Application of singular spectrum analysis to ground roll attenuation

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Summary

The attenuation of ground roll (GR) is a major problem in seismic data processing. It is common to use low-pass filters to attenuate GR. The latter has the side effect of attenuating low frequencies in the signal. In this abstract, we use Singular Spectrum Analysis (SSA) to separate low frequency data into signal and noise components. We show that it is possible to separate GR from reflections in a low frequency band. The model obtained for the ground roll is then subtracted from the original data. The amplitude of the reflections is shown to be less affected by the Singular Spectrum Analysis method than by low-pass filtering.

Introduction

A common problem in seismic data processing is the presence of ground roll (GR). The latter tends to obscure the seismic reflections. GR are surface waves characterize by high amplitudes, low frequency content and low velocity.

Several methods have been used to attenuate GR. For instance, one can use low-pass filtering to exploit the low frequency nature of the GR. The main problem with this approach is that reflections have low frequency components that need to be preserved.

We decompose the low frequency data into eigenimages using Singular Spectrum Analysis (SSA) in the f – x domain. This consists of organizing a 1D series into a Hankel matrix and then in applying a rank reduction (Oropeza and Sacchi, 2009). We then recover the signal using a subset of eigenimages. This method has been applied in geophysics to study climate dynamics and changes in global temperature by Ghil et al, (2002). It has also been applied to filter random noise in seismic records (Sacchi, 2009, Oropeza and Sacchi, 2009 and Trickett and Burroughs, 2009).

We propose an improvement to the low-pass filter by using SSA to avoid filtering low frequencies of the signal.

Theory and Method

Let $S_i(x) = S_1, S_2, S_3, \ldots, S_N$ be a spatial vector of a given frequency i of the f – x domain, then SSA constructs a Hankel matrix M from S (also called trajectory matrix),

$$M = \begin{pmatrix} S_1 & S_2 & \cdots & S_K \\ S_2 & S_3 & \cdots & S_{K+1} \\ \vdots & \vdots & \ddots & \vdots \\ S_L & S_{L+1} & \cdots & S_N \end{pmatrix}. \quad (1)$$

The Hankel matrix has the same components in its anti-diagonals. As proposed by Trickett, (2008), it is convenient to build a Hankel matrix as square as possible. This can be achieved by setting $L = \frac{N}{2} + 1$ and $K = N - L + 1$. The decomposition of the Hankel matrix into its eigenspectra is done via Singular Value Decomposition (SVD) of M (Freire and Ulrych, 1988). The SVD of the matrix M is,

$$M = \underline{U}\,\underline{\Sigma}\,\underline{V}^T, \tag{2}$$

where: $\underline{U} =$ eigenvectors of MM^T

$\underline{V} =$ eigenvectors of M^TM

$\underline{\Sigma} =$ Diagonal matrix of the singular values of M in descending order

The process of applying SSA in the f – x domain is similar to Spectral Matrix Filtering (Mari and Glanceaud, 1990). Each event can be reconstructed by recovering individual eigenimages of the Hankel matrix. This consists in setting the elements of the diagonal matrix $\underline{\Sigma}$ as $\underline{\Sigma}(\mathbf{1}) = \mathbf{1}$ and $\underline{\Sigma}(\mathbf{k}) = \mathbf{0}$, where $\mathbf{k} = \mathbf{2}, \mathbf{3}, \ldots, N$. The latter follows the same methodology applied by Sacchi (2009) and Oropeza and Sacchi (2009) for random noise attenuation. It is important to mention that SSA is performed independently to each frequency in the f – x domain.

For correct reconstruction by each eigenimage, the signal and noise need to have different velocities and different amplitudes. With this condition, the first eigenimage will recover the signal with the highest amplitude. In the case that the amplitude and velocities are the same, it will be impossible to reconstruct one of the events with only one eigenimage

Given that the main characteristic of GR is higher amplitude and a lower velocity than the reflections; we can use the SSA signal separation to differentiate them. The GR also has lower frequency content than the reflections. By applying the SSA to the band of low frequencies where the GR has higher amplitudes than the signal we ensure that the first eigenimage will always represent the noise. To remove the GR, the recovered noise from SSA is subtracted from the original data. The latter improves the results of low-pass filter when attenuating GR.

For optimal results, linear move-out (LMO) and static corrections on the GR can be applied to ensure that it is strongly correlated in the lateral direction before SSA is applied.

Examples

The methodology proposed in this paper was applied to a synthetic gather with two events of different velocity, amplitude and frequency content. Both events were produced using Ricker wavelets, and with frequencies of, respectively, 10 Hz to simulate GR and 30 Hz to simulate reflections.

Figure 1 illustrates the application of a low-pass filter, with a trapezoidal window of 0-3-19-22 Hz. This figure displays a) the section with both signals summed, b) and c) each signal independently, d) the result of the filter and e) the subtraction of the recovered signal from the original data. The normalized amplitude spectrum (to the maximum amplitude of the GR spectrum) is also shown. It is evident that the low-pass filter contains low frequency components of the reflection. The amplitude spectrum of the recovered signal (figure 1-h) shows how the low-pass filter truncates the curve.

Figure 2 shows the result of SSA signal separation to the low-pass filtered section. Since the GR have higher amplitude than the high frequency signal, SSA can recover the low frequencies attenuated by the filter.

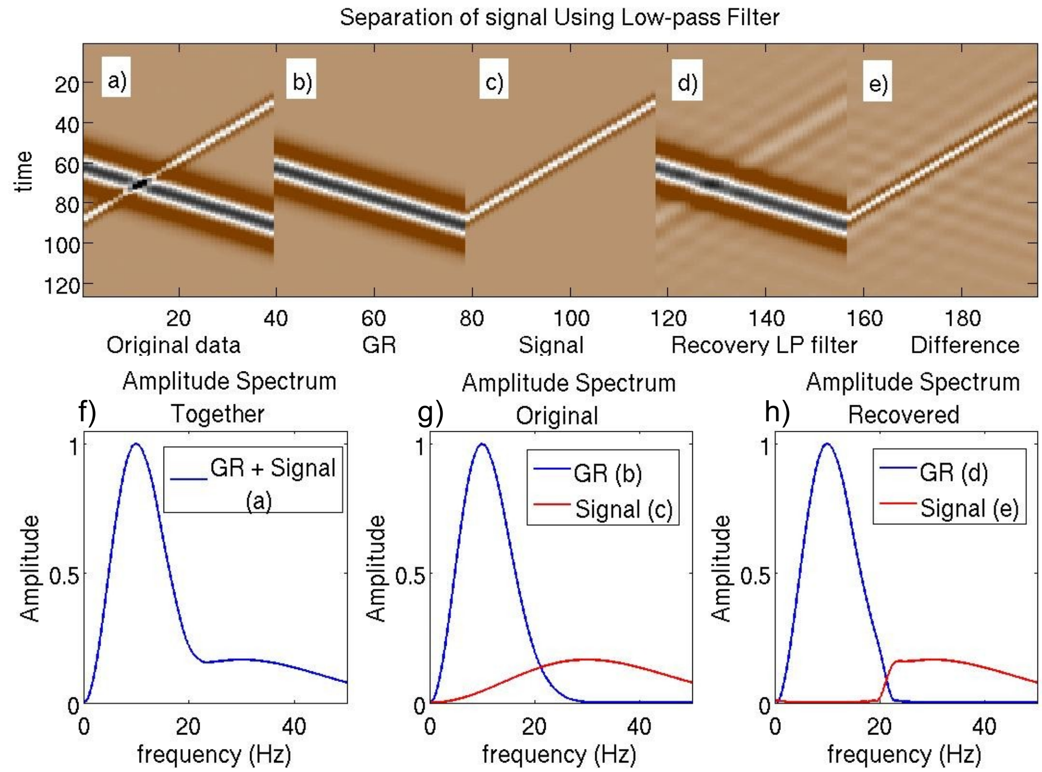

Figure 1: (a) Initial data presenting two events. (b) Low frequency event representing the GR. (c) High frequency event representing the reflection. (d) GR recovered using a low-pass filter. (e) Filtered data which result from the subtraction of (d) from (a). (f) Amplitude spectrum of (a). (g) Amplitude spectrum of (b) and (c). (h) Amplitude spectrum of (d) and (e). Figure 1 shows that low frequency content from the high frequency signal was recovered in (d) and filtered in (e). It is also evident in (h) that the signal (e) loses frequency content.

The method was also applied to a real shot gather with strong GR (Figure 3). The data correspond to shot number 25 from Yilmaz (2001). First, the data are filtered with a low-pass filter in a trapezoidal window of 0-3-15-20 Hz. After applying the low-pass filter, the section contains mostly GR and some low frequency signal from the reflections. A LMO and static correction is applied to this low frequency section to ensure that the method is applied where the GR is present and to improve the linearity of the events. The SSA method is then applied. The first 4 eigenimages are used to recover the GR.

Conclusions

When a low-pass filter is applied to a seismic section the result contains the full amplitude of the GR and amplitudes of the low frequency components of the signal. Given that the GR has a different velocity and amplitude than the signal, these events can be separated. This is achieved by recovering the first set of eigenimages from the SSA.

The GR is reconstructed using SSA on the low-pass filtered section. Afterwards, it is subtracted from the original data to attenuate the coherent noise without affecting the signal. The results show an improvement of the data signal to noise ratio. Also, the low frequencies of the reflections are better preserved by using SSA. This shows that the application of SSA after a low-pass filter can attenuate effectively the GR, maintaining the frequency content of the reflections.

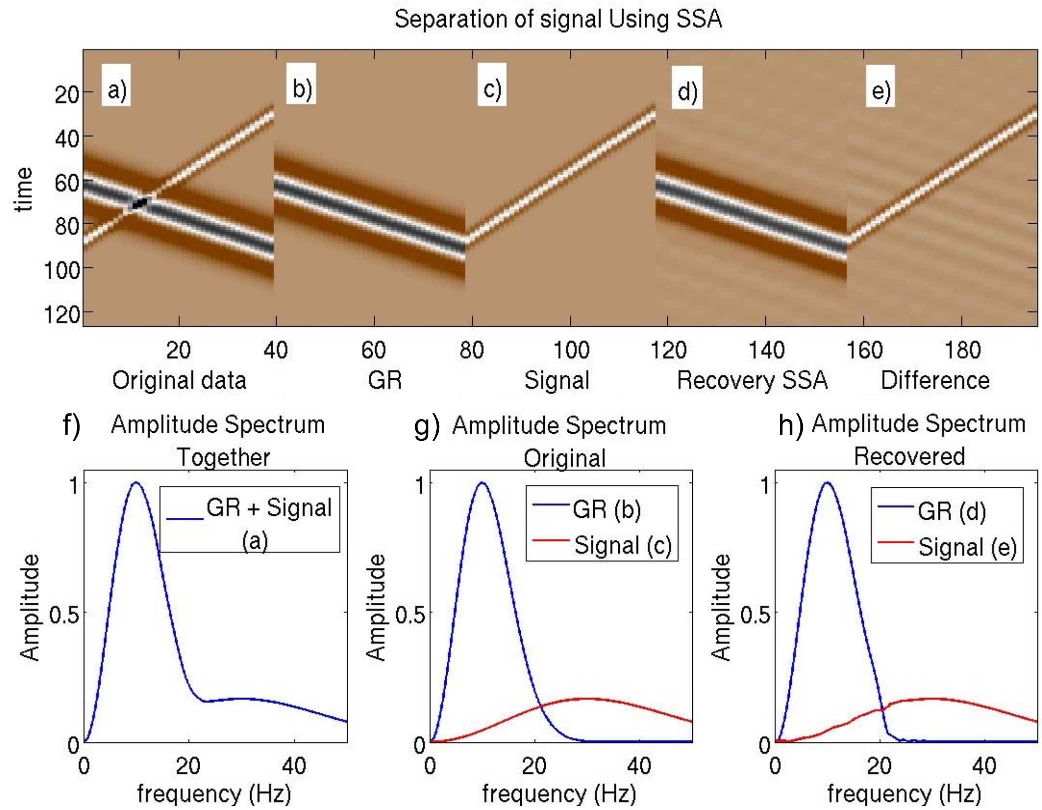

Figure 2: (a) Initial data presenting two events. (b) Low frequency event representing the GR. (c) High frequency event representing the reflection. (d) GR recovered from the first eigenimage of SSA. (e) Filtered data which result from the subtraction of (d) from (a). (f) Amplitude spectrum of (a). (g) Amplitude spectrum of (b) and (c). (h) Amplitude spectrum of (d) and (e). Figure 2 shows that there are no components of the signal in the recovered section (d). It is also evident in (h) that the signal (e) maintains its frequency content.

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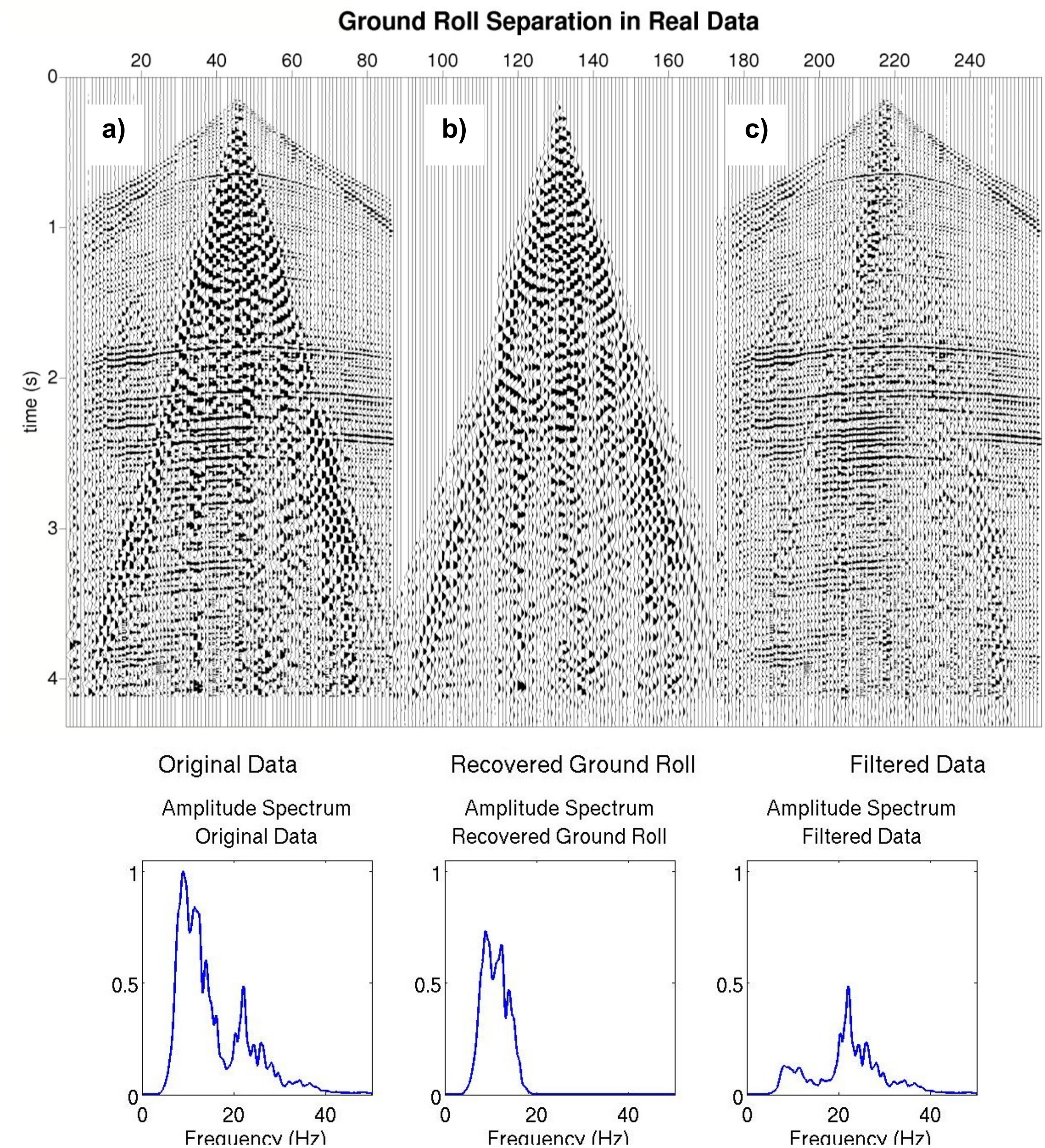

Figure 3: (a) Original Data (b) Recovered GR. (c) Filtered Data resulting from subtracting (b) from (a). Figure 3 presents the result of the application SSA to a real section. We can observe that the amount of signal present in (b) is very small. (c) Presents an improvement in its signal to noise ratio, while most of the low frequencies of the signal have been retained.