Reflectivity estimation using minimum-delay seismic trace decomposition

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ABSTRACT

Spiking deconvolution corrects for the effect of the seismic wavelet, assumed to be minimum delay, by applying an inverse filter to the seismic trace to get an estimate of reflectivity. In order to compensate for propagation and absorption effects one may use time-varying deconvolution where a different inverse filter is computed and applied for each output sample position. We modify this procedure by estimating a minimum-delay wavelet for each time-sample position of the seismic trace. This gives a decomposition of the seismic trace as a sum of minimum-delay wavelets, each multiplied by a reflectivity coefficient.

The reflectivity estimation is a single-trace process which is sensitive to non-white noise, and it does not take into account lateral continuity of reflections. We therefore have developed a new data processing strategy by combining it with adaptive SVD filtering. The SVD filtering process is applied to the data in two steps. First, in a sliding spatial window on NMO-corrected CMP or common shot gathers. Next, after local dip estimation and correction, on local patches in common-offset panels. After the SVD filtering, we apply the new reflectivity estimation procedure. The SVD filtering removes noise and improves lateral continuity while the reflectivity estimation increases the high-frequency content in the data and improves vertical resolution.

The new data processing strategy was successfully applied to land seismic data from North-east in Brazil. Improvements in data quality are evident in prestack data panels, velocity analysis and the stacked section.

INTRODUCTION

Prediction error filtering is one of the most commonly used techniques for processing seismic data (Robinson, 1980; Yilmaz, 1987). Prediction error filtering can be classified in two types: spiking deconvolution (Robinson, 1967) which aims at removing the effect of the seismic wavelet from the data, and predictive deconvolution (Peacock and Treitel, 1969) which aims at attenuating ringing and multiple reflections. In spiking deconvolution (Leinbach, 1995) a seismic trace is assumed to consist of a wavelet convolved with a reflectivity series (the response of the earth) plus additive noise. The reflectivity series and the noise are assumed to be uncorrelated with the statistical properties of random white noise. The wavelet is assumed to be minimum delay (Robinson, 1980). With these assumptions the autocorrelation function of the trace can be used to compute the spiking deconvolution filter by the (Levinson, 1947) algorithm.

This method is very robust, but the results are poor when the wavelet is mixed delay (Robinson, 1980; Yilmaz, 1987). When the wavelet is known, it can be used to design a pulse-shaping filter (Berkhout, 1977) so that the output is a minimum-delay wavelet. The wavelet can also be estimated from data and then used to compute an inverse filter (Porsani and Ursin, 1968; Ursin and Porsani, 2000). The filtered seismic trace is then an estimate of the reflectivity series. Misra and Sacchi (2007) and Misra and Chopra (2010) deconvolve the data with a standard spiking deconvolution filter. From the filtered, whitened data they estimate an all-pass phase filter which is then applied to the whitened data. This, again, represents an estimate of the reflectivity series. Van der Baan (2008) estimates the phase of the wavelet in a data window using kurtosis maximization. Combined with an estimate of the amplitude spectrum of the wavelet, this is used to design an inverse filter. The procedure may be applied in several time windows to achieve a time-variant deconvolution filter.

Due to propagation and absorption effects in the earth the wavelet in the data is varying with time. To compensate for this a time-varying deconvolution filter (Clarke, 1968) may be applied. From the autocorrelation function of the data in a time gate a new deconvolution filter is computed and applied for each time sample position. Wang (1969) gave a procedure for optimal selection of the length of the time gate. Griffiths et al. (1977) used a conjugate-gradient method to compute the deconvolved output, without computing the filter coefficients.

Our method is different from these classical approaches. We, also, start with the data in a time gate. From the autocorrelation function we compute a spiking deconvolution filter which is minimum delay. The inverse of this is an estimate of a local minimum delay wavelet. This procedure is repeated for each time sample position. The seismic trace can be represented by a sum of these wavelets multiplied by the sample values of the reflectivity series. This is a linear equation where the data vector is equal to a lower triangular wavelet matrix times the reflectivity vector. This equation can be solved recursively to obtain the reflectivity series. The new procedure is similar to, but different from, time-varying deconvolution, and the result is also slightly different. As a valuable by-product we obtain the time-varying minimum-delay wavelets which can be used for interpretation.

The new method has been test on land seismic data from the North-east of Brazil. The data was acquired with an explosive source, so that there should not be a problem with the source wavelet in the data processing. In order to improve the data quality we first enhance reflections by adaptive SVD filtering (Porsani et al., 2010). This is first applied on NMO corrected shot gathers and next on local patches of dip-corrected data in common-offset panels. From the SVD filtered data we estimate the reflectivity series with our new method. We show that the two methods are complementary: the SVD filtering removes incoherent noise and laterally coherent events which are not primary reflections, and the recursive reflectivity estimation improves vertical resolution and increases the high-frequency content of the output data.

SEISMIC TRACE DECOMPOSITION

We consider a seismic trace $d(t), t = 0, 1, \ldots, L$, and choose a data window $d(k+j), j = 0, 1, \ldots L_d$. The local auto-correlation function is

$$R_k(\tau) = \sum_j d(k+j)d(k+j+\tau)\,, \quad \tau = 0, 1, \ldots, L_d \quad (1)$$

From this we use the Levinson (1947) algorithm to compute a damped spiking filter (Robinson, 1967)

$$[R_k(\tau) + \lambda^2\delta_\tau] * g_k(\tau) = \sigma^2\delta_\tau \quad (2)$$

where $*$ denotes time convolution, σ^2 is the minimum sum of the squared error terms, and

$$\delta_\tau = \begin{cases} 1 & \tau = 0 \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad g_k(\tau) = \begin{cases} 1 & \tau = 0 \\ 0 & \tau > L_f \end{cases} \quad (3)$$

The inverse of the spiking filter is a minimum-delay wavelet (Robinson and Treitel, 1980) computed directly from

$$g_k(t) * w_k(t) = \delta_t \quad \text{with} \quad w_k(t) = \begin{cases} 1 & t = 0 \\ 0 & t > L_w \end{cases} \quad (4)$$

The seismic trace is now expressed as a sum of minimum-delay wavelets

$$d(t) = \sum_k r_k w_k(t-k) \quad (5)$$

This can be written in vector-matrix notation as

$$\mathbf{d} = \mathbf{W}\mathbf{r} \quad (6)$$

where $\mathbf{W}$ is an $L \times L$ lower triangular matrix with elements 1 on the diagonal. This equation is solved recursively for $r_k, k = 0, \ldots, L$, which gives an estimate of reflectivity with time-varying minimum delay wavelets.

Time−variant deconvolution

In time-varying deconvolution we compute and apply a different filter for each time sample. We have already computed the filters, $g_k(\tau)$, in equation 2. The output of the deconvolution process is

$$\hat{r}_k = \sum_\tau d(t-k-\tau)g_k(\tau) \quad (7)$$

This can be written

$$\hat{\mathbf{r}} = \mathbf{G}\mathbf{d} \quad (8)$$

From this equation we get the decomposition

$$\mathbf{d} = \mathbf{G}^{-1}\hat{\mathbf{r}} \quad (9)$$

in terms of wavelets defined by the columns of $\mathbf{G}^{-1}$. It is of the same form as the decomposition in equation 6, but the wavelets are not necessarily minimum delay. The matrix $\mathbf{F} = \mathbf{G}\mathbf{W}$ is also lower triangular with elements 1 on the diagonal. It is, however, different from the identity matrix, so the decompositions in eq. 6 and 9 are different.

From equation 6 we have

$$\mathbf{r} = \mathbf{W}^{-1}\mathbf{d} \quad (10)$$

The lines of $\mathbf{W}^{-1}$ can now be considered as time-varying filter impulse responses. They are, however, not necessarily minimum delay.

In conclusion, the new process is a decomposition of the seismic trace in minimum-delay wavelets. The recursive estimate of the reflectivity may also be considered to be the output of a mixed-delay time-varying filtering procedure.

APPLICATIONS AND RESULTS

The proposed method was tested on a land seismic line from the Tacutu basin, located in the North-east of Brazil, with an explosive source.

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 first SVD filtering was applied using a sliding spatial window. After inverse NMO corrections, the filtered data is subject to local dip estimation and a second SVD filtering on common-offset panels. Details are given in Porsani et al. (2010). From these SVD filtered data we estimate the reflectivity series with the new method. The data may then be subject to a refined velocity analysis before NMO corrections and stack.

Fig. 1 shows a single shot gather before and after SVD filtering and SVD filtering followed by reflectivity estimation. It is seen that SVD filtering removes noise and improves lateral continuity and that reflectivity estimation improves vertical resolution and boosts high frequencies.

Fig. 2 shows stacked sections. The stacking velocities used for NMO corrections are the same for all sections. Fig. 2a shows the original data with no extra processing. In Fig. 2b reflectivity estimation is applied before SVD filtering, and in Fig. 2c the two procedures were applied in reverse order. Both section represent improvement as compared to the ones in Fig. 2a.

By inspecting the two sections we believe that the section in Fig. 2c has less noise than the section in Fig. 2b. Thus, the optimal data processing procedure is to apply SVD filtering followed by reflectivity estimation. The reason for this may be that the reflectivity estimation algorithm is sensitive to noise, so that it is better to apply SVD filtering, with removes noise, before reflectivity estimation.

CONCLUSIONS

We have developed a new method for estimating seismic reflectivity by decomposition of a seismic trace in minimum-delay wavelets. The method improves vertical resolution for a source wavelet which is close to minimum delay. For a mixed-delay source wavelet one may apply an all-pass phase filter before or after the reflectivity estimation.

We have also developed a data processing strategy for noise removal and signal enhancement by combining adaptive SVD filtering with reflectivity estimation. The SVD filtering removes noise and improves lateral continuity while the reflectivity estimation increases the high-frequency content in the data and improves vertical resolution. The new data processing strategy was successfully applied to seismic land data, showing improvements in the prestack domain and on the stacked section.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to INCT-GP/CNPq/MCT, PETROBRAS, ANP, FINEP, FAPESB Brazil for financial support. We also thank PARADIGM and LANDMARK 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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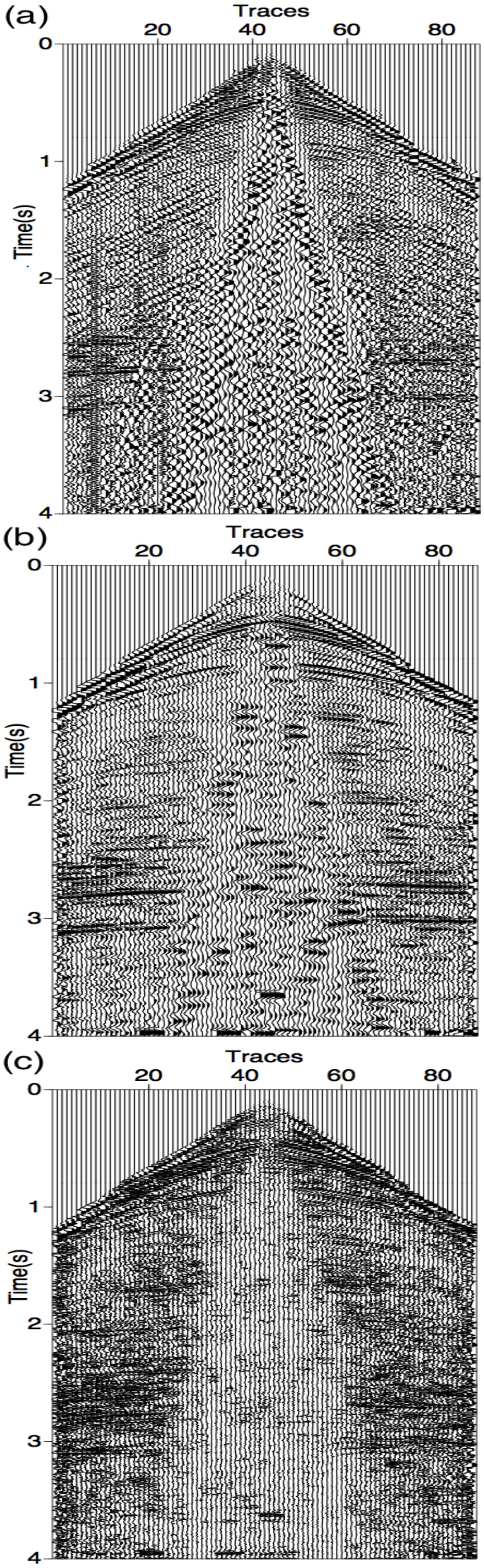

Figure 1: Input data in (a), after SVD filtering (b) and after SVD filtering followed by recursive reflectivity estimation (c).

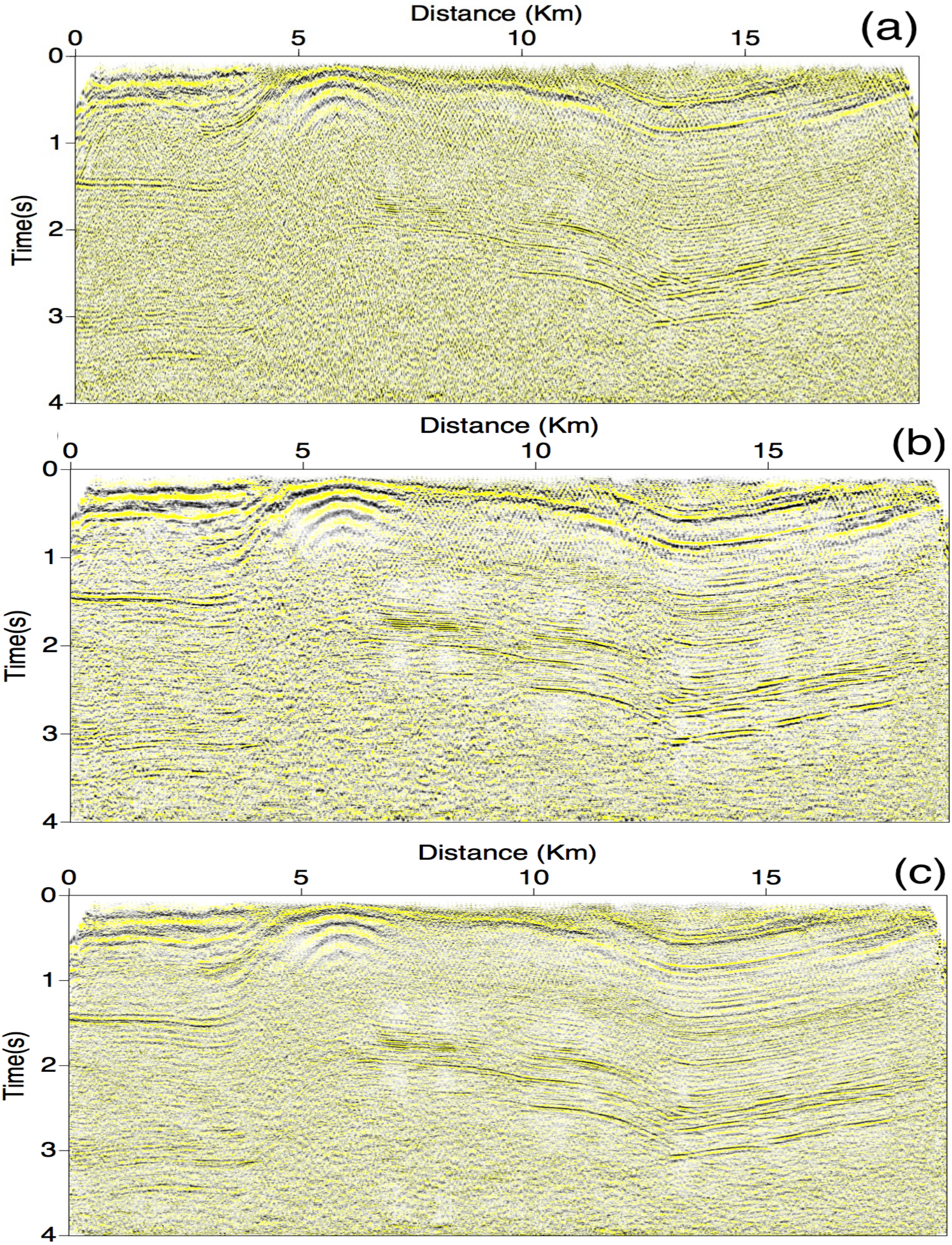

Figure 2: Stacked sections. Original data (a), after recursive reflectivity estimation followed by adaptive SVD filtering (a) and after adaptive SVD filtering followed by recursive reflectivity estimation (b).