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The optimum color operator for recovering low frequencies

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Summary

Most Seismic data processing algorithms try to shape seismic data into a white spectrum during deconvolution procedure. In reality most natural occurring reflectivity sequences have colored spectra instead of white spectra. Studying the actual earth reflectivity and its spectra's shape are showing that the effect of colored spectra is more significant in frequencies below than 50Hz.

We study the spectral property of seismic data, and by using the well reflectivity, we introduce a new technique to shape the white spectrum of deconvolved data into the colored spectrum of reflectivity. This leads to better recovery of the low frequency component and hence better inversion.

Introduction

In processing data conventional deconvolution tries to remove the wavelet effect from seismic data and shape the spectra to a white one (Gary Margrave, 2002). Walden and Hosken (1985) showed that the most reflectivities from wells sourced all over the world do not have white spectra. Therefore any result comes from conventional deconvolution will not estimate the reflectivity properly. On the other hand, the assumptions which are used in the deconvolution algorithm cannot satisfy the color effects. To correct the color properties of real reflectivity for estimated data we need to define an operator which can recover the lost data.

This can be done by designing a suitable color operator. A color operator is a convolutional minimum-phase operator which can be applied to the output of any deconvolved data to correct for a non-white reflectivity. The operator must be minimum phase because the deconvolution operator that whitened the spectrum was minimum phase. The desired color operator can be designed in many different ways. The main concept is to use real reflectivity which is available in well location and its Fourier transformation in frequency domain. Once the amplitude spectrum of real reflectivity is calculated, the amplitude spectrum of the color operator can be derived by curve fitting technique. We investigate several models for spectral color like the sigmoidal function or arctan function. The color operator should be applied to the seismic data right after deconvolution process to shape the whitened result from deconvolution into the reflectivity's colored spectrum. Once this is done the trace is said to be colored and further processing including inversion can proceed.

Theory

A frequency domain deconvolution is based on four assumptions: (1) wavelet should be minimum phase; (2) wavelet spectrum should be smooth; (3) wavelet should be stationary; and (4) reflectivity should be random so its spectrum becomes white. However, as was mentioned, the real earth reflectivity has a colored spectrum and trying to estimate this type of reflectivity via frequency domain deconvolution algorithm, it will be affected by white spectrum assumption (Figure 1).

In frequency domain deconvolution, correcting the white spectrum assumption can be done with an operator that, if applied to the deconvolved data, corrects the spectral shape at low frequencies.

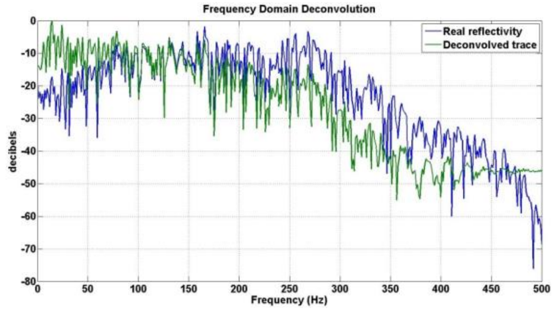

Figure 1. The effect of frequency domain deconvolution with white spectrum assumption on deconvolved data.

This operator should depend only on the observed spectral shape of the reflectivity, and be minimum phase. The color operator in frequency domain includes both amplitude and phase spectrum. Based on the amplitude spectral shape of earth reflectivity (figure 1), the amplitude spectrum of the color operator can be derived by fitting any appropriate function to the amplitude spectrum of reflectivity. Once the amplitude spectrum of color operator is calculated its phase can be calculated by Hilbert transform of the logarithm of the amplitude spectrum. From examination of Figure 1 the deconvolved data below than 75Hz follow a white spectrum and depart significantly from the colored spectrum of the reflectivity. Note that the spectral shape of the reflectivity for frequencies higher than 250Hz are not considered since these frequencies are shaped by an anti-alias filter. Thus the spectrum of color operator should be flat at high frequencies and roll off at low frequencies.

The Husky Hussar well 12-27, located in Alberta, has been used and two different functions (arctan and sigmoid function) to derive the color operator were fitted to the amplitude spectrum of reflectivity. In figures 2 these two operators in frequency and time domain have been shown.

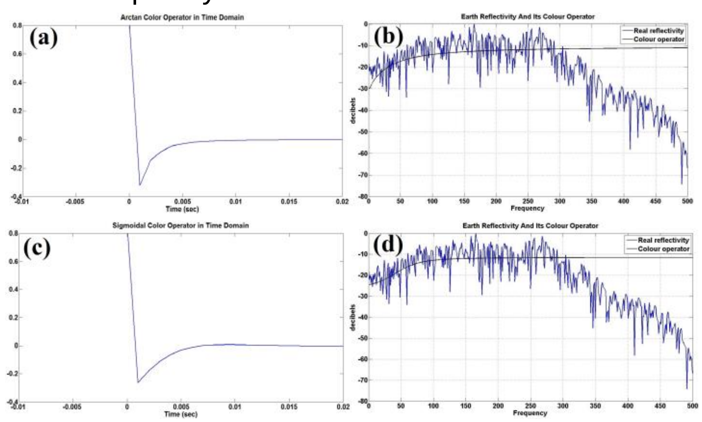

Figure 2. Minimum phase color operator derived from well reflectivity. (a) the Arctan color operator and (b) its amplitude spectrum in frequency domain, (c) the Sigmoidal color operator and (d) its amplitude spectrum in frequency domain.

The third approach for color operator we studied is significantly different from the first two. Suppose there is zero-offset receiver very near the well. Since all the information such as velocity, density and depth are available at the well location, we will form the ratio of the amplitude spectrum of the reflectivity divided by that of the deconvolved trace. After smoothing this ratio we will use it to construct a third minimum-phase color operator. Mathematically, this means

$$\alpha = \left[\frac{R(f)}{Tr(f)} \right] \bullet b(f), \qquad (1)$$

where *R(f)* and *Tr(f)* are amplitude spectrum of well reflectivity and deconvolved data and $b(f)$ is a suitable convolutional smoother. The function *α(f)* with be a smoothed representation of the color operator amplitude spectrum. Its phase can be calculated by Hilbert transform. Once the color operator is calculated it can be applied by convolution as in the first two cases.

Examples

In September 2011, CREWES initiated a seismic experiment with the goal to push the low-frequency content of seismic data as low as possible. This project was located near Hussar, Alberta, which is about 100km east of Calgary, Alberta. The line was 4.5km long and it includes three wells 12-27, 14-27 and 14-35. The synthetic data were created by *Syngram* with 15Hz minimum phase wavelet and log data from well 12-27 located in Hussar. The *Syngram* software assumes the same vertical velocity model for whole studied area. The source was located at the origin and the receivers were located from origin to 1000m with 50m interval. After applying frequency domain deconvolution to each trace, three color operator have been applied to every single trace. Removing normal moveout and then stacking all the traces in each case gives us the estimated reflectivity in the shot location.

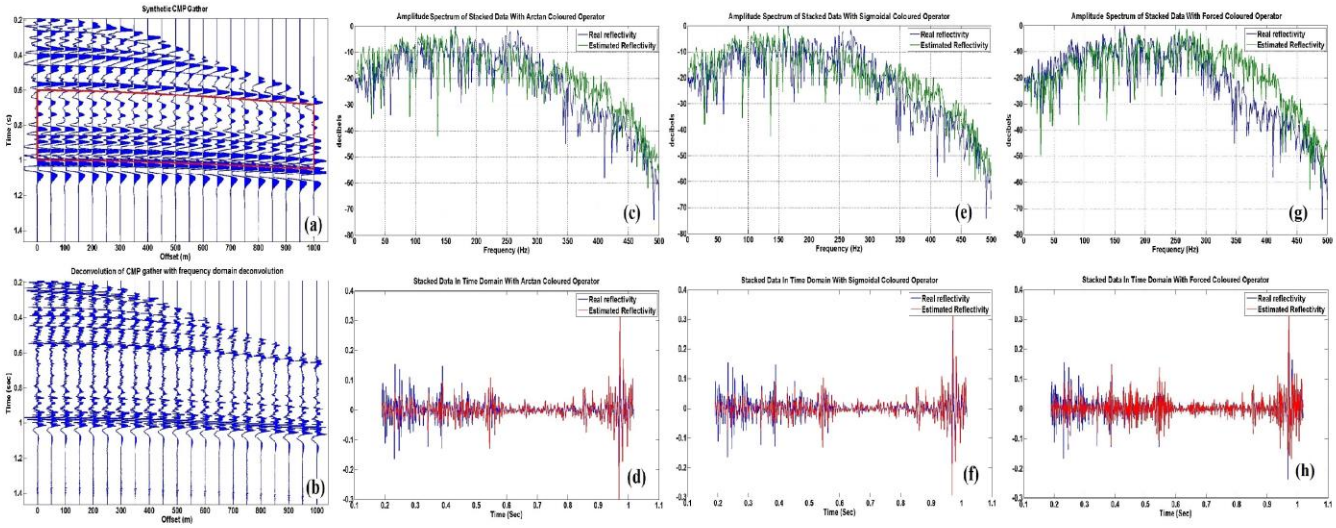

Figure 3. The effect of color operator in reflectivity estimation from synthetic CMP gathers (a), deconvolution of synthetic CMP gathers (b), amplitude spectrum of stacked data resulted from applying arctan color operator(c), stacked data for same color operator in time domain (d), (e) and (f) the same results with applying sigmoidal color operator, (g) and (h) with applying forced color operator.

Figure 3 illustrates the results of using different color operators after deconvolution. The results in both time and frequency domain show that using the color operator can improve the estimated data. In frequency domain we are more interested in the region between 0-75Hz which all three color operators be able to correct the misestimated frequency band came from white assumption in deconvolution algorithm.

We can also compute the acoustic impedance of earth to see how color operator can affect the impedance inversion. Acoustic impedance, which is the multiplication of velocity and density, is the rock property. It is possible to show that the acoustic impedance can be computed from the reflectivity (Oldenburg et al., 1983). Using the standard recursion formula to calculate impedance inversion need to be have broadband reflectivity which is not. For bandlimited reflectivity Ferguson and Margrave (1996) suggested new algorithm to invert acoustic impedance. Their algorithm is called BLIMP (BandLimited IMPedance) and it is based on recovering the missed frequencies from well log data. Figure 4 shows the result of impedance inversion using BLIMP algorithm with 1Hz low frequency and 300Hz high frequency cut-off for three different color operator.

In figure 5, in frequency domain all the results in frequencies below than 2 or 3 Hz are quite the same. This is because of using BLIMP algorithm with the same low frequency cut-off for all resulted reflectivity. But for frequencies higher than this as it is shown, the best choice in low frequency component is Forced color operator. However because of the procedure of deriving Forced color operator, we are not quite sure about the performance of this color operator in other type of data sets. The result of sigmoidal color operator, because it contains a flattened area in the frequencies below than 20Hz (Figure 2d), is clearly better than Arctan color operator. But after 25Hz their results are quite the same since their spectral shape was the same.

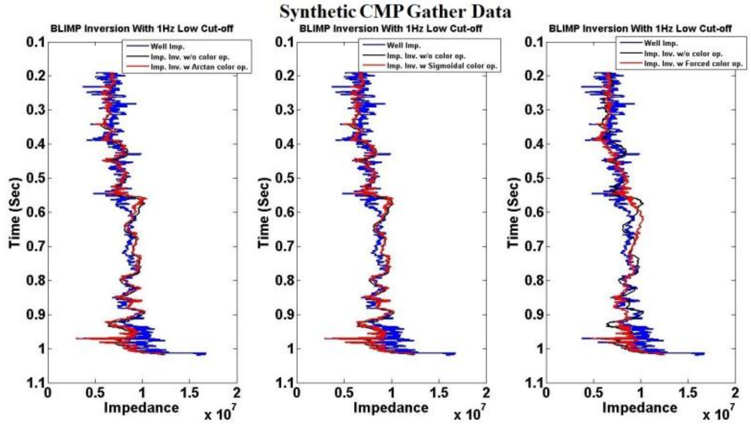

Figure 4. The result of Impedance inversion with BLIMP for different color operator (low cut-off frequency=1Hz).

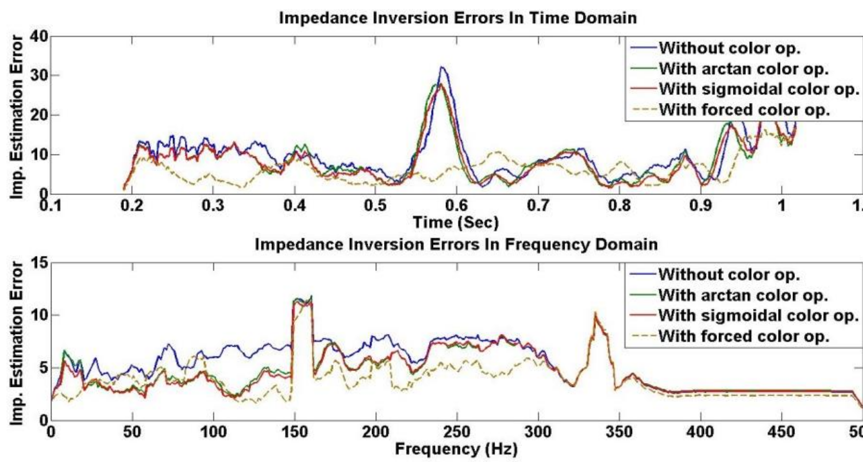

Figure 5. Effect of color operator on impedance estimation errors in time and frequency domain (synthetic shot gather data).

Conclusions

Conventional deconvolution shapes the spectra to a white one while the real reflectivity always has color spectrum. As was shown, the color operator was designed in different ways from earth reflectivity and when applied after deconvolution to the deconvolved traces, the result of reflectivity estimation was significantly improved. Also, the errors of computed acoustic impedance can be reduced if the color operator applied to the result of deconvolved data.

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