Time-frequency domain spectral balancing and phase dispersion compensation

Kui Zhang, Kurt J. Marfurt, Marcilio Castro de Matos, and Tim Kwiatkowski, University of Oklahoma*

Summary

Enhancement of seismic resolution for better reservoir characterization is one of the ultimate goals of seismic digital processing. Two of the major limitations to seismic resolution can be attributed to attenuation and dispersion – intrinsic attenuation and dispersion due to conversion of seismic to other forms of energy, and geometrical attenuation and dispersion due to scattering and transmission such as that associated with friendly multiples. We hypothesize that since time-frequency decomposition provides accurate amplitude and phase estimates of each spectral component that it can be a tool to not only spectrally balance the seismic data, but also help differentiate between intrinsic and geometrical attenuation. We find statistical time-frequency spectral balancing of the amplitude components which forms the basis of spectral-ratio Q-estimation techniques to be straightforward. However, we find phase dispersion compensation to be more difficult yet more promising because phase measurements are intrinsically more accurate than amplitude measurements. We test our application on a 3D land survey acquired over the Central Basin Platform, west Texas and find we are able to both increase the bandwidth of the data and sharpen the unconformities.

Introduction

Seismic waves propagating through the subsurface undergo strong energy dissipation and velocity dispersion due to both anelasticity and heterogeneity within the earth. High frequency data components suffers more loss than low frequency components that traveled along the same ray path, resulting in a relatively narrow-band, low-frequency spectrum. In general, the high frequencies travel at different velocities than the low frequencies resulting in a significant change in waveform shape Due to above two effects, the seismic wavelet become noticeably stretched, and display "ringing" characteristic as the travel-time increase.

Spiking deconvolution and time-variant spectral flattening are commonly used and often very effective means to boost the high frequency energy of the seismic data. However, if a given spectral component is more than 90 degrees out of phase with the reference frequency, spectral flattening will not compress the wavelet.

In contrast, inverse Q filtering (sometimes called Q-deconvolution or Q-compensation) attempts to correct for both the high frequency magnitude loss and phase dispersion through a process of backward wave propagation, typically using a frequency-independent Q model (e.g. Futterman, 1962; Kjartansson, 1979; Robinson, 1979). Significant improvement in spectral resolution is obtained when using Q amplitude and dispersion effects from either VSPs (Chopra and Alexseev, 2004) or well logs (Singleton et al., 2006). However, Irving (2003) and Wang (2002, 2006) show that the simultaneous estimation of amplitude compensation and phase correction from seismic alone poses significant instability problems that need to be carefully addressed.

Our approach differs and compliments those described above in two ways. First, we will treat the spectral magnitude and phase compensations separately. Second, since we anticipate that significant dispersion is due to geometric in addition to intrinsic attenuation, we will not restrict ourselves to compensating for the phase using the classical Q models. Our approach is motivated by an interpretational bias that seismic acquisition and processing results in seismic phases (including travel times) that are quite accurate but seismic amplitudes that are only approximate. Furthermore, out goal is to improve the resolution of seismic data that are in the hands of the interpreter, and have thus already been processed, stacked and migrated. Routine seismic processing usually includes some form of spectral balancing, either through deconvolution or some time-variant approaches.

We begin by decomposing the original seismic data into spectral magnitude and phase components using a matching pursuit algorithm described by Liu and Marfurt (2006). Next we statistically flatten the amplitude spectrum without touching the phase. Since the computed phase ranges between -180 and +180 degrees, we need to first unwrap the phase before phase compensation. Once balanced and phase compensated, we reconstruct the data through simple Fourier synthesis at each time sample.

Spectral balancing

Because those surface-consistent amplitude corrections, geometric spreading corrections, deconvolution, and time-variant spectral balancing may have been applied to the data before we receive the migrated, stacked volume, we do not anticipate that model-driven spectral balancing approaches such as those used by Wang (2006) will be effective. Since we are beginning with post-stack, migrated data, Instead, we make a simple assumption that the reflectivity character of the subsurface geology is white when averaged over a finite time window of thickness T over the entire survey, which is in general a good approximation other than for very small surveys over flat reflectors. The average spectral magnitudes are thus

Spectral balancing and phase dispersion compensation

$$< a(f,t) >= \sum_{y}\sum_{x}\sum_{\tau=t-T/2}^{t+T/2} a(f,\tau,x,y) \qquad (1)$$

To spectrally balance the data, we simply compute

$$a^{bal}(f,t,x,y) = \frac{a(f,t,x,y)\max_{f}[< a(f,t) >]}{< a(f,t) > + \varepsilon \max_{f}[< a(f,t) >]} \qquad (2)$$

Where, $\varepsilon \max[< a(f,t) >]$ denotes a user-defined noise threshold, which prevents low amplitude noise from being overly amplified.

Figure 1 shows the comparison of two spectra before and after spectral balancing. This normalization retains the originally strong low frequency and enhances the originally weak high frequency magnitudes, which, as a result, flattens the spectra of the data (Figure 1). Since every time slice is flattened in exactly the same way, lateral changes in continuity are preserved.

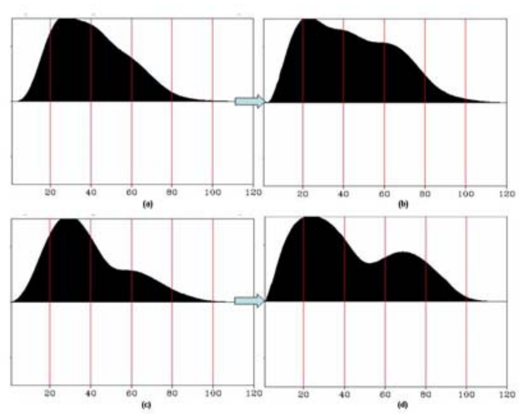

Figure 1: Comparison of spectra (a), (b) before and (c), (d) after spectrum balancing.

Phase correction

In general, seismic acquisition and processing does an excellent job in retaining accurate signal phase. Although less frequently used in the interpretation of spectral decomposition volumes, every time-frequency component has both a magnitude and a phase. Because of causality (Futterman, 1962), phase dispersion is always coupled with amplitude attenuation during the seismic wave propagation through the subsurface of the earth. As a consequence, the seismic wavelet becomes noticeably broader with traveltime, especially for low values of Q.

Aki and Richards (2002)，and Wang (2002) provide good summaries of the analytical solution of the scalar wave equation for anelastic media in the frequency domain. For a constant Q model, we relate a signal at $t=0$ to one that has undergone attenuation and dispersion at time t as:

$$U(f,t) = U(f,0)\exp[-(\frac{f}{f_0})^{-\gamma}(\frac{1}{2Q}+j)2\pi f t] \qquad (3)$$

Where, f_0 is a reference frequency, and γ is a constant given by:

$$\gamma = \frac{2}{\pi}\tan^{-1}(\frac{1}{2Q}) \qquad (4)$$

The phase part of equation 3 can be rewritten as

$$\varphi(f,t) = 2\pi f t + \varphi_Q(f,t)$$

$$= 2\pi f t + 2\pi f t[(\frac{f}{f_0})^{-\gamma} - 1] \qquad (5)$$

Equation 5 shows the phase including two parts: the phase shift ($2\pi ft$) caused by time delay and the phase dispersions resulting from finite values of Q. For the case of no attenuation and dispersion, Q is infinity and γ is zero, this case corresponds with a homogenous model in which φ is equal to $2\pi ft$.

Inverse Q filtering is a backward wave propagation process. In principle, we simply need to subtract the dispersion term in equation 5 from the time-frequency phase calculation. $\varphi(f,t)$ has three general components:

1. $\varphi_L(f,t)$=2πft which is the linear phase part caused by the time delay,
2. $\varphi_Q(f,t)$ which is a nonlinear phase delay that depends on both intrinsic and geometric Q dispersion, and
3. $\varphi_G(f,t)$ which is directly related to the underlying geology and impedance of the layers, including 180^0 phase changes associated with negative reflection coefficients, $\pm 90^0$ phase changes associated with thin bed tuning and upward fining/coarsening, as well as more complicated phase changes due to stratigraphic layering.

Our objective is to retain $\varphi_L(f,t)$ and $\varphi_G(f,t)$ and remove the effects of $\varphi_Q(f,t)$ to compensate for dispersion to obtain $\varphi^{comp}(f,t)$. The sum of the all complex frequency components will then give the spectrally balanced, phase-compensated reconstructed data:

$$d^{recon}(t) = \sum a^{bal}(f,t)\exp[j\varphi^{comp}(f,t)]. \qquad (6)$$

In Figure 2a we show a seismic line extracted from a 3D survey acquired over the Central Basin Platform, west Texas. In Figure 2b we show the impact of spectral balancing (equation 2) followed by waveform reconstruction (equation 6) but without any change in phase. The average magnitude of 2a and 2b are shown in 3a and 3b respectively. Obviously, the spectrum of 3b is much broader than that of 3a. We have evaluated two means of phase compensation. For the first one, we again assume that reflectivity character of the subsurface geology is white

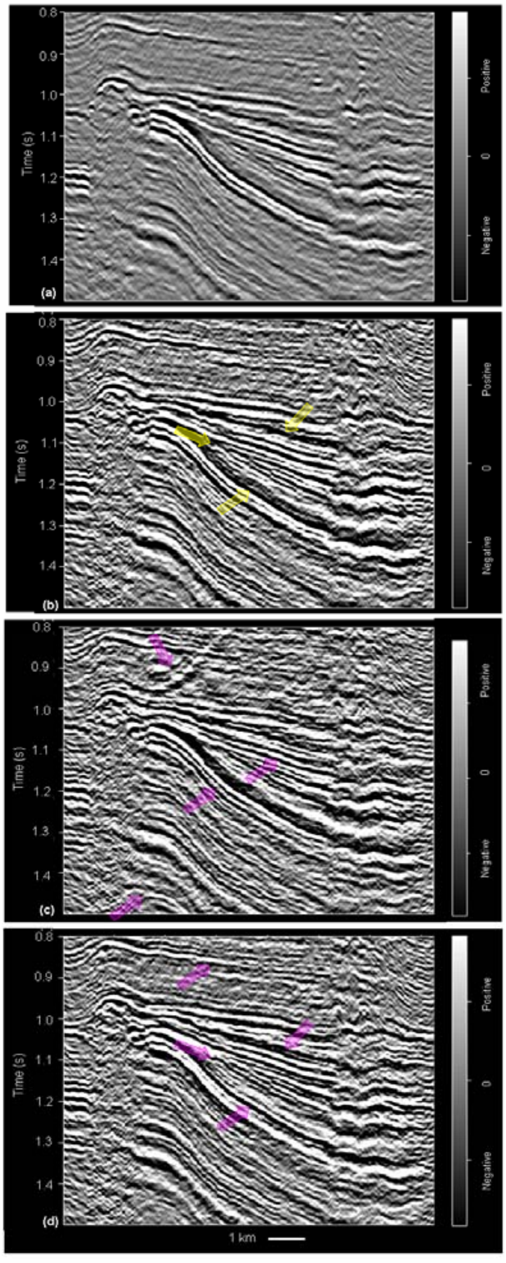

Figure 2: The original seismic (a), spectral balancing (b), phase compensation results (c) and (d) using statistical approach and constant Q=50 respectively. Yellow arrows show the areas on (b) that have high resolution than (a), while maganta arrows show the events become sharpening from (b) to (c) or (d).

when averaged phase over a finite time window of thickness *T* over the entire survey, which means that $\langle\varphi_G(x,y,f,t)\rangle=0$. Hence the subtraction of $2\pi ft$ from the average phase obtained from spectral decomposition gives the dispersion trend, which is then used in phase compensation. This approach, like that used in spectral flattening, is purely statistical. Because of wrap-around, we cannot simply average $\varphi\ (f,t,x,y)$ over a window as we did with the magnitude. Rather, first we must unwrap it. Stark (2006) has shown phase-unwrapping of the instantaneous phase to be a very powerful interpretation tool. We used a crude, frequency-by-frequency component phase unwrapping for each trace and display the result in Figure 3c. Note that there are some vertical stripes that remain in the data probably due to errors in the unwrapping. These errors may explain the artifacts seen in the statistical phase compensation result displayed in Figure 2c.

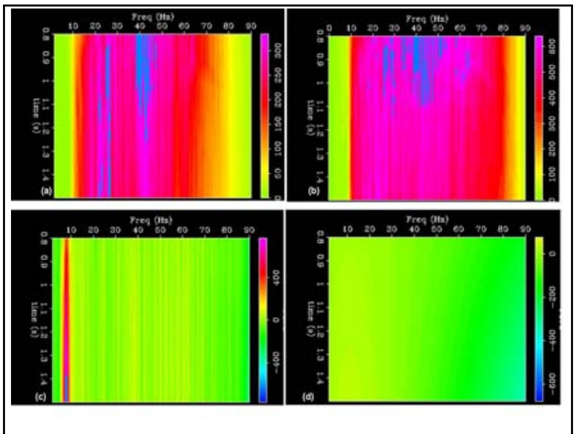

Figure 3: The average spectral magnitude before balancing (a), and after balancing (b), the average phase (c) ($2\pi ft$ part is subtracted) , and phase (d) for Q=50 ($2\pi ft$ is subtracted).

An alternative approach is model-based Q-compensation with the value of Q being estimated by either the interpreter or through some optimization scheme. Zhang et al (2002) calculated Q through peak frequency and dominant frequency using a least square scheme, while Bachrach et al (2006) presented a layer-based Q inversion approach. We chose a simple scanning method which ran a suite of Q panels that changed only the phase (and not the magnitude) and computed the L^2 norm of the dephased results. Theoretically, a good Q model produces more spiked results, thereby resulting in a stronger L^2 norm.

We used the above simple scanning method to obtain a value of Q=50, with the predicted phase changes displayed in Figure 3d, Applying this model-based Q-phase correction to our previous spectrally-balanced data shown in Figure 2b, provides good wavelet compression at our target level (Figure 2d).

Discussions

We have chosen the line shown in Figure 2 because it provides a very clear image of the Wolfcamp Unconformity. If our spectral balancing and phase compensation is poor, we might expect to see ringing events that interfere with each other. In contrast, a good spectral balancing and phase compensation will provide not only higher frequency events between the previously seen lower frequency reflectors, but further sharpen the Wolfcamp Unconformity.

It is important to remember that any kind of spectral balancing (including that provided by predictive deconvolution) rescales the data, such that we cannot create meaningful difference plots. However, Figures 2b-d are all plotted at the same scale. Yellow arrows indicate the Wolfcamp unconformity. We note that the simple spectral balancing provides improved resolution over the original data. The additional phase compensation displayed in Figures 2c and 2d provide further improvements on spectral balancing alone (magenta arrows). However, phase unwrapping as we currently implement it introduces undesireable artifacts.

Conclusions

We have shown how time-frequency decomposition can be used to spectrally balance and phase compensate 3D migrated data volumes. We find that statistically balancing the magnitude components almost always provides improved resolution (though if previously balanced these changes can be small) regardless of the preprocessing of the seismic data. Explicit phase compensation further enhances the shape of the seismic wavelet. We find statistical phase compensation after phase unwrapping to be promising, but prone to unwrapping errors. In contrast, a model-based Q approach is smoother and therefore more robust. We remain optimistic that in the future that the phase component of the time-frequency data can be utilized to differentiate intrinsic vs geometric dispersion effects, or perhaps to even estimate frequency-dependent values of Q.

Acknowledgments

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