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The Seismic Multipulse Deconvolution

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ABSTRACT: The multipulse model of linear predictive coding (LPC), which has been successfully used for compressing of speech signals into an impulse excitation, is here applied to seismic data which contains multiples. Multiples are happened by successive reflection between layers and make the seismic interpretation difficult. In this paper, the author applied the enhanced multipulse method to seismic traces to compress source-wavelets into spikes, and to eliminate/reduce multiples. The enhanced multipulse method which was applied to seismic traces extracted the amplitudes and locations of reflectivity function, which depicts the subsurface configuration, by iterative computation of autoregressive (AR) estimation method.

INTRODUCTION

Seismic reflection prospecting is a method used by geophysicists to map the configurations and nature of remote and inaccessible subsurface layers (Silvia *et al.*, 1979). One can map the subsurface structure by "contrast" between events/layers due to different physical interfaces. A seismic record is usually modelled as a reflectivity function (contrast between layers) of the earth along the transmission path convolved with a source wavelet, which is generally unknown. If the earth were a perfectly elastic solid, and if the disturbance were generated by a perfectly impulsive source like Kronecker delta function, then the recorded would be a series of spikes. However, in practice, the characteristic pressure wave created by an impulsive source, such as dynamite or air-gun, is band limited wavelet of finite duration. To improve vertical resolution, compression of the source wavelet into a spike is necessary, so that the seismic record appears as a sequence of impulse responses.

In addition to the source wavelet effect, multiple reflections are generated when the signal has undergone more than one reflection between layers, including the surface of the earth. Multiple reflections complicate seismic interpretation either by the generation of spurious regular noise patterns, which are likely to be interpreted as real reflections, or by interference with and obscureness of primary reflections (Shon, 1991; Silvia *et al.*, 1979; Yilmaz, 1985).

An important objective of seismic exploration is to construct an image of the subsurface of the earth based on the reflectivity function. In this paper, multipulse algorithm is improved to remove the effect of source wavelets and to eliminate/reduce multiple reflections.

THE MULTIPULSE METHOD

The digital signal processing technology used in speech processing is closely related to seismic deconvolution. Predictive deconvolution has its analog in linear predictive coding (LPC) of speech signals. The multipulse model for speech assumes that the speech signal is the result of several impulses which are not necessarily periodic. While the LPC of speech signals assumes a characteristic pitch period, the multipulse method assumes that the input sequence consists of sparse spikes (Cookey *et al.*, 1990; Taylor *et al.*, 1979; Wiggins, 1978; Yarlagadda *et al.*, 1985). The multipulse model of LPC has proven its performance for compressing speech into an impulse excitation which is comparable to seismic source-wavelet deconvolution (Singhal, 1983; Singhal *et al.*, 1989). Study of the multipulse model of LPC indicates that the direct derivation of pulse positions and their amplitudes is possible from a set of equations (Parker *et al.*, 1984; Shon, 1991). As explained above, seismic traces contain multiple reflections, in addition to source wavelet filtering effect. In this paper, the multipulse deconvolution has been applied to remove the source wavelet effect and to attenuate multiple reflections.

By conventional autoregressive (AR) model, a seismic trace $x(n)$ can be linearly represented by the past input signals:

$$x(n)=\sum_{i=1}^{p} a(i)x(n-i)+h(n) \qquad (1)$$

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where $x(n)$ is the n-th recorded data, $a(i)$ is the filter coefficient, p is the order of the model, and $h(n)$ represents the earth's impulse response, which contains the reflectivity function and multiples.

The estimated $x'(n)$ from its past value is:

$$x'(n)=\sum_{i=1}^{p} a'(i)x(n-1)+h'(n) \tag{2}$$

where $a'(i)$ is the approximation of $a(i)$, and $h'(n)$ is that of $h(n)$.

Then, error sequence $e(n)$ will be

$$\begin{aligned} e(n)&=x(n)-x'(n) \\ &=x(n)-\sum_{j=1}^{p} a'(i)x(n-1)-h'(n) \end{aligned} \tag{3}$$

In the multipulse method, it is assumed that the impulse response is made up I aperiodic pulses. By rewriting the equation (3) for I subsurface layers,

$$e(n)=x(n)-\sum_{i=1}^{p} a'(i)x(n-1)-\sum_{i=1}^{I} b(i)\delta(n-p) \tag{4}$$

where $b(i)$ is the amplitude of the i-th pulse and p_i represents the i-th pulse position.

The pulse positions and their corresponding amplitudes can be deduced from the prediction coefficients, and these coefficients can be inferred by minimizing the error energy, taken by partial differentiation with respect to a'_k

$$e(p_k)=x(p_k)-\sum_{i=1}^{p} a'(i)x(p_k-i)-b_k=0 \tag{5}$$

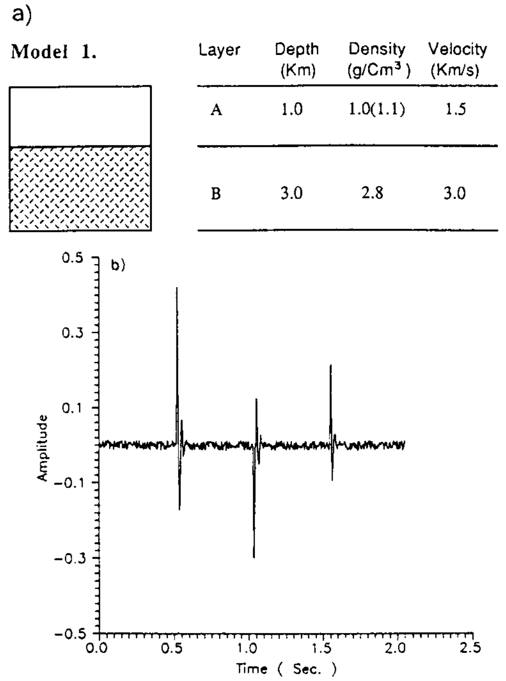
Thus,

$$b_k=x(p_k)-\sum_{i=1}^{p} a'(i)x(p_k-i) \tag{6}$$

The impulse response series contains primaries as well as multiples. Multiples at some future time x $(t+\alpha)$ can be predicted by adopting a multiple distance α. Multiple distance can be deduced by the use of autocorrelation. Periodic occurrence of multiples indicates that:

$$b_k=x(p_k)-\sum_{i=1}^{p} a'(i+\alpha)x(p_k-i) \tag{7}$$

From this iterative computation of equation (7), one can directly determine positions and amplitudes of primary pulses without source wavelet and effects of multiples. It is expected that by the iterative computation process, random assumption of impulse response is not necessary; unlikely for the case of predictive deconvolution (Parker *et al.*, 1984; Shon, 1991).



Layer	Depth (Km)	Density (g/Cm^3)	Velocity (Km/s)
A	1.0	1.0(1.1)	1.5
B	3.0	2.8	3.0

Fig. 1. Two-layer synthetic seismic trace: (a) model and physical constants and (b) seismic trace.

APPLICATION TO DATA

In this paper, a synthetic data and a real data example are used to test the algorithm. Synthetic seismic data (Fig. 1b) which includes primaries and multiples was made from the two-layer model of Fig. 1a.

Filter Order

The optimum filter length for the synthetic data was investigated. For this test the multiple distance (α) and the estimated number of reflections (r) are constant and only the filter length (n) is changed. When the filter length (the number of filter coefficients) is maintained within the range of source wavelet length, which can be deduced from autocorrelation, the result was successful (Figs. 2a and b). The filter length need not be of the same length as that of the source wavelet. The filter order is chosen so that the sum of squared errors, $E=\sum e^2$, is minimum. It is expected that E will decrease as the filter order increases until it reaches the correct value that fits the AR model best. However, as the filter order increases beyond the optimum value, E will increase

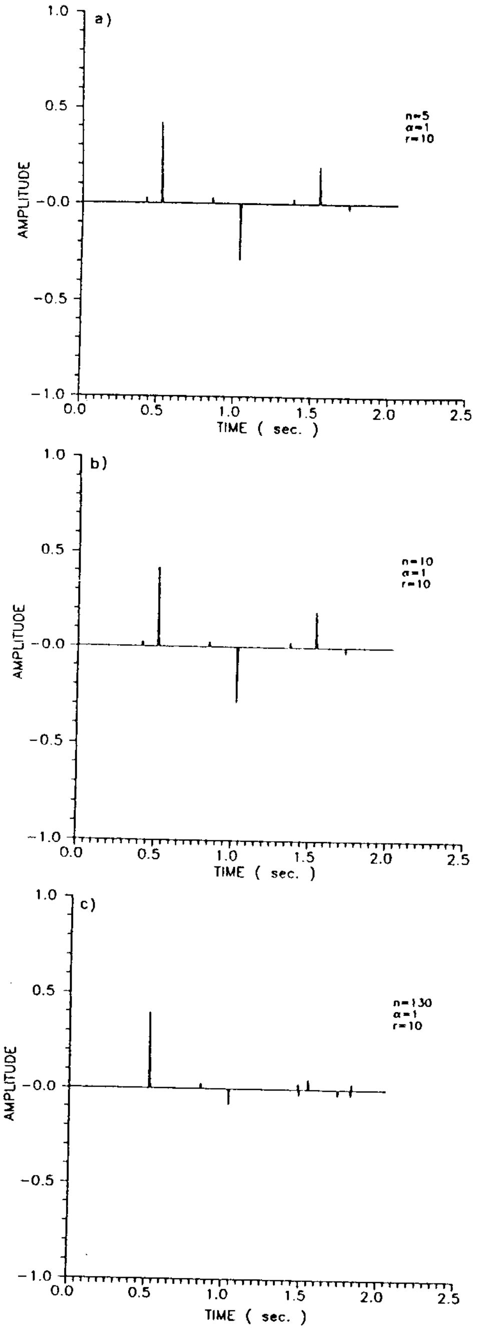


Fig. 2. Performances according to varying filter-length (n): (a) $n=5$, (b) $n=10$ and (c) $n=130$, where is the multiple distance, r is the estimated number of reflections and n represents the filter length.

and the predicted spikes will be masked by noise (Fig. 2c).

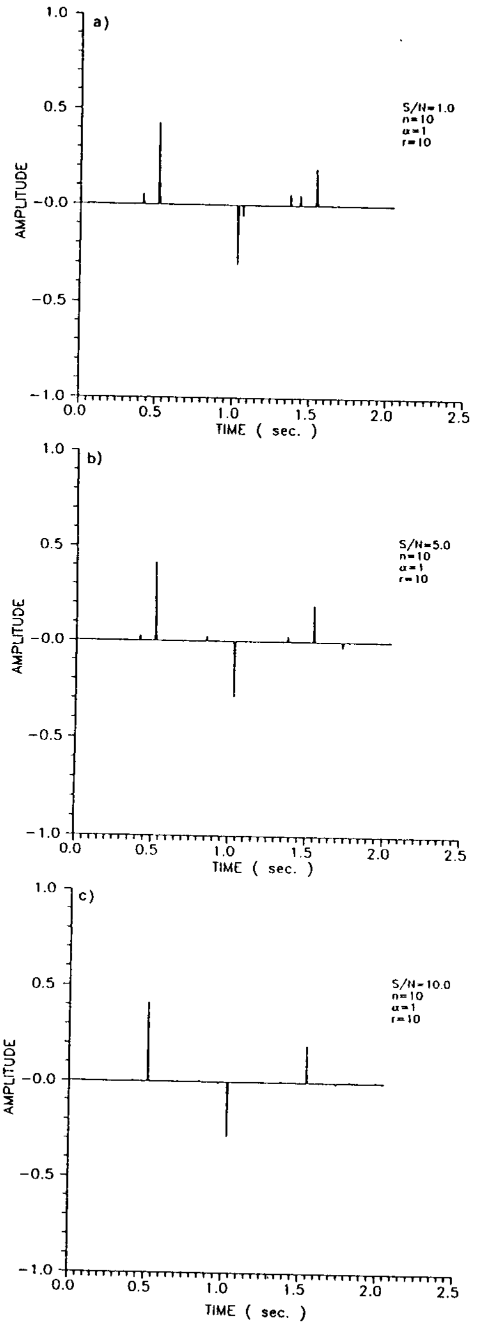


Fig. 3. Performances according to various signal-to-noise ratios (S/N): (a) S/N=1.0, (b) S/N=5.0 and (c) S/N=10.0.

Noise Effect

The multipulse method is based on the iterative computation. Pulse positions are determined from the

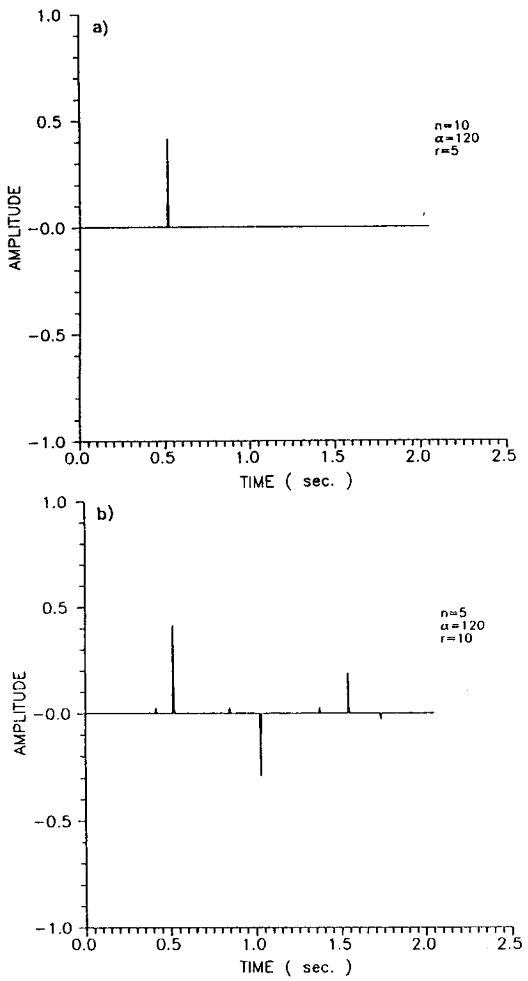


Fig. 4. Multiple deconvolution after source wavelet deconvolution: (a) the value of prediction-distance plus filter-length is within the range of the multiple distance and (b) the value of prediction-distance plus filter-length is smaller than the multiple distance.

prediction error. When the recorded signal is severely distorted by noise, naturally extracted pulses may not correspond to the exact pulse positions. Thus, it is expected that the result will be affected by the signal-to-noise ratio (S/N). As S/N decreases, the predicted reflectivity series exhibits more noise (Figs. 3a, b and c).

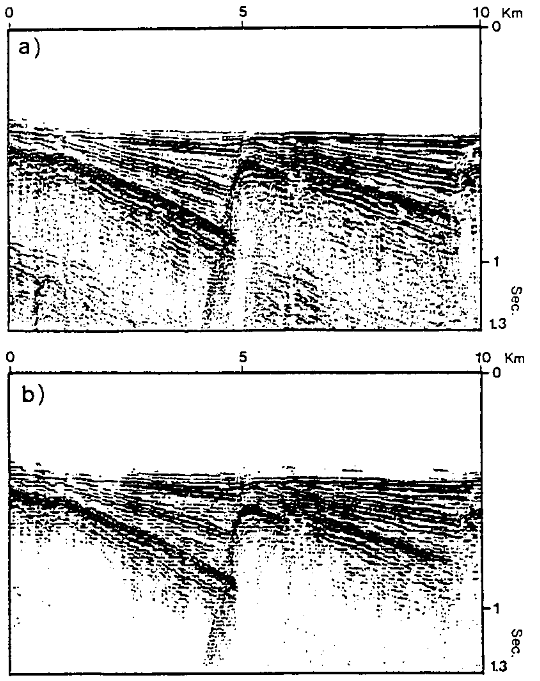


Fig. 5. Seismic reflection profile of the Nkhata Bay Province of Lake Malawi in Eastern Africa: (a) before and (b) after deconvolution.

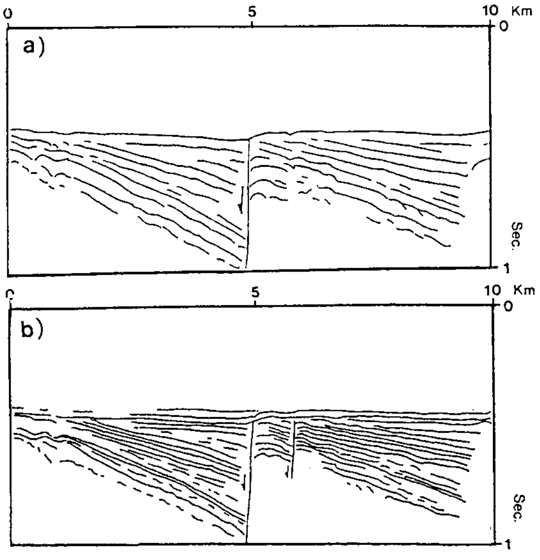


Fig. 6. Geological interpretations of Fig. 5: (a) before, and (b) after deconvolution.

Multiple Deconvolution

After source wavelet deconvolution, with multiple distance fixed at 1, multiple deconvolution was applied. For the multiple deconvolution, the optimum multiple and the filter length have been studied. The multiple distance is 0.512 sec. This multiple distance should contain the multiple distance plus the filter length: Fig. 4a exhibits a successful result, while Fig. 4b -the case which $n+\alpha$ is smaller than the multiple distance- is a failure for multiple deconvolution.

Application to Real Data

Fig. 5a is a seismic panel from Lake Malawi in Eastern Africa which shows a case with simple water-bottom multiples. Fig. 5b is the result after source wavelet and multiple-reflection deconvolutions. Pulses have been sharpened and multiples have been attenuated. The geologic interpretation before and after deconvolution for the Fig. 5a and b is shown in Fig. 6a and b, respectively. Truncation of reflections at faults and angular unconformities are better defined after deconvolutions. The top of the pre-rift section had been interpreted as the top of the four-cycle event, while the top of the pre-rift should be shifted to the base of the four-cycle event after deconvolutions.

CONCLUSION

Using the multipulse method, the seismic deconvolution has been applied to remove source wavelet effects and to eliminate/reduce multiple reflections. The multipulse method assumes that the impulse responses consist of aperiodic pulses and explicitly limits the number of subsurface interfaces. This method extracts the optimal pulse positions and their amplitudes. Results of the method indicate that it is successful in extracting amplitudes and locations of a reflectivity function, which depicts the subsurface structure.

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다중펄스 방법을 이용한 디컨벌루션

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요 약: 음성신호를 임펄스 반응으로 압축시키는데 사용되는 선형예측코드의 다중펄스 방법을 다중반사파를 제거시킬 수 있도록 개선시켰다. 다중반사파는 층사이에서 연속 반사에 의해 발생하는 것으로서 탄성파 해석을 어렵게 한다. 본 논문에서는 개선된 다중펄스방법을 이용하여 음원 파형요소를 스파이크로 압축시키고 다중반사파를 제거하도록 하였으며, 지하 정보를 갖고 있는 반사계수 함수의 크기와 위치를 연속 계산방식에 의해 이끌어 냈었다. 개선된 다중펄스 방법의 탄성파 자료에의 적용은 좋은 결과를 보여주고 있다.