3C receiver orientation estimation by stack power optimization of reflected PS data

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Summary

In land multi-component (MC) data processing, the orientation of each receiver's horizontal components in the field (H1 and H2) is seldom known accurately. Methods to derive the orientations from recorded data are in common use. They work by assuming a homogeneous, isotropic near-surface earth model and derive an orientation using P-wave first arrival amplitudes on the horizontal components. These methods are known to work well on marine OBC/OBN data and down-hole VSP data. For land data, the near-surface is often strongly inhomogeneous and anisotropic. The P-wave first-break methods can therefore yield inaccurate results. We show examples that illustrate the deviation of P-wave first-break amplitudes from what is expected from a homogeneous near-surface earth.

Estimating receiver orientations from the analysis of reflected PS data may be less influenced by the near surface than methods that analyze first-breaks because of the near vertical ray path of reflections near the surface. We present a new method for obtaining orientation estimates that analyzes reflection data on the horizontal components. This method allows either the presence or absence of HTI anisotropy. The method is based on maximizing the azimuthal-stack power of radial component reflection data and/or minimizing the azimuthal-stack power of the transverse component. We test this method on a real 3C/3D dataset where the true orientation is known.

Introduction

Conventional MC processing requires estimating the orientation of the horizontal components of the receivers from the data. These estimates are used to rotate the horizontal components to radial and transverse directions for further processing. Most methods of estimating the orientations assume a homogeneous isotropic earth model. They analyze first-break amplitudes of the P-wave first arrivals that are measured on the horizontal components to determine the respective orientations by vector decomposition.

It can be shown that for simple earth models the P-wave first-break waveform follows a radiation pattern whose amplitudes change polarity at a specific source-receiver azimuth depending on the orientation of the horizontal component sensor. Analytical methods can be used to determine the orientation estimates for each source-receiver pair and then to determine a statistical average (mean or median) to obtain the best fit measure e.g. Dellinger *et al.* (2001), Bale *et al.* (2012). Hodogram analysis of each shot-receiver pair followed by a best fit value over all shots for a given receiver is also proposed in Guevara & Stewart (1998) and Burch e*t al.* (2005). More recently, a projection method that scans a range of angles to obtain the maximum objective function followed by global analysis of the objective function was proposed in Grossman & Couzens (2012). After orientation estimation and rotation to radial and transverse components, one expects to observe maximum P-wave first-break energy on the radial component and minimum P-wave first-break energy on the transverse component.

Burch *et al.* (2005) have discussed at length why the assumption of a simple earth model such as that used by first-break methods does not necessarily hold. They have shown that near-surface complexities can change the apparent source-receiver azimuth and affect the behavior of P-wave first arrival amplitudes considerably. In addition, near-surface anisotropy may be changing the polarization of P-wave arrivals. Thus it seems that using a criterion that maximizes the P-wave energy on the radial component may fail to give reliable receiver orientations.

In this abstract, we start with examples showing when first-break methods do work well and when they do not work well. Then, we propose the azimuth-stack power method that estimates the orientation from reflected PS energy rather than from P-wave first-breaks. This new method finds a solution that minimizes the power of the stack over the azimuth of the NMO-corrected PS reflections on the transverse component. This is equivalent to maximizing the azimuth-stack power on the radial component. The potential advantage of this method is that, since the reflected PS events have nearly vertical ray-paths near the surface, they should not be affected as much by the near-surface variations that affect the first-break methods and in fact are capable of using HTI anisotropy information.

Traditional First Break Method

Figure 1 shows first-break picks and a P-wave radiation pattern for two receiver gathers from the Blackfoot 3C/3D data set from S. Alberta, Canada. In Figure 1a and 1b, vertical component data is shown for two receiver gathers over a range of offsets used in receiver orientation estimation. The blue line identifies the first-break times. The first-breaks were picked on trough maxima. It can be seen that the quality of first-break picks is reasonable. At the vertical component first-break times, the amplitudes were extracted on corresponding H1 and H2 components. A map of amplitudes for the two receiver gathers is shown in Figure 1c and 1d. In the map display, each amplitude value is plotted at the corresponding shot location relative to the receiver location. The positive amplitudes are identified by red squares and negative amplitudes by blue squares, with the receiver location identified by a triangle.

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The quality of the P-wave amplitudes on the H1 and H2 components was reasonable. However, the radiation pattern in Figure 1c is close to the expected while the pattern in Figure 1d is suggesting that the first-breaks are significantly affected by near-surface heterogeneities. This observation is consistent with the findings of Guevara and Stewart (1998), Burch *et al*. (2005) and Bale *et al*. (2012). However, Grossman and Couzens (2012) do not report similar findings. The actual receiver orientation for the Blackfoot dataset is known to be 90^0 east of north. In general, we find that the statistical average of the orientations estimated from all receivers in the survey corresponds well with the actual receiver orientation, but individual receivers deviate from the average, regardless of which first-break method is used for the analysis. In our estimation, a more reliable method of estimating the receiver orientations is needed.

Theory employing reflected data

To understand how reflection data can potentially be used to determine the receiver orientation, its amplitude behavior on radial and transverse components is first explained. Synthetic radial and transverse gathers with three events (E1, E2 and E3) are shown in Figure 2a, and their respective stacks as a function of trial H1 orientation are shown in Figure 2b and 2c. The first event has experienced no azimuthal anisotropy, the second event has passed through a single horizontal transverse isotropic (HTI) layer and the third event has passed through two HTI layers. The RMS amplitude of each of the events on the radial and transverse stacks is plotted in three panels in Figure 2b and 2c. The effect of azimuthal anisotropy on radial and transverse components is discussed by Cary (2002). A PS-wave reflection that passes through an HTI layer splits into fast (PS1) and slow (PS2) waves. The interfering PS1 and PS2 arrivals on the radial component reflections appear as a sinusoidal pattern. On the transverse component, the two interfering events appear as a single event that experiences a polarity reversal every 90 degrees. So the azimuth-stack of the transverse component is small in magnitude when the receiver orientation is correctly estimated. If the receiver orientation is incorrectly estimated, then the true radial energy partly appears on the estimated transverse component and the expected polarity change every 90^0 becomes smeared. As a result, the magnitude of the azimuth-stack of the transverse component will be larger in magnitude than that at the correct receiver orientation, as shown by the E2 RMS amplitude plot in Figure 2c. Analysis on the radial component results in maximum azimuth-stack power at the correct orientation (see the E2 RMS plot in Figure 2b). In general, the above argument holds when the medium supports birefringence. In the absence of shear wave splitting, the power of the azimuth-stack is also a minimum on the transverse component (see the E1 RMS plot in Figure 2c) and maximum on the radial component (see the E1 RMS plot in Figure 2b). Therefore an objective function that minimizes the azimuth-stack power of the transverse component should work in the absence of anisotropy or in the presence of a single HTI layer. Furthermore, these objective functions should be less affected by scattering in the near-surface than the first-break methods. The azimuthal-stack power on the transverse and radial components can be written as:

$$Et(\tau) = \sum_t [\sum_i (H1_i(t)\sin(\alpha - \theta_i) + H2_i(t)\cos(\alpha - \theta_i))]^2 \quad (1)$$

$$Er(\tau) = \sum_t [\sum_i (H1_i(t)\cos(\alpha - \theta_i) - H2_i(t)\sin(\alpha - \theta_i))]^2 \quad (2)$$

where Er and Et are the power of the radial and transverse stacks, respectively, over a time window centered at τ; $H1$ and $H2$ are the measured horizontal component amplitudes at time t within the time window; α is the trial orientation; θ is the shot-receiver azimuth; and the subscript i is the trace-azimuth index. The summation over traces of variable azimuth and over time t is as shown in Equations (1) and (2). To prevent the well-populated azimuths from biasing the calculation over the poorly-populated azimuths, partial stacking into discretely sampled azimuths can be done before calculating Equations (1) and (2).

To determine the best orientation, α, we minimized the azimuth-stack power on the transverse component but we could have choosen instead to maximize the power of the radial stack or to maximize the difference between stack power of radial and transverse components.

When a reflection event undergoes shear-wave splitting through layers with more than one HTI layer, the azimuth-stack power on the radial component may not be a maximum at the correct orientation and likewise not a minimum on the transverse component (see the E3 RMS plot in Figure 2b and 2c). In other words, the azimuth-stack power method is reliable when analyzing events influenced by HTI layers with a single S1 azimuth or when no influence of HTI anisotropy is present.

The proposed method was compared against two types of existing first-break methods. One of the first-break methods used an objective function that maximizes the energy on the radial component for each H1-H2 receiver pair. The method outputs an orientation estimate between 0° and 180° for each receiver pair and an average for each receiver gather. The second first-break method used a 2D mask function (derived from the expected amplitude distribution for the given trial orientation) for each receiver ensemble. Then the angle at which the mask best matched the H1 component (objective function was maximum) was chosen as the orientation estimate. Trial orientations from 0° to 360° were scanned. In theory, equivalent results are

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obtained if the appropriate 2D mask function for H2 is used to match the observed H2 component's first-break amplitudes. To distinguish the two first-break methods, we identify the first method as the analytical approach and the second as the projection method. Both first-break methods and the azimuth-stack power method yielded an orientation estimate for each receiver gather and a median/standard deviation of all receiver ensemble orientation estimates.

The H1, H2 receiver gathers were rotated to radial and transverse components using the estimated orientation for each gather. The transverse component was examined in order to verify the reliability of the estimate. The instances of individual receivers that deviated significantly from the true orientation estimate were analyzed.

Examples

We performed our tests on the Blackfoot 3C/3D dataset where the orientation of the H1 component of each receiver is reliably known to be 90° clockwise from north. Before analysis by the proposed method, NMO, statics corrections and some noise attenuation were applied to the H1 and H2 components. Receiver ensembles that were incorrectly wired were removed from the analysis. Common azimuth gathers were computed. The stack power method was applied to a window of reflection data over a range of offsets within the data. The statistical average of the estimated orientations by the proposed method was 85 +/-21°. The analytical first-break method predicted 90+/-15° and the projection method predicted 90+/-49° orientation. The projection method scanned over 0° to 360° while the analytical method scanned over 0° to 180°. The estimations of the projection method (between 180° and 360°) increased the standard deviation for this method.

Data quality is an important factor in obtaining a reliable orientation estimate by any method. While interfering noise can lower the reliability of the stack power method, the first-break methods can be sensitive to the P-wave amplitude perturbations due to near-surface heterogeneities or other factors. The stacking process of the azimuth-stack power method can mitigate the influence of noise on the result. Figure 3 shows noisy transverse gathers from nearby locations with indications of shear-wave splitting. At both locations, the stack power estimate was somewhat influenced by noise (Figures 3a and 3d) since the method predicted ~82° for the H1 orientation. In the same two locations, the estimate of the first-break methods (Figures 3b and 3e) depended on the quality of the first-break amplitude distribution (Figures 3c and 3f). The analytical method predicted an orientation of 88° when the amplitude distribution was as shown in Figure 3c, and when the amplitude distribution was poorer (shown in Figure 3f), the prediction was 120°. The projection method predicted 40° orientation in both locations. This method used the H1 receiver ensemble for maximizing the objective function. As can be seen in Figures 3c and 3f, the H1 amplitude distribution is considerably poorer compared to H2 and thus a biased orientation was estimated.

The azimuth-stack power method was adversely affected by poor data quality from inadequate cancellation of noise in areas dominated by noise or in low fold areas with high noise level. Improving signal-to-noise and the amplitude signature (through surface-consistent processing) improved the orientation estimates.

The first-break methods performed better in low fold areas only when the first-break amplitudes honored homogeneous, isotropic near-surface assumptions. We also compared the proposed method with the analystical first-break methods on a second data set and found that the global averages agreed exactly.

Conclusions

Reliable orientation estimation of H1 and H2 sensors is necessary for maximizing the potential of shear waves. Current standard methods assume a homogeneous isotropic near-surface and use vector decomposition of refraction data to obtain the orientation estimate. Near-surface complexities due to scattering or anisotropy appear to often change the behaviour of wave propagation and thus the standard methods can become inaccurate, as shown in this paper. Our findings on first-break methods are consistent with a previous study by Burch *et al.* (2005). In the presence of near surface heterogeneities, the individual receiver estimates can further be biased by low fold.

We have proposed a method that maximizes the azimuth-stack power on the radial component or that minimizes the azimuth-stack power on the transverse component of PS reflections. This method promises to work when the medium is isotropic or in the presence of a single anisotropic layer and is less affected by the near surface. The global median/standard deviation of orientations estimated by the azimuth-stack power method and the first-break methods were comparable within acceptable error bounds.

The individual receiver orientation estimates by the first-break methods are biased by near-surface heterogeneity. Thus the stack power method may be better suited for orientation estimation than methods that assume a homogeneous isotropic near-surface.

The azimuth-stack power method's reliability of individual receiver orientation estimation is influenced by factors such as fold and signal-to-noise ratio. A limitation of the azimuth-stack power method is that a limited number of traces within each receiver gather are available for the

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analysis of shallow reflectors. Although the azimuth-stack power method can cancel some noise, orientation estimation on data with noise attenuation can lead to improved estimation, even in low fold areas.

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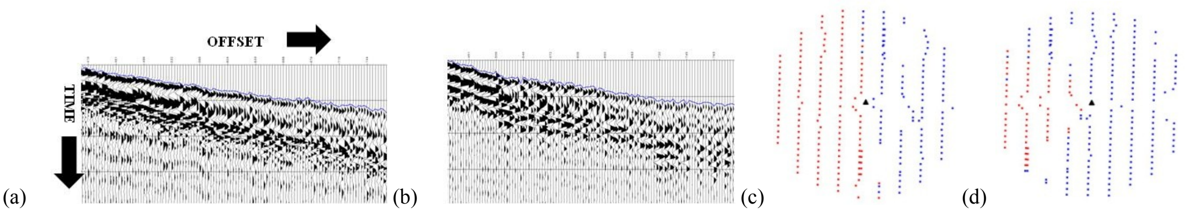

Figure 1 Vertical component receiver gathers from two locations are shown in (a) and (b). The first-break was picked on the trough maximum and the quality of first-break picks (blue line overlaying the gather) appears reasonable. (c) and (d) show the P-wave radiation pattern on the H1 component from the same location as in (a) and (b). Positive amplitudes are identified by red squares and the negative amplitudes by blue squares. The receiver location is shown by the black triangle.

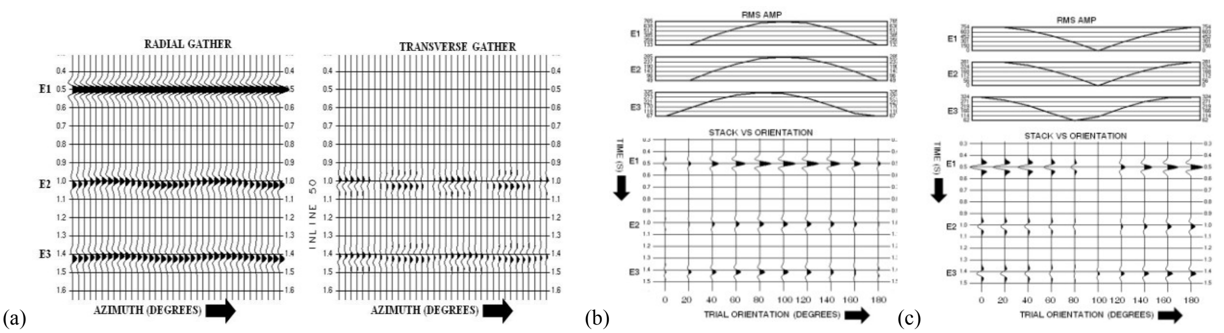

Figure 2 Illustration of the azimuth-stack power method on synthetic data with three events as a function of source-receiver azimuth is shown in (a). The top event (E1) is from an isotropic layer, the middle event (E2) is from passing through a single HTI layer and the bottom event (E3) is from passing through two HTI layers with differing S1 azimuths. In (b) radial stack and (c) transverse stack traces as a function of trial orientation are shown. The three panels on top of the synthetic data in (b) and (c) show RMS amplitudes of the stack as a function of trial orientation. The RMS amplitude of the stack for events E1 and E2 is a maximum on the radial at the correct orientation of 100° and is a minimum on the transverse at the correct orientation.

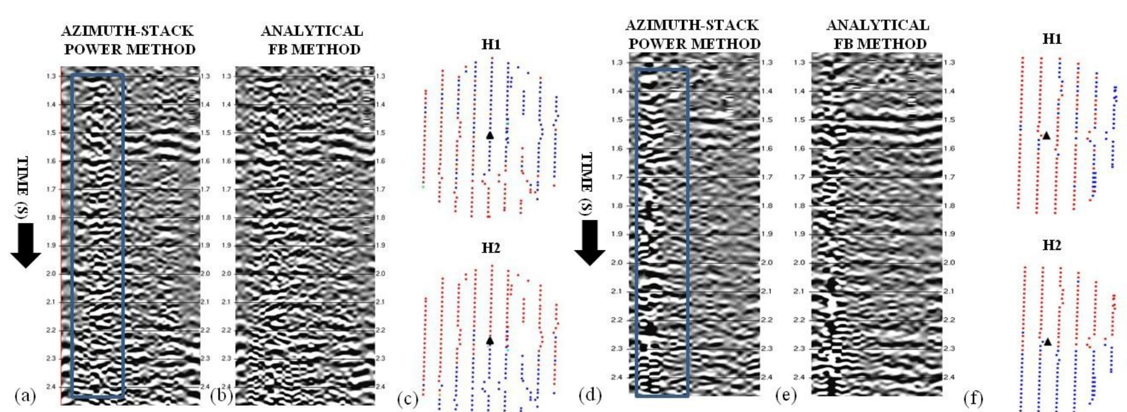

Figure 3 Noisy transverse component gathers are shown at two locations after rotation. In (a, d), orientation estimates from the azimuth-stack power method and in (b, e) orientation estimates from the analytical first-break method were used. Indications of shear-wave splitting can be observed between 1500 and 1600 ms. The P-wave amplitude map on the H1 and H2 components for both locations are shown in (c) and (f). The distribution of amplitudes is more reasonable in (c) than in (d) where it is perturbed from the homogeneous assumption significantly. Both methods predicted correct orientation within acceptable uncertainty in the first location (a, b, c). At the second location (d, e, f), the first-break method estimated 120° orientation and the azimuth stack method estimate was 83° (vs correct orientation of 90^0). The noise zone is identified in (a) and (d) by rectangles. Positive amplitudes in (c) and (f) are identified by red squares and negative amplitudes by blue squares. The receiver location is shown by the black triangle.

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