Ground roll removal using adaptive reflection mask function in Curvelet domain

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Summary

Ground roll is one of the most common coherent noise produced by surface waves during land seismic data acquisition. The removal of ground roll is of great importance during preprocessing, as it can conceal the small-amplitude reflected events. Curvelet transform decomposes seismic events in a time/space window based on their local frequency and dip information. Thus, the separation of ground roll noise and reflected events can be accomplished better in the curvelet domain than in other transformations. In this paper, we present a new curvelet-based ground roll suppression method. First, curvelet coefficient mask functions for reflection events are generated based on adaptive threshold for fine-scale panels. The reflection mask function will be downscaled to all scales and dipping angles. We then calculate another ground roll mask function in coarse scales. Combining these two mask functions we can generate the final adaptive reflection mask function for all scales and dipping angles. The adaptive mask function will be used to mute out curvelet coefficient and inverse transform to get the ground roll attenuated image. The real data tests indicate the proposed method can effectively suppress the ground roll energy and reveal the hidden reflection signals.

Introduction

Ground roll is a typical Rayleigh wave coherent noise existing in land seismic surveys. It has three distinct characteristics: low frequency, low velocity and large amplitude. The strong ground roll energy will overlap with shallow reflections at near offset and deep reflections at far offset, making these signals hard to observe. In order to retrieve a better-quality image, the ground roll noise should be removed before further processing. Various methods have been introduced for attenuating ground roll noise, including *f-k* filtering (Yilmaz, 1987), wavelet domain filtering (Deighan and Watts, 1997), S transform filtering (Askari and Siahkoohi, 2008) and curvelet transform filtering (Yarham el al., 2006). Most of the methods suffer from ground roll energy residue or reflection-signal deterioration. For example, *f-k* filtering is a simple way to suppress ground roll by filtering out the large dipping coefficient in the *f-k* domain. However, the low-frequency ground roll spectrum can overlap with high-frequency reflection energy with a similar dipping angle, making it hard to separate in the *f-k* domain. To better address this problem, dipping angle and frequency analysis in a spatially local window should be involved during the separation (Chiu and Howell, 2008). The curvelet transform is an effective way for this kind of analysis.

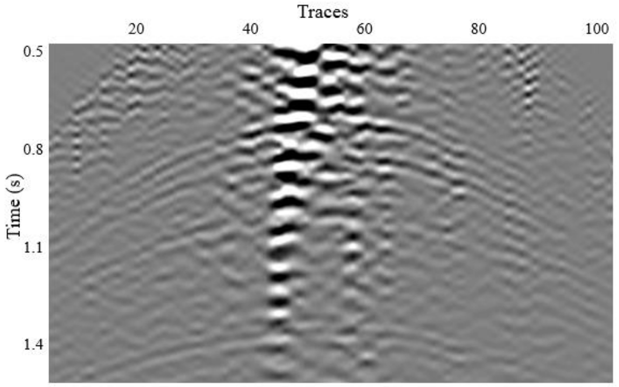

Figure 1: Example showing overlaped ground roll residue with reflection signal. In this example, the noise residue has similar dipping angle with the reflection signal at near offset. The downsclaed reflection mask cannot filtered out this kind of residue noise.

Curvelet transform decomposes the data into different scales (frequencies) and dipping angles (local wavelet directions) (Candes et al., 2005) for local time and space windows. Naghizadeh and Sacchi (2018) found that ground roll does not exist in the finest scale panels with small dipping angles. They generate a reflection energy mask in the curvelet domain at fine scale, downscaling this mask to coarse scale and mute out the ground roll energy. This method focused on two ground roll features: low frequency and low velocity. It works well in most of situations. From both synthetic and real data tests, the ground roll energy was suppressed significantly with very few reflection-signal loss. However, we found in some datasets, the high-frequency reflections may overlap with low-frequency ground roll residues at the similar spatial and temporal position with similar dipping angle. Figure 1 is an example of this situation. In this example, after ground roll suppression, there still exists some residue at the near offset. Also, even for the same dataset and same scale, the Curvelet coefficients at different angles have different amplitude levels. Adaptive threshold should work better for different scales and dipping angles panels. In this paper, we propose a new method which can remove this kind of ground roll residue while utilizing adaptive threshold for more balanced results at different panels.

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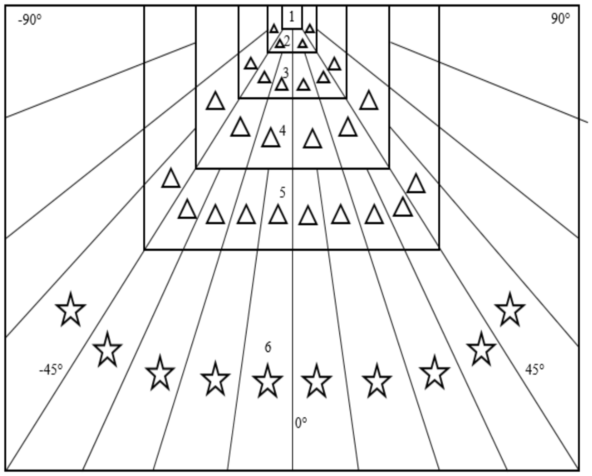

Figure 2: An example of curvlet coefficient panels used for ground roll suppression. Number 1 to 6 indicate the scales from low frequency to high frequency. The angle indicate the dipping angles for different scales. Stars represent the ground roll free panels used to calculate the reflection signal mask function, while the triangles mark the panels used to calculate the ground roll mask function.

Ground roll patterns in curvelet domain

In this paper we conduct the second generation discrete curvelet transform (DCT), which was introduced in (Candes et al., 2005). It decomposes the data into a digital table of curvelet coefficients, indexed by scale and dipping angle and spatial location. DCT has several advantages, it can sparsely represent the wave-propagation directions and objects with edges. That means, DCT is optimal for noise suppression and wave separation. Comparing with reflection signals, ground roll has much larger amplitude, lower frequency and smaller velocity. Converting to the curvelet domain, ground roll energy will dominate the low-frequency panels, especially at large dipping angles. From the curvelet analysis, ground roll energy does not exist in the finest scale with relatively small dipping angles. We utilize these features for mask function calculations. We use the fine scale, small dipping angle panels to generate reflection mask functions and downscale to coarse scales. Most of the reflection signals are concentrated in small dipping angles, so the large dipping angle panels will also be muted out to attenuate ground roll and other incoherent noises. Moreover, we suggest the large curvelet coefficient in a coarse scale is also related to ground roll noise. These coefficients will also be weighted to suppress the ground roll energy. Figure 2 is an illustration of the curvelet coefficient panels used for calculating reflection mask function and ground roll mask function. Notice that different scales have different number of dipping angles. The star marks indicate the ground roll free panels at the finest scale that used for calculating the reflection signal panels. The angle range here can be different depending on the seismic dataset. The triangle marks indicate the panels used for calculating the ground roll mask function. Those large dipping angle panels without any mark will be mute out because they don't have much information about the reflection signals.

Methodology

The processing work flow can be divided into two parts. In the first part, we calculate a reflection signal mask in ground roll free panels for Curvelet coefficients. As we mentioned before, ground roll energy does not exist in the Curvelet panels at the finest scale (high frequency) with small dipping angle. We take advantage of this feature and calculate the mask function using the following equation:

$$\mathbf{R}_{\mathbf{s,d}} = \begin{cases} 0 & |\mathbf{c}_{\mathbf{s,d}}| < \mu_{\mathrm{s,d}} \\ 1 & |\mathbf{c}_{\mathbf{s,d}}| \geq \mu_{\mathrm{s,d}} \end{cases} \qquad \text{when } \mathrm{s} \geq \mathrm{s}', |\mathrm{d}| \leq \mathrm{d}' \qquad (1)$$

where $\mathbf{R}_{\mathbf{s,d}}$ is the reflection mask function at scale *s* and dipping angle *d*, $|\mathbf{c}_{\mathbf{s,d}}|$ is the absolute value of curvelet coefficient at scale *s* and dip *d*. *s'* and *d'* are the ground roll energy-free scale and dip used for generating reflection mask function. In most cases, *s'* is the finest scale, and *d'* is depending on the dataset. $\mu_{s,d}$ is the adaptive soft threshold for scale *s* and dip *d* (Chang et al., 2000), defined as:

$$\mu_{s,d} = w_{user} \times \frac{\hat{\sigma}^2}{\hat{\sigma}_x}, \qquad (2)$$

here w_{user} is a user defined threshold weight, normally it can be set to 100%. $\hat{\sigma}$ is noise variance, it can be estimated by the robust median estimator as:

$$\hat{\sigma} = \frac{\mathrm{Median}(|\mathbf{c}_{\mathbf{s,d}}|)}{0.6745}, \qquad (3)$$

and $\hat{\sigma}_x$ is the reflection signal variance, estimated as:

$$\hat{\sigma}_{\mathrm{x}} = \sqrt{\max(\hat{\sigma}_{\mathrm{y}}{}^2 - \hat{\sigma}^2, 0)}, \qquad (4)$$

here $\hat{\sigma}_y$ is the variance of curvelet coefficient at scale *s* and dip *d*. We assume that within the ground roll energy free scale, the curvelet coefficient above the threshold represent the reflection signals only, so this mask function will mute out all other noise. Very few portions of reflection signals exist in large dipping angle panels. Within these panels the mask function will be simply set to zero.

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After generating the reflection mask function at scale *s*, we downscale it to coarser scales. Since the number of dipping angles at scale *s* and *s-1* may be different, the mapping for mask function at scale *s-1* will be based on the nearest three dipping angle panels at scale *s*. The frequency of ground roll is low while the frequency of reflection signals should be broader, so this mask will mute out the ground roll at low frequency that is spatially away from reflection signals.

However, in some situations like Figure 1, the ground roll residue can be hard to remove with the previous reflection mask only. The reflection signal used for calculating a mask function overlaps with the noise residue at the same location with similar dipping angles. So, the downscaled mask function cannot mute out these kinds of residues. So in second part, we adaptively change the reflection signal mask function at coarser scales by involving the ground roll mask function. In coarse scale (low frequency) panels, most of the Curvelet coefficients are dominated by the ground roll energy, so the ground roll mask function is generated based on the similar concept as the previous reflection signal mask function:

$$\mathbf{G}_{\mathbf{s,d}} = \begin{cases} 1 & |\mathbf{c}_{\mathbf{s.d}}| < \mu_{s,d} \\ 0 & |\mathbf{c}_{\mathbf{s.d}}| \geq \mu_{s,d} \end{cases} \qquad \text{when } s < s', \tag{5}$$

$\mathbf{G}_{\mathbf{s,d}}$ is the ground roll mask function, and $\mu_{s,d}$ is the adaptive threshold for each panels. This ground roll mask function will be subtracted from the reflection signal mask at each scale and dipping angles, and generating the final mask function $\mathbf{M}_{\mathbf{s,d}}$. The final image can be represented as:

$$\hat{\mathbf{m}} = \mathrm{IDCT}(\mathbf{Mc}), \tag{6}$$

where IDCT is the inverse discrete curvelet transform, and **c** is the vector of curvelet coefficients of the original data, **M** is the final mask function.

Examples

We applied this method to a 2D receiver line of the Firestone project. Firestone is a 1,231 square miles 3D survey acquired in east Ohio (Figure 3). Figure 4 shows images of the original data, the output data and difference between them. From the original data, we can find very strong ground roll energy. The ground roll noise covers some small amplitude reflection layers at a near-offset location. After applying the proposed method, most of the ground roll energy is attenuated, some clean and continuous reflection layers that are previously buried by the strong ground roll noise are revealed. From Figure 4(c) the difference image, we can confirm the loss of reflection signal is very limited.

Conclusions

We present an improved method for ground roll removal in the curvelet domain. We first generate the reflection signal mask function in ground roll free panels. We use an adaptive threshold instead of one hard threshold so that all panels will have a similar result. The curvelet coefficient with absolute value greater than the threshold will be considered as reflection signal. The reflection mask function will be downscaled to all scales and dipping angles. Then we further calculate a ground roll noise mask function using the similar scheme. In coarse scales, curvelet coefficients with absolute value greater than the adaptive threshold will be marked as noise. After all, we combine these two types of mask functions to generate our final adaptive reflection mask function. The curvelet coefficient panels will be filtered using this mask function, then inverse transformed to get the ground roll attenuated image. Our real data test shows the proposed method can effectively remove the ground roll energy with minimum reflection signal loss.

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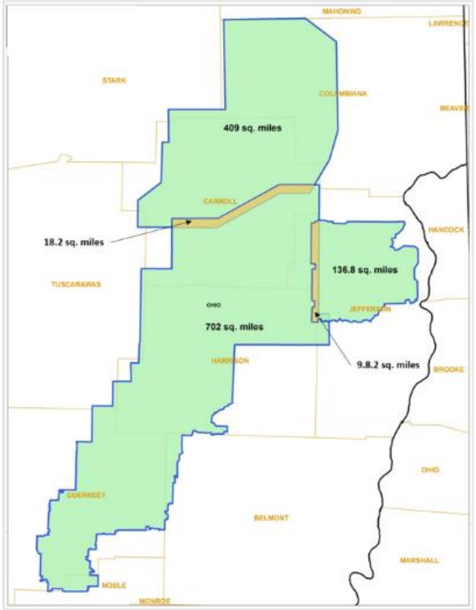

Figure 3: Firestone project map showing the location of the real data example

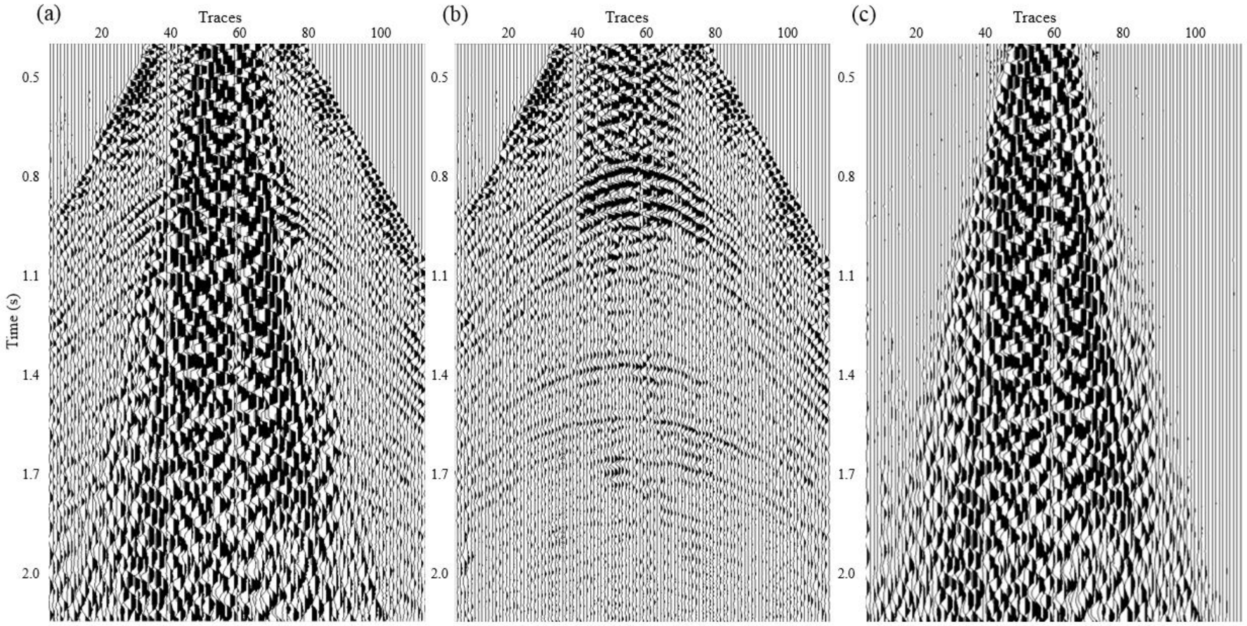

Figure 4: (a) A land seismic shot gather example contaning strong ground roll. (b) Output data after suppressing ground roll using the proposed method. (c) Difference between the original data and output data.

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