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Unbiased surface-consistent scalar estimation by crosscorrelation

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Summary

Surface-consistent scaling is used in standard processing flows to remove shot-to-shot and receiver-to-receiver amplitude variations present in land data. In an AVO compliant processing flow, surface-consistent scaling is necessary. In conventional surface-consistent scaling methods, the scalars are obtained by decomposing the RMS amplitudes of noise contaminated pre-stack traces. The result is a biased solution where the traces, which consist of the signal and the noise, are balanced in a surface-consistent manner but the signal remains unbalanced. As a solution to this problem, Cary and Nagarajappa (2013) proposed an unbiased scaling approach in which the shot and receiver consistent scalar estimates were obtained from the RMS amplitudes of the shot and receiver stacks. With this method, the underlying data must be nearly flat in order to stack in the shot or receiver domain and obtain accurate scalar estimates. When the data is not flat, then it first needs to be flattened with horizon-picking, which can be difficult when geology is complicated. In this paper, we propose an unbiased scaling method that does not require horizon picking. The proposed method computes the pre-stack amplitudes from the zero-lag value of the cross correlations between each pre-stack trace and its CDP stack trace. Such a cross correlation can provide unbiased pre-stack amplitudes. In addition, the pre-stack amplitudes are not dependent on the time variations in the structure. The shot and receiver consistent averages can then be computed to obtain the scalars in a surface-consistent manner.

Introduction

In land data, causes of amplitude variations between shots and between receivers include near-surface conditions, coupling, and source/receiver type differences. Surface-consistent scaling is routinely used to estimate and remove these variations. Surface-consistent scaling methods and their applications are discussed in Taner & Koehler (1981), Taner et al. (1991), Yu et al. (1985) and Garceran et al. (2013). In these methods, the RMS amplitudes of the pre-stack traces are used and a set of equations are formed. The equations are then solved to obtain the surface-consistent scalar estimates. These scalar estimates cannot balance the signal in the data because the RMS amplitudes of the pre-stack traces are biased by noise. Cary and Nagarajappa (2013) showed that the unbiased surface-consistent scalar estimates could be obtained by computing the RMS amplitudes of the shot stacks and of the receiver stacks. It was shown that these stack amplitudes estimate the shot and receiver consistent amplitude variations of the signal in the data and thus are unbiased scalar estimates. Henceforth in this paper, we refer to this approach as the unbiased scaling method.

As stated by Cary and Nagarajappa (2013), when the underlying data is nearly flat, the shot stacks and the receiver stacks can be used to estimate the surface-consistent scalars. If the structure is complex, then prior to stacking in the shot or receiver domain, the data must be flattened by picking a horizon. Horizon picking is not always a straight-forward process due to the noise, presence of complex features in the geology, discontinuous horizons etc. In this paper, we propose a method that can compute the unbiased scalar estimates, irrespective of whether the data is flat or not. We describe the method and then show the results on synthetic and real data.

Theory and Method

In the proposed method, we cross correlate each NMO corrected pre-stack trace with its normalized CDP stack trace. The cross correlation allows the algorithm to be independent of the structural delay term and also an unbiased estimate for each pre-stack trace can be computed from it. In particular, the zero-lag value of the cross correlation is used to obtain the unbiased pre-stack amplitude estimates. In this section, we derive the aforementioned properties of the cross correlated pre-stack traces and, show how the surface-consistent scalar estimates can be obtained.

Let us consider an NMO corrected data trace that has structure and surface-consistent amplitude variations. It can be represented as:

$$d_{srgh}(t) = a_s a_r a_g a_h S_g(t) + N(t) \quad ,$$

where t is time, $S_g(t)$ or equivalently $S(t\text{-}t_g)$ is the signal trace at CDP *g* whose delay due to the structure is given by t_g, $N(t)$ is the noise trace and is assumed to be zero-mean and uncorrelated with the signal trace,

s, *r*, *g* and *h* are the shot, receiver, CDP and offset indices, respectively, and

a_s, a_r, a_g, a_h are the shot, receiver, CDP and offset consistent amplitude scalars, respectively.

The term $S(t\text{-}t_g)$ indicates a structure dependent delay term. Although, the theory explained below holds for any structure, for simplicity, $S(t\text{-}t_g)$ is used to represent the CDP consistent delay term in the data. In this model, the time shifts as a function of offset are not considered.

We begin by normalizing each CDP stack trace to remove the influence of the CDP consistent scalar term on the solution. The same can be represented for a given CDP *g* as:

$$\frac{S(t-t_g)\widehat{a_g}}{RMS\left(S(t-t_g)\widehat{a_g}\right)} = \frac{S(t-t_g)}{k} \quad , \qquad (1)$$

where $\widehat{a_g}$ is the estimated CDP consistent scalar and *k* is the normalization constant. Note that in eqn(1), we have assumed that the noise term in the CDP stack trace is negligible. Next, the zero-lag value of the cross correlation between each pre-stack trace and its normalized CDP stack trace is computed:

$$a_s a_r a_g a_h S(t\text{-}t_g) \circ S(t\text{-}t_g)/k = a_s a_r a_g a_h\, a(0)/k \quad , \qquad (2)$$

where, ○ indicates correlation and *a(0)* is the zero-lag correlation value. In eqn(2), it was assumed that the noise component of the pre-stack trace is uncorrelated with its CDP stack trace.

Now the unbiased pre-stack amplitude estimates are obtained by dividing eqn(2) by the number of samples used in the correlation which simplifies eqn(2) to

$$a_s a_r a_g a_h\, k \quad . \qquad (3)$$

Eqn (3) shows a pre-stack trace amplitude estimate that is a function of the shot, receiver, CDP and offset that it belongs to. An important observation from eqn(3) is that the amplitude estimate is unbiased because unlike the conventional methods, it is not influenced by the noise. Further, the estimate we have derived is not influenced by the structural delay term. For each component, these unbiased pre-stack amplitudes are averaged in a surface-consistent manner to obtain the respective surface-consistent scalar estimates and their inverses are applied to the pre-stack traces. The computation of eqn (3), averaging in a surface-consistent fashion and applying the inverse, can be iterated several times until a reasonable solution is achieved. We call this approach the CCF unbiased scaling correction. Under the stated assumptions, the proposed method should produce the same scalar estimates as the unbiased scaling method when the data is flat. In areas of low fold and/or low signal-to-noise ratio, the CDP stack traces can be contaminated by noise that will correlate with the noise on the trace that it is correlated with. This will result in a biased estimate. In such cases, it is necessary to cross correlate each pre-stack trace with the CDP stack trace that is averaged over its neighbors. The averaging will minimize the noise content on the CDP stack traces. Further, the signal estimate is iteratively improved allowing the method to work effectively in noisy areas.

In practice, any offset consistent variations present in the real data can be removed prior to computing the shot and receiver consistent variations. The offset consistent scalars for each offset bin are determined by computing the estimates shown in eqn(3) and averaging them over the offset bin.

Examples

We first compared the proposed CCF unbiased scaling method with the unbiased scaling method on data with no dip. A synthetic dataset was modeled and surface-consistent shot and receiver signal variations were applied to it. Then shot and receiver consistent corrections were estimated and applied. The RMS amplitudes of the CDP, shot and receiver stack traces before and after surface-consistent scaling correction were plotted. Figure 1(a-c) show the RMS amplitude maps before any scaling correction, Figure 1(d-f) show the corresponding maps after the unbiased scaling correction and Figure 1(g-i) show the maps after the CCF unbiased scaling correction. As expected, in the absence of dip in the data, the results of the two scaling methods are equivalent. We then applied the proposed method to a second synthetic dataset that consisted of the shot and receiver consistent signal variations and a dip (2ms/trace) in the cross-line direction. The RMS amplitudes of the stacks were plotted in Figure 1(j-l). It can be seen that the proposed method balances the signal and the results are the same as the unbiased scaling approach. As a further test on the synthetic data with dip and surface-consistent signal variation, the shot and receiver consistent noise was added and the proposed scaling correction was applied. The results (Figure 2) show that the method has balanced the data very well. The standard deviation of stack amplitudes in all domains was less than 5%. In Figure 3, the result of the conventional surface-consistent scaling method is compared to that of the CCF unbiased scaling method. A stack from a shot line is shown for each method. Amplitude banding can be seen after applying the conventional method. The CCF unbiased scaling correction has balanced the signal. Note that the dip was removed before computing the shot and receiver stacks for display in Figures 1-3.

The proposed CCF unbiased scaling correction was also applied to a real 3D dataset that had NMO correction, final statics correction and two passes of conventional surface-consistent scaling applied to it. Before computing the scalars by either method, steps were taken to minimize the amplitude outliers and other factors that can degrade the solution, as discussed in Cary and Nagarajappa (2013). A design window from 600 to 1800 ms was used for computing the CCF unbiased scalars. The shot and CDP stacks are shown in Figure 4 before and after applying the proposed method. For display purposes, the structure in the data was removed by picking a horizon and then the shot stacks were computed. Before the scaling correction, a spatial amplitude banding can be observed on the shot stack. After the CCF unbiased scaling correction, the shot stacks are better balanced and also the CDP stacks are balanced. The results are shown after two iterations of the proposed unbiased scaling method.

Conclusions

In this abstract, we have discussed a method that can provide unbiased surface-consistent scalar estimates, regardless of whether the data is flat or not. The key step in this method is the cross correlation of each NMO-corrected pre-stack trace with its CDP stack trace. This cross correlation can be used to obtain an unbiased amplitude estimate for each pre-stack trace. The unbiased amplitude estimate is independent of the CDP-to-CDP delay variations and therefore obviates the need to flatten the horizon. The shot and receiver consistent scalars are computed by averaging the unbiased estimates in a surface-consistent method. This method is applicable when the data does not have offset dependent travel-time variations.

On the synthetic datasets with surface-consistent signal, irrespective of the dip, the CCF unbiased scaling method balanced the signal in a surface-consistent manner. In the presence of noise also, the CCF unbiased scaling method balanced the shot and receiver signal variations. With such noise, the conventional surface-consistent scaling result showed amplitude banding.

The CCF unbiased scaling method was also demonstrated on a real 3D dataset with amplitude banding visible on the shot stack. It was shown that after applying the shot and receiver corrections determined by the proposed surface-consistent method, the shot and CDP stacks were properly balanced.

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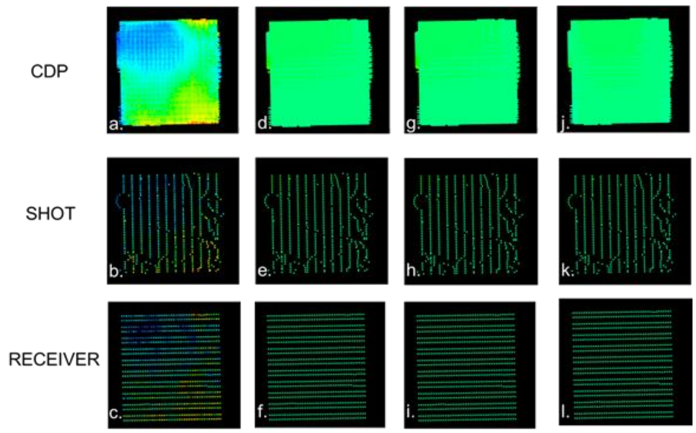

Figure1. Maps of the RMS amplitudes computed from the CDP, shot and receiver stacks of the synthetic data are shown. Subfigures a-c show the amplitude maps of input data that has surface-consistent signal and no dip. Subfigures d-f show the amplitude maps after applying the unbiased scaling correction and g-h show the amplitude maps after applying the CCF unbiased scaling correction to the input data in a-c. The result of the CCF unbiased scaling correction on synthetic data with dip is shown in subfigures j-l. All the maps were plotted on color scale range 1000 to 4500. After scaling corrections, the amplitude variation in each of the CDP, shot and receiver stack domains was about 2%.

Figure 2. Maps of the CDP, shot, and receiver stack amplitudes are shown after applying the CCF unbiased scaling correction to synthetic data with dip, surface-consistent signal, and surface-consistent noise variations. The standard deviation of stack amplitudes was less than 5% in all domains.

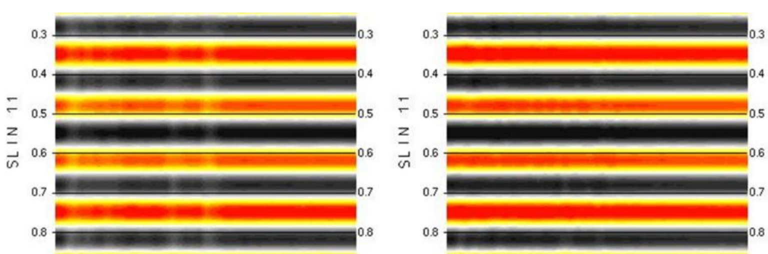

Figure 3. Synthetic data from a shot line is shown after conventional scaling correction (on the left) and after CCF scaling correction (on the right). Banding artefacts remain after conventional scaling correction. Data was flattened before plotting.

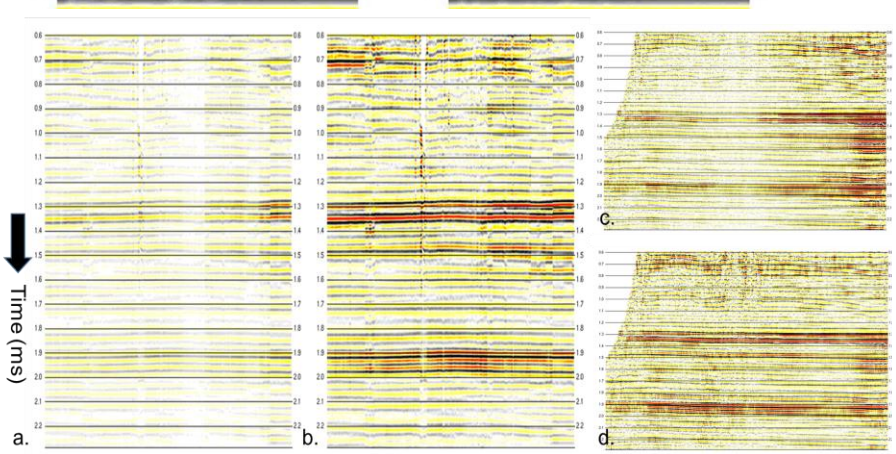

Figure 4. A shot stack from one shot line (a) before correction shows spatial amplitude banding and (b) after correction by the CCF unbiased scaling shows balanced amplitudes. A CDP stack from a cross-line is shown in (c) before and in (d) after the CCF unbiased scaling correction. The CDP stack appears balanced after the correction is applied. Data was flattened before plotting.