High-resolution separation of earthquake phases using sparsity-promoting polarization filtering method

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ABSTRACT

The extraction of body waves from seismic wave fields has always been a significant interest in the seismological community. Their study provides a picture of the Earth's crust, upper mantle, and critical continuities such as the Moho Transition Zone (e.g., 410 km and 660 km depth). In addition, it provides information for determining the source mechanism of earthquakes. However, due to their intrinsic weaker amplitude than other seismic waves, they are usually masked by surface waves. Their detection and extraction require advanced analysis and processing tools and methods. This study uses the sparsity-promoting polarization filter method to extract body waves from earthquake waveforms, exploiting their polarization properties in the time-frequency (TF) domain. The computed rectilinearity, directivity, and amplitude attributes calculated from the TF-domain polarization map of earthquake signals are used to discriminate between body and surface waves. Synthetic data examples show the performance of the proposed earthquake phase separation method.

Keywords: body wave, adaptive time-frequency filtering, earthquake waveform, polarization analysis, sparsity promoting.

INTRODUCTION

Body waves provide specific information about the earth's structure along their propagation paths in deep earth layers (Dahlen & Baig, 2002). In contrast, the Surface waves propagate along the surface, and the depth sensitivity follows the exponential decay of their amplitudes as an evanescent wave (Zhou et al.,2004). Therefore body waves can be more sensitive than surface waves to more refined structures in the deeper part (Nakata & Nishida, 2019). Despite a significant number of studies on surface wave extraction, few studies have focused on retrieving and examining body waves from records of continuous ground motion for imaging and monitoring underground structures.

Different studies showed that body-wave extraction from noise correlations is possible at various scales (Roux et al., 2005; Draganov et al., 2007; Zhan et al., 2010; Poli et al., 2011; Ryberg, 2011; Takagi et al.; 2014)(Tonegawa et al., 2021). Nakata et al. (2015) implemented the first passive 3-D P-wave velocity tomography from continuous ground motion recorded on a dense array of more than 2500 seismic sensors installed at Long Beach (CA, USA). Also, Taylor et al. (2016) have shown that extracting images of body wave reflections is possible by constructing stacked autocorrelograms of ambient seismic noise. Recently, to extract body waves from simulated passive signals, Hariri Naghadeh et al. (2021) proposed and tested a Radon correlation method. Their synthetic tests show that the introduced method can reconstruct reflection events at the correct time-offset positions hidden in results obtained by the general cross-correlation method.

Moreover, multicomponent processing techniques have been developed to analyze the nonlinear and time-varying processes behind the seismic sources and the propagating environment. Among these techniques, polarization analysis methods have attracted significant attention. The polarization analysis methods can be divided into three broad categories: time, frequency, and time-frequency (TF) domain methods (Mohammadigheymasi et al., 2021). In this study, due to the non-stationary nature of earthquake data, we use polarization analysis in the time-frequency domain. Our goal in this article is to separate body waves from other phases of an earthquake, but the milestone is the resolution of this extraction. Since the resolution is insufficient to discriminate between overlapping seismic phases, we benefit from sparsity-promoting time-frequency representation (SP-TFR) to obtain a high-resolution TFR.

METHODOLOGY

Suppose that $\boldsymbol{H} = [\boldsymbol{h}_1, \boldsymbol{h}_2, \boldsymbol{h}_3] \in R^{L\times 3}$ is a three-component time series (Transverse-Radial-Vertical) that records a waveform generated by an earthquake.

L is the number of samples during the time. Assuming a weakly stationary condition (the assumption is valid by applying DC-removal or detrending), the TF-domain polarization properties of H are calculated. The TF-domain spectrum of three components is obtained by applying ST and STFT. According to this equation, we calculate the correlation coefficients in the time-frequency domain, which leads to the polarization parameters in the time-frequency domain.

$$(\widehat{\boldsymbol{S}}(k.l) - \lambda_i(k.l)I)\boldsymbol{u}(k.l) = 0 \quad (1)$$

Polarization parameters are eigenvectors $(\lambda_1.\lambda_2.\lambda_3)$ that give direct principal axes of the polarization motion ellipsoid, and the eigenvalues $(\boldsymbol{u}_1.\boldsymbol{u}_2.\boldsymbol{u}_3)$ are the size of those axes. $\boldsymbol{S}$ is correlation matrix and k, l are time and frequency indexes, respectively. In the next stage we corporate sparsity promoting.

Linearity of the system of equations for STFT and ST allows us to define the TF coefficients Since the linear system is under-determined, as a solution of a linear system equation as $\boldsymbol{h} = \boldsymbol{C\alpha}$. there are infinitely many TF maps to represent the signal. The desired TF-map can be obtained using the regularization technique.

$$\boldsymbol{\alpha} = arg\min_{\boldsymbol{\alpha}} \frac{1}{2}\|\boldsymbol{C\alpha} - \boldsymbol{h}\|_2^2 + \mu\|\boldsymbol{\alpha}\|_1 \quad (2)$$

μ, controls the resolution of the TF map. The last step is to apply adaptive filtering to extract the desired phase. For this purpose, we use three attributes: rectilinearity attribute that is a critical parameter for discriminating between the elliptical and linear particle motion states. Directivity is another crucial parameter to discriminate between different seismic phases based on the direction of particle motion, and amplitude attribute is based on amplitude difference between body and surface waves. Finally, the total TF reject filter to reject a phase is obtained by combining rectilinearity, directivity, and amplitude filters.

$$\varphi_R = 1 - \{1 - \varphi_{\Re}\} \circ \{1 - \varphi_D\} \circ \{1 - \varphi_A\} \quad (3)$$

That $\varphi_{\Re}$ is the filter defined for rectilinearity, φ_D is a filter for directivity and φ_A is a filter for amplitude attribute. Similarly, a special seismic phase can be extracted by defining an extract filter using the below equation.

$$\varphi_E = 1 - \varphi_R \quad (4)$$

NUMERICAL EXAMPLE

To assessment the efficiency of SP-TFF method, we implement it on synthetic data example to extract body waves. The source mechanism of this synthetic data corresponds to the source mechanism of the *Mw* = 7.0 earthquake occurred in the 21.8 km of Guerrero, Mexico on 2021.09.08, 01:47:43(UTC), as a result of revers dip-slip faulting. The 3-D synthetic seismic data are generated using the 1-Dak135f earth model with spectral-element method assuming 3-D (an) elastic, anisotropic wave propagation in the spherical domain. The simulation is performed using the AxiSem library through the IRIS synthetics engine client as ObsPy software. In the simulation, the seismic wavefield is recorded by the united stated national seismic network. The source and network geometry is shown in this figure.

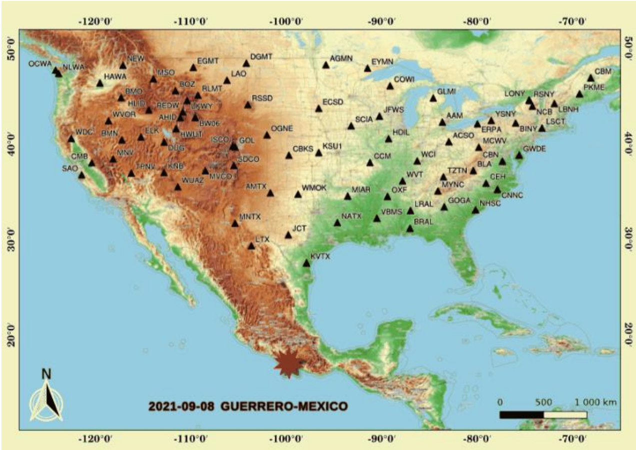

Figure 1. The source and network geometry of the *Mw* = 7.0 earthquake occurred in the 21.8 km of Guerrero, Mexico on 2021.09.08, 01:47:43(UTC).

The radial component of a three-component signal of this simulated earthquake is shown in fig.2 for example. As you can see, the filtered trace of rayleigh wave appropriately and accurately extracted from other phases of seismogram and what remains are the body waves.

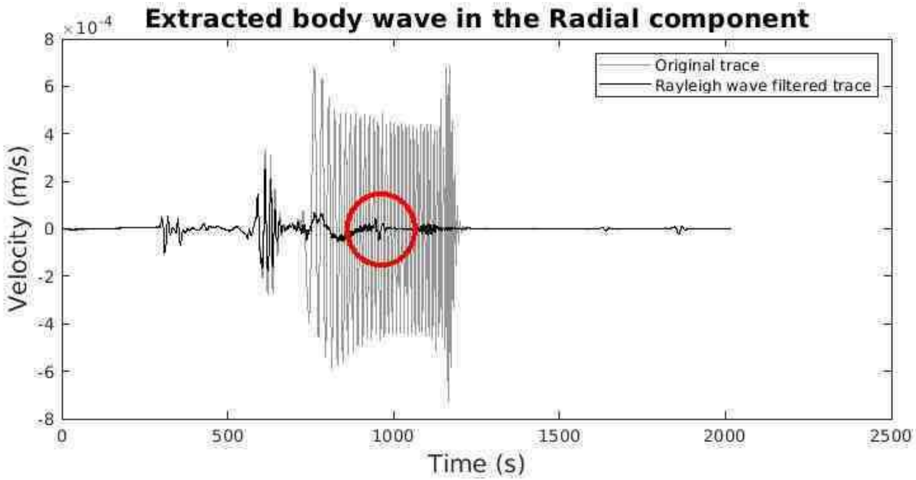

Figure 2. schematic representation of extracted body wave in the radial component of signal.

Fig.3 shows the filtered waveforms to extract body waves. The traces are plotted as a function of epicentral distance, and a linear move out were applied by 5.8km/s to a line the body waves.

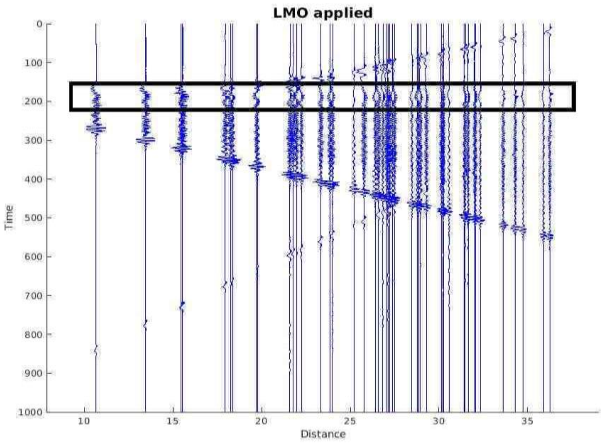

Figure 3. linear moveout were applied by 5.8km/s to align the body waves.

CONCLUSIONS

In this study, we demonstrated the performance of the SP-TFF method as a powerful processing tool to separate different phases of seismic waves by integrating TF-domain rectilinearity, directivity, and amplitude attributes. As a specific application, we have shown that the method is able to extract body waves masked by high amplitude surface waves. In addition, this method can be utilized for the high-resolution study of subsurface imaging. In the next phase of the study, we plan to process the noise correlation seismogram to extract body waves, a challenging problem in seismology.

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