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3D groundroll attenuation using hybrid Fourier and de-aliased Cadzow reconstruction

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Summary

We introduce a strategy for ground-roll attenuation using hybrid Fourier and de-aliased Cadzow interpolation. First, the receivers are reconstructed on a nominal coarse grid using Fourier reconstruction to fill in the gaps and create a 2D regular distribution of receivers. Next, the 2D de-aliased Cadzow reconstruction method is utilized to interpolate the data across the in-line and cross-line directions of receivers. The distinct energy separation between the reflections and ground-roll in the *f-k* domain after de-aliased interpolation is exploited to isolate and attenuate the ground-roll using an *f-k* domain dip filtering. The performance of the proposed method is examined on a real land seismic data example.

Introduction

Ground-roll attenuation is a challenging task in seismic data processing. The high amplitude ground-roll energy conceals the low amplitude reflected events on seismic shot gathers. Several signal processing methods have been proposed and applied for ground-roll attenuation. Saatcilar and Canitez (1988) used one-dimensional linear frequency-modulated matched filters to effectively separate ground-roll from reflections. They have also proposed using lattice filters for ground-roll attenuation (Saatcilar and Canitez, 1994). Halliday et al. (2011) investigated suitable acquisition geometries for model-driven interferometric ground-roll removal. Other ground-roll attenuation techniques that have been applied include S transform (Askari and Siahkoohi, 2008), radial trace filtering (Henley, 2003), curvelet transform (Naghizadeh and Sacchi, 2011), and eigen-image filtering (Cary and Zhang, 2009). In addition to the mentioned methods, one can also use a simple *f-k* domain dip filter to attenuate ground-roll from seismic records (Yilmaz, 1987).

Despite the effectiveness of *f-k* domain dip filtering, it can not remove the aliased ground-roll energy that overlaps with the reflections in the *f-k* domain. However, by utilizing a beyond-alias interpolation approach one can alleviate the spatial aliasing of ground-roll and effectively separate the ground-roll and reflection energies in the *f-k* domain. In this article, we propose a hybrid Fourier and de-aliased Cadzow reconstruction method that can be applied for 3D land shot gathers. First, the Fourier reconstruction is used to reconstruct the receivers on a coarse nominal spatial grid. Next, the de-aliased Cadzow reconstruction method used to interpolate data into a finer spatial grid of receivers. Finally, the de-aliased ground-roll energy is effectively separated from reflection energy. The effectiveness of the proposed approach is examined on a real 3D land shot gather.

Theory

First, we use the Minimum Weighted Norm Interpolation (MWNI) method (Liu and Sacchi, 2004) to reconstruct the receivers of a 3D land shot gather on a regular spatial grid in order to fill in any possible gaps between the receivers. The MWNI method reconstructs the missing spatial samples of any temporal frequency of seismic records by minimizing the following cost function (Tikhonov and Goncharsky, 1987)

$$J = ||\mathbf{d} - \mathbf{T}\mathbf{F}^H\mathbf{W}\mathbf{k}||_2^2 + \mu^2||\mathbf{k}||_2^2, \tag{1}$$

where, $\mathbf{k}$ is the Fourier coefficients vector, $\mathbf{W}$ is the diagonal weighting matrix, $\mathbf{F}^H$ is inverse Fourier transform, $\mathbf{T}$ is the sampling matrix, and $\mathbf{d}$ is the vector containing available spatial samples. The diagonal weighting matrix is iteratively calculated from the Fourier coefficients as

$$\mathbf{W} = diag(\mathbf{k} \odot conj(\mathbf{k})), \tag{2}$$

where, $\odot$ represents the element-wise multiplication and $diag$ transforms a vector to a diagonal matrix. The final MWNI reconstructed spatial samples is retrieved by taking the inverse Fourier transform of the final optimized Fourier coefficients, $\mathbf{x} = \mathbf{F}^H\mathbf{k}$.

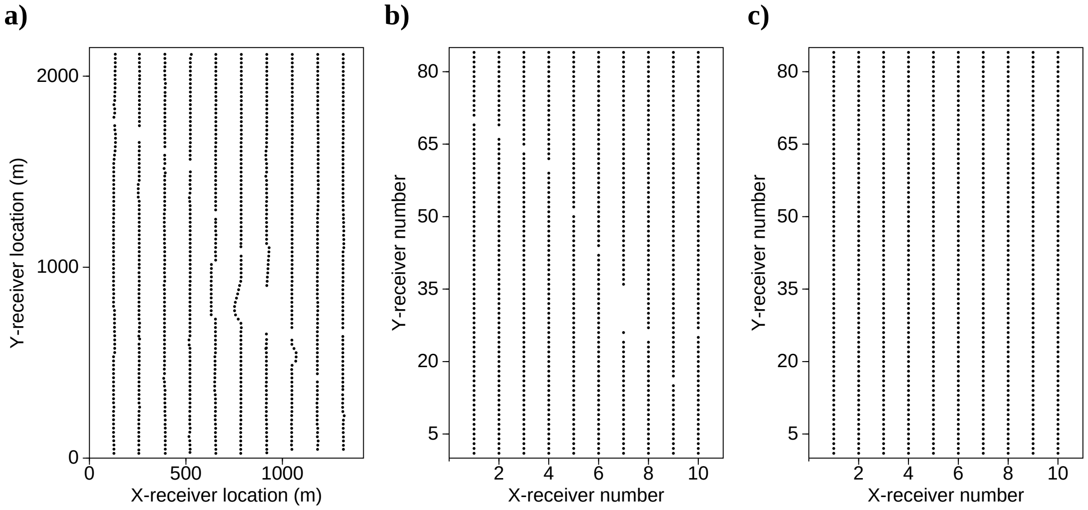

***Figure 1** a) Original receiver distribution of one shot from a real 3D land seismic survey. b) Distribution of receivers after binning on a nominal grid of 25×125 m. c) Regular distribution of Fourier reconstructed receivers.*

Once the receivers are reconstructed on an initial coarse grid, the 2D de-aliased Cadzow reconstruction is used to interpolate data into a finer spatial grid. The de-aliased cadzow algorithm, for increasing the number of spatial samples from N_x to $2N_x$ at the temporal frequency f, can be summarized as below (Naghizadeh and Sacchi, 2013)

$$\begin{array}{l} \text{Initialization}\\ \mathbf{x}^0_{int}(f)=\mathbf{G}\mathbf{x}(f),\\ \text{For}\quad i=1,2,3,\dots,n_{iter}\\ \qquad \mathbf{Q}=\mathbf{U}^{(f/2)}\mathbf{U}^{(f/2)^H}(\mathscr{H}[\mathbf{x}^{i-1}_{int}(f)]),\\ \qquad \mathbf{x}^i_{int}(f)=\mathbf{L}(\mathscr{A}[\mathbf{Q}])+\mathbf{G}\mathbf{x}(f).\\ \text{End}\end{array} \tag{3}$$

where the matrices $\mathbf{G}$ and $\mathbf{L}$ are defined as

$$\mathbf{G}=\begin{pmatrix} \mathbf{p} & \mathbf{0} & \cdots & \mathbf{0}\\ \mathbf{0} & \mathbf{p} & \cdots & \mathbf{0}\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{p}\end{pmatrix}_{2N_x\times N_x}, \quad \mathbf{L}=diag([0,1,0,1,0,1,\dots,0,1]_{1\times 2N_x}), \tag{4}$$

with $\mathbf{0}=[0,0]^T$ and $\mathbf{p}=[1,0]^T$. The operator $\mathscr{H}$ builds the Hankel matrix and $\mathscr{A}$ represents the anti-diagonal averaging. The matrix $\mathbf{U}^{(f/2)}$ is the rank-reduced left-hand-side rotation matrix obtained by Singular Value Decomposition (SVD) of the Hankel matrix built at the frequency $f/2$. In essence, we project the wavenumber information from half frequency $f/2$ to the desired frequency f in order to remove the aliased energy. The parameter n_{iter} represents the number of iterations and it can be determined by setting a threshold value for the error reduction rate calculated between the original available samples and newly interpolated ones, after each iteration.

Example

We used a real 3D land seismic shot gather to examine the effectiveness of the proposed ground-roll attenuation method. Figure 1a shows the original spatial distribution of receivers for the 3D shot gather. Figure 1b shows the distribution of the binned receivers on a coarse spatial grid. Figure 1c depicts the distribution of receivers after applying the MWNI method. Figures 2a, 2b, and 2c show the original, binned, and MWNI reconstructed shot gather, respectively. The reconstructed data on regular grid using the MWNI method was used as input for the 2D de-aliased cadzow reconstruction method.

Figures 3a shows the MWNI reconstructed data for the receiver-line 9. Figure 3b shows the de-aliased Cadzow reconstruction result for the receiver-line 9. Figures 3d and 3e depict the *f-k* spectra of the data in Figures 3a and 3b, respectively. The de-aliased Cadzow reconstruction has successfully de-aliased the ground-roll energy, making a distinct separation between the ground-roll and reflection energies in the *f-k* domain. Figure 3c shows the ground-roll attenuated data after *f-k* dip filtering of the de-aliased Cadzow reconstructed data. Figure 3f depicts the *f-k* spectra of data in Figure 3c. Due to the clear separation of ground-roll and reflection after de-aliased reconstruction, one can also utilize the removed ground-roll panels for surface wave analysis methods.

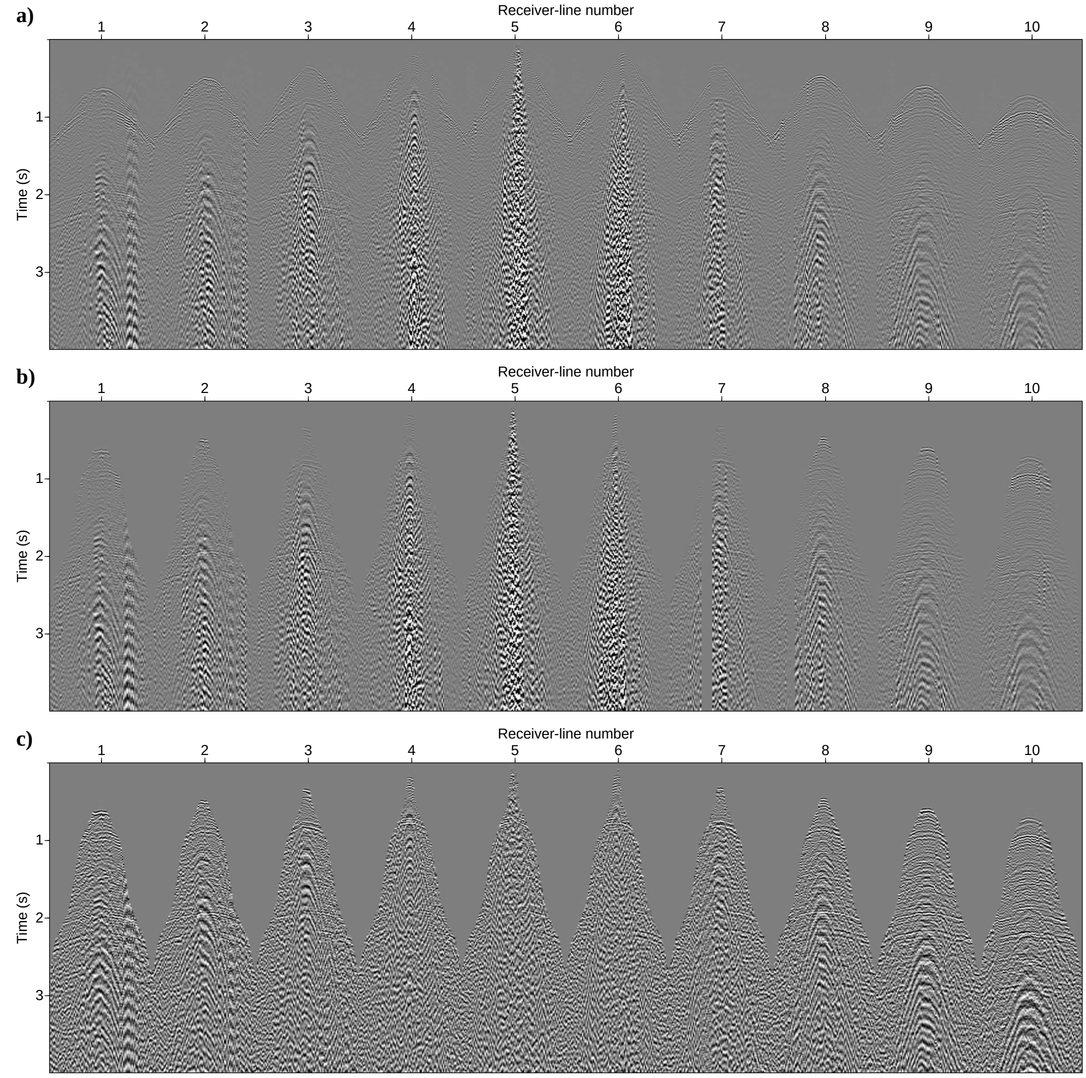

Figure 2 *a) Original receiver-line seismic data corresponding to Figure 1a. b) Binned seismic data corresponding to Figure 1b after applying mute outside the ground-roll cone. c) Fourier reconstructed receiver-lines on a regular grid corresponding to Figure 1c.*

Conclusion

We implemented a 3D ground-roll attenuation method by combining two types of seismic data reconstruction methods. First, using a Fourier reconstruction method, we reconstruct and fill in the gaps between the receivers on a coarse spatial grid. Next, we use the de-alised Cadzow reconstruction method to reduced the spatial sampling between the receivers until the ground-roll energy is no longer aliased. After de-aliasing the ground-roll energy, we use the *f-k* domain dip filtering to attenuate the ground-roll energy from seismic data. The real 3D land seismic data example shows the effectiveness of the proposed ground-roll attenuation method.

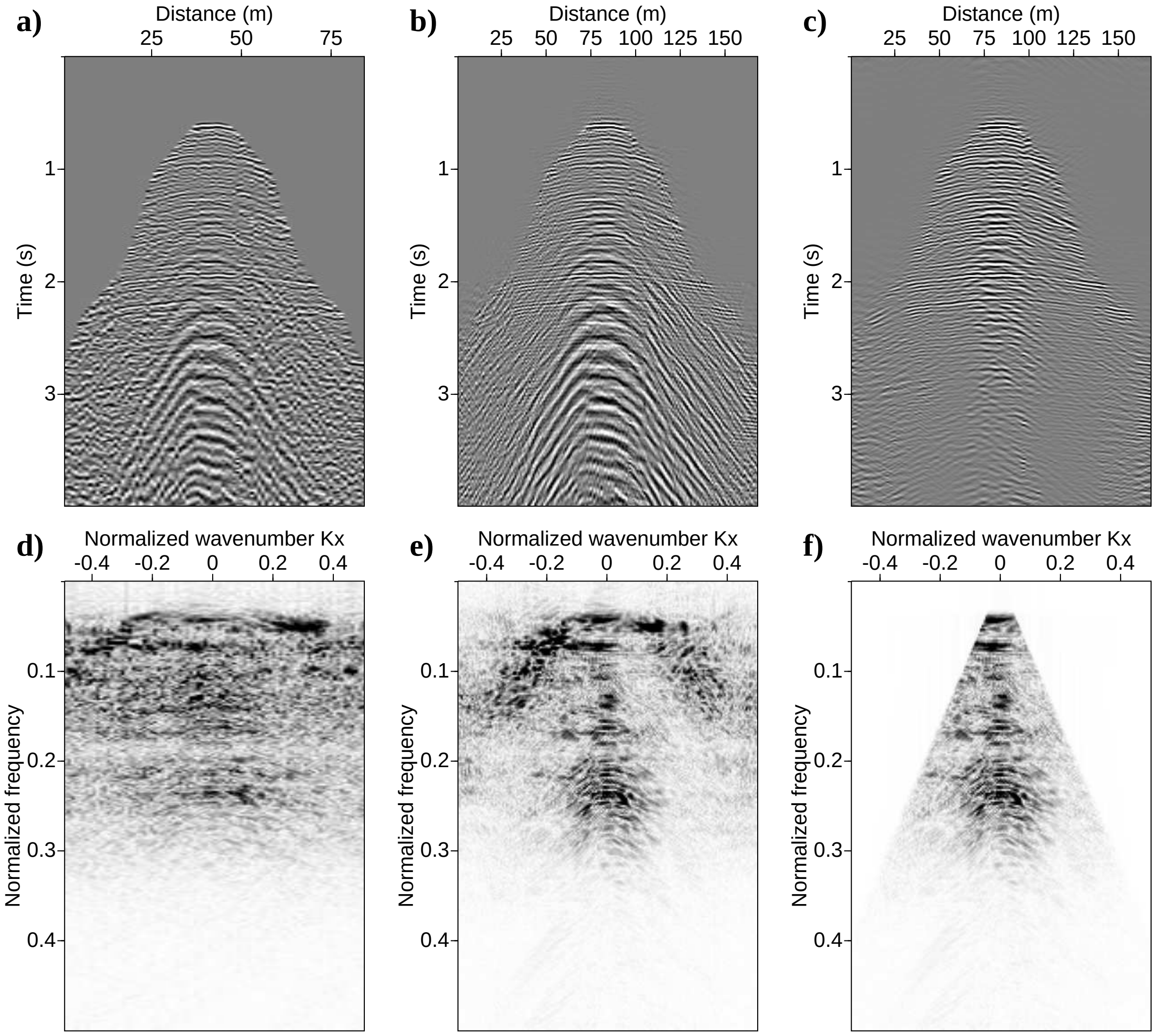

***Figure 3** a) Original receive-line 9. b) Interpolated receiver-line 9 using 2D de-aliased Cadzow reconstruction. c) Seismic refelections after attenuation of ground-roll. d)-f) show the f-k spectra of the data in a-c.*

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