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# GROUND ROLL ATTENUATION USING SHAPING FILTERS AND BAND LIMITED SWEEP SIGNALS

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**ABSTRACT.** Onshore seismic data often have low signal to noise ratio due to, among other factors, the presence of ground-roll, a noise characterized by coherent, linear and dispersive events with high amplitudes, low frequencies and velocities. This noise overlaps with reflections, hindering the data processing and interpretation. When the attempts to reduce the ground-roll during data acquisition (using source and receiver arrays) fail, several methods can be used in seismic processing. Here we discuss a filtering method based on Wiener shaping filter, its implementation and its main parameters. We also present a different approach based on the direct deconvolution algorithm. The results of the application of direct methods to a real seismic data set are quite satisfactory when compared with those obtained with conventional FK and low-cut filters.

**Keywords**: ground roll, shaping filters, seismic data processing.

**RESUMO.** Os dados sísmicos terrestres, geralmente, apresentam baixa razão sinal-ruído devido, entre outros fatores, à presença de *ground roll*, um ruído caracterizado por eventos coerentes e lineares, com altas amplitudes, baixas frequências temporais e baixas velocidades e, na maioria dos casos, dispersivos, que se sobrepõem às reflexões, prejudicando o processamento e a interpretação dos dados. Quando a tentativa de atenuar o *ground roll* durante a aquisição dos dados (utilizando arranjos de fontes e receptores) falha, diversos métodos podem ser empregados no processamento. Neste trabalho, discute-se um método de filtragem baseado no filtro de forma de Wiener, sua implementação e seus principais parâmetros. Também é apresentada uma variante do método, baseada no algoritmo de deconvolução direta. Os resultados da aplicação da filtragem direta em dados sísmicos reais são bastante satisfatórios, quando comparados com aqueles obtidos com os métodos convencionais FK e corta-baixas.

**Palavras-chave**: ruído de rolamento, filtros de forma, processamento sísmico.

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## INTRODUCTION

In the exploration for oil and gas the onshore seismic data usually present a low signal to noise ratio due to the presence of ground roll, generated by the Love and Rayleigh surface waves. Since the geophones used in land acqusitions usually only capture the vertical oscillations of the ground, in this article, ground roll will be used solely as a synonym of the Rayleigh's wave vertical component.

Ground roll appears as coherent and linear events in two-dimensional acquisition seismograms. In three-dimensional data, these events are approximately linear in record lines closer to the source, and hyperbolic in the farther lines. The main noise's characteristics are wide amplitudes, low temporal frequencies and velocities and, in most of the cases, the dispersion, that is the variation of the speed with the frequency. This last characteristic implies in long duration of the ground roll in the seismic traces, overlaping reflections.

Traditionally, when acquiring data, there is a first attempt of ground roll attenuation using source and receiver arrays. According to a technique known as stackarray (Morse & Hildebrandt, 1989), it is possible to determine field arrangements that, in accordance with certain premises, and associated with stacking, are capable to filter the noise's spatial frequencies. When success is not achieved, the attenuation is carried out during data processing.

Along the last decades, given the importance of the problem, several filtering methods were proposed. They take into consideration the different noise characteristics, such as coherence, temporal frequency and velocity (Claerbout, 1983; Saatçilar, 1988; Liu, 1999; Henley, 2003; Melo et al., 2009; Porsani et al., 2010). Two-dimensional filtering in the frequency domain, known as FK filtering, is a much used method applied in the temporal frequency and spatial domain. The FK method uses the 2D discrete Fourier transform (Embree et al., 1963; Wiggins, 1966) and linear events in the seismograms are mapped as linear events in the FK domain. The ground roll, represented by low velocity linear events, is mapped in the FK domain and, consequently, can be filtered suppressing the amplitudes inside the polygon that confines that noise in the FK domain. Despite the proved effectiveness of the FK method removing of linear events, it also interferes attenuating the primary reflections in the ground roll's frequency band.

This article studies the Karsli & Bayrak's proposal (2004), where a noise estimate is calculated using the available data and, later, subtracted. Wiener shaping filters are used for calculation, applied on a trace containing a referential 'noise', known as sweep, to adapt its amplitudes and phases to the contaminated seismic trace. A different approach is also presented, based on the direct deconvolution (Porsani & Ursin, 2007), that gives back the filtered data without the need of calculating the shaping filter, the input signal autocorrelation or the crosscorrelation between the input and the desired signal.

Results of the Wiener filtering method applied to real seismic data are analyzed and relevant aspects are discussed such as the frequency-band used in the sweep construction, the whitening coefficient and the filter's number of coefficients (that is equal to the iterations' number, in the case of direct filtering). The results are quite satisfactory when compared with the conventional FK and low-cut filters.

## WIENER-LEVINSON FILTERING METHOD

The use of the Wiener shaping filters for ground roll attenuation was originally proposed by Karsli & Bayrak (2004). Such filters have the property of transforming any digital signal into another wanted signal, and they are calculated through the least-squares method. The different modalities of Wiener filters and their applications can be found in Robinson & Treitel (2000) and Yilmaz (2001).

In the linear systems theory, the seismic trace can be represented as a result of the seismic pulse convolution with the ground impulse response, also called reflectivity function (Yilmaz, 1987). Mathematically it can be written,

$$x(t) = p(t) * z(t) + g(t) \tag{1}$$

where:
$x(t)$ – seismic trace
$p(t)$ – seismic pulse that accompanies each reflected event
$z(t)$ – impulse response or reflectivity function
$g(t)$ – additive noise

In this article, the term $g(t)$ only refers to the ground roll. A noise of additive nature can be subtracted from the seismic trace, provided it is known. Then, Karsli & Bayrak (2004) suggest, it should be estimated with a Wiener shaping filter, applied to a referential "noise", known as sweep or chirp. The word sweep describes an oscillatory signal of constant amplitude and limited band, whose instantaneous frequency varies monotonically with the time (Goupillaud, 1976). The shaping filter purpose is of adjusting the sweep's amplitudes and phases to the ground roll present in the seismic trace.

The choice of the sweep is due exactly to the variation of its frequency with time, what also happens with the ground roll, when dispersive. Analytically, it can be formulated as

$$s(t) = \begin{cases} \mathrm{sen}(2\pi F(t)t) & \text{to } 0 \leq t \leq T \\ 0 & \text{to } t < 0 \text{ and } t > T \end{cases} \tag{2}$$

where $T$ is its duration and $F(t)$ is the function that determines the frequency variation with time and, therefore, it determines its character, if it is linear or not. For the linear case, used in this article,

$$F(t) = f_i + \frac{f_f - f_i}{2T} t \,, \tag{3}$$

where $f_i$ and $f_f$ represent, respectively, the sweep's initial frequency and final frequency. To smooth the spectrum it is commonly used some type of windowing at the sweep extremities.

Figure 1 exemplifies the effect of a $\mathrm{sen}(t)$ type window, with 0.5 second of duration, resulting in a well behaved spectrum in the edges, used in this work.

For the ground roll estimate, the frequency band $(f_i, f_f)$ should be chosen where there is noise predominance. It can be chosen from the analysis of data in the FK domain or even in the FX domain.

Upon generation of the trace line with a reference "noise", a $\tilde{h}(t)$ shaping filter should be formulated, in such a way that the input signal be the sweep, $s(t)$, and the wanted signal be the seismic trace to be filtered. Mathematically, the ground roll, $g(t)$, will be approximated by

$$\tilde{g}(t) = s(t) * \tilde{h}(t). \tag{4}$$

Under the form of a total sum,

$$\tilde{g}(t) = \sum_{\tau} \tilde{h}(\tau) s(t - \tau) \,, \tag{5}$$

where $\tau = 0, 1, 2, \ldots, N - 1$, and $N$ is the number of coefficients of the filter. The Wiener filter is obtained minimizing the function (sum of the square $e(t)$ errors)

$$\begin{aligned} Q(\tilde{h}) &= \sum_t e(t)^2 = \sum_t [x(t) - \tilde{g}(t)]^2 \\ &= \sum_t \left[ x(t) - \sum_{\tau} \tilde{h}(\tau) s(t - \tau) \right]^2 \,, \end{aligned} \tag{6}$$

what takes to the system of normal equations

$$\begin{bmatrix} r_0 & r_{-1} & \cdots & r_{-n+1} \\ r_1 & r_0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & r_{-1} \\ r_{n-1} & \cdots & r_1 & r_0 \end{bmatrix} \begin{bmatrix} \tilde{h}_0 \\ \tilde{h}_1 \\ \vdots \\ \tilde{h}_{n-1} \end{bmatrix} = \begin{bmatrix} r_{sx,0} \\ r_{sx,1} \\ \vdots \\ r_{sx,n-1} \end{bmatrix} . \tag{7}$$

On the left there are representations for: the autocorrelation matrix with the $r_k$ coefficients of the autocorrelation function (FAC) of the input signal and shaping filter or modeling filter,

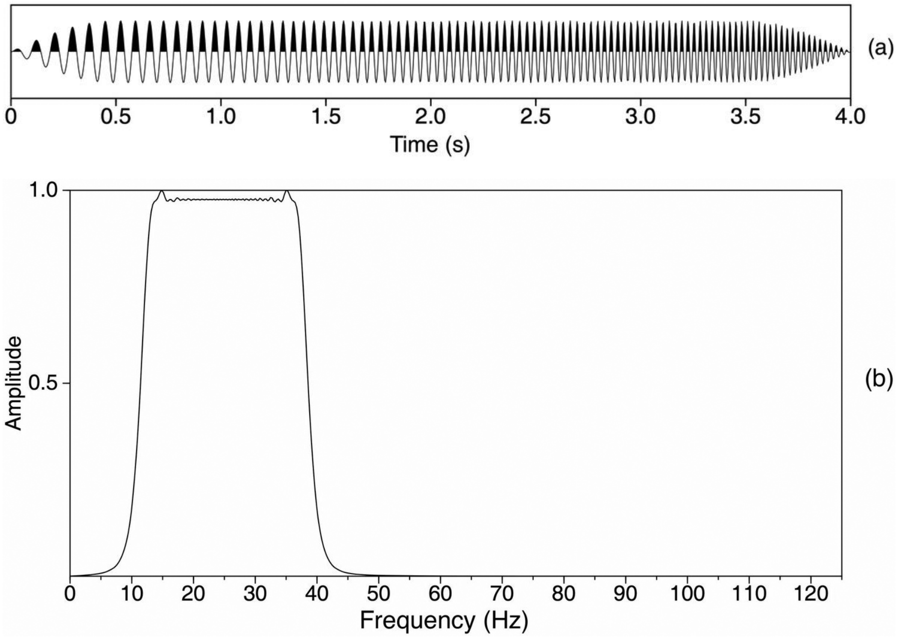

**Figure 1** – Linear sweep with $\mathrm{sen}(t)$ type windowing in (a) and its respective amplitudes spectrum.

while on the right side there is the $r_{sx}$ crossed correlation between the input and the wanted signal. It should be noticed that $r_k = r_{-k}$. This is the system of normal equations to be solved. It is worth to point out that, in a family with $nt$ traces (for instance, a common-shot family), since the sweep is unique, its autocorrelation needs to be calculated only once. The characteristics of the autocorrelation matrix (called Toeplitz matrix) make possible a fast solution for the system through the Levinson's recursion (Levinson, 1947). That's why filters obtained through this way are known as the Wiener-Levinson filters.

Once calculated the shaping filter, its convolution with the sweep gives the ground-roll estimate

$$s(t) * \tilde{h}(t) = \tilde{g}(t) \approx g(t)\,, \tag{8}$$

that should be, then, subtracted from the input seismic trace, and the result is the filtered trace:

$$x(t) - \tilde{g}(t) \approx p(t) * z(t)\,. \tag{9}$$

Notice that the filtered trace is nothing else than the ground-roll's own modeling error (please, see equation 6).

In order of stabilizing the solution of the equations system, a small amount is added to the matrix's main diagonal, normally given in terms of a percentage of the FAC $r_0$ coefficient of the input signal.

On the right side of the system, it is observed that $s(t)$ is displaced in relation to the $x(t)$ trace. Therefore, when using just the correlation's positive positions, the higher frequencies of the band $(f_i, f_f)$, that are concentrated on the sweep extremity, tend to correlate only with the final samples of the trace, hindering the filtering result in the initial portion. Then, it is possible to choose the use of positive and negatives positions as well, and the number of the filter samples will be smaller, making use of some criterion for choosing the best portion of the crossed correlation. In this work, the criterion of minimum energy of the filtered trace was tested. Reminding that, when displacing the crossed correlation, it implies that the result of the filter convolution with the sweep is also displaced, what should be properly corrected before the subtraction.

On the other hand, if all positions of the crossed correlation are used, including the negative positions, this will guarantee that all frequencies within the chosen band will be correlated with the entire seismic trace. In this case, the filter's number of coefficients should be equal to the number of $x(t)$ samples, multiplied by two.

It was noticed that in the classic Wiener-Levinson (WL) filtering method there are three stages involved:

(i) obtainment of the coefficients of the autocorrelation functions and crossed correlation,

(ii) solution of the system of normal equations (eq. 7) for obtaining the filter, and

(iii) application of the filter at the input signal, by convolution.

## DIRECT FILTERING METHOD (WIENER-LEVINSON TYPE)

Traditionally, the WL shaping filter is obtained solving, through the Levinson's recursion, the system of equations 7, that is built from the autocorrelation of the input trace (sweep) and the crossed correlation between the input and the wanted signal (seismic trace to be filtered). This recursion is based on the Levinson's relationship, according to which the $j$ order solution can be calculated starting with the linear combination of the direct and reverse solutions of the $j-1$, $j = 2, 3, \ldots, N$ order.

In the previous section, the conclusion was that, with the filtering method discussed in this work, the ultimate objective is to obtain the modeling error $e(t)$. Procedures for obtaining directly the modeling error, according to Porsani and Ursin method (2007), are presented below:

The Levinson's relationship used in the recursive solution of equation 7, may be represented as a matrix notation under the following form,

$$\begin{bmatrix} 1 \\ h_{j,1} \\ h_{j,2} \\ \vdots \\ h_{j,j} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ h_{j-1,1} & c_{j-1,j-1} \\ \vdots & \vdots \\ h_{j-1,j-1} & c_{j-1,1} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ h_{j,j} \end{bmatrix}, \tag{10}$$

where the vector $\begin{bmatrix} c_{j-1,j-1} & \ldots & c_{j-1,1} & 1 \end{bmatrix}^T$ represents the reverse filter of unitary prediction error. It is observed that, for updating the filter, it is necessary to know just the filter's last coefficient in each iteration.

Porsani & Ursin (2007) proposed an algorithm that makes possible to directly obtain the modeling error's vector. With this purpose, the Levinson's relationship is directly applied on the input trace, generating the iteratively filtered trace, from the linear combination of the lower orders prediction errors. Its implementation is quite simple, and there is no need of calculating the autocorrelation, the crossed correlation and the filter. The authors showed algorithm applications in the predictive deconvolution for attenuation of multiple reflections. In this work that algorithm has been adapted for the problem of the ground-roll prediction. More details for the algorithm may be found in Santos (2010).

The steps of the Wiener-Levinson-type (TWL) algorithm are presented bellow.

**Definitions:**

$\{s_n\}$ – sweep samples (input signal).

$\{x_n\}$ – samples of the seismic trace (wanted signal).

$\{c_{j,j}\}$ – coefficients used in Levinson's recursion for obtaining the Wiener-Levinson filter of unitary prediction.

$\{^{+}e_{cj}\}$ – vector of the prediction errors of the WL filter applied in the causal form.

$\{^{-}e_{cj}\}$ – vector of the prediction errors of the reverse WL filter (applied in the anti-causal form).

$\{h_{j,j}\}$ – coefficients used in the Levinson's recursion for obtaining the Wiener-Levinson shaping filter.

$\{e_{hj}\}$ – vector of the prediction errors of the wanted signal from the input signal.

## STEPS OF THE WIENER-LEVINSON-TYPE (TWL) ALGORITHM

**Beginning:**

$$^{-}e_{c,0}{}^{T} = {}^{+}e_{c,0}{}^{T} = [s_0\, s_1\, \ldots\, s_m] \tag{11}$$

$$E_{c,0} = {}^{-}e_{c,0}{}^{T\,-}e_{c,0} \tag{12}$$

$$e_{h,0}{}^{T} = [x_0\, x_1\, \ldots\, x_m] \tag{13}$$

$$h_{1,1} = -\frac{\begin{bmatrix} 0 & {}^{-}e_{c,0}{}^{T} \end{bmatrix} \begin{bmatrix} e_{h,0} \\ 0 \end{bmatrix}}{E_{c,0}} \tag{14}$$

$$e_{h,1} = \begin{bmatrix} e_{h,0} \\ 0 \end{bmatrix} + h_{1,1} \begin{bmatrix} 0 \\ {}^{-}e_{c,0} \end{bmatrix} \tag{15}$$

**Making $j = 1, 2, \ldots, n-1$:**

- $c_{j,j}$ is calculated

$$c_{j,j} = -\frac{\begin{bmatrix} 0 & {}^{-}e_{c,j-1}{}^{T} \end{bmatrix} \begin{bmatrix} {}^{+}e_{c,j-1} \\ 0 \end{bmatrix}}{E_{c,j-1}} \tag{16}$$

- the energy of the unitary prediction error is updated

$$E_{c,j} = E_{c,j-1}(1 - c_{j,j}{}^{2}) \tag{17}$$

- the direct and reverse errors of unitary prediction are updated

$$\begin{bmatrix} {}^{+}e_{c,j} & {}^{-}e_{c,j} \end{bmatrix} = \begin{bmatrix} {}^{+}e_{c,j-1} & 0 \\ 0 & {}^{-}e_{c,j-1} \end{bmatrix} \begin{bmatrix} 1 & c_{j,j} \\ c_{j,j} & 1 \end{bmatrix} \tag{18}$$

- the $h_{j+1,j+1}$ is calculated

$$h_{j+1,j+1} = -\frac{\begin{bmatrix} 0 & {}^{-}e_{c,j}{}^{T} \end{bmatrix} \begin{bmatrix} e_{h,j} \\ 0 \end{bmatrix}}{E_{c,j}} \tag{19}$$

- and the filtered trace is updated (modeling error)

$$e_{h,j+1} = \begin{bmatrix} e_{h,j} \\ 0 \end{bmatrix} + h_{j+1,j+1} \begin{bmatrix} 0 \\ {}^{-}e_{c,j} \end{bmatrix}. \tag{20}$$

**The end**

It should be noticed that for updating the filtered signal in each iteration, while the classic WL method requires three stages, the TWL method just requires to know the filter's last coefficient (either the $h_{j,j}$ modeling filter or the $c_{j,j}$ of unitary prediction). The number of coefficients of the filter corresponds, in this case, to the number of the recursion's iterations. It was also noticed that in the TWL method the white light is added increasing the $E_{c,0} = r_0$ coefficient of the wanted percentage.

The possibility of using different positions of the crossed correlation was discussed, for the proper sweep adaptation, $s(t)$, to the wanted signal, $x(t)$. In the direct filtering algorithm, this is carried out simply displacing the wanted signal within the $e_{h,0}$ vector, being completed with zeros.

## APPLICATION IN REAL SEISMIC DATA

The filtering method under study was tested in real 2-D seismic data (line 220-197) acquired, in the eighties, in the Potiguar Basin – Brazil.

The results presented were obtained with the filtering methods: Wiener-Levinson (TWL) type, FK filtering frequency and low-cut.

The processing sequence previous to the filtering methods application was the following: 1) setting-up the geometry; 2) edition of very noisy traces and traces with inverted polarity; 3) static corrections; 4)correction of the geometric spreading; 5) muting in the upper portion of the common-shot families, and 6) AGC (Automatic gain control).

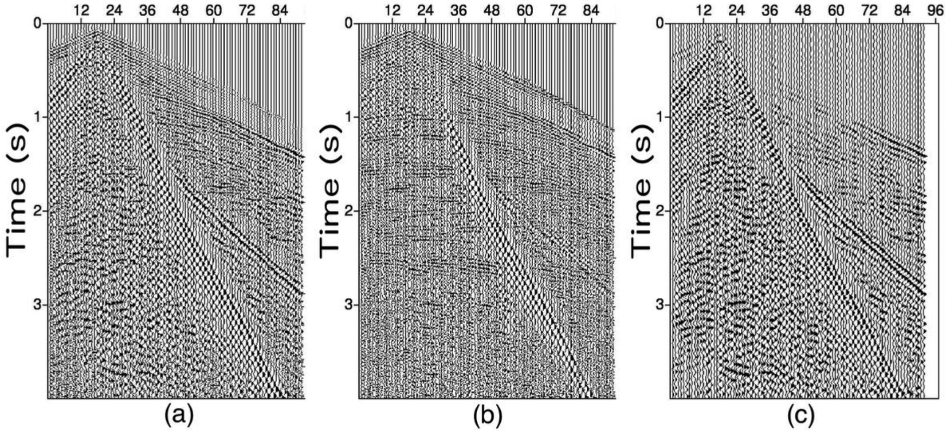

**Figure 2** – Filtering result in a common-shot family. Original data in (a), result of the TWL filtering with 2000 iterations (equivalent to WL filter of 2000 coefficients), 2% white light, in (b), and noise (difference between original and filtered data) in (c).

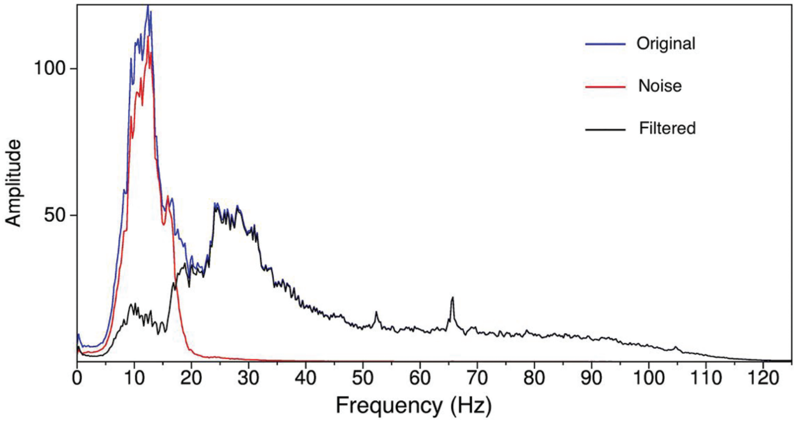

**Figure 3** – Average amplitude spectra corresponding to Figures 2a, 2b and 2c.

The frequency-band for construction of the sweep signal was 1-18 Hz. This band was chosen through the data spectral analysis.

Figure 2 illustrates the seismic records filtering from a common-shot family using the TWL filtering. Two thousand iterations were used (twice the number of samples from seismograms), equivalent to a WL filter with 2000 coefficients. This way, all samples from seismic records are correlated with all sweep samples. A 2% white light was used. The common-shot family is presented in (a), the TWL filtering result in (b), and the noise (difference between the original and filtered) in (c).

Figure 3 shows the average amplitude spectra, corresponding to seismograms shown in Figure 2. It is noticed that the TWL filtering attenuates amplitudes from the low frequencies, associated to the ground roll, however, without suppressing them completely.

Figure 4 illustrates the result obtained applying twice successively the TWL filtering. The TWL filtering was carried out with 30% white light, and 500 iterations. Original data in (a), filtered in (b) and noise in (c).

Figure 5 displays the average amplitude spectra related with the three seismograms shown in Figure 4. It should be noticed that data with high frequency content remain unaltered, while the low frequencies are quite attenuated.

The good results and equivalent in quality, presented in Figures 2b and 4b show the white light effect in the TWL filtering. Low white light may be used in the TWL filtering or the filtering (cascaded filtering) may be reiterated using high white light, with equivalent results. Comparing the spectra of the filtered signals shown in Figures 3 and 5, it is observed, however, that the cascaded filtering causes a more effective attenuation of the ground roll's low frequencies.

In Figure 6, the above results are compared with those obtained with the velocity filtering in the FK domain, and with the

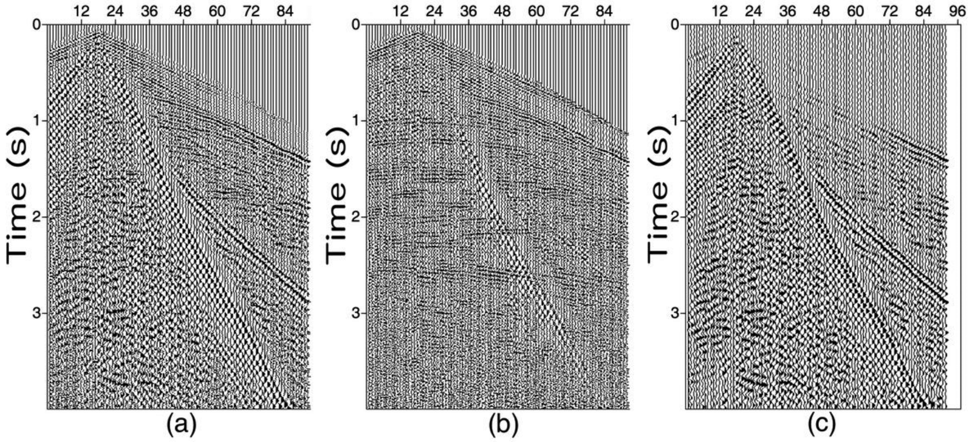

**Figure 4** – Result of the filtering in a common-shot family. Original data in (a), results of the TWL filtering with two successive applications and with 500 iterations (equivalent to a WL filter of 500 coefficients), 30% white light in each application, in (b), and noise (difference between the original and filtered data) in (c).

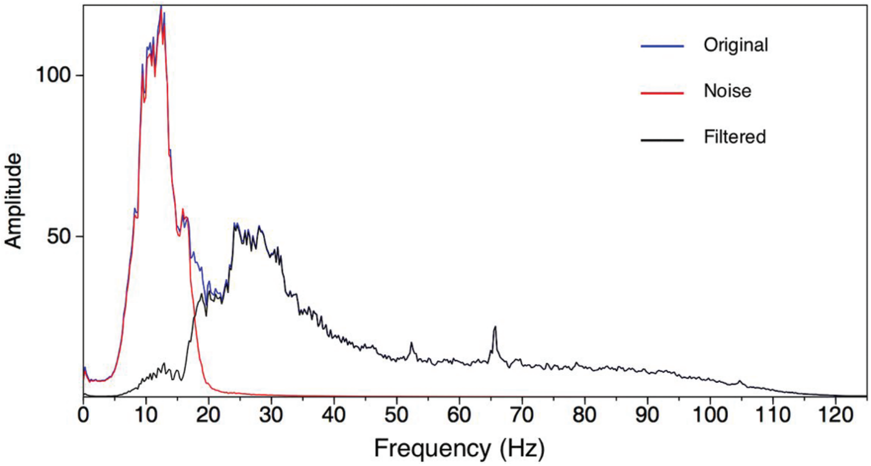

**Figure 5** – Average amplitude spectra corresponding to Figures 4a, 4b and 4c.

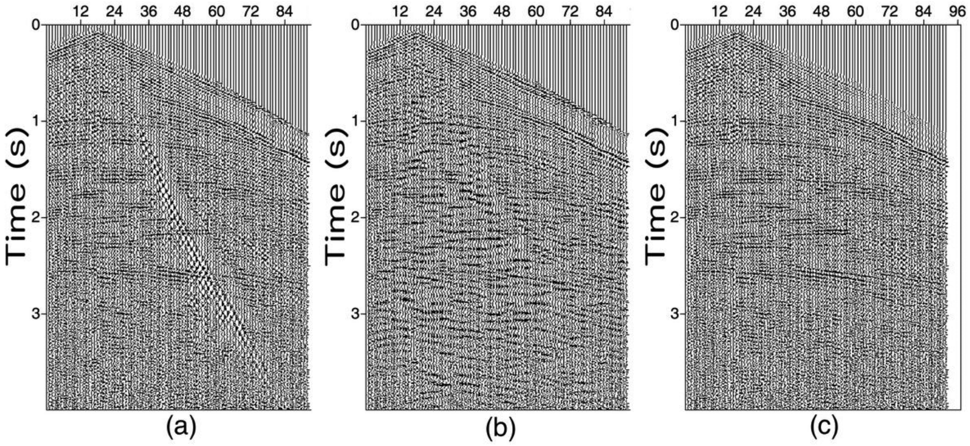

**Figure 6** – Comparison of the results of a common-shot family filtering. Using the TWL in (a), FK filtering in (b), and low-cut filter in (c).

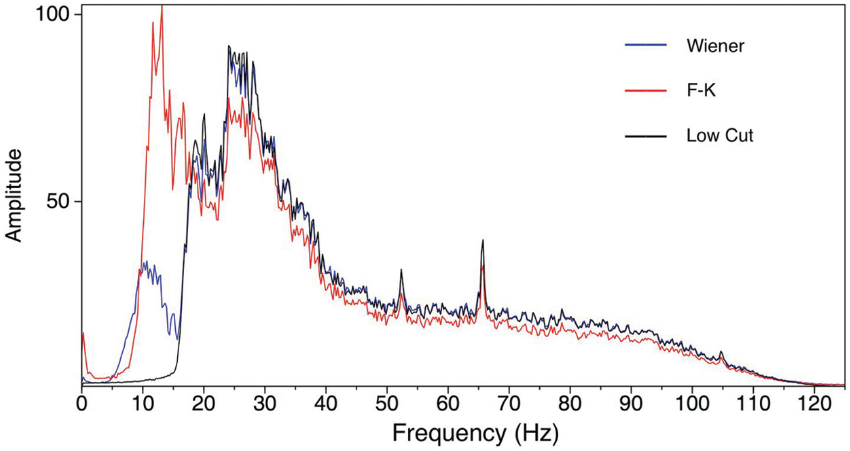

**Figure 7** – Average amplitude spectra corresponding to Figures 6a, 6b and 6c.

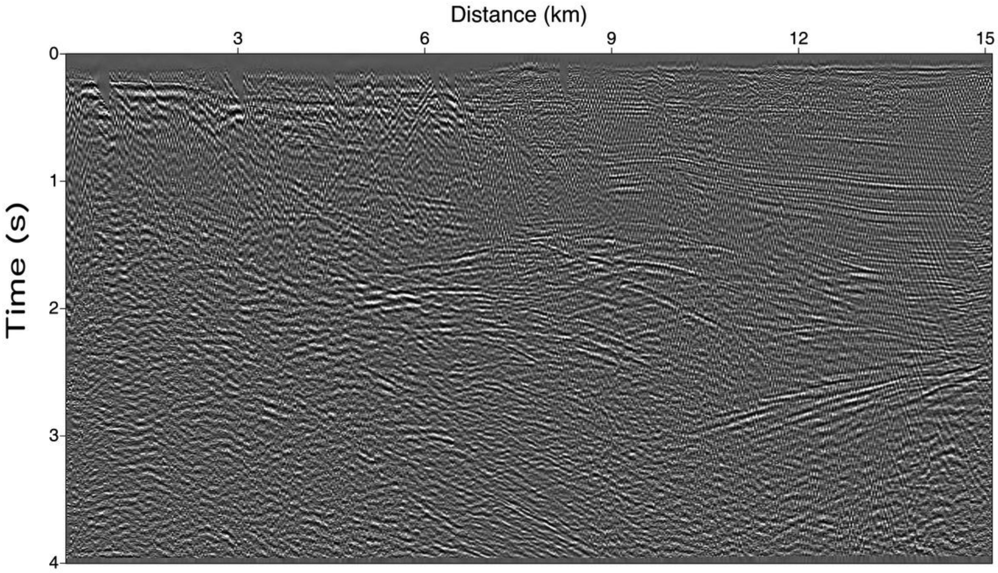

**Figure 8** – Stacked seismic section without any ground roll filtering.

low-cut frequency filter, demonstrating the method's effectiveness, and a better control over the amplitude losses in the low-frequency portion of the spectrum. Figure 7 illustrates the corresponding spectra.

The stacked section, without the application of filters for the ground roll attenuation, can be seen in Figure 8. It should be noticed the great amount of linear events, associated with the ground roll, and they confuse the reflections continuity. The section resulting from the direct filtering presents a good quality, with more continuous reflections, due to the absence of the characteristic linear events, as shown in Figure 9. In the deepest portion, with times greater than 3 seconds, occurs the basin's basement and no reflection of interest is evidenced in Figure 9.

## CONCLUSIONS

This article, presents, in detail, an approach for ground roll attenuation that uses Wiener shaping filters, applied to a sweeping signal of limited band (sweep), to adequate their amplitudes and phases to the contaminated seismic trace, obtaining, then, an estimate of the noise, that later is subtracted. The sweep should contain the frequency band where the noise prevails, obtained through the spectral data analysis.

In addition, a modification of the method was proposed, based on the direct deconvolution, that precludes the autocorrelation calculations, the crossed correlations and filters as well, giving back the modeling error (filtered trace), directly, after a certain number of iterations.

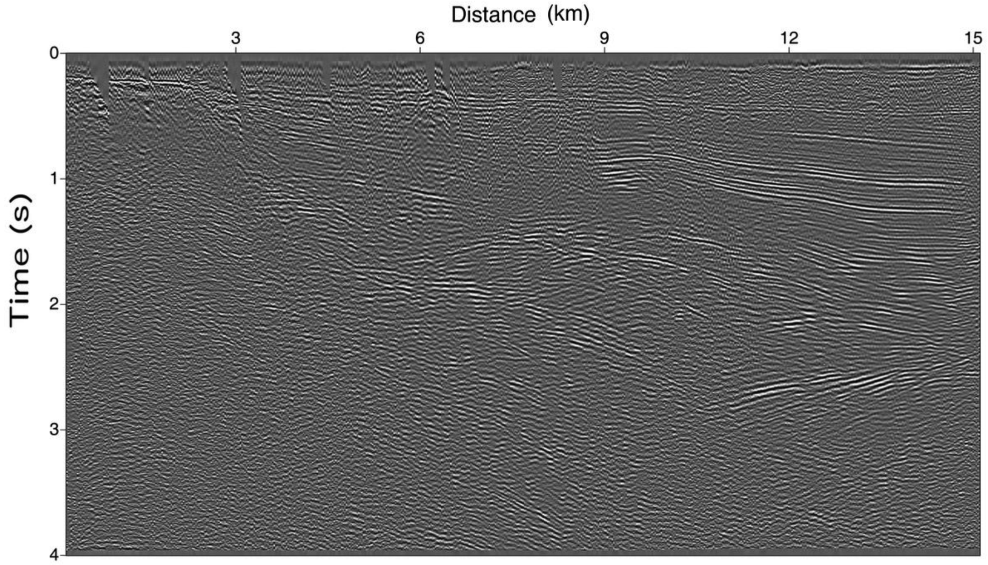

**Figure 9** – Stacked seismic section resulting from the TWL filtering.

Then, the TWL filtering was tested in real seismic data from the Potiguar Basin. It was observed that the most effective result consists in two successive applications, with 2000 iterations and 30% white light. This result was compared with those obtained with the filtering in the FK domain and with the low-cut frequency filter. The corresponding stacked section presents good quality, with more continuous and well defined reflections.

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