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Velocity analysis using high-resolution semblance based on sparse hyperbolic Radon transform

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ABSTRACT

Semblance measures the lateral coherency of the seismic events in a common mid-point gather, and it has been widely used for the normal-moveout-based velocity estimation. In this paper, we propose a new velocity analysis method by using high-resolution semblance based on sparse hyperbolic Radon transform (SHRT). Conventional semblance can be defined as the ratio of signal energy to total energy in the time gate. We replace the signal energy with the square of the sparse Radon panel and replace the total energy with the sparse Radon panel of the square data. Because of the sparsity-constrained inversion of SHRT, the new approach can produce higher resolution semblance spectra than the conventional semblance. We test this new semblance on synthetic and field data to demonstrate the improvements in velocity analysis.

1. Introduction

Building a velocity model is important to seismic exploration, which affects many processes of seismic data processing, such as velocity stack, Radon demultiple, compensation for geometrical spreading, and imaging. The high-resolution (HR) velocity spectra have gained more importance when dealing with the simultaneous-source data (Gan et al., 2016). A kind of method of building velocity model is picking the stacking velocity of zero-offset time from the velocity spectra (Taner and Koehler, 1969). To improve the resolution of stacking-velocity spectra, a good coherency estimator is therefore necessary. The semblance spectra are the commonest approach and it measures the lateral coherency of the multichannel data by scanning a set of the tentative stacking velocities (Neidell and Taner, 1971). Although many techniques have been developed to increase the resolution of the velocity spectra (Key et al., 1987; Key and Smithson, 1990; Sacchi, 1998; Abbad et al., 2009; Abbad and Ursin, 2012), the resolution of conventional semblance degrades significantly when the gather contains nonzero mean noise and closely-spaced events (Sacchi and Ulrych, 1995).

For a HR semblance, Fuller and Kirlin (1992) introduced a modified semblance by weighting the correlations of trace pairs on the basis of differential moveout, which enhanced the resolution of stacking-velocity spectra. Larner and Celis (2007) selected subsets of crosscorrelations rather than all possible combinations in a gather to improve both the reliability and resolution of stacking-velocity spectra. Similar to this strategy, Fomel (2009) weighted the semblance spectra by multiplying the amplitude trend of normal moveout (NMO) corrected gather. He named this method as AB semblance and considered the AVO anomaly of the CMP gather. He set the trace trend via the least-squares inversion to retrieve the AB parameter. Although AB semblance reduced twice of the resolution compared with conventional semblance, it was very suitable to the amplitude reversal condition and it could pick more puncture than conventional semblance in the case of AVO anomaly. Offset-dependent weighted function was proposed by Luo and Hale (2012). By minimizing semblance, the resolution of semblance spectra was promoted because it increased the resolution of existing peaks. Their method was tested on synthetic and field data to confirm that far-offset traces were more sensitive and this method potentially afforded a higher resolution. Tognarelli et al. (2013) replaced the real signal with the analytic signal to enhance the semblance resolution and successfully applied in the subsalt seismic exploration. Chen et al. (2015) changed the weighted function by local similarity and named it similarity-weighted semblance. This produced high-resolution semblance because the local similarity was more sensitive when even a slight moveout weighted the gather effectively. Ebrahimi et al. (2016) proposed a new weighting function for the AB semblance to handle the resolution and AVO anomaly simultaneously.

The conventional semblance which is related to an energy-normalized correlation equals the ratio of signal energy to total energy in a linear signal-noise model (Neidell and Taner, 1971). Therefore, if we increase the resolution of signal energy and total energy, the resolution of semblance will be definitely improved. Based on hyperbolic Radon transform (HRT), the sparse Radon panel can be obtained to recalculate the signal energy and the total energy. Furthermore, the velocity spectra and the Radon panel have the similar characteristic. Both approaches can focus energy coming from reflection events in a gather.

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Therefore, HRT can be considered as a good velocity analysis coherency estimator. Actually, HR velocity gather is calculated by sparse HRT (SHRT), which has been widely used for velocity stacking and data reconstruction. Thorson and Claerbout (1985) first proposed the stochastic inversion to obtain the sparse velocity gather for stacking. Sacchi and Ulrych (1995) applied Bayes's rule for introducing a priori probability density function to build the artifacts-free aperture-compensated velocity gather and reconstruct the offset space. Trad et al. (2003) reviewed the strategy of the mixed frequency-time domain Radon transform and precondition conjugate gradient algorithm for linear inversion problem. Zhang and Lu (2014) proposed an accelerated sparse time-invariant Radon transform and successfully regularized the 2D and 3D prestack seismic data. In this paper, we present a new approach to calculate the HR semblance based on the sparsity-constrained inversion of SHRT. We utilize the sparsity-promoting technique to calculate a sparse Radon panel for the HR semblance spectra. Synthetic and field gather examples confirm the successful performance of this proposition. The calculation of HR semblance by SHRT is described in the next section.

2. High-resolution semblance

The conventional semblance measures the coherency of multichannel data. The semblance is defined by Neidell and Taner (1971) as:

$$s(t_0)=\frac{\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\left(\sum_{i=1}^{Nx}d(t,x_i)\right)^2}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\sum_{i=1}^{Nx}d(t,x_i)^2}. \tag{1}$$

where t_0 is the zero-offset travel time, $s(t_0)$ denotes the semblance coefficient, l is the width of the time window, and Nx is the number of traces in the gather. The hyperbolic traveltime path of $d(t, x_i)$ along the time axis is summed which is also known as the normal moveout equation: $t(x)=\sqrt{t_0^2+\frac{x_i^2}{v^2}}$, and x_i is the offset at trace number i and v is a set of different tentative stacking velocities. The conventional semblance can be realized as the crosscorrelation coefficient between the sequence series and constant value, and the value of semblance coefficient is maximized when the sequence has a uniform distribution (Fomel, 2009). The resolution of the semblance can be improved by multiplying the weighted functions $w(t, x_i)$ with the hyperbolic summation curve. Generally, the weighted semblance can be written as:

$$s_w(t_0)=\frac{\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\left(\sum_{i=1}^{Nx}d(t,x_i)w(t,x_i)\right)^2}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\left(\sum_{i=1}^{Nx}d(t,x_i)^2\sum_{i=1}^{Nx}w(t,x_i)^2\right)}. \tag{2}$$

The weighted function $w(t,x_i)$ has many different forms. The original weighted function was proposed by Fuller and Kirlin (1992), they gave a weighted coefficient to standard semblance by beam forming theory. When $w(t, x_i)$ is a selected window of all traces, Eq. (2) turns to selective-correlation semblance (Larner and Celis, 2007); when $w(t, x_i) = A(x_i) + B(x_i)\varphi(t, x_i)$, where $\varphi(t, x_i)$ is a known function, A and B are the coefficients of Shuey's approximation (Shuey, 1985), Eq. (2) turns to the AB semblance (Fomel, 2009). Otherwise, $w(t, x_i)$ can be defined as a set of weighted offset values to increase the weight in the large-offset data (Luo and Hale, 2012). It is also defined as a set of local similarities to weight different traces to dramatically improve the resolution of the semblance spectra (Chen et al., 2015).

The semblance coefficient can be defined as the signal energy to total energy ratio in the gate (Neidell and Taner, 1971). For a linear signal-noise model, the data equals to the summation of signal and noise:

$$d(t,x)=sig(t,x)+nos(t,x). \tag{3}$$

where $sig(t,x)$ and $nos(t,x)$ denote signal and noise, respectively. Under an ideal condition, the signal has a uniform distribution and the noise is random along the offset. For the statistic approach we have

$$\sum_{i=1}^{Nx}sig(t,x_i)=Nx\cdot sig(t,x), \tag{4a}$$

$$\sum_{i=1}^{Nx}nos(t,x_i)=0. \tag{4b}$$

After substituting Eq. (3) and Eqs. (4a) and (4b) into the Eq. (1), we have the semblance coefficient as:

$$s(t_0)=\frac{\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\left(\sum_{i=1}^{Nx}[sig(t,x_i)+nos(t,x_i)]\right)^2}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\sum_{i=1}^{Nx}[sig(t,x_i)+nos(t,x_i)]^2}=\frac{\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\left[\left(\sum_{i=1}^{Nx}sig(t,x_i)\right)^2+\left(\sum_{i=1}^{Nx}nos(t,x_i)\right)^2\right]}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\sum_{i=1}^{Nx}\left[sig(t,x_i)^2+2sig(t,x_i)nos(t,x_i)+nos(t,x_i)^2\right]}=\frac{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}sig(t,x_i)^2}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}sig(t,x_i)^2+\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\sum_{i=1}^{Nx}nos(t,x_i)^2}. \tag{5}$$

For the Eq. (5), the numerator stands for signal energy and the denominator stands for the summation of signal energy and noise energy (total energy), thus semblance is precisely the ratio of signal energy to total energy over the selected window (Neidell and Taner, 1971). If the signal energy at t_0 can be convergent, the semblance coefficient will also be convergent. However, noise with nonzero mean and closely events in the same window can cause a poor velocity resolution. To construct a HR semblance, we compensate for the limited-aperture integral by HR velocity gathers (Sacchi and Ulrych, 1995). The Radon panel is similar to stacking velocity gather by flipping the slowness axis, so we replace the numerator of Eq. (1) with the Radon panel $m(\tau, v)$ of SHRT and replace the denominator of Eq. (1) with the Radon panel $m'(\tau, v)$ of the data energy (the square of the gather). To improve the resolution of the Radon panel, SHRT is implemented in the mixed frequency-time domain to qualify the sparsity of Radon panel. The detailed illustration of SHRT can be found in the following section. The equations of SHRT can be written as:

$$m(\tau,v)=\boldsymbol{R}[\boldsymbol{d}(\boldsymbol{t},\boldsymbol{x})], \tag{6a}$$

$$m'(\tau,v)=\boldsymbol{R}\left[\boldsymbol{d}(\boldsymbol{t},\boldsymbol{x})^2\right]. \tag{6b}$$

where $\boldsymbol{R}$ denotes the SHRT operator which is detailed in the following section, τ is the intercept time, v is the stacking velocity which is equivalent to reciprocal of the slowness. With the Eqs. (6a) and (6b), HR semblance coefficient is:

$$s_R(t_0,v)=\frac{\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}m(\tau,v)^2}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}m'(\tau,v)}. \tag{7}$$

In order to obtain a smooth semblance coefficient, the 2D low-pass filter is applied to smooth the peaks of the Radon panel. The smoothed HR semblance coefficient is written as:

$$s_R(t_0,v)=\frac{\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\Phi[m(\tau,v)]^2}{Nx\sum_{t=t_0-\frac{l}{2}}^{t_0+\frac{l}{2}}\Phi[m'(\tau,v)]}. \tag{8}$$

$S_R(t_0, v)$ is a higher resolution semblance than the conventional semblance because of the sparsity of Radon panel. Furthermore, $S_R(t_0, v)$ also