

IMPROVED REGIONAL SEISMIC EVENT DEPTH ESTIMATION

Anca C. Rosca

Weston Geophysical Corporation

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ABSTRACT

The primary objective of this research is to improve the accuracy of regional seismic depth estimation, which is essential to enhance national nuclear test monitoring capabilities. While the cepstral F-statistic, and other depth estimation techniques, have proved effective at teleseismic distances, regional depth estimation is still problematic. However, identifying regional secondary phases is necessary to accurately calculate the depth of small ($3 < m_b < 4$) events recorded by only a few stations. To develop a reliable tool for depth phase detection and screening of small events recorded at regional arrays and sparse networks we test a preprocessing technique based on wavelet analysis and moveout corrections. The wavelet filtering method we propose, similar to de-noising, preserves and enhances the most prominent features from the waveform. With this method, it is possible to remove noise with little loss of details. We test thresholding criteria that preserve only a few large coefficients from the wavelet decomposition and enhance depth phase related features. Our test events show that the apparent velocity of the depth phase can differ significantly from the first arrival. We investigate an array of techniques to determine lag-times between phases. Applying moveout corrections enhances depth phase arrivals providing a better input for the depth estimation procedure. The processed waveforms are then input into a depth phase estimation algorithm, such as the cepstral F-statistic technique. This method improves the performance of regional depth estimation for our test events.

OBJECTIVE

Identifying regional secondary phases is critically important to accurately calculate the depth of small ($3 < m_b < 4$) events recorded by only a few stations. While the cepstral F-statistic, and other depth estimation techniques, have proved effective at teleseismic distances, regional depth estimation is still problematic. To continue our effort for improved depth estimation at regional distances we are developing a preprocessing technique based on wavelet analysis and moveout corrections. The preprocessed waveforms will be input into a depth phase estimation algorithm, such as the cepstral F-statistic technique. The preprocessing method we propose will improve the performance of regional depth estimation procedures.

RESEARCH ACCOMPLISHED

The starting date for this contract, in late July is after the paper submission date. Since research has not yet begun, we will review the motivation for this project.

Introduction

At regional distances depth phases are difficult to detect and identify in the complex coda of the first arrival. Over the past several years Weston Geophysical has been developing procedures that improved detection and identification of secondary phases. The cepstral F-statistic analysis method (Reiter and Shumway, 1999; Bonner *et al.*, 2000) was successfully used to detect depth phases from teleseismic recordings, but the results were mixed when the method was applied to regional events. At regional distances improper classification of cepstral F-statistic peaks sometimes results in depth miscalculations. This has led us to further investigate preprocessing methods that might enhance the success of the cepstral F-statistic depth phase detection method, specifically for regional arrays and sparse networks.

Technical Approach

Accurate determination of the focal depth of seismic events continues to be one of the most important monitoring problems. If the event hypocenter can be confidently found to be more than a few kilometers beneath the surface, the event can be ruled out as a nuclear explosion. Currently available techniques are not always robust, especially at regional distances. Using depth phase arrivals (*pP* and *sP*) becomes critically important to obtain precise locations for small events recorded by few stations (Reiter *et al.*, 2002).

Depth phases can be difficult to detect in seismic data due to path effects, focal mechanism and coda complexity. At regional distances, depth phases of interest are sometimes obscured by a multitude of arrivals. Furthermore, since *pPn* arrives with a different apparent velocity compared to the first arrival, the amplitude of this phase does not benefit from stacking. To compensate for these problems we propose a three-step procedure. First we use a wavelet analysis technique to enhance the important features in the waveforms, secondly we apply moveout corrections to better stack depth phases, and thirdly the resulting signal is input into the cepstral depth estimation method. The wavelet processing method we use, a version of the denoising procedure, preserves and enhances depth phase related features from the waveform. We will evaluate a cross-correlation technique to estimate moveout corrections for depth phases. The cepstral F-statistic method is our favored method for depth estimation, but we will evaluate other approaches as well (e.g., Murphy *et al.*, 1999). The three steps outlined above - wavelet filtering, moveout corrections, and phase detection - are discussed below.

Wavelet Processing

We investigate the use of wavelet analysis to isolate depth phases in the P coda of regional array signals. This category of signal processing tools has been proved to be effective in seismic waveform processing (e.g., Anant and Dowla, 1997; Bear and Pavlis, 1999). A wavelet analysis technique that has proven very successful in other fields, such as image processing, is wavelet de-noising (Strang and Nguyen, 1996). We investigate its potential as a waveform preprocessing tool to aid in seismic depth phase detection. Wavelet de-noising is accomplished by calculating the Discrete Wavelet Transform (DWT) of a signal and then thresholding the resultant wavelet coefficients. To evaluate this technique, we analyzed ILAR waveforms for an event with a 31.8 km depth reported by the Alaska Earthquake Information Center (AEIC). The test thresholding criteria preserve only a few large coefficients from the wavelet decomposition details with most energy and the reconstructed waveform shows only a few prominent features most likely corresponding to phase arrivals (Figure 1).

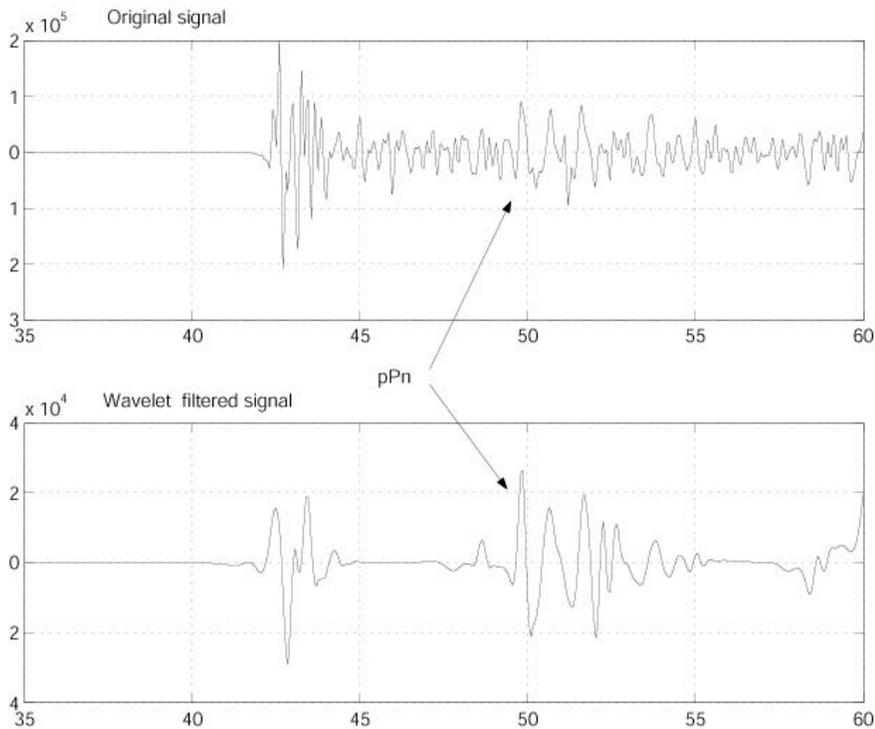


Figure 1. Waveform reconstructed from the most important wavelet coefficients compared to the original seismogram.

The reconstructed signal has properties that facilitate further processing. First, signal amplitude between phase arrivals is very low. This would allow us to “stretch” the seismogram for moveout correction by cutting and shifting a portion corresponding to the depth phase and inserting zeros for the missing values. Compared to time scale contraction (Woodgold, 1999) this procedure preserves the frequency content for each arrival. We will investigate if preserving the frequency content can aid with depth phase detection. Secondly, the consistency between peaks at different scales in the wavelet decomposition is an indication that a seismic phase is present. The most prominent features, those extracted for waveform reconstruction, are seen at multiple scales and correspond to phase arrivals. We will examine the use of this important characteristic of the wavelet decomposition method to select features based on a statistical evaluation of wavelet coefficients rather than the cepstral method. Thirdly, an analysis of the series of decomposition coefficients reveals that the frequency content of the first arrival, compared to later arrivals, is quite different for this event. Since the shapes of the various arrivals differ, cross-correlation would likely perform poorly on the original waveform but will work better with the wavelet-processed signal. We will investigate using cross-correlation of the wavelet-processed waveforms for lag time estimation.

Moveout Corrections

Theoretical IASPEI91 times calculated for the Pn and pPn phases across the 20 km array for this event, using the AEIC-reported depth, show differences in the individual element $pPn-Pn$ lag times, leading to poor stacking of the depth phase. Such variation could explain why the cepstral F-statistic method developed for teleseismic distances can fail in its present form for regional cases in which the secondary arrivals of interest do not align. Applying moveout corrections may be a key component to improving the success of depth phase estimation methods such as the cepstral F statistic.

Lag time differences between the first arrival and the depth phase calculated from the array processing parameters in our test are on the order of 0.2 s. Correcting such differences may enhance the depth phases considerably, since it has been demonstrated that removing residuals as small as 0.02 s for local events (Bear and Pavlis, 1999) significantly improves the stack of the data for the first arrival. We will evaluate the range of moveout corrections

for regional distances and various array configurations. We will also investigate using the cross-correlation of wavelet coefficients or wavelet-processed waveforms to calculate these parameters. When the apparent velocity of the depth phase differs significantly from the first arrival, applying moveout corrections will enhance depth phase arrivals providing a better input for the depth estimation technique.

The Depth Phase Detector

We will first evaluate applying the cepstral F-statistic method for depth estimation (Reiter and Shumway, 1999; Bonner *et al.*, 2000). This technique showed promising results at teleseismic distances, and we will evaluate its potential when used with the corrected regional waveforms. The cepstral F statistic attaches a statistical significance to peaks in the cepstrum through a signal-to-noise ratio computed from the beam cepstrum and the sum-stacked cepstrum. We estimate the cepstra from windows of data that contain the P arrival and its coda. The F-statistic is then formed by dividing the beam (mean) cepstrum by the error between the beam and the sum-stacked cepstra. Peaks associated with potential depth phase delay times appear in both the beam cepstrum and the F-statistic estimate. The three delay peaks with the highest confidence above a certain significance level are converted to candidate event depths using the IASPEI91 model. Multiple stations and arrays are then stacked to isolate the best network depth estimate. In addition to the cepstral F-statistic technique, we will test other methods, for example the network beamforming technique (Murphy *et al.*, 1999), as possible candidates for extracting the depth phases from the preprocessed waveforms. We will develop a rigorous statistical framework to compare the success rate for each depth detector and determine the improvement after applying the proposed waveform preprocessing technique.

CONCLUSIONS AND RECOMMENDATIONS

Since this research will be funded starting in late July, no conclusions have yet been reached.

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REFERENCES

- Anant, K. S. and F. U. Dowla, (1997), Wavelet transform methods for phase identification in three-component seismograms, *Bull. Seis. Soc. Am.*, **87**, 1598-1612
- Bear L. K. and G. L. Pavlis, (1999), Multi-channel Estimation of Time Residuals from Broadband Seismic Data Using Multi-wavelets, *Bull. Seis. Soc. Am.*, **89**, 681-692.
- Bonner, J.L., D.T. Reiter, R.H. Shumway, (2002), Application of a cepstral F statistic for improved depth estimation, *Bull. Seis. Soc. Am.*, **95**, 1675-1693.
- Murphy J.R., R. W. Cook, and W.L. Rodi, (1999), Improved focal depth determination for use in CTBT monitoring, *Proceedings of the 21st Seismic Research Review: Technologies for Monitoring the Comprehensive Nuclear-Test-Ban Treaty*, Los Alamos National Laboratory, LA-UR-99-4700, **50-55**.
- Reiter D. T., and R. H. Shumway, (1999), Improved seismic event depth estimation using cepstral analysis, *Proceedings of the 21st Seismic Research Review: Technologies for Monitoring the Comprehensive Nuclear-Test-Ban Treaty*, Los Alamos National Laboratory, LA-UR-99-4700, **599-606**.
- Reiter, D., J. Bonner, C. Vincent, and J. Britton, (2002), Incorporating secondary phases in 3D regional seismic event location: Application to the sparse network problem, *Proceedings of the 24th Annual Seismic Research Review: Nuclear Explosion Monitoring: Innovation and Integration*, Los Alamos National Laboratory, LA-UR-02-5048, Vol. I, **375-384**.
- Woodgold, C.R.D., (1999), Wide-aperture beamforming of depth phases by timescale contraction, *Bull. Seis. Soc. Am.*, **89**, 165-177.