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USING SVD FILTERS FOR VELOCITY ANALYSIS AND GROUND-ROLL ATTENUATION

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ABSTRACT. This study investigates the adaptive filtering approach based on the Singular Value Decomposition (SVD) method to improve velocity analysis and ground-roll attenuation. The SVD filtering is an adaptive multichannel filtering method where each filtered seismic trace keeps a degree of coherence with the immediate neighboring traces. Before applying the adaptive filtering, in order to flatten the primary reflections the seismogram is corrected using the Normal Move Out (NMO) method. The SVD filtering helps to strengthen the spatial coherence of reflectors. It works as multichannel and can be applied by selecting a set of seismic traces taken from around the target trace. Thus traces from different shots can be represented by a five-point areal operator, which we call five-point cross operator. In this paper we run this operator along the coverage map of the seismic survey. At each operator position, the filtered trace (center of the operator) is obtained by taking the first or adding the first eigenimages. Thereby we enhance the coherence corresponding to the primary reflections in detriment of the remaining events (ground-roll, multiples, and other non-correlated events) remained in the other eigenimages. The method was tested on a seismic line of the Tacutu Basin, Brazil. The obtained results show the velocity spectra with better definition, as well as better post-stacked section exhibiting better continuity of seismic reflections and lower noise, compared with the raw processing results (without SVD filtering).

Keywords: CMP stacking, seismic processing, SVD filtering, ground-roll attenuation, velocity analysis.

RESUMO. No presente trabalho aplicamos o método de filtragem adaptativa baseada no método SVD (*Singular Value Decomposition*) para a melhoria da análise de velocidades e atenuação do ruído coerente associado à fonte sísmica (*ground-roll*). A filtragem SVD pode ser vista como um método de filtragem adaptativa multicanal onde cada traço filtrado guarda certo grau de coerência com os traços imediatamente vizinhos. Antes da aplicação do método é feita a correção de decalagem normal (*normal move out – NMO*) dos sismogramas, tendo como finalidade deixar as reflexões de interesse aproximadamente horizontais. A filtragem SVD permite reforçar a coerência espacial dos refletores. Ela trabalha na forma multicanal e pode ser aplicada seguindo um procedimento padrão que consiste na seleção de um conjunto de traços tomados ao redor do traço alvo da filtragem. Desta forma traços de diferentes tiros podem ser utilizados na filtragem SVD. A coleta de traços pertencentes a diferentes tiros, no mapa de cobertura, pode ser representada por um operador espacial de cinco pontos que denominamos de operador em cruz. No presente trabalho utilizamos um operador de cinco pontos que opera sobre todos os traços do mapa de cobertura do levantamento sísmico. A cada posição do operador, o traço filtrado (centro do operador) é obtido tomando-se a primeira ou somando-se a(s) primeira(s) autoimagem(ns) do painel de 5 traços selecionados. Desta forma, reforçamos a coerência correspondente às reflexões primárias, em detrimento dos eventos restantes (*ground-roll*, múltiplas e demais eventos não correlacionados), localizado nas demais autoimagens. O método foi testado sobre uma linha sísmica terrestre da Bacia do Tacutu, Brasil. Os resultados obtidos mostram espectros de velocidades com melhor definição, como também seções empilhadas exibindo melhor continuidade das reflexões e menor ruído *ground-roll*, comparado com os resultados do processamento bruto (sem a filtragem SVD).

Palavras-chave: empilhamento CMP, processamento sísmico, filtragem SVD, atenuação do *ground-roll*, análise de velocidade.

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INTRODUCTION

The quality of the stacked section is directly correlated to a good estimate of the velocities used in the NMO correction, the so-called NMO velocity (v_{NMO}). This estimation is performed in the velocity analysis stage, in which the NMO velocity is defined manually on the semblance of some previously selected CMP's. Velocity analysis uses a semblance measurement within a time window to choose the best velocity profile along the trajectory of the hyperbolic reflection events. Low S/N (signal/noise) ratio directly affects the quality of the velocity spectrum, which is one of the problems with NMO velocity estimation thus impacting the final quality of the seismic image generated by CMP stacking.

SVD filtering method has important applications in seismic data processing. SVD filtering can be used to enhance spatial coherence of the seismic data by strengthening reflections while simultaneously attenuating the coherent noise. This technique has been implemented and applied to various kinds of problems in seismic data processing (Freire, 1986; Freire & Ulrych, 1988; Bekara & van der Baan, 2007; Porsani et al., 2009, 2010a,b).

Kendall et al. (2005) use the SVD method to obtain polarization filters for ground-roll attenuation of multicomponent data. Tyapkin et al. (2003) use events alignment method to flatten the noise in one or more horizontal sections of common shot point seismograms. In each section, the coherent noise (ground-roll) is preserved in the first eigenimages. The other eigenimages represent the signal and are transformed back to the time-space domain. Chiu & Howell (2008) proposed a method that uses SVD to generate eigenimages, which represent the coherent noise in a given window in the time-space domain. The data within the windows are transformed into analytical signal, followed by the SVD decomposition complex, when eigenimages are extracted from the coherent noise.

SVD filtering, as used by Porsani et al. (2009, 2010a,b), operates with the SVD decomposition of a subset of traces extracted from a 2D seismic line or 3D seismic volume. Only one trace from within the mobile window (2D or 3D), associated with the first eigenimages, is chosen to represent the filtered trace. This procedure preserves the relative amplitude while enhancing the continuity and consistency of reflection events, further reducing the noise associated to the other eigenimages that are discarded.

In this paper we use the method proposed by Porsani et al. (2010b) for processing one onshore (land) seismic line. In this case the filtering process uses seismic traces collected in areas of common shot point and common midpoint gathers. We illustrate the SVD filtering method showing the results obtained using a subset of traces of this seismic line from the Tacutu Basin. The results show that the SVD filter is capable of increasing the velocity resolution of the spectra as well as attenuating the ground-roll from the final stacked section.

SVD FILTERING

Considering the subset of M seismic traces selected from a 2D seismic section or a 3D seismic volume given by: $d(t, x_n)$, $t = 1, \dots, N_t$ and $n = 1, \dots, M$. The data matrix $D = [d_1 \dots d_M] = \{d(t, x_1), \dots, d(t, x_M)\}$, $t = 1, \dots, N_t$ can be decomposed by the singular value decomposition (SVD) method as shown below (Golub & Van Loan, 1996).

$$D = U \Sigma V^T \tag{1}$$

where, U and V are orthogonal and unitary matrices such as $U^{-1} = U^T$ and $V^{-1} = V^T$.
$\Sigma = diag\{\sigma_1, \dots, \sigma_M\}$ matrix of singular values $(M \times M) \sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_M \geq 0$;
$U = [u_1 \dots u_M]$ matrix of eigenvectors $(N_t \times N_t)$ associated with the time dimension;
$V = [v_1 \dots v_M]$ matrix of eigenvectors $(M \times M)$ associated with the space dimension.

When $\tilde{U} = U\Sigma = [\sigma_1 u_1 \dots \sigma_M u_M]$, we can rewrite equation (1) as follows,

$$\begin{aligned} \begin{bmatrix} d_1 & \dots & d_j & \dots & d_M \end{bmatrix} &= \tilde{U} V^T \\ &= \begin{bmatrix} \sigma_1 u_1 & \dots & \sigma_M u_M \end{bmatrix} \begin{bmatrix} V_1^T \\ \vdots \\ V_M^T \end{bmatrix} \\ &= \begin{bmatrix} \sigma_1 u_1 & \dots & \sigma_j u_j & \dots & \sigma_M u_M \end{bmatrix} \\ &\times \begin{bmatrix} v_{1,1} & \dots & v_{1,j} & \dots & v_{1,M} \\ \vdots & \dots & \vdots & \dots & \vdots \\ v_{M,1} & \dots & v_{M,j} & \dots & v_{M,M} \end{bmatrix} . \end{aligned}$$

From the above relations we get the equation for SVD decomposition of one trace of the subset of M traces from the original section.

$$\begin{aligned} d_j &= \begin{bmatrix} \sigma_1 u_1 & \dots & \sigma_M u_M \end{bmatrix} \begin{bmatrix} v_{1,j} \\ \vdots \\ v_{M,j} \end{bmatrix} \\ &= \widehat{d_1^J} + \cdots + \widehat{d_k^J} + \cdots + \widehat{d_M^J} \\ &= \sum_{k=1}^{M} \sigma_k u_k v_{k,j} . \end{aligned} \tag{2}$$

Note that the seismic trace $d(t, x_j)$ (columns j of matrix D) can be obtained by the linear combination of eigenvectors associated with the time dimension. The weights used in the linear combination are the coefficients of the eigenvectors associated with the spatial dimension scaled by the corresponding singular values.

Another way to write equation (1) is as follows,

$$\begin{aligned} D &= \begin{bmatrix} u_1 & \dots & u_M \end{bmatrix} \begin{bmatrix} \sigma_1 v_1^T \\ \vdots \\ \sigma_M v_M^T \end{bmatrix} \\ &= \sigma_1 u_1 v_1^T + \dots + \sigma_M u_M v_M^T \\ &= \hat{D}_1 + \dots + \hat{D}_k + \dots + \hat{D}_M \\ &= \sum_{k=1}^{M} \sigma_k u_k v_k^T \,. \end{aligned} \tag{3}$$

$\hat{D}_k = \sigma_k u_k v_k^T$ is an unitary matrix also known as eigenimage k of the data matrix D, while $\widehat{d_k^J}$ in equation (2) is the trace j of eigenimage $\hat{D}_k$.

Equation (2) represents the SVD decomposition of one trace, while equation (3) represents the SVD decomposition of the whole image associated with the original matrix. Limiting the summation in these equations, we can obtain approximate representations of either each separate seismic trace or the entire image.

The first singular values have the highest amplitude causing the associated eigenimages to preserve the features of higher spatial correlation (Freire, 1986). Thus, the first eigenvectors are responsible for the reconstitution of predominantly horizontal or sub-horizontal events of high magnitude. Porsani et al. (2009) used this method to emphasize the horizontal and sub-horizontal events and to attenuate inclined events associated with the ground-roll.

For each trace of a 2D seismic section or a 3D volume that needs to be filtered, a subset of immediate neighboring M traces is collected to perform the SVD decomposition of the corresponding data matrix and partially restore the $\tilde{d}_j$ trace through the equation,

$$\tilde{d}(t, x_j) = \sum_{k=1}^{K} \sigma_k u_k(t) v_k(x_j)\,. \tag{4}$$

Thus, the trace $\tilde{d}(t, x_j)$ obtained from the first K eigenvectors represents the filtered trace. The first eigenvectors, that is, the small values of K, are responsible for generating traces, sections and volumes, with stronger spatial coherence. Thus, the SVD filtering can be seen as a multichannel filtering method where each filtered trace keeps a degree of consistency with immediate neighboring traces.

The proposed SVD filtering method consists of the systematic application of equation (4) over all traces of a seismic line or a 3D volume, following the procedure:

(i) Selection of the subset of M traces immediately neighboring each trace $d(t, x_j)$ of the section or seismic volume;

(ii) SVD decomposition; and,

(iii) Partial reconstitution of the trace $\hat{d}(t, x_j)$ using only the singular K values.

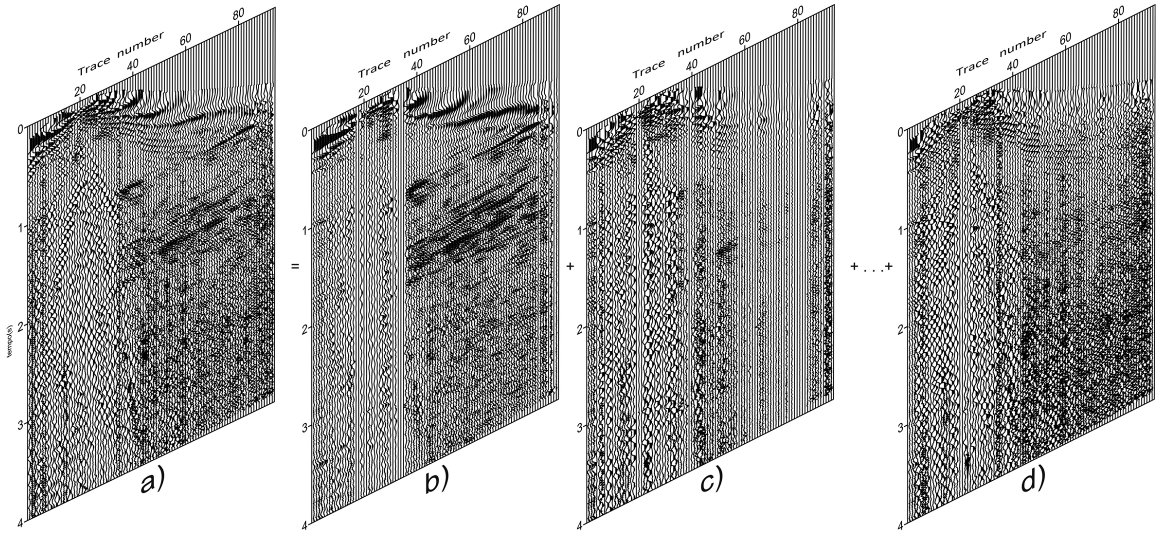
Figure 1 shows the schematic representation of SVD decomposition of the D matrix (seismogram). It is possible to verify that each eigenimage contributes to the building of D, proportionally to the magnitude of the corresponding singular value.

The 2D or 3D operator of the SVD filtering is shifted spatially over all data of the 2D section or the 3D seismic volume. A natural application of SVD filtering is to choose an odd number of traces and the central target trace of the operator as the trace we want to filter. At each new operator position, the SVD decomposition is performed and a new filtered trace is generated. The result represents the filtered seismic volume with the same dimensions of the input data.

METHOD APPLICATION

The SVD filtering method was applied to the 204-RL-242 land seismic line from the Tacutu Basin. The line contains 462 shots with a sampling rate of 4 ms. The survey used 96 channels per shot and split-spread geometry with asymmetric haul of 1050-100-0-100-3850 m. The distance between geophones (receivers) and between shot points was 50 m.

The pre-processing of the data was performed using the Focus software system including the following steps: data reading and importing, assembling of the acquisition geometry, static correction, editing and silencing of traces and amplitude correction (spherical divergence). Data was organized into groups of common midpoint (CMP) gathers, and a preliminary velocity analysis was then performed. Subsequent to the NMO correction, data was reorganized into shot gathers, and the SVD filter was applied using a cross operator. Finally, after applying an inverse NMO, the filtered data was grouped according to CMP gathers and the stacked section was generated.



$$\mathbf{D} = \sigma_1 \mathbf{u}_1 \mathbf{v}_1^T + \ldots \sigma_2 \mathbf{u}_2 \mathbf{v}_2^T + \sigma_M \mathbf{u}_M \mathbf{v}_M^T$$

$$\mathbf{D} = \widehat{\mathbf{D}}_1 + \widehat{\mathbf{D}}_2 + \ldots + \widehat{\mathbf{D}}_M = \sum_{k=1}^{M} \sigma_k \mathbf{u}_k \mathbf{v}_k^T$$

Figure 1 – Matrix D eigenimages resulting from the decomposition using SVD singular values. $\hat{D}_k = \sigma_k u_k v_k^T$ is the eigenimage of D data matrix. a) D Data Matrix; b) first eigenimage; c) second eigenimage; d) M eigenimage.

VELOCITY ANALYSIS

NMO correction is the basis for determining the velocities from seismic data. The calculated velocities can be used to correct the normal move out so that the reflections are flattened out in the traces of a CMP gather prior to stacking. Thus, the CMP stacking method depends on the availability of the velocity field which is obtained from the velocity analysis applied to the data.

Velocity analysis has limited accuracy and resolution due to several factors, especially the signal/noise ratio. Thus the accuracy of the velocity spectrum is limited when the signal to noise ratio (S/N) is low. The presence of random noise of relatively strong intensity in a CMP family will hamper the signal strength along the hyperbolic paths. Some events may be chopped while others will be difficult to distinguish due to the presence of high noise level.

Various options such as the use of a band-pass filter and automatic gain control (AGC) may be used to improve the velocity spectrum especially when the input CMP gathers have a low signal to noise ratio.

Therefore, SVD filtering was used to generate a more coherent velocity spectrum that allows both a good estimate of the velocities to be applied in the NMO correction and a better quality final stacked section.

AREAL SVD FILTERING (CROSS) OPERATOR

SVD filtering, as used by Porsani et al. (2009), is made on a panel of seismic traces corrected for NMO in the common shot point domain. A moving window of three or five traces, for example, collects the traces along the entire panel, and submits them to SVD filtering. However, the geometry of the field survey allows other traces of neighboring shots to be used as well. Therefore, we developed a SVD filtering operator that filters the target trace using the closest neighboring traces of each CMP of the data. In this case, we selected the central trace and the four immediately neighboring traces, thereby resulting in a cross shape operator (Fig. 2). This 5-point spatial operator operates covering the entire survey map, extracting the five traces that undergo the SVD filtering. After trace selection, the SVD decomposition is performed and a new filtered trace is generated in the position of the central trace of the operator.

Figure 3 shows the velocity analysis in the supergather formed by 50 CMP's gathers. Ground-roll present in the data seriously degrades the velocity analysis. The same supergather after using the SVD cross operator filtering, along with its velocity spectrum is shown in Figure 4. It is observed that in this velocity spectrum the maximum semblance values are better defined than the one shown in Figure 3.

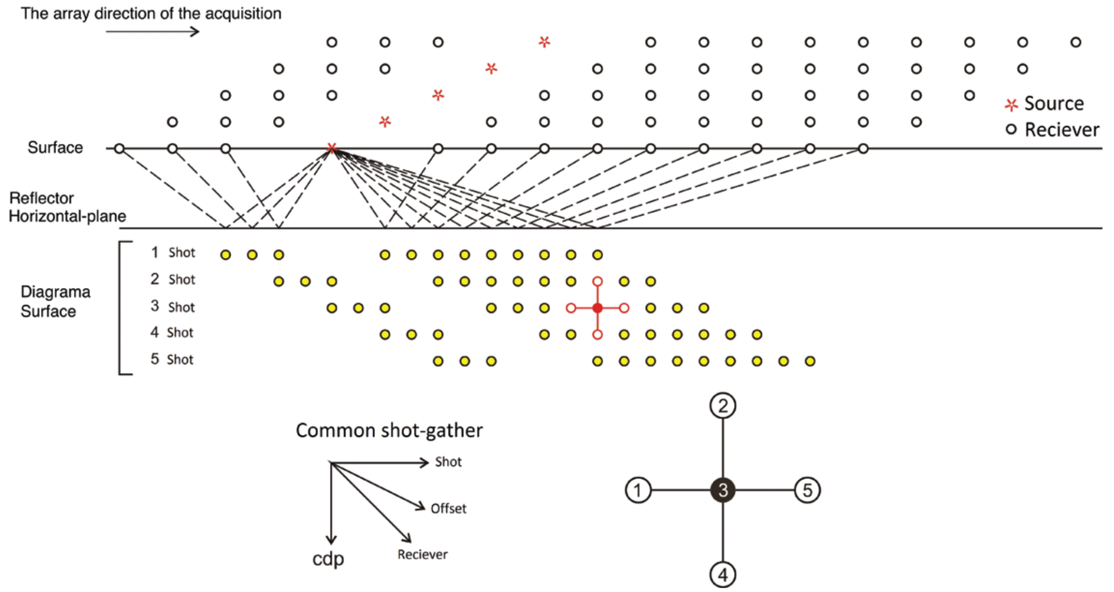


Figure 2 – Coverage map and the five-point spatial operator adopted to select the traces, using as reference the central trace (SVD filtering target) represented by the filled circle.

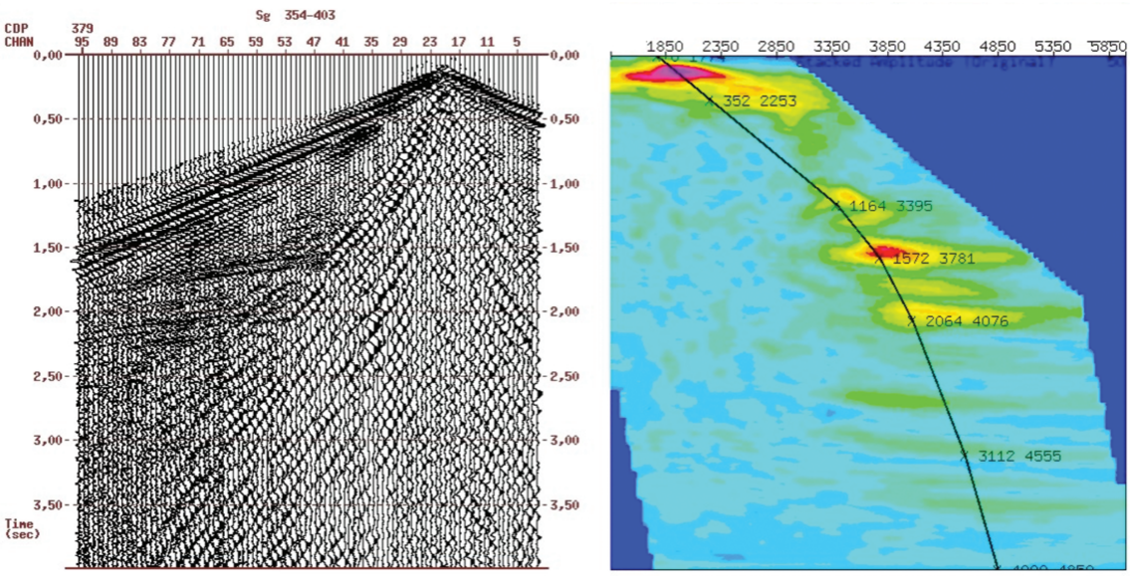


Figure 3 – Original data and the corresponding velocity spectrum.

Figure 5 shows the NMO corrected original shot (Fig. 5a), the shot filtered with the SVD cross-operator method associated with the first eigenimage (Fig. 5b) and the SVD filtered shots with the second, third and fifth eigenimages in Figures 5c and 5d, respectively. We can see that the first eigenimage preserves most events correlated with the seismic trace. Figure 6 shows the seismograms after the inverse NMO correction of the data in Figure 5. The average amplitude spectrum, which corresponds to the results of Figure 6, is shown in Figure 7. It can be observed that the low frequency content is mostly concentrated in the second to fifth eigenimages while the first eigenimage is noticeably smaller, that is, the SVD filtering removes a substantial part, but not all of the low frequency of the original data.

Figure 8 shows the results obtained with the SVD and the classic F-K filtering methods. Figure 8a shows the original common shot gather. The F-K and SVD filtering results are shown

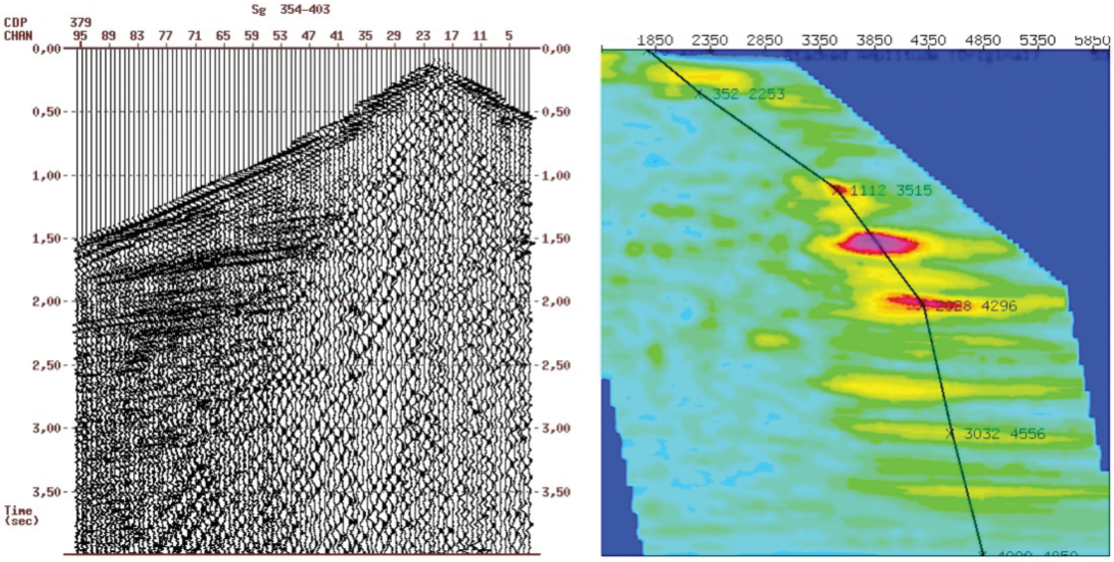
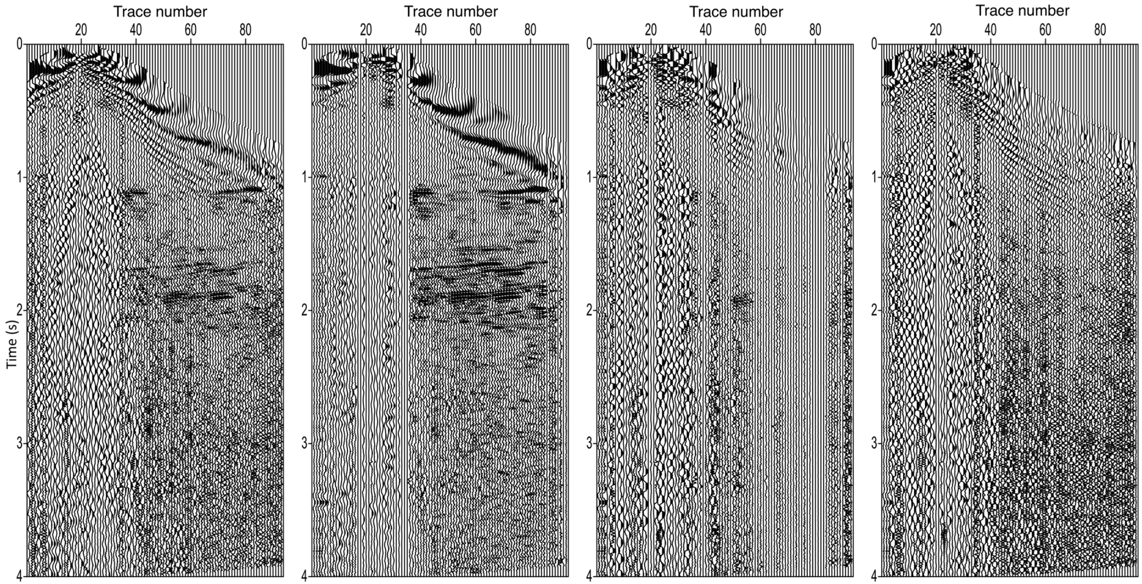


Figure 4 – SVD filtered data using the cross operator and the corresponding velocity spectrum.



(a) (b) (c) (d)

Figure 5 – SVD filtering results (cross operator) for a group of NMO corrected common shot. a) the original data; b) SVD filtered data with the first eigenimage; c) second eigenimage; and d) third, fourth and fifth eigenimages, respectively.

in Figures 8b and 8c, respectively. The SVD filtering using the cross operator displays the best results since it removed the noise more effectively than the F-K filter. Figure 9 shows the CMP stacked sections for the data from the Tacutu Basin, as well as the original stacked seismic section (Fig. 9a), and the stacked section after the SVD filtering using the cross operator (Fig. 9b). Significant attenuation of the noise and improved definition of the reflectors are observed, which are clearly seen when comparing the results shown in Figures 10a and 10b, showing a detail of Figure 9.

CONCLUSIONS

SVD filtering is an adaptive multichannel filtering method where each filtered trace keeps a certain coherence degree with immediately neighboring traces. The method can be used pre and post-

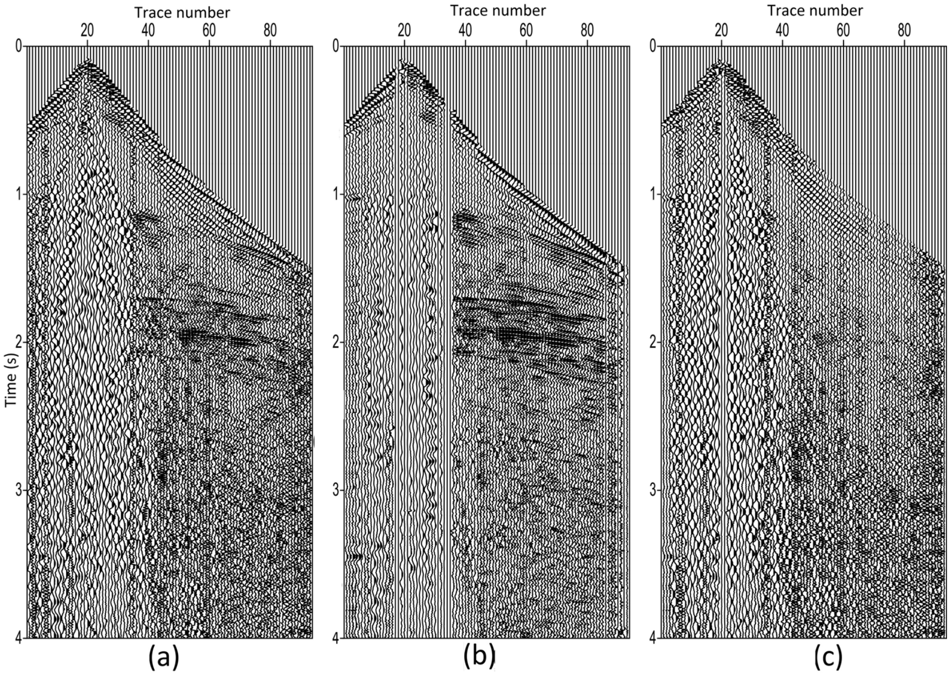


Figure 6 – SVD filtering results (cross operator) after applying the inverse NMO correction in the seismograms of Figure 5. a) original data; b) SVD filtered data (cross operator) with the first eigenimage (signal); and c) other eigenimages from the SVD decomposition.

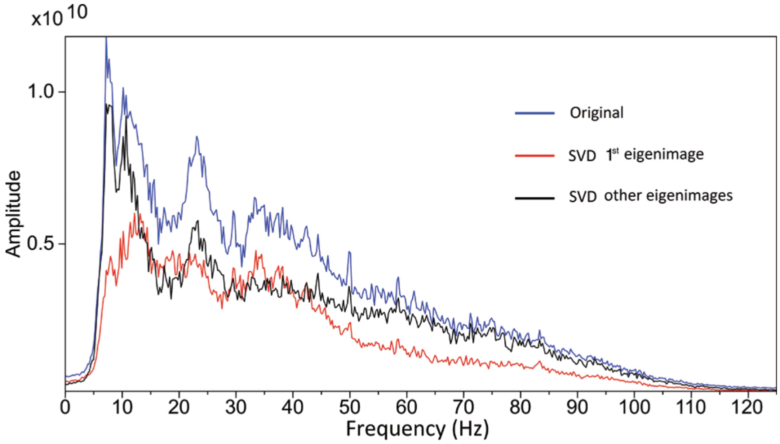


Figure 7 – Average amplitude spectrum of the seismograms shown in Figure 6.

stacking, using mobile linear operators (extracted from a single domain: CMP, common point shot, common offset domain), or areal operators using traces of two domains (common shot point and offset, for example).

The method was tested in an onshore (land) seismic line from the Tacutu Basin. The results show velocity spectra with better definition than with no filtering, as well as stacked sections exhibiting better continuity of the reflections and lower ground-roll noise, as compared with the results of raw processing (without SVD filtering).

The results presented in this paper show the effectiveness of the adaptive SVD filtering method to attenuate ground-roll and improve consistency of reflectors in the seismic sections. SVD filtering enables an increase in the signal/noise ratio, a limiting factor in the resolution of velocity spectra and analysis. The proposed method is very efficient, easy to implement and with a computational cost equivalent to multichannel filtering methods such as, F-K and deconvolution.

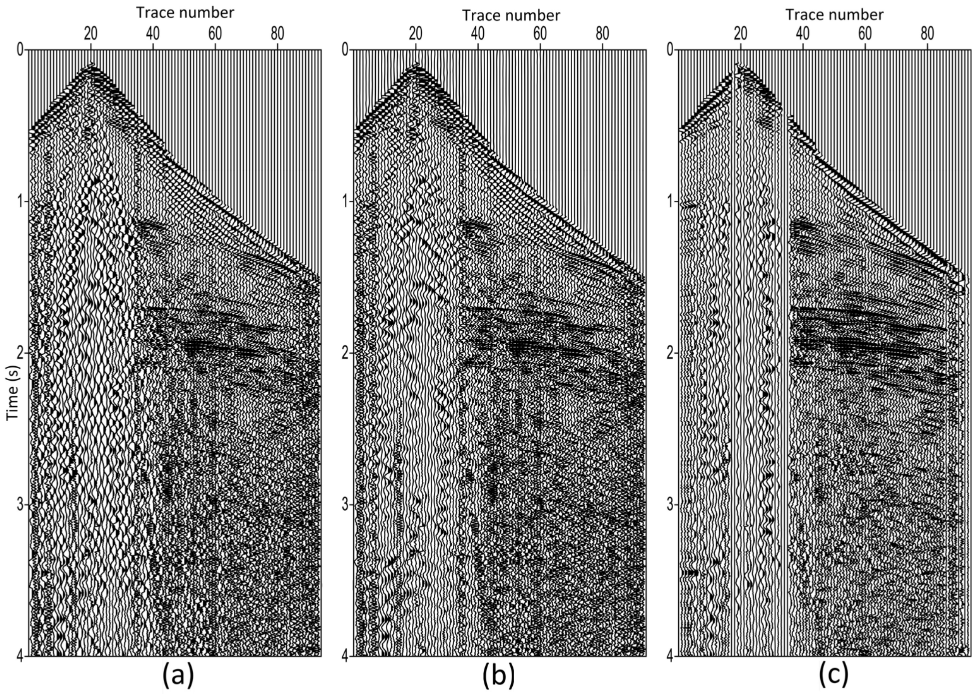


Figure 8 – Comparison of the results between F-K and SVD filterings (cross operator). (a) Original data; (b) F-K filtering results; and (c) SVD filtering (cross operator) results.

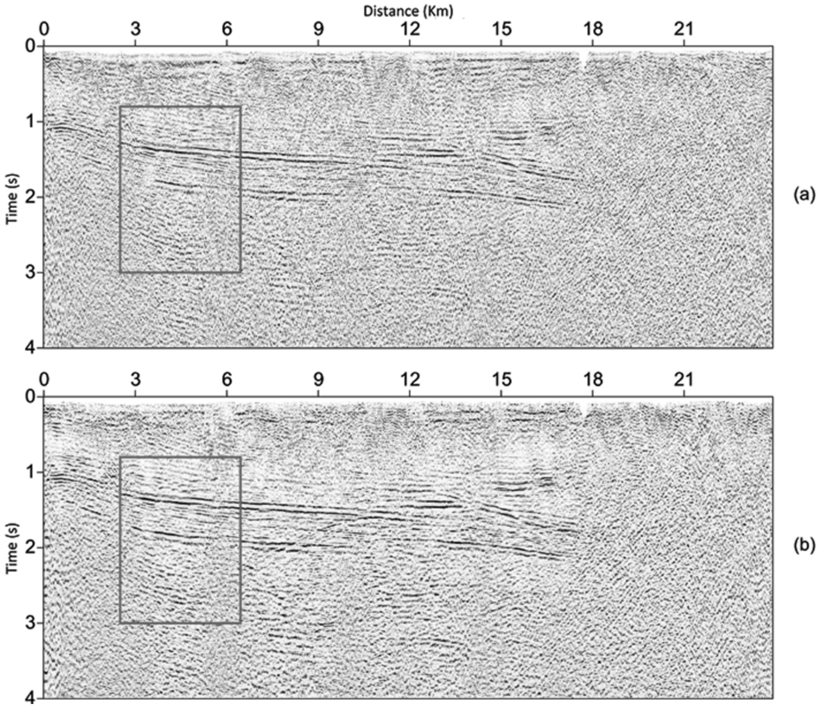


Figure 9 – Stacked sections. (a) original data; and (b) SVD filtered data (using the cross operator).

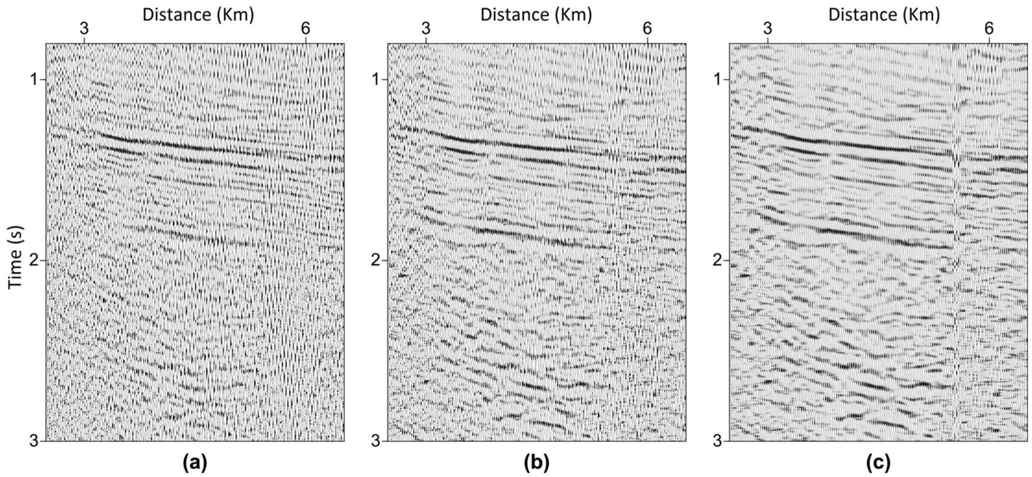


Figure 10 – Details of the stacked sections. (a) original data; (b) SVD filtered data (cross operator); and (c) post-stacking SVD filtering results.

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