APPLICATION OF SEISMIC INTERFEROMETRY TO BROADBAND AMBIENT NOISE RECORDINGS IN AND AROUND THE PHILIPPINES ISLANDS

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ABSTRACT

This study examines the possibility of ambient noise seismic interferometric applications to the Philippines, consisting of many large and small islands. We explored the use of conventional data processing methods and their effectiveness in generating dispersion measurements in the period from 5 s to 50 s. We used 10 months of data for 27 broadband seismic stations. The component rotation was also performed for the extraction of Rayleigh waves from body wave contaminated cross-correlation functions. Dispersion measurements were conducted, although there were still several challenges to the application of interferometry. Parameters such as signal-to-noise ratio, stack number, interstation distance, power spectral density plots and cross-correlation symmetry were analyzed in relation to the feasibility of obtaining dispersion measurements. The Rayleigh-wave phase velocities were stably estimated for selected station pairs in comparison to group velocities. The phase velocities were also obtained regardless of azimuth, indicating that the directional dependency of seismic ambient noise is small.

Keywords: ambient noise, interferometry, dispersion measurements, Rayleigh wave, the Philippines.

1.INTRODUCTION

The omnipresent signal present in seismograms known as seismic ambient noise is a superposition of body waves, surface waves, microseisms and micro tremors. Seismic interferometry is a popular tool aimed at extracting a deterministic information from ambient noise. The deterministic signal remains concealed within a superposition of body waves and surface waves. The pioneering work of Aki and Claerbout initiated the idea that the abundant ambient noise often seen in seismic records may hold valuable information. Claerbout (1968) later demonstrated it experimentally and proved theoretically through rigorous investigation and mathematical derivations. Several studies have been made in interferometry leading up to the first geophysical application by Campillo and Paul (2003), who provided details on how the impulse responses between receiver pairs are derived from cross-correlation of seismic coda waves.

Several assumptions need to be made for the results to hold. One of them, equipartition, generally means that energy arrives equally in all directions. If diffusivity exists within the earth it can create ideal conditions for equipartitioning. The diffusivity exists under conditions of multiple scattering and random distribution of uncorrelated noise sources. Wapenaar (2001) assumed that the earth structure is heterogeneous, lossless, and anisotropic medium to be able to retrieve elastodynamic Green's function. Based on these theories and considering that cross-correlation of ambient noise corresponds to an inter-station Green's function, we conduct seismic interferometry. Green's function between two receivers is retrieved from cross-correlation of the ambient noise field. Given the existence of complex geological phenomena in the Philippines, owing to its location in the ring of fire, it would be

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quintessential to study the crustal structure in and around the Philippine islands. Previous techniques in seismology focused on obtaining structural information based on earthquake activity or active source imaging. The method introduced in this paper however focuses on the use of ambient noise and the technique of seismic interferometry. Seismic interferometry was initially applied to a continental setting, but recent studies have shown successful examples in island nations such as Japan and New Zealand. This study will be the first application of seismic interferometry in Philippine islands. We will now assess the feasibility of obtaining dispersion measurements for the Philippines.

2.DATA

Broadband data used in this study has been maintained and monitored by the Philippine Institute of Volcanology and Seismology. Ten months of data from August 01, 2018 to May 31, 2019, recorded at 27 stations with availability greater than 80 percent was used. Data from Nanometrics Trillium 120 PA/QA and Trillium 240 sensors were utilized for the 10-month period. It was however challenging due to the satellite-telemetered seismic data being intermittent. This was resolved by inserting a zero-amplitude waveform after which the gaps became time jumps. And it was discovered that to keep variations in data processing results to a minimum, it is best to only use data with time jumps less than 25 s. Considering the sensor-to-sensor distances ranging from 31 km to 1,721 km, dispersion measurements are observed between 5 s and 50 s.

3.THEORY AND METHODOLOGY

The data processing goes through several phases following Bensen et al. (2007) and utilizes an in-house program for seismic interferometry (partially used in Hayashida et al., 2014). The first phase involves the removal of instrument response, de-meaning, de-trending, bandpass filtering, time-domain normalization, and frequency domain normalization. These steps encompassing single station data preparation are aimed at reducing the effect of earthquakes and instrument irregularities. Amongst the time domain normalization techniques, the running-absolute-mean normalization (Bensen et al., 2007) was selected since the technique is expected to reduce the effects from regional/far-field earthquakes and some former studies showed the cross-correlation functions with higher signal-to-noise ratios (SNRs). The running-absolute-mean-normalization is described by the formula

$$\widehat{\omega}_n = \frac{1}{2N+1}\sum_{j=n-N}^{n+N}\left|\widehat{d_j}\right| \qquad (1)$$

Where $\widehat{\omega}_n$ is the temporal weight for a bandpass filtered seismogram, $(2N+1)$ the width of the normalization window and $\widehat{d_j}$ the seismogram bandpass filtered in the earthquake band. Besides normalizing in the time domain, the spectral amplitudes of ambient noise is not flat in the frequency domain, so that we also need to perform frequency-domain normalization. The ambient noise spectrum peaks were seen at two frequency bands, which are the result of storms and interaction of ocean waves (the primary and secondary microseisms). The frequency domain normalization acts to reduce the effect of these microseisms. The results of both time and frequency domain normalizations at seismic station ABPP are shown in Figure 1(a) and (b).

Next we conducted cross-correlation analyses and stackings to extract approximate Green's functions between two stations. To speed up the process, the cross-correlation is performed in the frequency domain before returning the signal to the time domain. Also, to improve efficiency of computation (Lin et al., 2008), the cross-correlograms of the vertical (Z), north-south (N) and east-west (E) components are rotated to transverse (T) and radial (R) components. Since amplitudes of seismic ambient noise in the vertical wavefield is dominant in comparison to the horizontal components, the usage of vertical component gives better results when estimating Rayleigh waves. We conducted further isolation of Rayleigh waves by using the method described by Takagi et al., (2014). In considering P wave contamination in the derived cross-correlation functions we eliminated the body-wave contribution by subtracting ZR component from RZ component (here we call it ZRRZ component). Figure 2 shows the difference between ZZ and ZRRZ components. The waveforms in the ZRRZ component show noiseless traces in the middle indicating successful removal of P-waves.

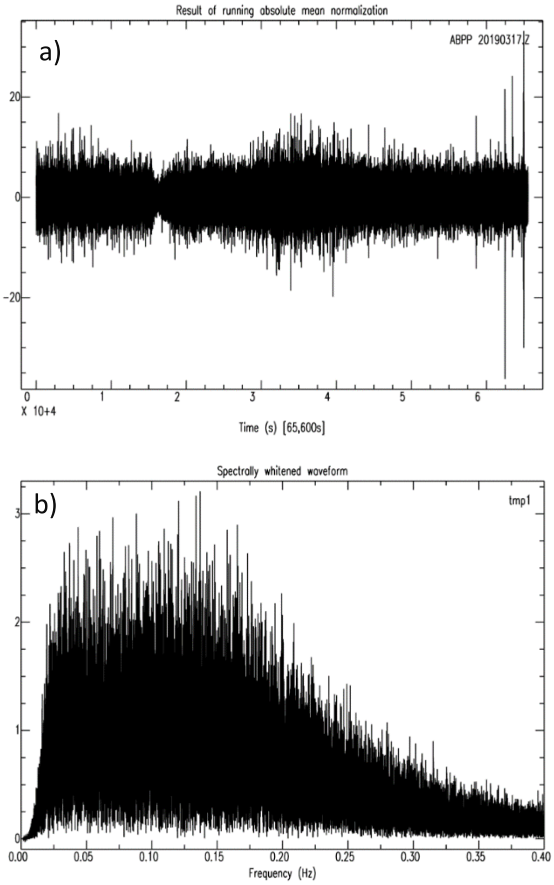

Figure 1. Examples of (a) running absolute mean normalization and (b) spectral whitening or frequency domain normalization at station ABPP. The effect from an earthquake (Ms 4.4, epicenter, on UTC March 17, 2019) was successfully removed.

A substantial assumption at this stage is the equivalence between cross-correlation function and Green's function. This equivalence has been proven theoretically in normal-mode summation, plane wave and representation theorem (Weaver and Lobkis, 2001). This assumption stands in the absence of weak scattering, high attenuation and heterogeneous noise source distribution. Heuristically, the Green's function may be retrieved from cross-correlations given that the azimuth from which the noise sources originate are in the end-fire lobe directions at 0° and 180° with respect to a particular station pair. The definition for Green's function used in this study is based on Lin et al. (2008) which states that Green's function is equivalent to the negative time derivative of the symmetric cross-correlation function as shown in Equation (2).

$$G_{AB}(t) = -\frac{d}{dt}\left[\frac{C_{AB}(t)+C_{AB}(-t)}{2}\right] \quad 0 \leq t < \infty \tag{2}$$

Estimated Green's function is now used to obtain dispersion measurements. Following Bracewell (1978), we define an analytic signal which is then used to obtain Equation (3)

$$s_{a(t)} = A(t)\exp(i\emptyset(t)) \tag{3}$$

Where $s_{a(t)}$ is the analytical signal, $A(t)$ is the envelope function and $\emptyset(t)$ is the phase function. Dispersion measurements are conducted using $A(t)$, which gives the group velocity, and $\emptyset(t)$, which gives the phase velocity. Here we used a program package provided by the University of Colorado Boulder (aftan1.1; http://ciei.colorado.edu/Products/) for automatic frequency-time analysis (AFTAN) of the cross-correlation functions. The AFTAN conducts both the conventional frequency-time analysis (FTAN; Levshin et al., 1972) and match filtered FTAN (Bensen et al. 2007) analyses, so we adopt the results from the match filtered FTAN analysis.

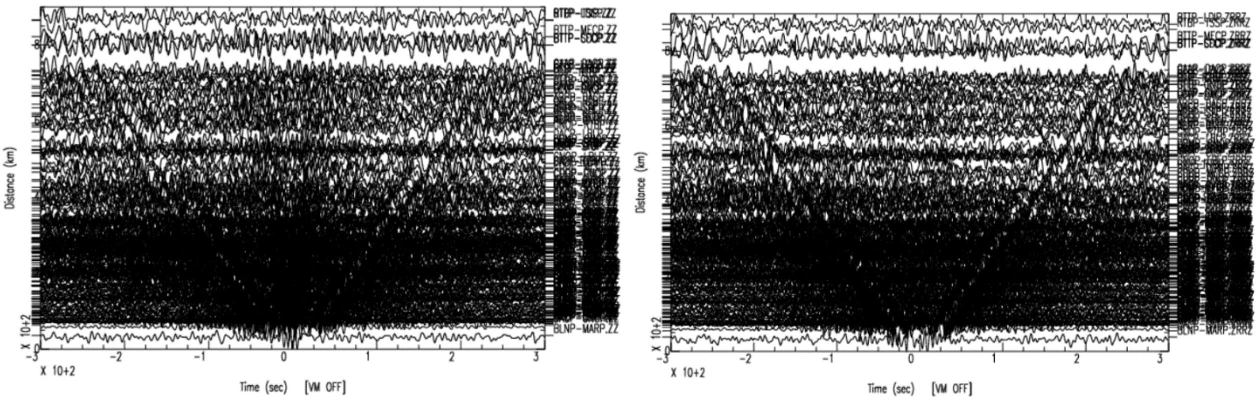

Figure 2. Removal of P wave contamination still visible in ZZ component cross-correlogram (left) in comparison with ZRRZ component cross correlogram (right).

Station performance and SNR are important parameters for quality control. We found that SNR decrease with interstation distance and increase with stack number. Stations with erroneous PSD plots and showing no clear cross-correlation result were removed from consideration.

4.RESULTS AND DISCUSSION

To assess the feasibility of seismic interferometric applications, we looked into whether Rayleigh or Love waves would result in high signal-to-noise ratio. In comparing cross-correlation functions in the ZRRZ (for Rayleigh waves) and TT (for Love waves) components, it is discovered that there are more station pairs with high signal-to-noise ratio for Rayleigh than Love waves. Comparing the cross-correlation functions and single-station power spectral density (PSD) plots revealed that asymmetric cross correlograms were obtained when the PSD levels of the two stations are similar to each other. This can be an indication of the existence of very local noise sources (Lin et al., 2006) at certain stations, which cause the higher levels of PSD plot levels and yield asymmetric cross correlograms. A stark difference can be seen in the SNR between station pairs from which dispersion curves could be obtained as compared to those with no dispersion measurements.

After rigorous data processing and SNR-based quality evaluations, dispersion measurements were finally obtained with a final consideration being that the wavelengths need to be less than one-third of the inter-station distance (Bensen et al., 2007). Figure 4 shows the derived dispersion curves in the ZRRZ component for 353 station pairs. Comparing station pairs that have the similar propagation path show similar dispersion curves, demonstrating little variation in directional dependency with change in azimuth (Figure 5). We also found the regional pattern of the derived dispersion curves, possibly indicating the difference of the crustal thickness (Figure 6).

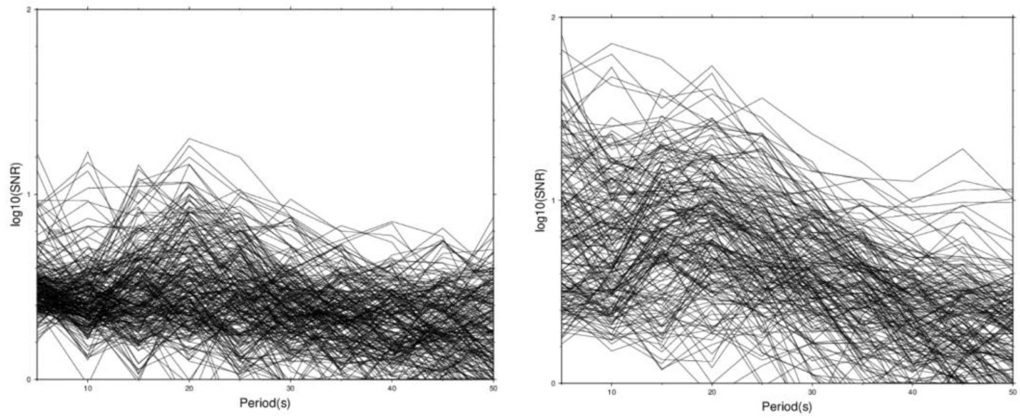

Figure 3. Comparison of SNR for station pairs with dispersion curves (left) and without (right).

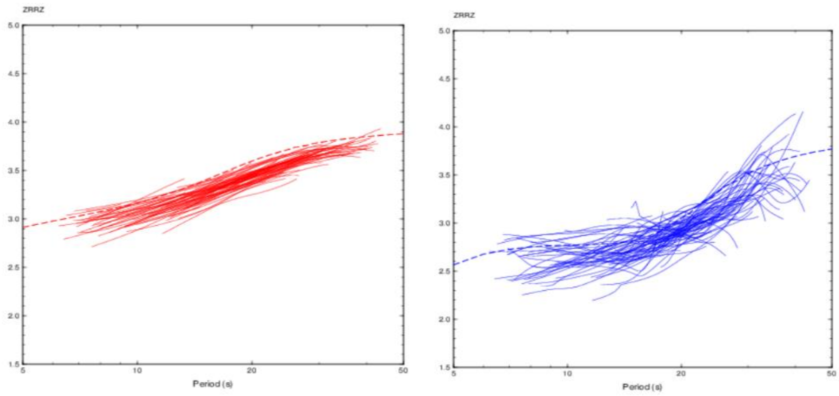

Figure 4. Dispersion curves for phase velocities (red) and group velocities (blue).

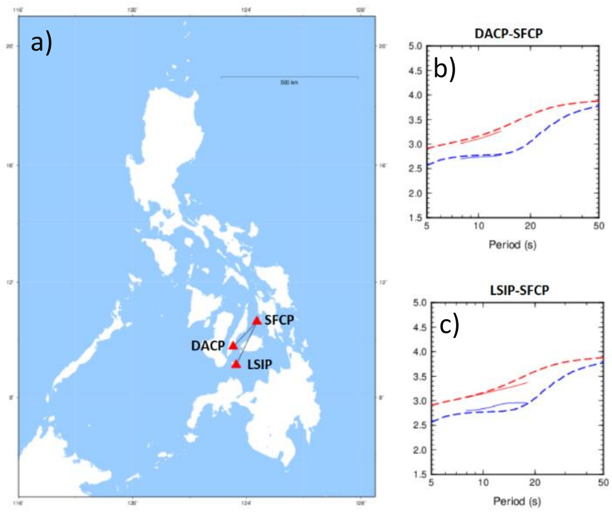

Figure 5. Station pairs demonstrate that directional dependency of ambient noise is small with change in azimuth. The map (a) shows station location and path while the plots (b) and (c) are dispersion measurements for phase and group velocity.

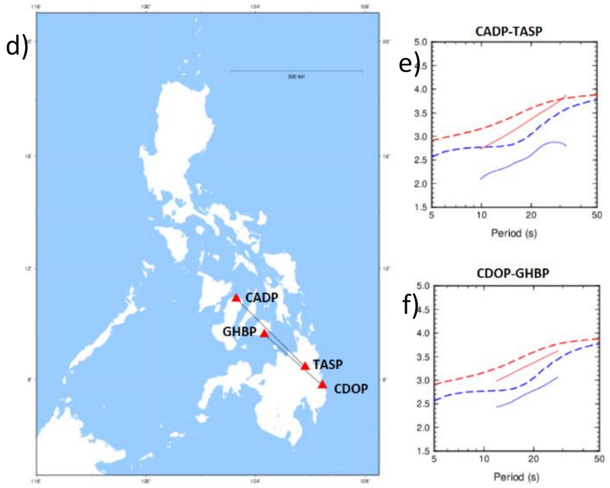

Figure 6. Station pairs parallel to each other show a possible region of thin crust. The map (d) show station location and path while the plots (e) and (f) are dispersion measurements for phase and group velocity.

5.CONCLUSION

Conventional ambient noise data processing techniques effectively overcame challenges for data gaps, contamination by earthquake signals and microseism peaks in the spectral domain. After resolving these problems dispersion measurements could be obtained for the Philippine islands. Although it must be said that ambient noise interferometry requires an increase in both the quality and quantity of data.

6.RECOMMENDATION

Increased period of observation increases signal-to-noise ratio and time jumps less than 25 s results in the inclusion of more data. The dispersion measurements can therefore significantly improve with a longer period of observation data and less intermittent signal. With these improvements the emergence of Love wave dispersion measurements may also increase in feasibility.

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