Application of high-resolution linear Radon transform for Rayleigh-wave dispersive energy imaging and mode separating

Yinhe Luo¹, Jianghai Xia¹, Richard D. Miller², Jiangping Liu¹, Yixian Xu¹, and Qingsheng Liu¹
¹. Institute of Geophysics and Geomatics, China University of Geosciences
². Kansas Geological Survey, the University of Kansas

Summary

Multichannel Analysis of Surface Waves (MASW) analysis is an efficient tool to obtain the vertical shear-wave profile. One of the key steps in the MASW method is to generate an image of dispersive energy in the frequency-velocity domain, so dispersion curves can be determined by picking peaks of dispersion energy. In this paper, we image Rayleigh-wave dispersive energy and separate multimodes from a multichannel record by high-resolution linear Radon transform (LRT). We first introduce Rayleigh-wave dispersive energy imaging by high-resolution LRT. We then show the process of Rayleigh-wave mode separation. Results of synthetic and real-world examples demonstrate that (1) compared with slant stacking algorithm, high-resolution LRT can improve the resolution of images of dispersion energy by more than 50%; (2) high-resolution LRT can successfully separate multimode dispersive energy of Rayleigh waves with high resolution; and (3) multimode separation and reconstruction expand frequency ranges of higher mode dispersive energy, which not only increases the investigation depth but also provides a means to accurately determine cut-off frequencies.

Introduction

In the Multichannel Analysis of Surface Waves (MASW) method, generating a reliable image of dispersion energy in the frequency-velocity (f-v) domain is a key step. Imaging high-resolution dispersion energy, however, is a difficult task for current available four algorithms in calculating image of high-frequency dispersion energy: the F-K transformation (e.g., Yilmaz, 1987), the Tau-p transform (McMechan and Yedlin, 1981), the phase shift (Park et al., 1998), and slant stacking algorithm (Xia et al., 2007). Those four algorithms are kinds of standard discretized linear Radon transform (LRT). Because standard LRT suffers from typical problems of loss of resolution and aliasing that arise as consequence of incomplete information, including limited aperture and discretization (Trad et al., 2003), achieving a high resolution dispersion image with a standard LRT is difficult.

An appealing alternative solution to efficiently image dispersive energy can be obtained by high-resolution LRT (Sacchi and Ulrych, 1995; Trad et al., 2002 and 2003; Ethan and Matthias, 2006; Luo et al., 2008, In review). In this paper, we image Rayleigh-wave dispersive energy and separate multimodes from a multichannel record by high-resolution linear Radon transform (LRT). We first introduce Rayleigh-wave dispersive energy imaging by high-resolution LRT. We then show the process of Rayleigh-wave mode separation. Results of synthetic and real-world data demonstrate the effectiveness of using high-resolution LRT to image higher-resolution dispersion energy and separate multi-mode Rayleigh waves.

Rayleigh-wave dispersive energy imaging

Imaging dispersive energy by high-resolution LRT is straightforward (Luo et al., in press). First, the shot gather is transformed along time into the frequency domain. Then the high-resolution LRT is completed for each frequency slice and the Radon panel is transformed from the frequency-slowness domain to the frequency-velocity domain using a linear interpolation operation.

A synthetic shot gather (the vertical component, Figure 1a) based on a two-layer model was generated using a finite-difference method (Xu et al., 2007). The model consists of a 10 m thick surface layer with Vp = 800 m/s, Vs = 200 m/s, and ρ=2000 kg/m³, over the half-space where Vp=1200 m/s, Vs= 400 m/s, and ρ=2000 kg/m³. Dispersive Rayleigh-wave energy is clearly modeled in the synthetic 60-channel shot gather (Figure 1a). The nearest offset trace in the shot gather is 1 m with a subsequent 1-m receiver interval. The shot gather is transformed along the time direction to the frequency domain and set the slowness p range from 0 s/m to 0.01 s/m with 0.0001 s/m interval (101 slowness points). We obtained the image in the f-v domain by high-resolution LRT (Figure 1b).
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Rayleigh-wave energy is dominant in the image (Figure 1b). We use the analytical results (solid dots, Figure 1b) calculated by the Knopoff method (Schwab and Knopoff, 1972) to assess the accuracy of the image. The image indicates less than 5% difference phase velocity compared with the analytical results. Possible reasons include near-field effects (e.g., non-plane wave propagation and body-wave energy) and artifacts of the finite-difference approximation (Xu et al., 2007).

Figure 1. (a) Synthetic vertical-component data due to a two-layer model. (b) An image of dispersive energy in the f-v domain generated by high-resolution LRT. (c) An image of dispersive energy in the f-v domain generated by the slant stacking algorithm (Xia et al., 2007). Solid dots were analytical results calculated by the Knopoff method (Schwab and Knopoff, 1972).

We used the slant stacking method (Xia et al., 2007) to generate a dispersion image (Figure 1c) for comparison with the high-resolution LRT results (Figure 1b). We notice that (1) the image of dispersion energy generated by high-resolution LRT possesses much higher resolution. Lengths of double-end lines at frequencies 20, 24, and 36 Hz at different modes are the distance between half of the maximum value of dispersion energy in Figure 1c. The same double-end lines are superposed in Figure 1b. It is obvious that the double-end line almost spans one length longer than the half-value in Figure 1b. We may conclude that the resolution increases more than 100% by high-resolution LRT; (2) Because the image of dispersive energy in the low-frequency range possesses lower resolution is an intrinsic property (Forbriger, 2003), high-resolution LRT improves the resolution more than 200% in the frequency range lower than 20Hz; and (3) Dispersion energy of different modes generated by the high-resolution LRT (Figure 1b) can much more easily be distinguished, which is very important for determining phase velocities of surface waves.

Real-world data were employed to study the effectiveness and applicability of high-resolution LRT for dispersive energy imaging. Twenty-one channel surface-wave data (Figure 2a) were acquired at Virginia Key, Florida using twenty-one channel recording and 14-Hz vertical geophones. The geophone interval was 0.6 m with the source to nearest offset 4.5 m. The objective of this survey was to use surface-wave techniques to image the subsurface to a depth of 12 m.

The shot gather (Figure 2a) is transformed along the time direction to the frequency domain and sets the slowness p range from 0 s/m to 0.02 s/m with 0.0001 s/m interval (201 slowness points). We obtained the image in the f-v domain by high-resolution LRT. We can pick phase velocities by following higher amplitude peaks along energy trends (Figure 2b).

We used the slant stacking method (Xia et al., 2007) to generate a dispersion image (Figure 2c) for comparison with the high-resolution LRT results (Figure 2b). We use a double-end line at frequency 30, 50, and 60 Hz at different modes between the half-value of dispersion energy at Figure 2b and Figure 2c. The lengths of the double-end line in Figure 2c are about 100%, 80%, and 40% longer than those in Figure 2b. High-resolution LRT improves the resolution of the dispersive energy, especially in a low-frequency range. The dispersion energy of higher modes generated by high-resolution LRT (Figure 2b) possesses more distinguished trends than that generated by slant stacking (Figure 2c), which is very helpful in picking multimodes for joint inversion (Xia et al., 2003; Luo et al., 2007).
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Rayleigh-wave dispersive energy imaging and mode separating (a) Data acquired from Virginia Key, Florida, with a 21-channel system. (b) A dispersive image in the f-v domain calculated by high-resolution LRT. (c) An image of dispersive energy in the f-v domain generated by the slant stacking algorithm (Xia et al., 2007).

Rayleigh-wave mode separation

Rayleigh-wave mode separation by high-resolution LRT needs three more steps: selecting modes, transforming different modes back to the t-x domain along the time coordinate, and imaging different mode dispersive energy in the velocity-frequency domain.

We use the two-layer model described previously (Figure 1a) to show the process of Rayleigh-wave mode separation. After performing mode separation and reconstruction, we obtain the f-v domain dispersive image (Figure 3). Comparing with Figure 1b, different modes of dispersive energy (Figure 3) after mode separation and reconstruction are enhanced without losing any accuracy. Several key characteristics of surface-wave energy can be observed on synthetic shot gathers and associate dispersion images (Figures 1 and 3).

First, different high-frequency (≥5Hz) Rayleigh-wave modes interfere with each other in the t-x domain. Therefore, in practice it is difficult to achieve multimode separation for high-frequency Rayleigh waves by applying MFT (Multiple Filter Technique) or FVF (Frequency Variable Filter) technique in spite of the fact these techniques do well for low-frequency (<5Hz) Rayleigh-wave separation.

Second, different modes of dispersive energy (Figure 3) are imaged and dispersion curves are much easier to be picked on these figures than on the dispersive image before mode separation (Figure 1b). Further more, high modes of dispersive energy extend to lower frequencies and therefore increase the potential investigation depth and accuracy in determining the cut-off frequency (Xia et al., 2006).

We use the real-world data (Figure 2a) to study the effectiveness and applicability of high-resolution LRT for mode separation. After performing mode separation and reconstruction, we obtain the f-v domain dispersive image (Figure 4).
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Rayleigh-wave fundamental mode energy is dominant and possesses nearly 43% of energy in the shot gather. The fundamental, first higher, second higher, and third higher modes account for over 84% of energy. It is almost impossible to predict energy distribution for various modes due to heterogeneous ground conditions (Zhang and Chan, 2003). The fundamental mode energy is dominant in the lower frequency range (<56 Hz), while the first higher mode and the third higher mode energies are dominant in frequency ranges of 56-64 Hz and 76-80 Hz (Figure 2b). Dispersion curves picked based on energy levels do not always reflect pure fundamental mode, resulting in lowered precision and reliability of inverted results, and can even lead to completely erroneous inverted results (Xia et al., 2003; Luo et al., 2007). So mode separation is in high demand.

Different modes of dispersive Energy (Figure 4) are more consistent than the dispersive energy before mode separation (Figure 2b). Further more, the fundamental dispersive energy extends to higher frequencies and higher mode dispersive energy extends to lower frequencies, which lets S-wave velocities, obtained by inverting the fundamental mode and higher modes (Xia et al., 2002 and 2003), possess higher vertical resolution. The continuity of dispersive energy of different modes after mode separation and reconstruction is significantly improved in comparison with the dispersive energy before mode separation (Figure 2b). The reconstructed image enhances the different energy modes. Phase velocities of the fundamental mode energy range from 17 to 100 Hz with first higher mode energy range from 53 to 98 Hz in the reconstructed image (Figure 4) can be picked without any difficulty. However, phase velocities can only be picked from 17 to 80 Hz and 55 to 90 Hz for the fundamental and first higher mode energy before mode separation (Figure 2b), respectively. We can also confidently pick continuous dispersion curves for the second and third higher modes (Figure 4) while it is extremely difficult to pick continuously second or third mode dispersion curves in the dispersive energy before mode separation (Figure 2b).

Conclusions

We have used high-resolution LRT to image and separate multimode dispersive Rayleigh-wave energy. We introduced the standard and high-resolution LRT and the process of Rayleigh-wave mode separation by high-resolution LRT. Synthetic and real-world examples demonstrate that (1) high-resolution LRT methods can improve the overall resolution of dispersive images by more than 50% in comparison to commonly used slant stacking algorithms; (2) After mode separation, dispersive energy from each mode is uniquely imaged and allows much easier picking of frequency-velocity dispersion curve pairs used in shear-wave velocity inversion. Further more, higher mode dispersive energy expands to encompass a larger frequency range thereby increasing its potential imaging depth, improving resolution, and allowing cut-off frequencies to be determined more accurately.

The ultimate goal of Rayleigh-wave techniques is to estimate accurate S-wave velocities. This requirement relies on accurate extraction of dispersion curves from raw data. We have successfully imaged dispersive energy and separated different Rayleigh-wave modes using high-resolution LRT, which is an appealing alternative for high-resolution multimode separation of dispersive energy, allowing accurate picking of fundamental or higher mode dispersive curves across a wider frequency range. More importantly, Rayleigh-wave mode separation by high-resolution LRT opens the door for increase of horizontal resolution images of near-surface features using Rayleigh-wave techniques (e.g., Xia et al., 1999, Miller et al., 1999). Ultimately extraction of fundamental mode dispersion curves from a pair of traces after fundamental mode shot gathers separation and reconstruction by high-resolution LRT is one of our goals for increasing horizontal resolution of Rayleigh-wave techniques.

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