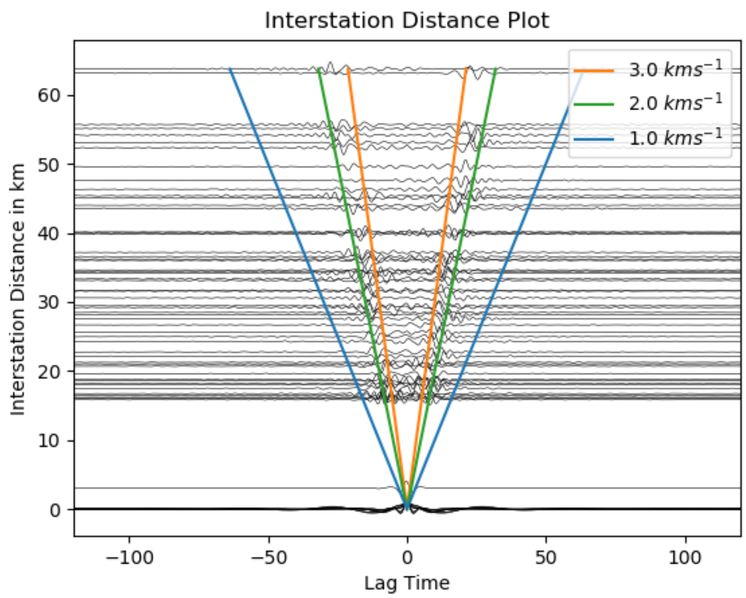

Figure 3: Plot of all interstation reference cross correlation functions against interstation distance

5 Impulse Response Validation

Figure 3 is a plot with each reference CCFs plotted against the distance between stations. This serves as proof that the seismic surface wave speed can be deduced from our CCF stacks. It is observed that the peak of the CCFs occurs between $2 - 3kms^{-1}$ for each of the stations, validating the CCF method for deducing interstation impulse responses.

6 Seismic Velocity Variation

6.1 Causes of Seismic Velocity Variation

Temporal Variation in the surface velocity between two stations can be the result of changes to the material properties between them. Precipitation has been attributed to these changes, where it was found that around the Merapi Volcano, periods of increasing seismic velocity were caused by falling groundwater levels [7]. In the event of an incoming volcanic event, an increase in seismic velocity may be observed with the rising magma creating pressure on the earth above, closing cracks and allowing energy to propagate faster between stations [11]. Earthquakes can result in stress changes in the earth, lowering the seismic velocity [11].

Apparent seismic velocity change can also be the result of a change in the source of ambient seismic noise. This differs the amount of energy travelling along a station path from the reference, creating a different impulse response, and a different seismic velocity reading. This effect can be minimised using a moving window reference, or increasing the stack length [6].

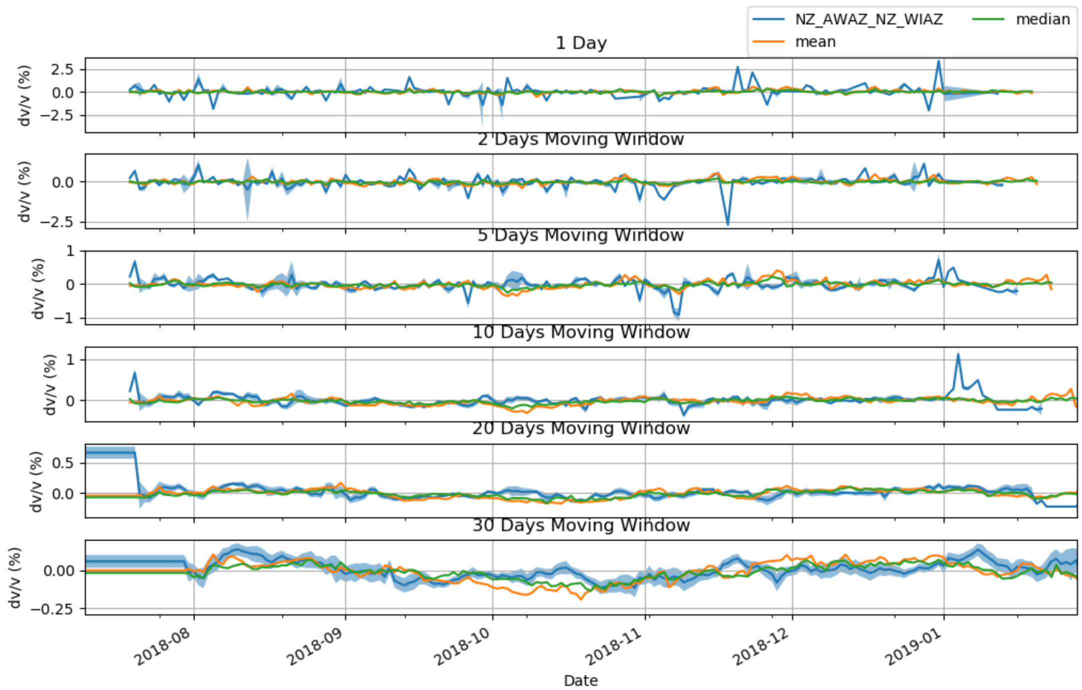

Figure 4: Seismic velocity change between station pairs in the Auckland Volcanic Field, using difference moving window/stack length, with AWAZ-WIAZ pair as an example of a single stations $\delta v/v$.

6.2 Method for Temporal Velocity Change Investigation

For the change in seismic velocity under the Auckland Volcanic Field to be determined, a reference must first be defined. In this investigation, each reference is the sum of all CCFs for a given station pair for the entire duration of the data archive. This sum of CCFs is known as a stack. This process removed any small fluctuations through destructive interference, leaving behind the impulse signal.

Once the reference is defined, data is stacked according to the window length required. In this investigation stacks were 1, 2, 5, 10, 20 & 30 days long. As stack length increases the resolution of the data and small variations is lost, and larger seasonal trends become more apparent. The change in seismic velocity, $\delta t/t$ is determined as the gradient of the delay against the lag time, calculated using weighted linear regression. The option of it the slope being forced through the origin is being user defined. Theoretically perfect data would go through the origin, however this method can be used to study clock errors [5]. In Figure 4, it appears that the 30 day stack has the largest error, however the y-axes of the plots are not the same, so the error of the single station is more or less consistent across the plots.The change in velocity, $\delta v/v$ can them be determined from the $\delta t/t$, where $\delta v/v = -\delta t/t$
[5].

Figure 4 is an example of a $\delta v/v$ graph for station pairs in the AVF. Seismic velocity changes are best observed as a mean, as the individual station lines can have great fluctuations between them, however once averaged out between station paths, this variance is reduced. This can be observed as the single station line for AWAZ-WIAZ is more variable than the mean or median line.

The impact of the moving window size is easily observable, with larger windows showing less fluctuations. The moving window for a given experiment depends on the time frame of the event you are trying to observe. Groundwater monitoring would be suited to a 10-day window length, whereas our study of the 2011 Rugby World Cup below uses a window length of 1 day as we hope to isolate the impact of the games to the days they occurred.

7 Example:Auto Correlation and the Rugby World Cup

Auto-correlation is the same process used to obtain CCF for station pairs except using data from the same station, effectively creating a zero-interstation distance CCF. The resulting impulse response is from a station back to itself. The auto correlation (AC) is aimed to observe reflections off impedance boundaries in the earth. The other use of AC is that by using only one station, the impact of local events and the seismic profile they create can be seen, as the magnitude of seismic noise from such events would not be sufficient penetrate the larger distance between stations.

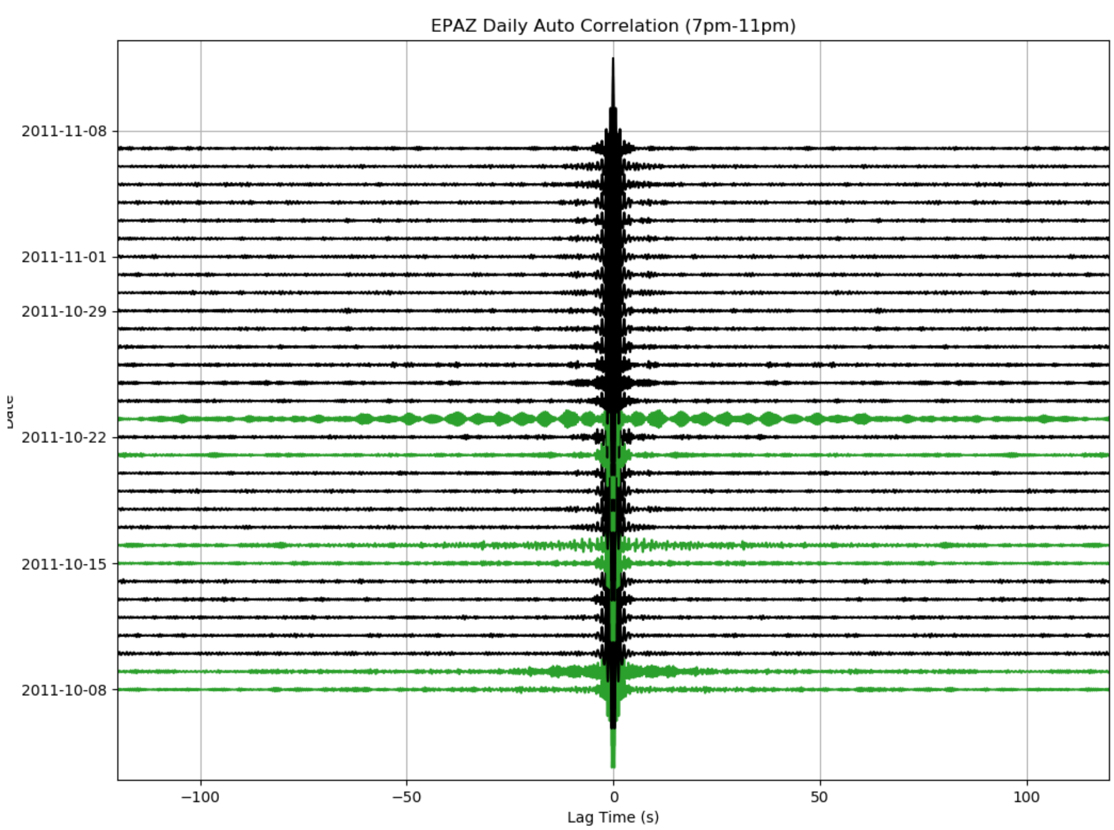

Figure 5: Auto Correlation from the Eden Park Station (EPAZ) from 07/10/2011 to 07/11/2011. The green lines represent nights where games were held.

Using data collected from 7-11pm around the dates of the Rugby World Cup Final (7 October

2011 to 7 November 2011) at Eden Park (EPAZ station), auto-correlations were created from 1-hour stacks. These were filtered between 1.0-2.0 Hz. Typically anthropogenic noise sources are observed between 1-35Hz[2], however this window was chosen based on AC frequencies observed in the Thesis of A.S Yates [11]. These ACs were then plotted over time to observe the influence of games on the impulse profile of Eden Park.

It can be seen that there is greater disturbance in the AC on game nights (shown in green in Figure 5) due to the extra people and traffic associated with a Rugby World Cup game.

8 Conclusion

Using MSNoise to process seismic data, an impulse response function can be obtained from cross correlations between stations in the Auckland Volcanic Field. The surface wave velocity can be accurately determined, and the changes tracked continuously, to provide insight into variations of the subsurface of Auckland. Typically, surface seismic waves travel between 2-3km per second along interstation paths, however this differs between station pairs depending on the material properties of the earth along station paths. Auto correlation has been shown to pick up local ambient noise seismic sources such as large anthropogenic events like the Rugby World Cup.

8.1 Future Work

Using MSNoise we have the framework to investigate the elastic propagation of the earth under Auckland. Future work can build on this to examine temporal changes in these properties. They are as follows:

- Investigating the correlation between seismic velocity changes and precipitation/ground water level [7] .
- Using Auto Correlations from stations with strong ambient noise signals to work out the depth of the Moho discontinuity beneath Auckland[10].
- Using cross correlation functions to locate the exact direction of the source of ambient ocean noise, and observe the changes over time [6].
- Investigating the impact of using a moving reference.
- Investigating the use of other components of the seismic signal, not just ZZ.

8.2 Acknowledgements

I would like to thank my supervisor Kasper, not only for the opportunity to explore the realm of geophysics, but for his guidance, knowledge and time spent helping me understand and enjoy this project. Thanks need to be given to Guy Casey for all his help setting up the VM and helping with the technical side of running MSNoise. Finally, I wish to acknowledge the community of the honours room for the endless support and entertainment.

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