SVD filtering applied to ground-roll attenuation

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Abstract

We present a singular value decomposition (SVD) filtering method for attenuation of the ground roll. Before the SVD computation, normal move-out (NMO) correction is applied to the seismograms, with the purpose of flattening the reflections. SVD is performed on a small number of traces in a sliding window. The output trace is the central trace of the first few eigenimages. These contains mostly horizontally aligned signals, and other noise in the data will be suppressed. By performing this action with the sliding window moving in steps of one trace, the number of output traces is equal to the number of input traces. The new method preserves the character and frequency content of the horizontal reflections and attenuates all other type of events. We illustrate the method using land seismic data of the Tacutu basin, located in the north-east part of Brazil. The results show that the proposed method is effective and is able to reveal reflections masked by the ground-roll. The new SVD filtering approach provides results of better quality, when compared with results obtained from the conventional f-k filtering method.
Introduction

Ground roll is a particular type of Rayleigh wave and has high amplitude, low frequency, and low velocity, being the main type of coherent noise in land seismic surveys. Ground roll is also dispersive and normally overwhelms the desired reflected signal. Because of its dispersive nature, ground-roll masks at short offsets the shallow reflections, and at long offsets the deeper reflections (Claerbout, 1983; Saatçilar and Canitez, 1988; Henley, 2003). Many authors have shown that the ground roll can be attenuated by proper acquisition design and filtering (Harlan et al., 1984; Anstey, 1986; Shieh and Herrmann, 1990; Pritchett, 1991; Brown and Clapp, 2000). Such a strategy may either have logistical limitations or may not be applicable to data already acquired.

One of the most simple filtering approaches used in the ground roll attenuation problem is f-k filtering, which is applied in the frequency \times spatial wave-number domain. The f-k method uses 2-D Fourier transform (Embree et al., 1963; Wiggins, 1966) and the ground-roll, represented by linear events with low velocities, is mapped as lines in the f-k domain. It can consequently be filtered using a 2D band-pass filter. This has the disadvantage that it also eliminates reflected energy which contributes to the character of reflected events.

Various methods to filter ground roll have been proposed in recent years. Deighan and Watts (1997) proposed the use of wavelets which does not assume that the signal is stationary. Liu (1999) and Montagne and Vasconcelos (2006) proposed the use of the Karhunen-Loève transform to estimate and subtract the ground roll from the common-shot gathers. SVD is a coherency-based technique that provides both signal enhancement and noise suppression. It has been implemented in a variety of seismic applications (Freire and Ulrych, 1988, Bekara and van der Baan, 2006). Kendall et al. (2005) proposed a SVD-polarization filter for ground roll attenuation on multicomponent data. Tyapkin et al. (2003) proposed to use the data alignment method of Liu
(1999) to make the coherent noise horizontally aligned in one or more time sections of a common shot gather. In each of the time sections the noise is represented by the first eigenimages (with a given fraction of the total energy). The remaining eigenimages represent the signal, and this part is transformed back to the original time-space domain. Chiu and Howell (2008) proposed a method that uses SVD to compute eigenimages that represent coherent noise in a localized time-space windows. The data in the local windows is transformed into analytic signal and followed by a complex SVD to decompose the analytic signal into eigenimages that represent the coherent noise model. Yarham et al. (2006) proposed a two stage method of identifying and removing ground roll using the curvelet transform. Karsli and Bayrak (2008) proposed to use a Wiener filter in the estimation of ground roll via a reference noise such as a linear or nonlinear sweep signal. Melo et al. (2009) presented a filtering method for ground-roll attenuation that uses a 2-D time-derivative filter.

Bekara and van der Baan (2006) proposed a local SVD approach to noise removal. In each data window the signal is horizontally aligned in time, and after SVD only the first eigenimage is retained. Then the procedure is repeated in the next data window using sliding windows with 50% overlap. Here we proposed a new approach to local SVD noise removal. In each data window (consisting of an odd number of traces) the signal is aligned in time. After SVD only the middle trace of the first one or two eigenimages is retained. Then the data window is moved one trace position and the procedure is repeated. This preserves the amplitude and character of horizontal events and attenuates all other events.

We illustrate the method using land seismic data from the Tacutu basin (located in the north-east part of Brazil) acquired by PETROBRAS in 1981 (Eiras and Kinoshita, 1990). The results are compared with f-k filtering.
SVD Filtering

We consider a seismic data set \(d(t, x_n), t = 1, \ldots, N_t, n = 1, \ldots, N_x\) where the primary reflections have been corrected for NMO so that they are horizontally aligned in the \(x\)-direction. A windowed data set of \(2M + 1\) traces centered at \(x_n\) is given by the matrix \(D^n\) with components \(D^n_{tj} = d(t, x_{n+j}), t = 1, \ldots, N_t, j = -M, \ldots, 0, \ldots, M\). It can be represented by the reduced SVD (Golub & van Loan, 1996):

\[
D^n = \sum_{k=1}^{2M+1} \sigma_k u_k v_k^T
\]  

(1)

where the left singular vectors \(u_k\) are orthogonal and the right singular vector \(v_k\) also are orthogonal. The singular values are sorted such that \(\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_{2M+1} \geq 0\). In component form the SVD is

\[
D^n_{tj} = d(t, x_{n+j}) = \sum_{k=1}^{2M+1} \sigma_k u_k(t)v_k(j)
\]  

(2)

with \(t = 1, \ldots, N_t\) and \(j = -M, \ldots, M\).

In the filtered output data set only the first \(K\) eigenimages or the center trace is being used. That is, the output is

\[
\tilde{d}(t, x_n) = \sum_{k=1}^{K} \sigma_k u_k(t)v_k(0)
\]  

(3)

The procedure is started at \(n = M + 1\) where the filtered output is the \(K\) eigenimages of the first \(M + 1\) traces:
\[
\hat{d}(t, x_{M+1+j}) = \sum_{k=1}^{K} \sigma_k u_k(t)v_k(j), j = -M, \ldots, 0. \quad (4)
\]

Then \(n\) is increase by one and equation (3) is used until \(n = N_x - M\) where the output data are given by the \(K\) first eigenimages of the last \(M + 1\) traces. That is

\[
\tilde{d}(t, x_{N_x-M+j}) = \sum_{k=1}^{K} \sigma_k u_k(t)v_k(j), j = 0, \ldots, M \quad (5)
\]

The sliding window scheme is shown in Figure 1 for a window of 5 traces \((M = 2)\).

The result is a filtered data set \(\tilde{d}(t, x_n)\) of the same dimension as the input data set where energy which is not coherent in the \(x\)-direction has been attenuated. Both the character and amplitude of the horizontal events are well preserved as they are represented by the first eigenimages which have the largest energy.

**Data Results**

The proposed method of SVD filtering was tested on the RL-5090 land seismic line. It contains 179 shots recorded at 4 ms sampling interval. There are 96 channels per shot in a split-spread geometry with offsets 2,500-150-0-150-2,500 m and 50 m between the geophones. The distance between the shots is 200 m giving a low CMP coverage of 12 fold.

The data processing was very basic. First a standard processing sequence was applied: geometry, edit, preliminary spherical divergence correction, standard velocity analysis and NMO correction. Due to the limited CMP coverage, the
data were then resorted into shot gathers before the SVD filtering was applied. In the filtering process we used a 5-trace window \((M=2\) in equation (1)) for the SVD analysis, and we kept the two most significant central eigentraces \((K=2\) in equation (3)). The results were compared to a classical f-k filter method where all non-horizontal events were filtered out.

Fig. 2a shows a shot gather after NMO-correction. The results after f-k filtering and SVD filtering are shown in Fig. 2b and 2c, respectively. The ground roll is very well filtered in both cases, and the horizontal events which are associated with the reflections of interest are preserved. However, the SVD filtered data exhibit less smear and have more lateral character than the f-k filtered data.

In order to compare f-k spectra of the three shot gathers, they were muted, as shown in Fig. 3. The corresponding f-k spectra in Fig. 4 show the severe cut-off characteristic of the f-k filter. The spectra of the f-k filtered ground roll are shown in Fig. 5. From the two last figures one can see that the f-k filter separates the input data in two separate regions of the f-k domain (as expected). The SVD filter has a less dramatic effect, leaving estimated signal in the larger wave-number domain, and it reduces noise also in the low wave-number domain.

The three shot-point gathers in Fig. 2 are shown in Fig. 6 after the removal of NMO correction. The effect of f-k filtering and SVD filtering are similar as seen in the NMO corrected gathers. The SVD filter seems to have removed noise in a better way than the f-k filter, preserving the character of the data.

The two filtering procedures were applied to the complete NMO corrected data set before stacking. Details from the resulting stacked sections are shown in Fig. 7. Both f-k filtering and SVD filtering have reduced the noise. And again, the SVD filtered section has less smear and more character than the f-k filtered section.
Conclusions

We have developed a new and efficient SVD filter method which enhances horizontal events on seismic sections. The SVD filter process preserves the character and frequency content of the horizontal reflections and attenuate all other types of events. The method was successfully applied to ground roll attenuation on a land seismic data set. In particular, ground roll was virtually absent from the filtered pre-stack gathers. f-k filtering of the same data set also removed the ground roll, but it resulted in loss of lateral variation in the data.

Acknowledgements

The authors wish to express their gratitude to FINEP, FAPESB and CNPq, Brazil, for financial support. We also thanks PARADIGM, LANDMARK, SEISMIC-MICRO TECHNOLOGY and Schumumberger for the licenses granted to CPGG-UFBA. Bjorn Ursin has received financial support from the VISTA project and from the Norwegian Research Council through the ROSE project.
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Figures

FIG. 1. Sliding window SVD filtering scheme.

FIG. 2. Comparison of SVD filtering with f-k filtering. (a) input data, (b) output after f-k filtering, (c) output after SVD filtering.

FIG. 3. Muted seismograms preserving the ground-roll area. (a) muted input data, (b) after f-k filtering, (c) after SVD filtering.

FIG. 4. f-k spectrum of the muted original and filtered seismograms shown in Fig. 3. (a) input data, (b) f-k filtering, (c) SVD filtering.

FIG. 5. f-k spectrum of the filtered ground-roll. (a) after f-k filtering and (b) after SVD filtering.

FIG. 6. Comparison of SVD filtering with f-k filtering after inverse NMO correction. (a) input data, (b) output after f-k filtering, (c) output after SVD filtering.

FIG. 7. Details from the stacked sections: (a) original data (b) f-k filtered data, (c) SVD filtered data.
Figure 1: Sliding window SVD filtering scheme.
Figure 2: Comparison of SVD filtering with f-k filtering. (a) input data, (b) output after f-k filtering, (c) output after SVD filtering.
Figure 3: Muted seismograms preserving the ground-roll area. (a) muted input data, (b) after f-k filtering, (c) after SVD filtering.
Figure 4: f-k spectrum of the muted original and filtered seismograms shown in Fig. 3. (a) input data, (b) f-k filtering, (c) SVD filtering.
Figure 5: $f-k$ spectrum of the filtered ground-roll. (a) after $f-k$ filtering and (b) after SVD filtering.
Figure 6: Comparison of SVD filtering with f-k filtering after inverse NMO correction. (a) input data, (b) output after f-k filtering, (c) output after SVD filtering.
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