AVO Compliant Spectral Balancing

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Summary

Spectral balancing is often performed after surface consistent deconvolution to further flatten the frequency spectrum. However, unless carefully implemented this might have the undesirable effect of altering the amplitude versus offset relationship introducing systematic error into subsequent AVO analysis. Further, spectral balancing is often performed after NMO correction is applied in order to help remove NMO stretch. The presence of wavelet stretch or non-stationary frequency loss in offset and time affects amplitude relationship with offset. Not compensating for the frequency loss alters the AVO gradient and reduces the resolution of stacks. Worse yet, a false gradient can appear due to the wavelet stretch caused by moveout correction. In this paper we present a method to flatten spectrum and remove stretch while preserving the AVO. It does not require prior knowledge of the AVO/AVA relationship or of the kinematics. The designed operator is non-stationary in offset and time. The operator is made robust in the presence of random noise by averaging over a zone of traces. However, averaging over offsets alters the AVO and stretch relationships, thereby distorting the operator. To avoid this effect, we present an operator that averages over traces within a common-offset plane, where the frequency loss is constant.

Introduction

The primary goal of controlled amplitude processing is to precondition the seismic data in a manner that meets the theoretical assumptions inherent in AVO or prestack inversion (Downton, 2005). Reliable estimation of AVO attributes depends on preserving the amplitude versus offset information in the seismic data. Loss of bandwidth due to NMO stretch or other processing steps must be compensated not only to improve the AVO attribute resolution but also to remove false AVO effects caused by these processes. NMO stretch introduces an additional challenge by creating a spectrum that is non-stationary with offset and time, where the far offsets undergo frequency loss. In other words, after NMO, seismic data bandwidth is less than optimal, which reduces the resolution and continuity of AVO attributes. Spectral whitening helps improve the spectral bandwidth.

Most spectral whitening methods use mean scaling to whiten the data. This scaling destroys AVO compliance (Figure 1). In this paper, we propose a new spectral whitening method that honors AVO. We also show that the method is applicable in removing NMO stretch.

Previous studies have shown the effects of NMO stretch on the data (Dunkin and Levin, 1973). The effect of NMO stretch on AVO was quantified by Lin and Phair (1993), Swan (1997) and Dong (1999). Stretch varies with time and offset. To account for time and offset varying stretch, we derive a data adaptive, non-stationary time-domain operator for each offset to whiten the spectrum of the gathers in an AVO complaint way. Further it should be noted that prior knowledge of stretch or AVO is not required by the proposed spectral flattening method.

Theory

The proposed spectral whitening is a stochastic deconvolution approach that flattens the spectrum by dividing the data into multiple frequency windows. In order to preserve the AVO trend it is assumed that over some reference band the frequency spectrum is flat and has a high signal-to-noise ratio. Each frequency window within the trace is then whitened to the same energy level as the reference band, thus preserving the amplitude trend. The resulting operator is data-adaptive and non-stationary in time and offset, thereby optimizing the operator when time and offset variations exist (eg. NMO stretch). The whitening range is constrained by the bandwidth of the zero offset wavelet. The potential weakness of this approach is that the S/N ratio can vary spatially depending on noise conditions, potentially introducing systematic error into the AVO gradient. In order to mitigate this we employ ensemble averaging in the offset domain, providing a better estimate of the signal power.

The method is shown to preserve AVO when tested on synthetic models and real data. Synthetic models with and without stretch were built with same Class 3 AVO responses. The model without stretch (the reference model) is shown in Figure 2a, the model with stretch is shown in Figure 2b. A Class 3 AVO response is characterized by a negative peak followed by decreasing amplitude with offset, i.e. the far-offset amplitudes are more negative than the near-offset amplitudes. For the Class 3 model used, the far offset above 60 degrees lost more than half the bandwidth that was present at zero offset after NMO, indicating significant stretch. The amplitude spectrum maximum of the far offset increased compared to the near offset spectrum. The new spectral balancing method was applied on the stretched data with the results shown in Figure 2c. As seen, the stretch in the data is removed. Figure 2d shows the amplitude spectra of model with and without spectral balancing. NMO correction introduces a null space in the spectrum which cannot be recovered. Amplitude vs. offset at the peak of the event was measured on the model whose stretch was removed and compared with the reference model (top panel of Figure 2e). For angles less than 50 degrees, the amplitude at the trough of the event agreed within 10% of the reference model (bottom panel of Figure 2e). For most offsets, the percentage error was less than 10%.

The single trace approach outlined above can be sensitive to random noise. A variant of the spectral balancing approach that averages operators within a zone of interest can overcome sensitivity to random noise. However, when the operator is averaged over a range of offsets, the AVO and the stretch factors are averaged across the offset, resulting in degradation of AVO attributes. On the Class 3 AVO response model with stretch, ensemble based spectral balancing was applied where operators across offsets are averaged. Figure 3a shows the model gathersin time domain after applying operator that is averaged across offsets. The amplitudes at the trough of the event are altered considerably, rendering the spectral balanced data unsuitable for AVO analysis. The resulting spectra are shown in Figures 3b and c. It can be seen that the near offset's high frequencies are over-estimated by the average operator while at far offsets, they are under-estimated. This is due to applying a stationary operator to a nonstationary wavelet (i.e NMO stretch changes the spectrum as a function of offset) and this operator averages over offsets.

To take advantage of the noise averaging of ensemble based approaches, we apply this approach to data in common offset planes. Instead of averaging over offsets, the operators within an offset plane are averaged. Further, the ensemble approach is applied over a spatial zone of traces so that the method is applicable to structured geology.

Examples

Zone averaged spectral balancing was applied on real 3D gathers in common-offset domain to flatten the spectrum and determine whether spectral whitening preserved AVO or not. The spectral whitening was applied after move-out correction was applied. Figure 4 shows gathers and corresponding spectra with and without spectral whitening around a known well location. Notice that the stretch in the data has been removed by flattening the spectrum. The AVO attributes based on Aki-Richards 2-term approximation were obtained on supergathers with and without spectral whitening. Forward modeling the well logs indicated a class I AVO response at the Viking, and Joli Fou horizons (880 and 912 ms). The AVO attributes (intercept and gradient) obtained at these horizons matched the modeled response. S-impedance reflectivity was obtained from weighted difference of intercept and gradient (Figure 5). The intercept and gradient and therefore S-impedance reflectivity are well preserved by spectral whitening. Better resolution and continuity are obtained when spectral whitening is performed, which resulted in better resolved AVO attributes.

Conclusions

This paper has demonstrated a spectral whitening approach to improve the seismic bandwidth in an AVO compliant way. The method was demonstrated on synthetic and real data with NMO stretch with good results. The use of a reference band preserves the AVO trend, overcoming the disadvantages of a mean scaling approach. However, estimating the signal amplitude from one limited frequency window on a trace by trace basis is sensitive to random noise. Therefore an ensemble-based approach that averages random noise may increase the approach's reliability. From modeling studies (Figure 3), the ensemble based approaches when applied in CDP or shot domain can be harmful to AVO. To overcome this, we use a common-offset ensemble.

The advantage of the proposed method is that it does not require estimating the wavelet or require prior knowledge of the AVO. NMO stretch poses an additional challenge where stretch is non-stationary with offset and time. Therefore, the operator used is non-stationary in offset and time, which flattens the spectrum honoring the local stretch.

Acknowledgements

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References

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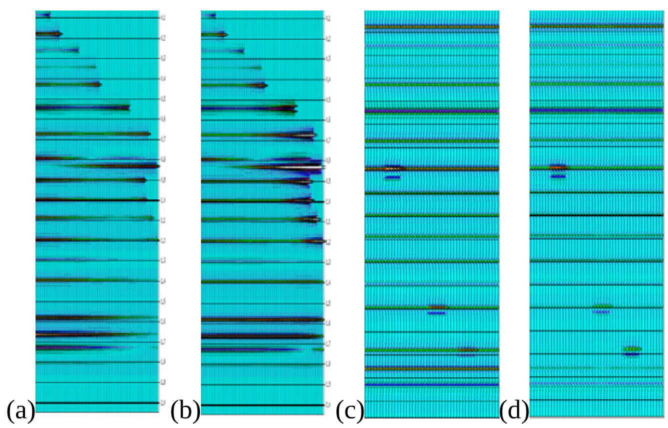

Figure 1. Model data after pre-conditioning using (a) surface consistent scaling (b) mean scaling. S-wave impedance reflectivity when pre-conditioned using (c) surface consistent scaling (d) mean scaling. Using mean scaling, amplitude information at far offsets changed in a non-consistent manner as compared to surface consistent scaling. In this case, the partition of input amplitudes into intercept and gradient spaces differed from that of surface consistent scaled input gathers as shown by the S-impedance reflectivity estimate. (With permission from Downton, 2005)

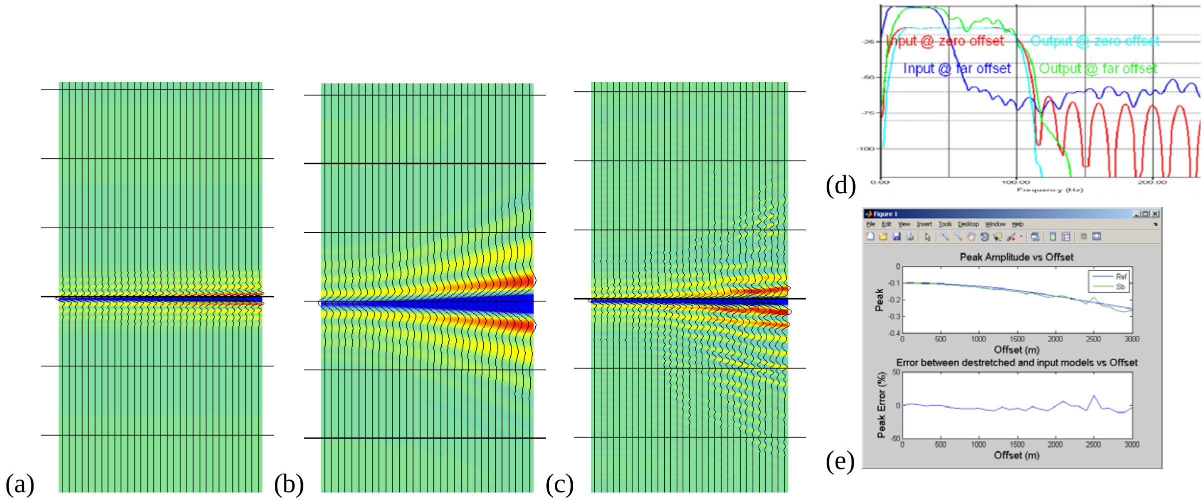

Figure 2. Synthetic model with Class 3 AVO anomaly (a) without stretch (reference model) (b) with stretch (same AVO as model without stretch) caused by move-out correction (c) after moveout correction and spectral balancing, (d) amplitude spectra of stretched model before and after spectral balancing . The colored spectra are marked by text in the same color. In Figure 2e, the measured amplitude vs offset at trough of the event is shown. The top panel in Figure 2e shows the amplitude vs offset plot for reference (blue) and spectral balanced gathers (green). The bottom panel in Figure 2e shows the error between reference and spectral balanced output at the trough of the event. From the error plot, it can be seen that for most offsets , the error is less than 10%.

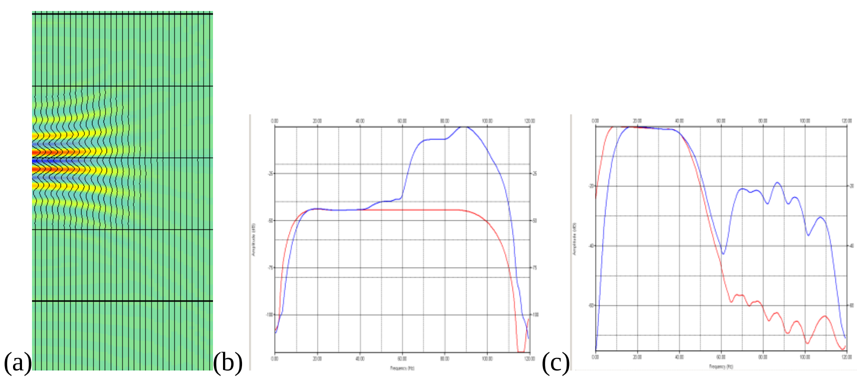

Figure 3. (a) Class 3 model gather shown in the time domain after applying ensemble operator in CDP domain (section was gained down to show the amplitudes unclipped). The amplitudes are severely distorted by applying ensemble operator in CDP domain. Note that the gradient has changed. (b) zero-offset trace spectrum and (c) far-offset trace spectrum. Red - without applying ensemble operator, Blue - after applying ensemble operator.

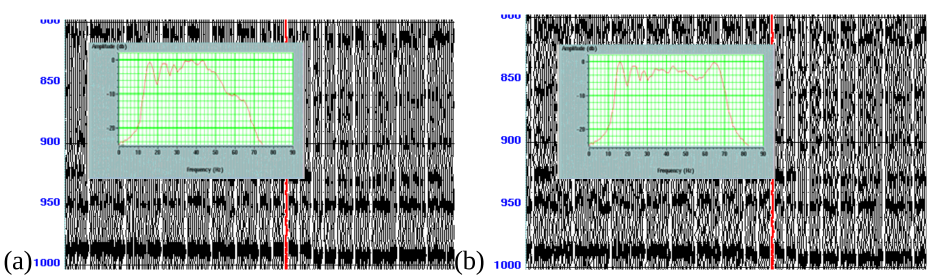

Figure 4. Seismic gathers shown (average spectra –inset) around a well location in CDP domain. Gathers (a) without spectral balancing (b) with spectral balancing. Ensemble based spectral balancing was done on data in (b) in common-offset domain. The red line indicates the location of the well.

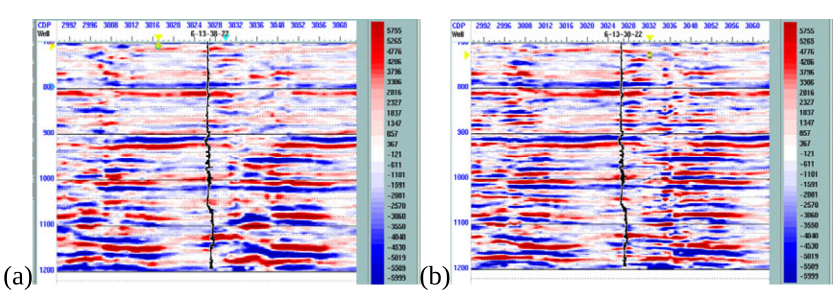

Figure 5. S-impedance reflectivity computed at well 1 location (a) section without spectral balancing (b) section with spectral balancing. Improved resolution and detail in gradient section resulted in improved S-impedance reflectivity using spectral balancing. The measured intercept, gradient responses matched the response predicted from logs at Viking, and Joli Fou horizons (880 ms and 912 ms).