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Push the Limits of Seismic Resolution Using Surface Consistent Gabor Deconvolution

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Summary

The Gabor deconvolution methods capture and remove the time-variant earth filter effects embedded in recorded seismic traces, instead of the temporally stationary earth wavelet assumed in conventional deconvolution methods. There are several approaches on the practical applications of the Gabor decon method. We have implemented a full scale surface consistent Gabor deconvolution method. Surface consistency provides powerful geophysical constraints on the seismic wavelets and significantly reduces the effects of noises. Surface consistent decompositions and applications of the wavelet components allow Gabor deconvolution be a part of controlled amplitude processing sequence. Our experiments show that surface consistency combined with time-variance in Gabor domain broaden the data spectrum at large time ranges with reliable lateral stability. Compared with conventional surface consistent deconvolution algorithms, test results from Gabor decon are superior overall in both frequency content and lateral continuity. The Gabor deconvolution has the potential to push the resolution limit of the seismic reflection signals, especially when earth substantially attenuates the signal at higher frequencies and later times.

Introduction

The Gabor transform of a time series is a lossless representation of the time series in the time-frequency domain (we call it Gabor domain). The Gabor deconvolution method uses the Gabor representation of seismic traces to capture and the time-variant earth wavelet in a nonstationary convolutional trace model, which can be approximately factorized in the Gabor domain as (Margrave et al, 2003)

$$G[s](n,f) = W(n,f)G[r](n,f). \qquad (1)$$

The time series s and r are the seismic trace and the embedded reflectivity series, respectively. The discrete Gabor transform, $G[.](n, f)$, is defined on a number of time windows (called Gabor windows) indexed by n, and f is the temporal frequency. The function $W(n, f)$ represents the nonstationary earth filter which behaves as a Gabor domain scalar in the model. When W does not change with n, i.e., the earth wavelet does not change with time, equation (1) reduces to the conventional stationary convolutional trace model. Equation (1), as a nonstationary trace convolutional model and with the whiteness assumption of the reflectivity and the minimum-phase assumption of the earth wavelet, forms the fundamental theory of Gabor decon.

The first implementation of the Gabor deconvolution method results in an algorithm on a trace-by-trace basis. This algorithm and its promising results are presented in a number of early papers by Dr. Margrave and his colleagues. Recent developments on Gabor deconvolution have focused on stabilizing the earth wavelet estimation by using the readily available redundancy of seismic data, against various types of noise contamination. Ensemble methods and surface consistent algorithms are natural choices. Henley (2006) compares the ensemble version and the trace-by-trace version of the Gabor deconvolution algorithms and points out that ensemble methods are able to better stabilize the lateral phase continuity. Henley et al (2007) and Montana et al (2006) present details on their implementations of surface consistence Gabor decon algorithms. One common challenge in these methods is to seek optimal ways to decompose the Gabor-spectra into geophysically meaningful components, such as source and receiver components, so that the data redundancy can be utilized to minimize the influence from localized noises.

We have implemented a full scale surface consistent Gabor deconvolution algorithm. By "full" we mean the Gabor-spectra computation of the entire input data, and a decomposition of the spectra into 5 components, namely, one component for the entire line (survey), and four residual components for each source, each receiver, each CDP location, and each offset range, respectively.

Surface consistent Gabor deconvolution method

Our algorithm of surface consistent Gabor deconvolution is a natural extension of the conventional surface consistent spiking deconvolution algorithms (Cary and Lorentz, 1993). We assume that the earth wavelet $W(n, f)$ of a trace can be approximately decomposed into a source component, a receiver component, a subsurface geology (CMP) component, and an offset component. Thus, equation (1) can then be written as

$$G[s](n.f) = w_s(n, f) \cdot w_r(n, f) \cdot w_c(n, f) \cdot w_o(n, f) \cdot G[r](n, f). \tag{2}$$

The minimum-phase assumption allows us only consider the amplitude spectra, and the whiteness (or close-to-whiteness) assumption of the reflectivity series implies that the amplitude spectra of reflectivity $|G[r]|$ is close to constant at all frequencies. In the log-Gabor domain, the $\log(|G[r]|)$ is close to zero and can be considered as part of the residual error in the following equation,

$$\log(|G[s]|) = \log(w_s) + \log(w_r) + \log(w_c) + \log(w_o), \tag{3}$$

where (n, f) is omitted for simplicity. Equations of the form (3) for all available traces construct a classic linear inverse problem (Wiggins et al, 1976) that can be solved using known numerical methods. Following one commonly used approach (Cary and Lorentz,1993), we take the average of all equations (3) (the line component) out of the system, and solve for residual components for each source, receiver, CMP and offsets. Mathematically, the inverse problem consists a set of independent problems at each (n, f) sample in the Gabor domain. They can be solved independently, similar to conventional algorithms where frequency samples of the wavelet are estimated independently. Figure 1 shows examples of the Gabor amplitude spectra of the decomposed components from some field 2D land data. Note that the line component is usually a very smooth function and its amplitude level is much higher than those of other components.

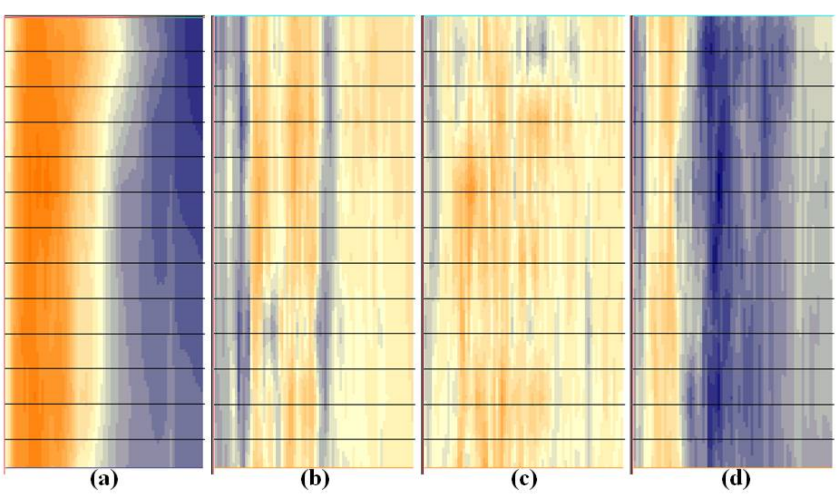

Figure 1: Decomposed line component (a), a source component (b), a receiver component (c), and a CDP component (d) from a 2D land survey. In each panel, the vertical axis is time and the horizontal frequency. All four panels contain the amplitude log-Gabor spectra and they are displayed in the same scale. The line component has significant larger (about 25 dB in this example) amplitude than the other components. The line component is very smooth in time and frequency. All spectra have mush weaker time variations relative to the changes with frequency, especially for the source and receiver components.

In our Gabor nonstationary trace model, the components have different geophysical meanings and they pose restrictions on component independency between different Gabor windows. Especially, the time variance of the source and receiver components should be restricted (but not necessarily disallowed) since we assume the effects from sources and receivers are mostly determined to their surface locations. Experiments show that more restriction on the time variances of the source and receiver components can actually improve the lateral continuity of the deconvolution results. Note also in Figure 1 that the relative weak time variations on the source and receiver components.

Examples

The Shorncliffe 3D is a small survey at the mid-east of Alberta, Canada. It consists of 1267 shot records and 2503 receiver stations. The traces are sampled at 2 ms and recorded 3 seconds. The data quality is good. Prior to the experiments with Gabor decon and other decon methods, refraction statics, geometric spreading correction, surface consistent scaling and some noise attenuation were applied to the data. The stacking velocity field and mutes used to create the stacks shown in this paper are exactly the same for all different versions of decon results. The displays aim at showing the differences deconvolution methods can make, therefore we used the same decon design window for all experiments, which is from 300 ms to 1600 ms at near offsets. Any signal below 1400 ms seems to have significantly lower amplitude than earlier times in the 40-70 Hz range, and this could be due to high attenuation at that depth level.

Besides our Gabor surface consistent deconvolution program, two algorithms of conventional surface consistent spiking decon are also involved. One conventional algorithm (we call method 1) tends to boost high frequencies less than the other algorithm (we call method 2).

Figure 2 shows evidently preferable differences the Gabor decon can make on the data, compared with the results from the conventional method 2. The three panels are respectively the average Gabor amplitude spectrum of a line of stacked traces from their corresponding datasets. The left panel is from data without decon applied; the center panel is from the conventional method 2; and the right panel is from our surface consistent Gabor decon. The conventional and the Gabor decon are able to boost the higher frequencies (60-120 Hz) in the design window time range. As expected, major differences are at later times (from 1200ms to the trace end in this example). Not only the lower frequencies (25-70Hz) are insufficiently boosted and balanced, the higher frequencies with significant amount of noise are also over-boosted. With stacked sections displayed, Figure 3 and Figure 4 convincingly confirm the observations from Figure 2. Figure 3 and Figure 4 show the different time ranges from the same line in their corresponding stacked volumes. Figure 4 displayed with a much higher gain since the overall amplitudes after 1400 ms are substantially lower than those at earlier times. The wider bandwidth and good lateral continuity from SC Gabor decon in Figure 4 are clearly shown, comparing with the stacks from two conventional SC methods. Since no bandpass filtering was applied on the data, the early sections contain noises from outside of the signal band.

Conclusions

The surface consistent Gabor deconvolution method can improve the resolution of seismic date at larger time ranges. This is especially important when significant spectral variations in time occur due to reasons such as seismic attenuation. Conventional deconvolution methods may create ill-balanced frequency spectra due to such nonstationarity of the earth wavelet. Also of critical importance is that even in the design window of conventional decon operators, the Gabor decon can still produce superior results. We expect surface consistent Gabor deconvolution methods to extend the limit of seismic resolution.

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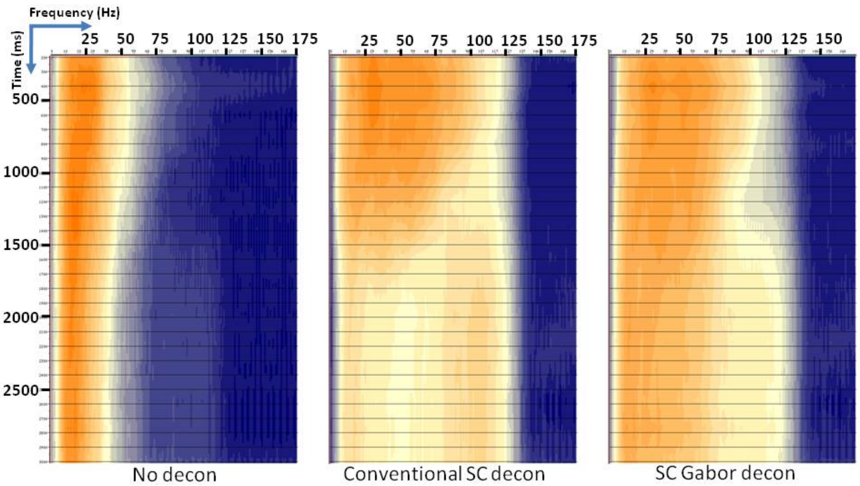

Figure 2: Averaged Gabor amplitude spectra of a line of stacked traces, where the left panel is from the data without decon applied, the middle panel is from data with a conventional surface consistent decon applied, and the right panel is from data with Gabor surface consistent decon applied.

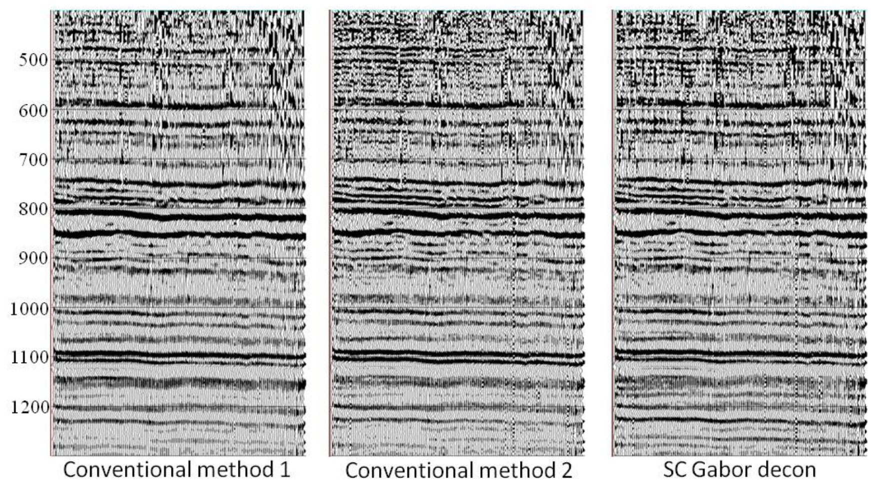

Figure 3: Stacked sections in the decon operator design window (300ms to 1600ms) time range. The frequency content and lateral continuity from the SC Gabor decon (the right panel) is superior overall, compared to the results from conventional surface consistent methods (two panels in the left).

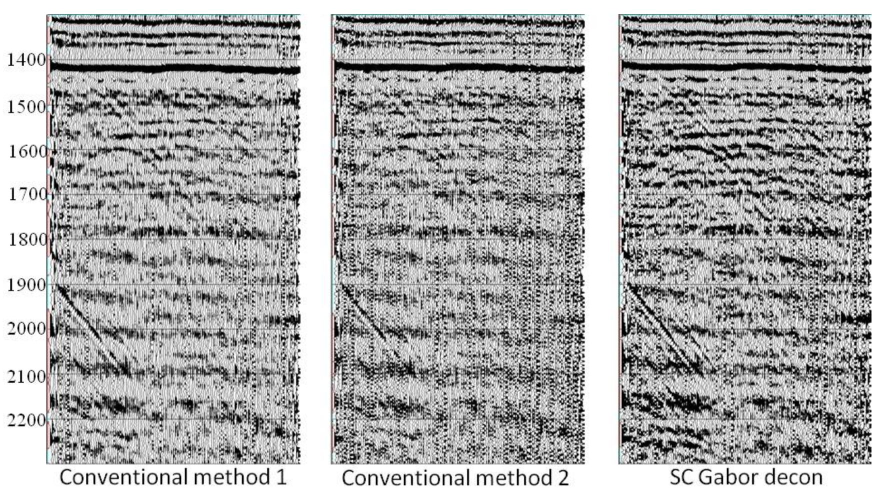

Figure 4: Stacked sections in the later time range. The quality of the stack from the SC Gabor decon (right panel) is evidently better than the sections stacked from two different conventional surface consistent decon methods. Note that the method 1 result (left panel) has reasonable lateral continuity but with insufficient high frequency content; while the method 2 result (middle panel) has too much of the high-frequency noises but poor lateral continuity. The Gabor SC decon produced a section with both good frequency content and lateral continuity.