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Horizon-Based and Frequency-Dependent Surface-Consistent Scaling

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Summary

For many years, surface-consistent scaling has been a standard step in land AVO-compliant processing flows to remove amplitude variations caused by different source and geophone types, coupling and near-surface conditions. The conventional method treats surface-consistent amplitude variation as a frequency-independent and stationary problem. Due to varying near-surface conditions, the surface-consistent amplitude issue may be frequency-dependent. Furthermore, a non-stationary element can be incorporated by formulating a time-variant solution. In this paper, we propose a new approach called horizon-based and frequency-dependent surface-consistent Amplitude (HFSCA) scaling, handling the frequency-dependent non-stationary surface-consistent amplitude variation as well as minimizing the effect of random noise on the estimation of surface-consistent scalars. The method includes CDP, azimuth and offset components in the solution to prevent shot and receiver scalars from being affected or biased by geology, NMO stretch and anisotropy. Synthetic data and real data demonstrate that the proposed HFSCA scaling method can preserve AVO and yield more balanced and consistent amplitude gathers for further noise attenuation, 5D interpolation and imaging.

Introduction

Variations in source type and strength, receiver type and coupling, and near-surface anomalies are a few of the factors affecting amplitude that need addressing in land AVO-compliant processing flows. Surface-consistent amplitude scaling reduces such influences on amplitude.

Taner & Koehler (1981) first discussed surface-consistent corrections. For surface-consistent scaling corrections, their method decomposed the RMS amplitudes of the pre-stack traces into average line, shot (source), receiver (geophone), CDP and offset components and then applied residual shot and receiver scalars to the data. Garceran and Le Meur (2012) proposed a method that simultaneously estimates surface-consistent amplitude scalars and surface-consistent deconvolution operators since both use the same generalized surface-consistent equation. They observed the surface-consistent attributes from the simultaneous solution to be more reliable than those obtained from the traditional cascade approach. Garceran et al. (2013) discussed a method called data-constrained surface-consistent amplitude correction, which uses a fixed bin term that distributes its natural medium and long wavelength components into the source and receiver components in the inversion, to obtain better medium and long wavelength solutions.

Spatially variant random noise in the data may bias the estimation of shot and receiver scalars.

To mitigate this issue, Cary and Nagarajappa (2013) obtained unbiased surface-consistent scalars by computing the RMS amplitudes of the shot and receiver stacks. Nagarajappa and Cary (2015) recently proposed a method that computes the pre-stack amplitudes from the zero-lag value of the cross-correlations between each pre-stack trace and its CDP stack trace. Then the shot- and receiver-consistent averages are computed to obtain the scalars in a surface-consistent manner. The limitation of these methods is the stack, which is a function of stacking velocities, geologic structure and anisotropy.

The amplitude variations due to near-surface attenuation are time-variant and frequency-dependent. Conventional surface-consistent scaling methods usually ignore this complication by assuming that shot and receiver surface-consistent scalars are stationary. In this paper, we propose a new approach called horizon-based and frequency-dependent surface-consistent amplitude (HFSCA) scaling to handle the non-stationary surface-consistent amplitude variation and minimize the effect of random noise on the estimation of surface-consistent scalars.

Theory and Method

Conventional surface-consistent scaling assumes the RMS amplitude D of an NMO-corrected seismic trace for a user-specified time window can be expressed as a multiplicative form of average term A_l **,** source R_s , receiver R_g , CDP R_c , azimuth R_a and offset R_h residual terms plus added random noise n:

$$D = A_l R_s R_g R_c R_a R_h + n$$

CDP R_c **,** azimuth R_a and offset R_h residual terms are incorporated into the solution to prevent amplitude anomalies due to geology, azimuthal anisotropy and amplitude variation with offset (AVO) to leak into the residual shot and receiver terms. If the near-surface variation and attenuation are negligible, this conventional approach is adequate to remove the amplitude variations due to different source/geophone types and/or coupling. Although all five residual terms are calculated, only the source and receiver residuals are applied to the data D as:

$$D' = D/(R_s R_g)$$

However, near-surface variation and attenuation are often not negligible. In this case, the attenuation is non-stationary, i.e., the relative amplitude attenuation due to near surface anomalies is different for reflectors at different depths (times). The conventional surface-consistent method with large time windows can find only the average surface-consistent scalars for events with different depths in a time window. Also, the attenuation for high frequencies is stronger than that for low frequencies. Considering time and frequency dependencies, the multiplicative form of the RMS ampitude of a seismic trace is:

$$D(t,f) = A_l(t,f) R_s(t,f) R_g(t,f) R_c(t,f) R_a(t,f) R_h(t,f) + n(t,f)$$

For each frequency band (*f*) and horizon-based time window (*t*), we need to solve for frequency-dependent and time-variant average amplitude term $A_l(t,f)$ **,** source $R_s(t,f)$, receiver $R_g(t,f)$, CDP $R_c(t,f)$, azimuth $R_a(t,f)$ and offset $R_h(t,f)$ residual terms. Then the frequency-dependent and horizon-based source and receiver residuals are applied to the data after being linearly interpolated in the frequency and time domains:

$$D'(t,f) = D(t,f)/[R_s(t,f) R_g(t,f)]$$

In the inversion of the residual scalars, we use the L_1 norm to prevent smearing of the solutions. We stabilize the inversion by automatically detecting the larger outliers (very high or low amplitudes) and balancing fold with optimized and flexible offset bin sizes and super CDP bin sizes. By using the time-variant CDP residual term $R_c(t,f)$, we can better preserve the time-variant amplitude variations due to geology. The time-variant offset term $R_h(t,f)$ preserves time-variant amplitude variation with offset (AVO), and helps to prevent solutions being biased by time-variant NMO-stretch with different frequency content. The horizon-based multi-window approach extracts the amplitudes based on data with high signal to noise ratio (S/N), which minimizes the effect of spatially-variant random noise on the calculation of source and receiver terms. When applied to NMO-corrected data with a mild mute, the proposed HFSCA approach reduces the bias of deeper events over shallow events.

Examples

We applied the proposed HFSCA scaling to both synthetic data and real data.

Synthetic data example:

We applied HFSCA first to synthetic data generated with real acquisition geometry. There are four reflectors with different amplitude levels and different classes of AVO. The event shown in Fig. 1b is a reflector with class 3 AVO as shown in Fig. 1a. Then time-variant and frequency-dependent surface-consistent anomalies are applied to the data to obtain the gather (Fig. 1c) with incorrect AVO. The RMS amplitudes for the small time window along the event are shown on the top of the gather. After HFSCA correction applied to data shown in Fig. 1c, the RMS amplitude distortions by surface-consistent anomalies are corrected, as shown in in Fig.1d. In this example, HFSCA has recovered the true AVO distorted by near surface attenuation.

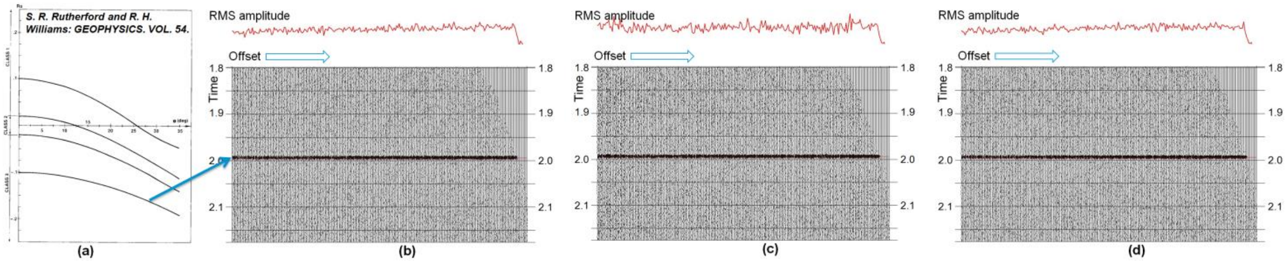


Fig. 1: AVO classes and synthetic CDP gather. (a) Type 3 AVO (bottom curve) was selected for the synthetic test, (b) CDP gather with class 3 AVO without surface-consistent amplitude issue, (c) CDP gather with class 3 AVO with surface-consistent amplitude issue and (d) CDP gather after HFSCA of (c).

Real data example:

Our HFSCA scaling method was applied to a real dataset which shows significant near-surface attenuation. The dataset was NMO-corrected, and two passes of conventional surface-consistent scaling before and after deconvolution have already been applied with great care by excluding amplitude outliers, properly solving the long-wavelength element and attenuating random noise. The comparison at this stage is the last surface-consistent scaling before 5D interpolation. In Fig. 2 we show horizon-varying shot and receiver surface-consistent scalars. For the selected horizon, we show in Fig. 3 frequency-varying shot and receiver surface-consistent scalars from the application of HFSCA.

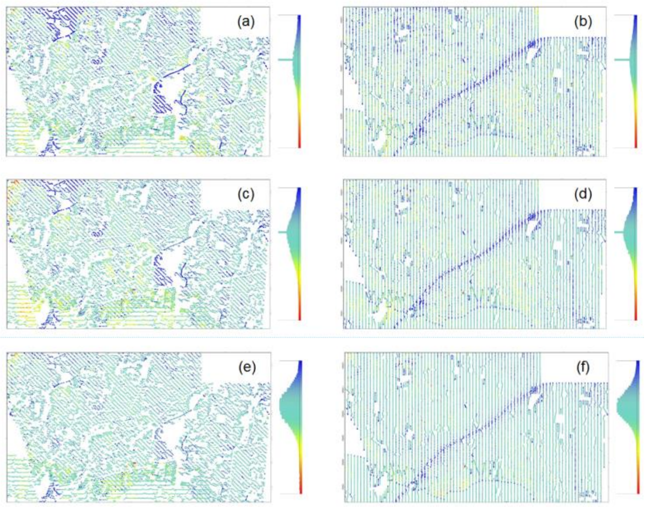


Fig. 2: Shot (left panel) and receiver (right panel) surface-consistent scalars for different **horizons** H1 (a and b), H2 (c and d) and H3 (e and f) as shown in Fig. 4 for frequency band 10 Hz to 20 Hz.

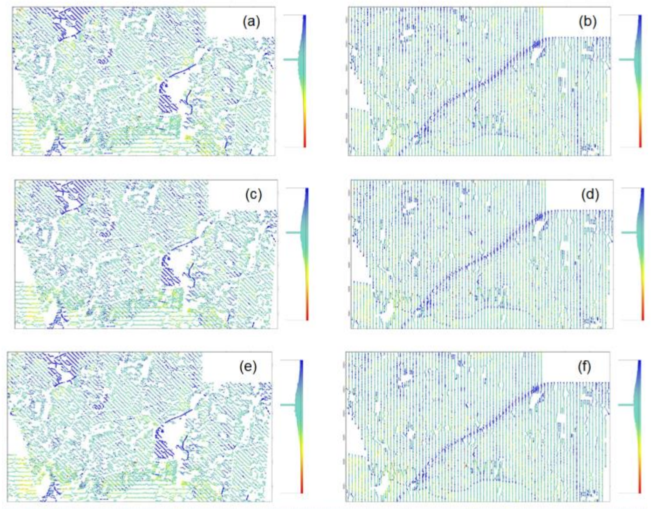
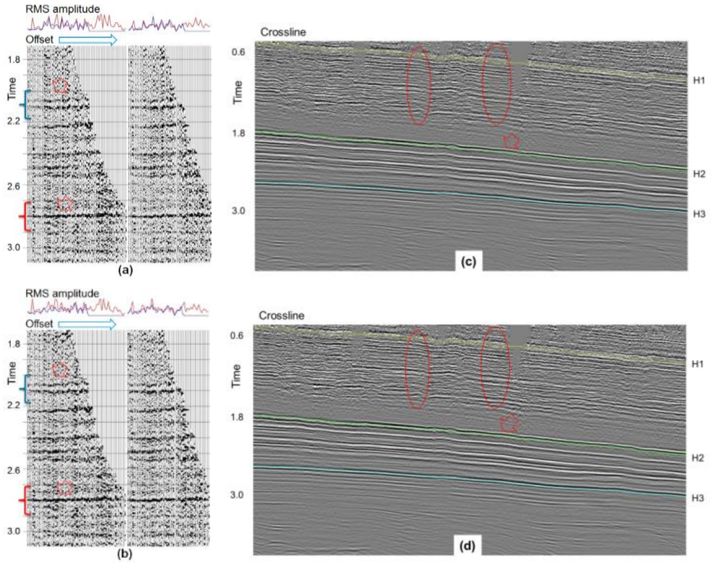


Fig. 3: Shot (left panel) and receiver (right panel) surface-consistent scalars for **different frequency bands** 10 Hz to 20 Hz (a and b), 20 Hz to 30 Hz (c and d) and 30 Hz to 40 Hz (e and f) for horizon H1.

The gather comparison after conventional surface-consistent scaling and HFSCA scaling is shown in Fig. 4a and Fig. 4b, respectively. The amplitudes after HFSCA scaling vary gradually with offset when compared to the conventional surface-consistent scaling. The RMS amplitude curves for the selected two time windows also confirm this observation. The stacked sections (Fig. 4c and Fig. 4d) demonstrate that not only are the shallow events (ellipses around horizon 1) better balanced, the target zone (arrow) around horizon two that was dimmed by near-surface attenuation is also better recovered after HFSCA scaling.

The extracted RMS amplitudes along different horizons with time window sizes of 100 ms are shown in Fig. 5. The comparisons between a and b, c and d, e and f, show that the overall amplitude level is more consistent, and the amplitude variation due to geology is better preserved, after HFSCA scaling. The long wavelength term due to different near-surface attenuation is also properly solved.



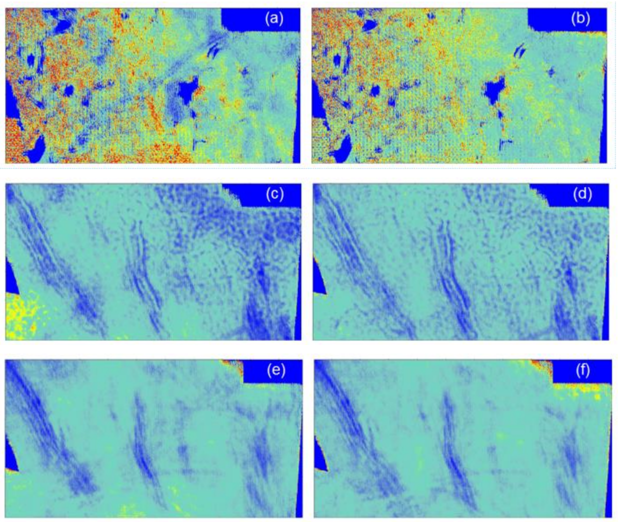


Fig. 4: Comparisons of gathers and stacks between conventional surface-consistent scaling (a and c) and HFSCA scaling (b and d), respectively. The RMS amplitudes for different time windows (blue and red) are displayed on the top of the gathers (a and b).

Fig. 5: RMS amplitudes along horizons H1 (top), H2 (middle) and H3 (bottom) with conventional surface-consistent scaling (left panel) and HFSCA scaling (right panel) methods.

Conclusions

Surface-consistent amplitude scaling should be frequency-dependent because attenuation from the weathering layer near source and receiver locations is frequency-dependent. It should also be time-variant because of the multiplicative form of average and residual terms, and the time-variant nature of near-surface effects on the events at different depths. Including frequency-dependent and time-variant CDP, azimuth and offset components into surface-consistent scaling reduces the effects on shot and receiver scalars from frequency-dependent and / or depth-variant geology, NMO stretch and anisotropy. The horizon-based approach reduces the effect of random noise on the calculation of shot and receiver scalars. Incorporating these elements into HFSCA has produced a robust surface-consistent scaling method that is more accurate than the conventional approach. Synthetic data and real data demonstrated that horizon-based and frequency-dependent multi-window HFSCA can preserve AVO and yield balanced and consistent amplitude gathers for further noise attenuation, 5D interpolation and imaging. The RMS amplitude maps along the horizons after HFSCA are more consistent than those after conventional surface-consistent scaling. This allows better preservation of amplitude variation due to geology than the conventional approach.

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