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Structurally Consistent Amplitude Q Compensation Using tau-px-py Inversion

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Summary

Absorption in the Earth attenuates high frequency seismic signal progressively with depth, reducing resolution and limiting the interpretability of the data. While absorption may be corrected for in migration, for many geological settings this is not necessary and application of a post-migration Q compensation offers a flexible alternative. Conventional post-migration Q compensation methods often rely on artificial mechanisms to limit amplification of noise, at the cost of unintentionally restricting recovery of signal. In this paper we propose an amplitude Q compensation technique using 3D sparse inversion. Comparisons with a conventional approach on synthetic and field datasets highlight improved signal recovery and noise suppression with the proposed method. We also describe an extension to our technique which additionally accounts for spectral shifting effects inherent in seismic data after migration. Finally, we show how our method may be combined with spectral enhancement techniques to further broaden signal bandwidth.

Introduction

Seismic energy is absorbed as it propagates through the Earth, attenuating high frequencies increasingly with depth. This absorption must be compensated for to recover high resolution signal. A common approach is based on the quality factor Q which describes energy loss per cycle of the signal. Ideally, Q compensation may be incorporated into migration algorithms (Wang 2008). However, in many cases this is neither practical nor necessary, and a variety of post-migration alternatives exist, many of which can be categorized as inverse Q filtering. Processes of this kind are often differentiated by the domain in which the compensation is modelled or applied. Recent examples include the frequency domain (van der Baan 2012) and the continuous wavelet transform domain (Braga and Moraes 2013). Q compensation may also be considered as an inversion problem (Peng et al. 2016).

The Q effect modifies both the amplitude and the phase of the seismic signal. As noted, for example, by Braga and Moraes (2013), the amplitude component of the absorption may be modelled as

$$a(f,t,x,y) \propto \exp(-\pi f t/Q(t,x,y)), \tag{1}$$

in which $a(f,t,x,y)$ is the attenuation factor experienced by a signal at frequency f and time t, with spatial coordinates x and y. The Q field is denoted by $Q(t,x,y)$. Braga and Moraes (2013) remark that a conventional inverse Q filter may be obtained by changing the sign of the exponent in Equation (1). Though approaches of this type are widely used, they indiscriminately amplify both signal and noise. In practice, a gain limit is often introduced to prevent excessive boosting of incoherent noise. This also artificially inhibits the compensation of the signal, particularly for higher frequencies at depth.

In this paper we describe a 3D spatially consistent amplitude Q compensation using τ-p_x-p_y inversion. Here, p_x and p_y refer to time domain slownesses in the inline and crossline directions respectively. Our use of sparseness weights in the τ-p_x-p_y domain penalizes incoherent energy in the inversion so that an artificial gain limit is unnecessary, allowing for greater signal recovery than in the conventional case.

Methodology

The input dataset $d(t,n)$ is a post-migration time domain volume in the t-x-y domain exhibiting the effects of Q absorption, where x and y refer to inline and crossline directions. Traces in this domain are indexed by n. Here, we assume a post-stack input dataset, though our method could be applied to a pre-stack common offset volume with appropriate considerations for proper time referencing (Xia 2005). We define the inversion problem as

$$d(t,n) = A(t,n)L(t,n,\tau,m)W(\tau,m)u(\tau,m), \tag{2}$$

where $u(\tau,m)$ is an unknown dataset in the τ-p_x-p_y domain, free of the effects of Q absorption, to be found by inversion. Traces in this domain are indexed by m. $W(\tau,m)$ is a linear operator encoding sparseness weights in the τ-p_x-p_y domain. The linear operator $L(t,n,\tau,m)$ is a 3D reverse τ-p_x-p_y transform in the time domain. Following Poole et al. (2015), it may be more efficient in practice to use an equivalent frequency domain definition for L, wrapped by 1D FFTs transforming between time and temporal frequency domains. $A(t,n)$ is a linear absorption operator describing Equation (1) for a known effective Q field. Effective Q values consider attenuation due to the overburden of a given layer, in addition to the layer itself. They differ from interval Q values which take into account absorption due only to the layer itself. Our method accommodates an effective Q field which is a function of t, x and y. Strategies for estimation of the Q field include the long established spectral ratio method and the more recently developed approach of Q tomography (Xin et al. 2008).

The inversion problem can be solved, for example, by the method of Iteratively Reweighted Least Squares (Trad et al. 2003). Sparseness weights can be initialized by taking them to be unity everywhere. Thereafter, weights for a given iteration may be derived from the solution in τ-p_x-p_y of the previous iteration. Amplitudes in τ-p_x-p_y represent a measure of coherency for the t-x-y domain, so this approach discriminates between signal and noise by assigning high weights to energy coherent in t-x-y, and low weights to incoherent energy. Once the inversion is solved for $u(\tau,m)$, the Q compensated result $d'(t,n)$ in the t-x-y domain is obtained by omitting $A(t,n)$ from Equation (2),

$$d'(t,n) = L(t,n,\tau,m)W(\tau,m)u(\tau,m). \tag{3}$$

As with any inversion, there will be a small amount of residual energy in the input data not described by $u(\tau, m)$. If required, this energy may be accounted for by applying a conventional Q compensation to the residual with an appropriate gain limit, then adding the Q compensated residual to $d'(t, n)$.

Our approach may be extended to include a dip-dependent Q compensation that accounts for the spectral shifting effects of migration (Lin et al. 2013, Khalil et al. 2015). In this case, the absorption operator used in the inversion is modified to describe the following absorption model:

$$a'(f,t,x,y) \propto \exp(-\pi f t / Q(t,x,y)\cos(\theta)) = \exp\left(-\pi f t \sqrt{1+\sigma_x^2+\sigma_y^2} / Q(t,x,y)\right), \qquad (4)$$

where θ is a 3D geological dip, and the depth domain slownesses σ_x and σ_y can be computed from the corresponding time domain slownesses p_x and p_y using a time-to-depth mapping based on a velocity field appropriate to the data, which may be assumed to be locally invariant. As the absorption model is now a function of p_x and p_y, the operators A and L are now coupled as a function of dip, and need to be evaluated simultaneously in the inversion, on a dip-by-dip basis.

Examples

For convenience, we take Q = 150 in all examples. The synthetic example is a proof of concept. Figure 1 shows an inline (taken from a larger 3D volume) for a flat event at t = 4000 ms. The top half of the figure shows results for all frequencies, while the bottom half displays corresponding results after 30-60 Hz band-pass filtering. The reference data (a) comprises a broadband spike. Q absorption is then applied to (a) using a conventional Q absorption algorithm based on Equation (1), followed by addition of Gaussian noise, to create a second dataset (b), used as the input to Q compensation. The results of applying a conventional Q compensation to (b) are shown in (c), (d) and (e), with gain limits of 10 dB, 20 dB and 30 dB respectively. Results using our proposed approach are shown in (f).

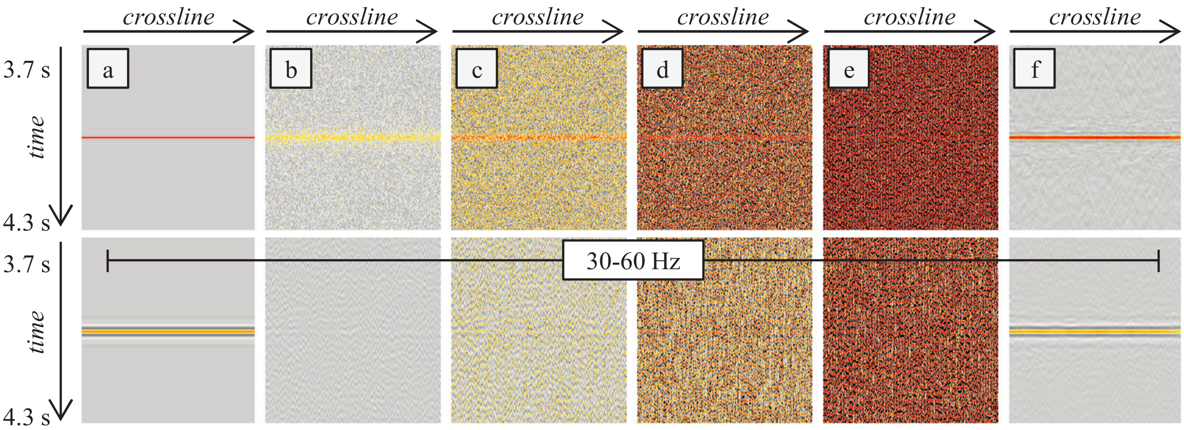

***Figure 1**. A comparison of conventional Q compensation and the proposed approach, for a single synthetic event. (a) is the reference data, (b) is the input to Q compensation, (c)–(e) are conventional results with gain limits of 10 dB, 20 dB and 30 dB respectively, (f) is the 3D inversion result.*

The results from the conventional algorithm demonstrate the problem of noise contamination, particularly on the band-limited displays where the signal is less clearly identifiable. The central frequency on the band-limited displays is 45 Hz, where we find from Equation (1) that a gain of approximately 30 dB is required to recover the signal completely. However, a considerably lower gain limit than this is necessary for the conventional method to avoid obscuring the signal almost entirely with noise. The proposed method (f) recovers (a) much more effectively without significant boosting of noise. Standard random noise attenuation techniques could be used to improve the conventional compensation results, but are unlikely to be effective where the noise contamination is most severe.

The first real data example comes from a 3D North Sea towed streamer dataset. Figure 2 shows an inline stack after conventional Q compensation with gain limits of (a) 35 dB and (b) 50 dB, together with (c) the 3D inversion. In each case, the absorption model used is that given by Equation (1). At 70 Hz, at least 50 dB of gain is required for signal below 4 seconds to be compensated fully. However,

Figure 2(b) shows that using a gain limit of this magnitude in the conventional method leads to a result almost completely dominated by noise at high frequencies. Figure 2(a) shows that lowering this limit reduces the impact of noise, but at the cost of only partially recovered signal. The 3D inversion in Figure 2(c) retrieves high frequency signal and suppresses noise more effectively than the conventional results, as highlighted by the boxes on the figure.

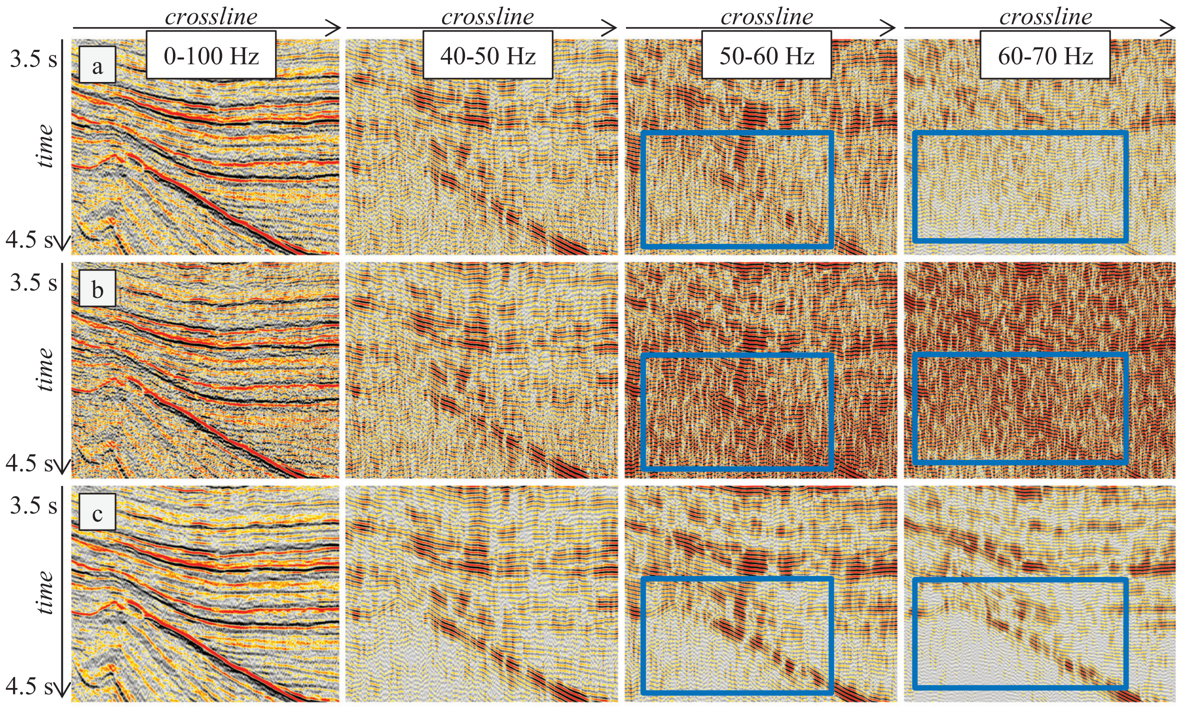

***Figure 2**. A comparison on North Sea field data of conventional Q compensation with gain limits of (a) 35 dB and (b) 50 dB, together with (c) the 3D inversion result.*

Another example, taken from the same North Sea dataset, illustrates the effects of the dip-dependent Q compensation based on Equation (4). Figure 3 shows time slices at 3.6 seconds after the proposed method (a) without and (b) with the dip-dependent correction, together with (c) the difference between the two approaches. The dip-corrected results show improved resolution on the steep salt flanks, highlighted by the boxes on the figure. Elsewhere, where the geology is less steep, the differences are more subtle.

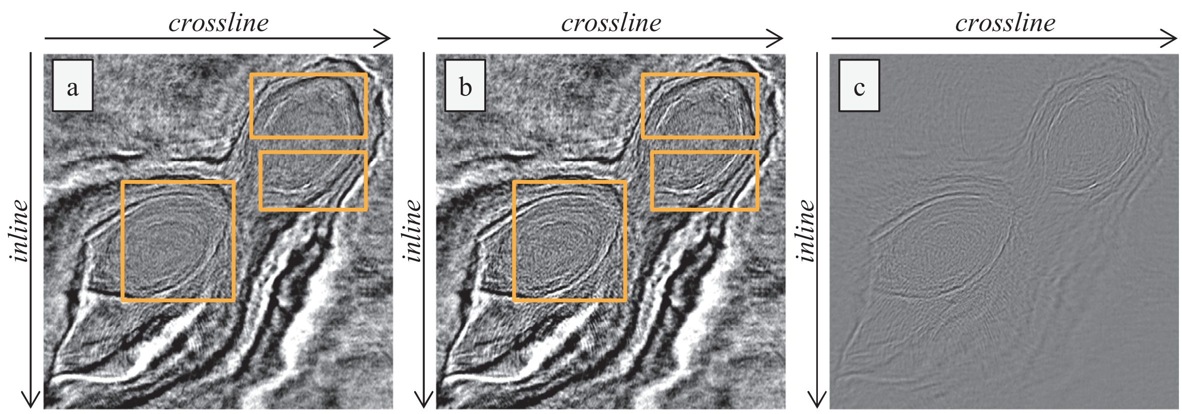

***Figure 3**. A comparison of the proposed method (a) without and (b) with dip-dependent correction, together with (c) the difference between the two applications.*

Finally, we show how our methodology can be combined with residual spectral broadening techniques which may be applied after Q compensation. Figure 4 shows an inline stack from a second North Sea dataset after (a) a conventional Q compensation with a 25 dB gain limit, (b) the proposed method, and (c) the proposed method followed by spectral enhancement described by JafarGandomi

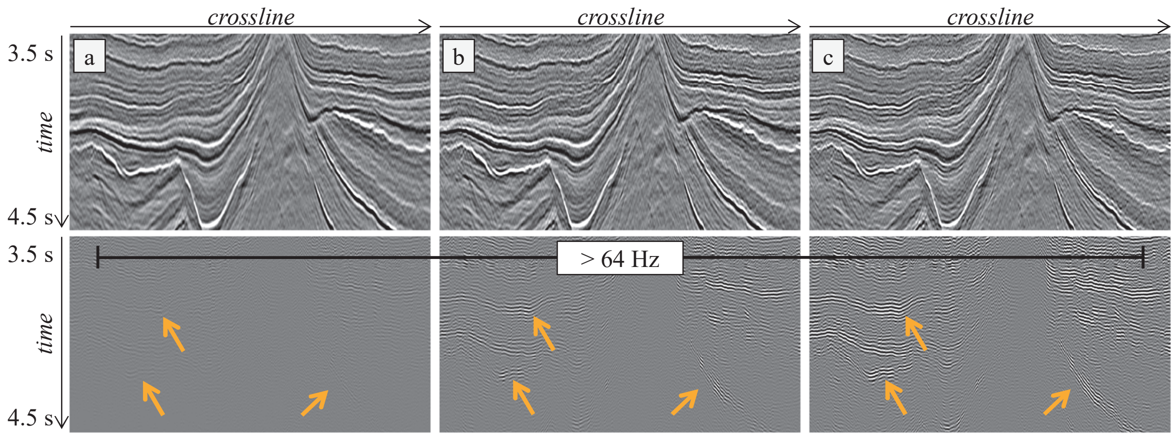

***Figure 4**. A comparison of (a) conventional Q compensation, (b) the proposed method, and (c) the proposed method followed by spectral enhancement described by JafarGandomi and Hoeber (2016).*

and Hoeber (2016). As shown by the arrows on the figure, combining the latter two approaches extends signal bandwidth beyond that obtained with the proposed method alone, and significantly beyond that obtained with the conventional Q compensation.

Conclusions

We have demonstrated a robust 3D Q compensation methodology for data exhibiting incoherent noise. Comparisons on synthetic and field data highlight clear benefits of the proposed approach over conventional Q compensation. Unlike the conventional algorithm, our use of sparseness weights avoids the need for an artificial gain limit in the compensation to control noise. The removal of this limit improves signal recovery, particularly at high frequencies. Defining the inversion problem in the τ-p_x-p_y domain ensures spatial consistency, and allows an optional dip-dependent correction to be incorporated into the algorithm that is consistent with the spectral shifting effects of migration.

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