POLARIZATION FILTER BASED ON LINEAR RADON TRANSFORM TO EXTRACT SURFACE WAVES IN 3C SEISMIC DATA

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Summary

Polarization filters can be used when multicomponent seismic data are available. These filters can separate surface waves and body waves by discriminating between elliptical versus linear particle motion. The most important advantage of the existing polarization filters is that they work in single-station. Therefore, they are an alternative when surface waves are aliased. However, in most cases, polarization filters do not get better results than f-k filters because they do not operate in multitrace, and there is no velocity discrimination. We present a new polarization filter to extract surface waves from multitrace 3C seismic data. The filter works in the frequency-slowness domain as a mask on elliptic elements obtained from the linear Radon model of the seismic data in the frequency domain. We applied this filter on a 3C real shot gather from land seismic data acquired in the Middle Magdalena Valley in Colombia. The result shows that this polarization filter can extract the surface waves accurately.

Introduction

In seismic exploration, surface waves extraction is an indispensable stage in the signal processing workflow. Surface waves, also named ground roll, are considered coherent noise that masks the information of body wave reflections from deeper structures. Predominantly, surface waves are composed of Rayleigh waves, which are elliptically polarized waves that propagate with lower frequency and velocity than reflected waves. All these characteristics can be used to design filters to extract surface waves in seismic shot gathers.

Filters in the $f-k$ domain are commonly used to separate surface waves and body wave reflections by exploiting their differences in frequency and wavenumber (Yilmaz, 2001). However, $f-k$ filters require regularly sampled data in time and space. But, this is not always the case for seismic exploration. One alternative to address this limitation is the linear Radon transform (LRT) in the frequency domain, which maps a model in the frequency-slowness space into the data space in the frequency-offset domain. LRT filters can accurately extract surface waves (Luo et al. 2009; Hu et al. 2016). Nevertheless, $f-k$ and LRT filters fail when the energy of surface and body waves overlap in frequency and velocity. In the case of multicomponent data, another alternative is using polarization filters to extract surface waves (Kendall et al. 2005; Pinnegar 2006; Sánchez-Galvis et al. 2016). The filters presented by these authors can separate elliptically and linear polarized in single-station, and multitrace information (such as velocity) is not used. We present a new polarization filter that extracts elliptically polarized events in the frequency-slowness domain. The filter works as a mask over elliptic elements obtained from the linear Radon model of the seismic data in the frequency domain. We applied the filter on a 3C shot gather from real seismic data acquired in the Middle Magdalena Valley in Colombia. The results show that the filter can extract the surface waves accurately, including backscattering.

Elliptical elements of 3C seismic data

3C seismic traces can be represented by $\mathbf{d}(t) = \{d_x(t), d_y(t), d_z(t)\}$, where $d_x(t)$, $d_y(t)$ and $d_z(t)$ are the radial, transverse and vertical data components, respectively. The 3C seismic trace can be also represented in the frequency domain by $\mathbf{d}(f) = \{d_x(f), d_y(f), d_z(f)\}$ via the Fourier transform of each single component. For any particular frequency f, the 3C seismic trace can be decomposed by elliptical elements in the three-dimensional space:

$$\mathbf{d}(f) = L(a(f), b(f), I(f), \Omega(f), \omega(f), \phi(f)) \tag{1}$$

where a is the semi-major axis of the ellipse, b is the semi-minor axis of the ellipse, I is the inclination angle, Ω is the longitude of ascending node, ω is the argument of pericentre, and ϕ the phase respect to the time of maximum displacement. The operator L is the relationship between the spectra of 3C seismic signal components and the spectra of elliptical elements. The forward and inverse expressions for this relationship are presented by Pinnegar (2006). For each shot gather, the 3C seismic data can be represented as a vectorial field $\mathbf{d}(t,x)$ in the time-space domain. After a temporal Fourier transformation, every single component of the 3C data can be mapped from the Radon model $m(f,p)$ in the frequency-slowness domain by using the forward LRT in the frequency domain as follows:

$$d(f,x) = \sum_{p=p_{\min}}^{p_{\max}} m(f,p)e^{i2\pi fpx} \tag{2}$$

where p is the slowness. The Radon model that best fits the data can be found by using an inversion scheme with sparsity constraint (Trad et al. 2003 Luo et al. 2009). The radon model for 3C data can be represented by $\mathbf{m}(f,p) = \{m_x(f,p), m_y(f,p), m_z(f,p)\}$ where m_x, m_y and m_z are the radon models for the radial, transverse and vertical data components, respectively. The elliptical elements can be now obtained in the frequency-slowness domain by substituting $\mathbf{m}(f,p)$ in place of $\mathbf{d}(f)$ in equation 1:

$$\mathbf{m}(f,p) = L(a(f,p), b(f,p), I(f,p), \Omega(f,p), \omega(f,p), \phi(f,p)) \tag{3}$$

Polarization Filter

The 3C seismic data $\mathbf{d}(t,x)$ can be expressed as a sum of surface waves $\mathbf{d}^{\mathrm{SW}}(t,x)$ and body waves $\mathbf{d}^{\mathrm{BW}}(t,x)$ events, where:

$$\mathbf{d}(t,x) = \mathbf{d}^{\mathrm{BW}}(t,x) + \mathbf{d}^{\mathrm{SW}}(t,x) \tag{4}$$

By applying frequency domain adjoint LRT in both sides, the equation 4 becomes:

$$\mathbf{m}(f,p) = \mathbf{m}^{\mathrm{BW}}(f,p) + \mathbf{m}^{\mathrm{SW}}(f,p) \tag{5}$$

where $\mathbf{m}^{\mathrm{BW}}(f,p)$ and $\mathbf{m}^{\mathrm{SW}}(f,p)$ are the Radon models of the surface waves and body waves in the 3C seismic data, respectively. The 3C surface waves radon model $\hat{\mathbf{m}}^{SW}(f,p)$ is estimated by applying a filter mask in the semi-major and semi-minor of the decomposition of the elliptical elements. By omitting the arguments (f,p), we have:

$$\hat{\mathbf{m}}^{SW} = L(aF, bF, I, \Omega, \omega, \phi) \tag{6}$$

where F is the filter mask in the frequency-slowness domain. The filter mask is defined as follows:

$$F(f,p) = \begin{cases} \tanh\left(\alpha \dfrac{b(f,p)}{b_{\max}}\right) & \text{if } |p| > p_{\mathrm{ref}} \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

where $b_{\max}$ is the maximum value of $b(f,p)$, the parameter p_{ref} is the minimum absolute slowness $|p|$ where the filter operates. This parameter can be set by using the relation $p_{\mathrm{ref}} = 1/v_{\max}$, where $v_{\max}$ is the maximum surface waves velocity. Finally, α is a positive parameter that controls the filter aggressiveness, for $\alpha \to \infty$ the filter acts as a velocity filter, and for $\alpha = 0$, none energy of surface waves is extracted. The extracted 3C surface waves $\hat{\mathbf{d}}^{SW}(t,x)$ are obtained by applying the forward LRT of $\hat{\mathbf{m}}^{SW}(f,p)$ and, subsequently applying the temporal inverse Fourier transform. Finally, the 3C body waves $\hat{\mathbf{d}}^{BW}(t,x)$ are obtained by the difference between the original data and the extracted surface waves.

$$\hat{\mathbf{d}}^{BW}(t,x) = \mathbf{d}(t,x) - \hat{\mathbf{d}}^{SW}(t,x) \tag{8}$$

Results

We applied the polarization filter on a 3C shot gather from real seismic data acquired in the Middle Magdalena Valley in Colombia. The original shot gathers for the vertical, radial, and transverse components are displayed in figures 2a, 3a and 4a, respectively. Figures 1a and 1b show the semi-major and semi-minor axis of elliptical elements in the frequency-slowness domain, respectively. The polarization filter mask is shown in figure 1c. For these seismic data, we set $\alpha = 4$ and $p_{\mathrm{ref}} = 1/1000$ s/m since the maximum surface wave velocity is 1000 m/s. The extracted surface and body waves for all the component are shown in Figures 2, 3, and 4. It is observed that the filter is able to extract the surface waves accurately, including the backscattering. It is also noticed that the body wave reflections are clearer than the original data. However, some artifacts appear in the direct waves region. These artifacts can be removed by applying a mute dip filter to the extracted surface waves.

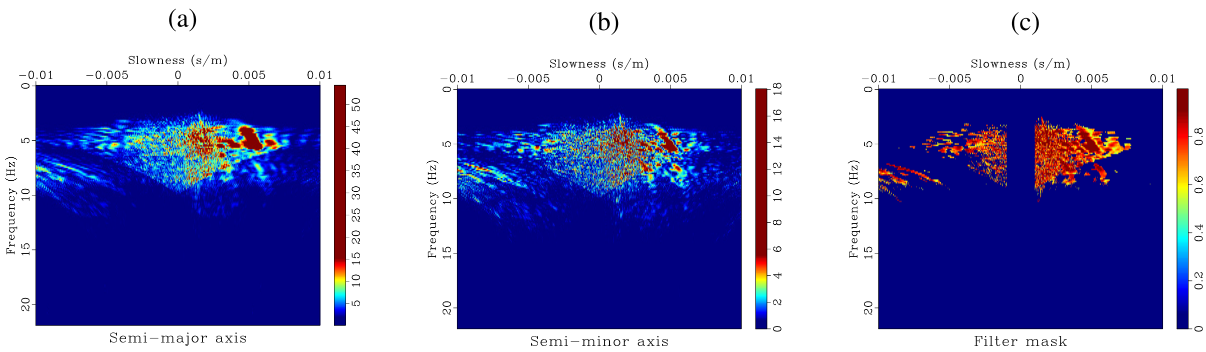

Figure 1: (a) Semi-major axis $a(f,p)$, (b) semi-minor axis $b(f,p)$, and (c) polarization filter mask $F(f,p)$ using $\alpha = 4$ and $p_{\text{ref}} = 1/1000$ s/m.

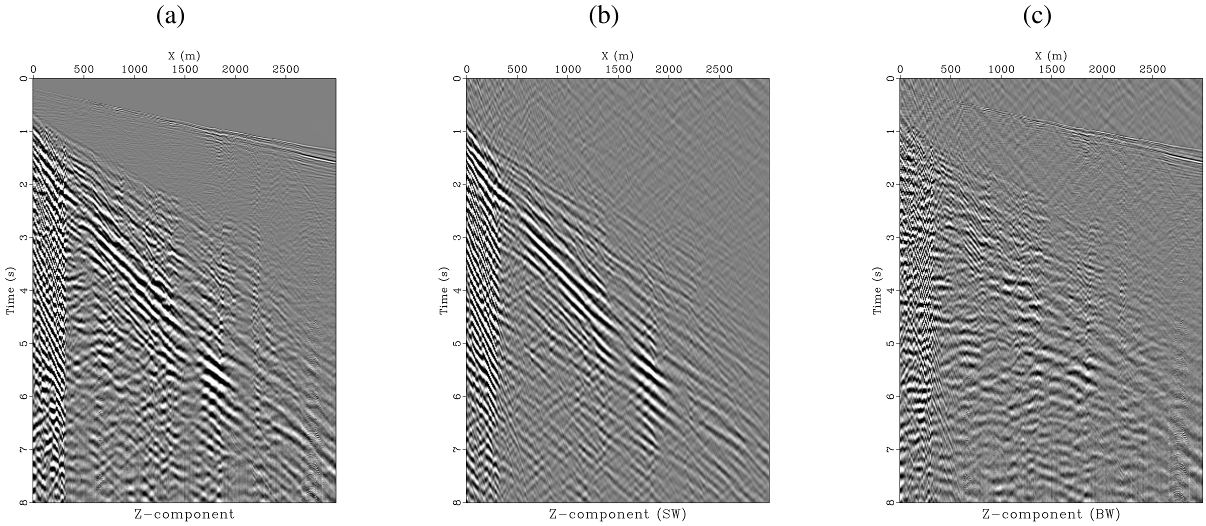

Figure 2: Vertical component shot gather. (a) Original data, (b) extracted surface waves, (c) extracted body waves (difference between (a) and (b)).

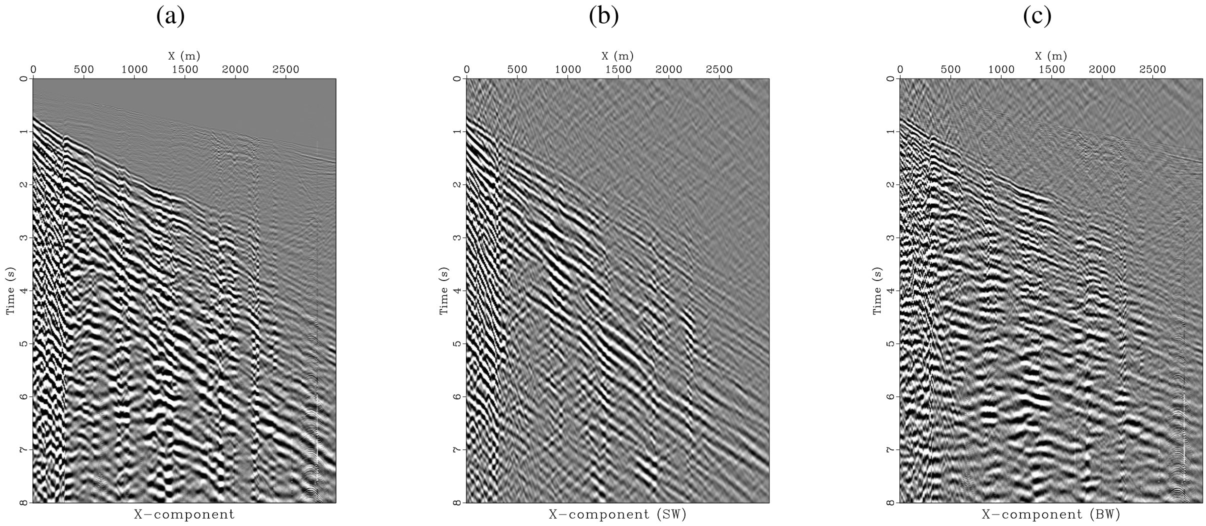

Figure 3: Radial component shot gather. (a) Original data, (b) extracted surface waves, (c) extracted body waves (difference between (a) and (b)).

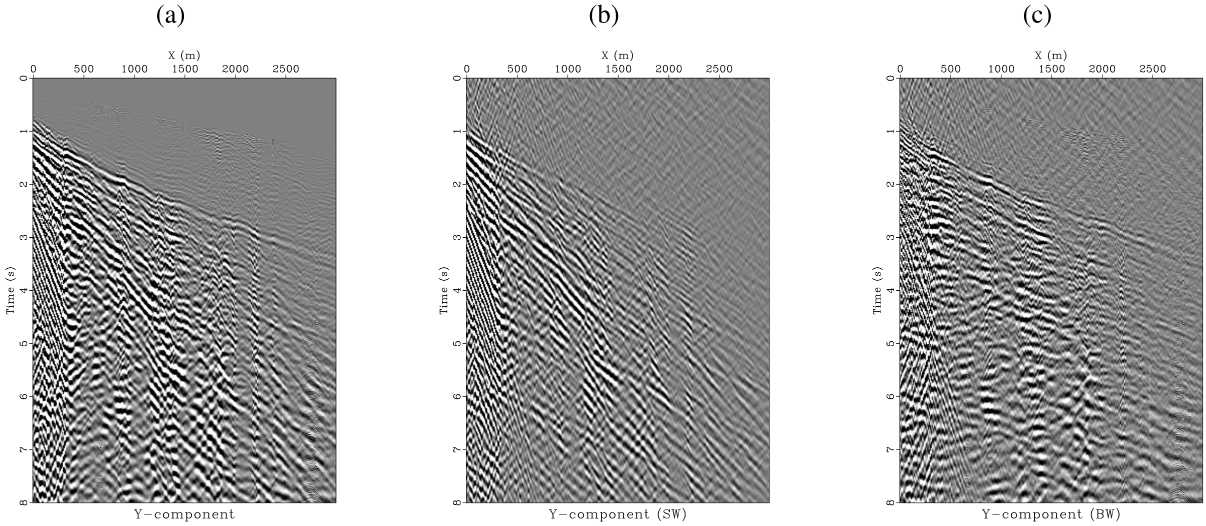

Figure 4: Transverse component shot gather. (a) Original data, (b) extracted surface waves, (c) extracted body waves (difference between (a) and (b)).

Conclusions

We have presented a polarization filter to extract surface waves from 3C seismic data. The filter operates in the frequency-slowness domain as a mask on elliptic elements obtained from the linear Radon model of the seismic data in the frequency domain. The result obtained with real data shows that this polarization filter can extract the surface waves and clean the body-waves reflections. In this work, we only used the semi-minor axis to design the filter mask. However, additional elliptical elements can be included in tailored filters for different events, for instance, events with a specific incidence angle such as scattered surface waves.

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