Recursive-iterative SSA method to filtering of the land seismic data

Ana Carolina C. Mançúr, Daniel Walter S. Mascarenhas, Michelângelo G. da Silva and Milton J. Porsani, CPGG/IGEO/UFBA and INCT-GP/CNPq/Brazil

This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society, held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Abstract

Normally the singular value decomposition (SVD) filtering is applied in the time $\times$ distance domain, exploring the spatial correlation between a set of seismic traces. In the present work we explore the Singular Spectrum Analysis (SSA) method in the time direction using a recursive-iterative algorithm. The SSA method extract the correlation between reflected events along the time variable and decompose seismic traces in the low (first eigenimage only) and high frequency parts (sum the rest of the eigenimages). We illustrate the effectiveness of this new approach to the prediction and subtraction of the ground roll and improve velocity analisys and stacking of the seismic data.

Introduction

The singular value decomposition method (SVD) for filtering of seismic data has become common in recent decades, as it promotes significant improvements of the signal-to-noise ratio, highlighting reflections in seismograms. Porsani et al. (2010, 2013) used SVD filtering to attenuate 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 which constitutes a sliding window. The SVD filtering process works as a multi-channel filter where several traces are used adaptively, allways in a sliding window (Porsani et al., 2010, 2013).

One particular way to apply SVD in a single (or multivariate) time series is the Singular Spectrum Analysis (SSA) method. It is based on the SVD of a specific matrix constructed upon the time series (Golyandina and Zhigljavsky, 2013). Within seismic processing, there are many papers applying SSA on constant-frequency slices in one or many spatial dimensions, for random-noise attenuation for 3D seismic data and for data reconstruction via multichannel SSA (Oropeza and Sacchi, 2011; Cheng, 2016).

We explore the SSA method in the time direction and apply a recursive-iterative SSA algorithm, which discard only the first eigenimage of the data matrix and sum the rest one, to decompose seismic traces in the low and high frequency parts. The computational implementation of the recursive-iterative SSA method may be done using a recursive scheme, increasing the size of the data matrix, by increasing the number of shifted traces. This improves the separation of the input data in a low-frequency and high-frequency component. This separation may be further improved by adding iterations and restarting the recursion with the remaining high-frequency component.

The recursive-iterative SSA method was apply on land seismic data of the Tacutu basin located in the north of Brazil. This basin consist of a aborted rift and has a area about of 15000 km^2. The geological structures tends to NE-SW direction and this strutuctures are related to a extensional regime, that is, it is possible to see normal falts, horts, grabens and some other associated to this context.

Singular Spectrum Analysis - SSA Method

Below we summarize the SSA as presented in Silva et al. (2016) as single-channel Singular Value Decomposition. Let the vector $\mathbf{d} = (d_1, \ldots, d_M)^T$ represent the seismic trace and $\mathbf{D}_N$ represent the matrix with the seismic trace shifted in each column. τ represents the variable associated with the time shift, $\tau = 0 \ldots, N-1$. Matrix $\mathbf{D}$ has dimensions, $(M+N-1) \times N$.

$$\mathbf{D}_N = \begin{bmatrix} \mathbf{d} & 0 & \ldots & 0 \\ 0 & \mathbf{d} & \ldots & 0 \\ \vdots & \vdots & & \vdots \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & \ldots & \mathbf{d} \end{bmatrix}. \quad (1)$$

The reduced SVD of the matrix $\mathbf{D}_N$ may be represented as (Golub and Van Loan, 1996),

$$D_N = \sum_{\tau=0}^{N-1} \sigma_\tau \mathbf{u}_\tau \mathbf{v}_\tau^T = \sum_{\tau=0}^{N-1} \widetilde{\mathbf{D}}_{N\tau}, \quad (2)$$

where $\widetilde{\mathbf{D}}_{N\tau} = \sigma_\tau \mathbf{u}_\tau \mathbf{v}_\tau^T$ represent the eigenimage of index τ associated to a ST-SVD decomposition of order N. We define a linear operator $J\{.\}$ such that once applied to the matrix $\mathbf{D}_N$ it: (i) remove the linear moveout, (ii) stack the columns of the matrix, and (iii) average the result. We note that by applying the operator to the matrix $\mathbf{D}_N$ we obtain the original seismic trace, the first column of the matrix.

$$J\{\mathbf{D}_N\} = \mathbf{d}. \quad (3)$$

So, by considering the SVD decomposition (equation 2) and using the $J\{.\}$ operator, it is possible to decompose the seismic trace in terms of N eigentraces,

$$J\{\mathbf{D}_N\} = \sum_{\tau=0}^{N-1} J\{\widetilde{\mathbf{D}}_{N\tau}\} = \sum_{\tau=0}^{N-1} \widetilde{\mathbf{d}}_{N\tau} = \mathbf{d}. \quad (4)$$

A recursive-iterative SSA method

The SSA method may be applied recursively, increasing the order of the $\mathbf{D}$ matrix. A lower frequency trace $\widetilde{\mathbf{d}}$, and its corresponding residue, $\mathbf{e} = \mathbf{d} - \widetilde{\mathbf{d}}$, may be computed following the steps:

- Initial vector: $\widetilde{\mathbf{d}}_0 = \mathbf{d}$;
- DO $\tau = 1, \ldots, N$;

  - Form the matrix $\mathbf{D}_\tau$ from $\widetilde{\mathbf{d}}_{\tau-1}$;

  - Form the first eigenimage $\widetilde{\mathbf{D}}_{\tau 0} = \sigma_0 \mathbf{u}_0 \mathbf{v}_0^T$;

  - Obtain the first eigentrace $\widetilde{\mathbf{d}}_\tau$,
- ENDDO

The vectors $\widetilde{\mathbf{d}}_N$ and $\mathbf{e}_N = \mathbf{d} - \widetilde{\mathbf{d}}_N$ correspond to the lower and higher frequency components of the seismic trace, respectively. We remark that only the first eigenimage of the matrix $\mathbf{D}_\tau$ is required to compute the first eigentrace. The obtaining can be done efficiently through the Power Method, (Golub and Van Loan, 1996).

We may iterate with the above procedure, by encompassing the above algorithm inside a loop of K iterations.

Results

The recursive-iterative SSA method was tested on a land seismic line RL-5089 from the Tacutu basin, Brazil. It contains 114 shots recorded at 4 ms sampling interval. There are 96 channels per shot in a split-spread geometry with sets from -2500 m to 2500 m and 50 m between the geophones. The distance between the shots is 200 m, giving a low CMP coverage of 12 fold. The Figure 1 show the steps of the seismic processing.

In the Figure 2 shows a shot-gather filtered. We have used the recursive-iterative approach with N = 4 (number columns of the matrix $\mathbf{D}_N$) and 4 iterations. The original data is shown in Fig. 2a and filtered one in Fig. 2b. The ground roll noise was greatly attenuated and reflections preserved and highlighted.

We use the method to attenuation of the linear events in shot gather domain. To this procedure was apply a linear moveout correction using the velocity of the direct wave and applied the recursive-iterative SSA method. The first eigenimage is discarded again. After the filtering a inverse linear moveout correction is apply on data. The Fig. 3a shows a shot-gather with linear events and filtered one in Fig. 3b.

The Figure 4 shows a supergather of the original and filtered data and its corresponding velocity spectrum. The original data and velocity spectrum are shown in Figs. 4a and 4b, and the supergather of the filtered data and its velocity spectrum in Figs. 4c and 4d. Better definition of the velocities may be identified between 1 s and 2.0 s. Already, in the supergather of filtered data, we have the major definition and continuity the of reflections events.

Figure 5 shows the stacked sections of the original and the filtered data. Original stacked section is shown in 5a, stacked section of the filtered data in 5b. The stacked section filtered has better temporal resolution and signal to noise.

The Figure 6 shows the corresponding average amplitude spectra. We can see that in the curve referring to the original data preserves high amplitude of the signal of low frequency. In the filtered data, we observed that the amplitudes of the low frequency data (associated with noise) were very small.

Conclusion

The recursive-iterative SSA method is a zero-phase process which effectively separates high frequency and low frequency parts in the data. The zero-phase property preserves the traveltime information in the data, and the low-frequency and high frequency amplitude parts are also preserved. The algorithm showed produce excellent results when applied pre-stack to ground roll attenuation and an excellent resolution in velocity analysis of the real seismic data from Tacutu basin.

References

Cheng, J.and Sacchi, M., 2016, Fast and memory-efficient singular spectrum analysis for seismic data reconstruction and denoising: SEG Technical Program Expanded Abstracts 2016, 4064–4068.

Golub, G. H. and C. F. Van Loan, 1996, Matrix computations: Johns Hopkins University Press.

Golyandina, N. and A. Zhigljavsky, 2013, Single spectrum analysis for time series: Springer.

Oropeza, V. and M. Sacchi, 2011, Simultaneous seismic data denoising and reconstruction via multichannel singular spectrum analysis: Geophysics, **76**, V25–V32. doi: 10.1190/1.3552706.

Porsani, M., M. Silva, P. Melo, and B. Ursin, 2010, An adaptive local-slope svd filtering approach to enhance events on seismic section: SEG Expanded Abstracts, **29**, 3717–3722.

Porsani, M., B. Ursin, M. G. S. Silva, and P. E. M. Melo, 2013, Dip-adaptive singular-value decomposition filtering for seismic reflection enhancement: Geophysical Prospecting, **61**, 42–52.

Silva, M., M. Porsani, and B. Ursin, 2016, A single-trace singular value decomposition method with application to the ground-roll removal: 86th Annual Meeting, Dallas, Expanded Abstract, 4659–4663.

Acknowledgements

The authors wish to express their gratitude to brazilian agencies: INCT-GP/CNPq/MCT, CAPES, PETROBRAS, ANP and FINEP for financial support.

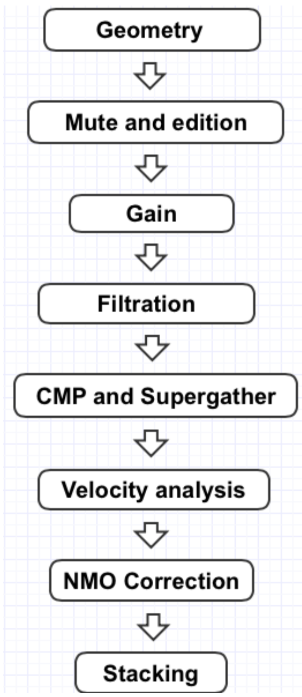

Figure 1: Flowchart of the seismic processing

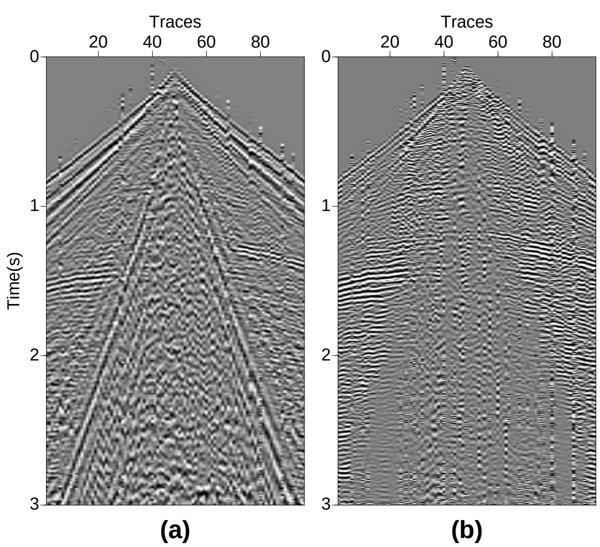

Figure 2: Ground roll filtering. The original shot gather in (a) and the high-frequency part in (b).

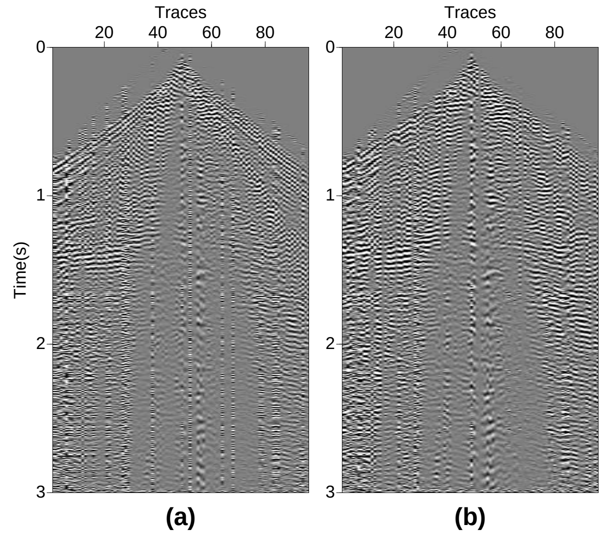

Figure 3: Direct wave filtering. The shot gather after ground roll attenuation (a) and shot gather obtained after the direct wave attenuation in (b).

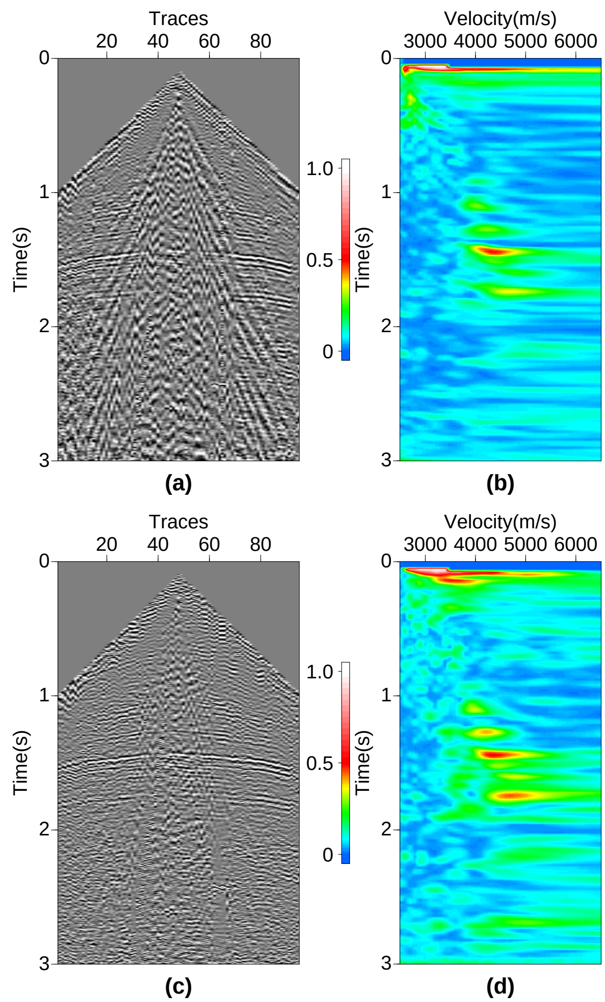

Figure 4: Supergather and velocity spectrum of the original data in (a) and (b) and supergather and velocity spectrum of the filtered data in (c) and (d).

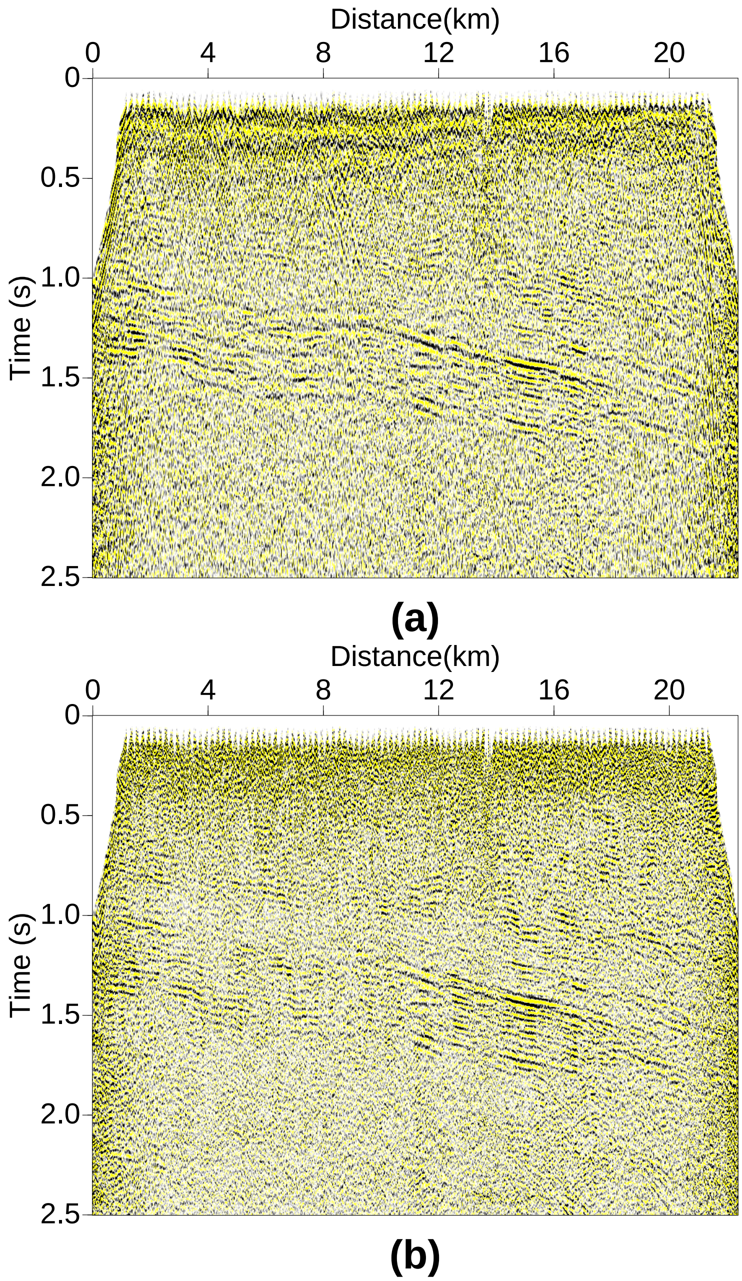

Figure 5: Stacked sections. Original stacked section in (a) and stacked section of the filtered data in (b).

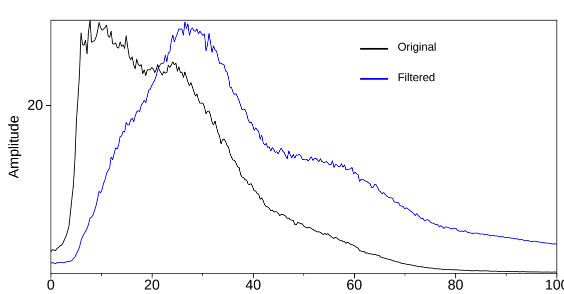

Figure 6: Amplitude spectrum with the curve referring to the original stacked section and the filtered stacked section.