The Deconvolution of Multicomponent Trace Vectors

Xinxiang Li*, Peter Cary and Rodney Couzens
Sensor Geophysical Ltd., Calgary, Canada
xinxiang_li@sensorgeo.com

Summary

Deconvolution of the horizontal components of converted-wave data typically uses operators computed only from the radial component of the data. This approach assumes that no significant energy is present on the transverse component, which may not be the case when shear waves propagate in anisotropic rock formations. A new deconvolution method based on the vector trace power spectrum is introduced in this paper. It treats the horizontal components as trace vectors so that the energy on both components is always included in the process. Vector deconvolution is shown to be independent of rotation and time shift. It is thus more compatible with the theory of shear-wave splitting analysis and its related layer-stripping process than the conventional radial component based approach.

Introduction

Land multicomponent surveys have become increasingly popular because of the reduced costs of acquiring these surveys, the high quality P-wave data recorded by multicomponent phones, and the additional shear wave data that are recorded. 3-C seismic datasets include a vertical component dataset and two datasets of horizontal components, which are referred to as the H1 and H2 components. The current standard processing flow for converted waves starts with a rotation that transforms the H1 and H2 components into the source-to-receiver radial and transverse components. If the subsurface rock seismic properties have little spatial or azimuthal variation, the radial component contains all the signal and the transverse component contains only noise. Only the radial component dataset would need to be processed in that situation. The processing of the radial component data can essentially follow a similar processing sequence to that used in conventional P-wave data processing except for special treatment regarding issues like statics, limited frequency bandwidth, and common conversion point imaging.

For many reasons, shear wave energy often ‘leaks’ onto the transverse component data. Shear wave splitting is one of them. Azimuthal anisotropy causes shear waves to split into fast and slow modes, and the two modes propagate with different speeds and different polarizations. The polarizations of the fast and slow shear waves are determined by the anisotropy of the rock formations, and often changes laterally and with depth. It is usually impossible to use a simple rotation to form a scalar trace to fully represent the signals on both the H1 and H2 components. Azimuthal anisotropy may not be the only reason for shear waves to polarize in directions other than the radial direction (Jenner 2010), but, fortunately, the maturing theory of shear-wave splitting analysis, along with its companion layer-stripping technique, is able to extract substantial amounts of the ‘leaked’ signal from the transverse component traces in order to form new ‘radial’ component traces that contain most of the signal; and the new ‘transverse’ component traces can be ignored, again, in further processing. Shear-wave splitting analysis and its compensation have become routine processes in modern converted-wave data processing since severe shear-wave splitting has been found in many areas, especially in shallow unconsolidated layers (Cary et al, 2010). Moreover, the splitting analysis attributes, namely the time delay between the fast and slow shear waves and the orientation of the fast shear wave, provide valuable information regarding the rock properties, such as the characteristics of pore pressure and fracture systems.

Cary (1995) discussed a dilemma regarding data scaling/deconvolution and birefringence layer-stripping. High quality converted-wave data processing needs the removal of shear-wave splitting effects; on the other hand, high quality birefringence analysis relies on successful completion of many processing steps, such as trace scaling, deconvolution, statics, moveout correction or even prestack migration. Cary (2006) provided a solution to the problems caused by the interaction between shear wave splitting and statics. This paper attempts to remove the deconvolution process from this dilemma. Currently, deconvolution of converted-wave data usually designs deconvolution operators only with the radial component data and applies these operators to both the radial and the transverse components. A better solution might be to perform shear-wave splitting analysis and its compensation before deconvolution in hopes of extracting the correct signal energy out of the transverse component. This may help in some cases, but there certainly are limitations on the quality of shear-wave splitting analysis and compensation due to the lack of resolution in the data. This can be a more serious issue than the deconvolution itself. Instead, we propose a vector deconvolution scheme that is independent of the shear-wave splitting analysis and the layer-stripping process.

The vector trace deconvolution method

The two traces from the horizontal components of one 3C phone form a 2-element trace vector. We denote the trace vector formed by the H1 and H2 components as [H1 H2], and the trace vector formed by the radial and transverse components as [R T]. The relative energy level and possible phase differences between the two scalar traces carry essential information, such as the shear wave polarization, and they cannot be arbitrarily altered. To maintain such vector fidelity, identical trace scaling and deconvolution need to be applied to both scalar traces.

The spiking deconvolution method, especially its surface-consistent version, is probably the most widely used deconvolution method in land seismic data processing. With the white reflectivity and minimum phase assumptions, the deconvolution of a seismic trace is determined by the autocorrelation of a segment of the trace. In the Fourier domain the autocorrelation of a trace is its power spectrum. Extending the discussions in Cary (1995), we define the power spectrum of a trace vector as follows:

$$P(H_1, H_2) = \begin{bmatrix} H_1 & H_2 \end{bmatrix} \begin{bmatrix} H_1 & H_2 \end{bmatrix}^* = P(H_1) + P(H_2),$$

where P represents the power spectrum. For simplicity we also use H1 and H2 to represent the Fourier transforms of their time domain scalar traces and the superscript '*' to represent the conjugate transpose. Intuitively the power spectrum of a vector trace is defined as the sum of the power spectra of its component traces. A deconvolution operator designed from the power spectrum of a trace vector can then be applied to both of its scalar components. This extension of the power spectrum concept ensures that the vector deconvolution method is independent of surface source-receiver orientation, the subsurface anisotropy orientation and shear-wave splitting.

Backwards compatibility

The vector extension of the power spectrum concept reduces to the conventional scalar trace power spectrum case when one of the components contains no signal. When the radial component contains all reflection signal and the transverse component contains only noise, the vector deconvolution operator should be very similar to that designed only on the radial component, especially since the smoothed power spectrum is used to compute deconvolution operators.

Rotation Independence

Any rotation from one trace vector to another, such as the rotation from [H1, H2] to [R, T], does not change the vector power spectrum. This can be seen by noting that the conjugate transpose of a rotation matrix is its inverse matrix. For example, when [H1 H2] = [R, T] [Rot] (where [Rot] denotes a 2x2 rotation matrix), the vector power spectrum is

$$P(H_1, H_2) = [H_1 \quad H_2][H_1 \quad H_2]^* = [R \quad T][Rot][Rot]^*[R \quad T]^* = [R \quad T][R \quad T]^* = P(R,T).$$

Time-shift independence

We can also show that a time shift on one of the components does not change the vector power spectrum. At each frequency ω, a time shift Δt in the time domain is a multiplication by $exp(i\omega\Delta t)$ in the Fourier domain. The conjugate transpose of a time shift matrix is again its inverse matrix. Replacing the rotation matrix with a time-shift matrix, the above derivation leads to the time-shift independence of the vector power spectrum.

An immediate conclusion from the above properties is that our vector deconvolution process is independent of the shear-wave splitting effect in a 1-D vertical propagation HTI model. As described extensively in the literature, when a vertically travelling shear wave reaches an HTI layer, it “splits” into two shear waves with polarization directions perpendicular to each other. This splitting can be approximated by a simple rotation, ignoring possible transmission amplitude differences between the splitting shear waves. When the splitting waves travel through the HTI layer, the slow shear wave has a time delay relative to the fast shear wave. If we ignore the possible amplitude differences between the waves, this process can be approximated by a simple time-shift between the two waves. Thus the shear wave splitting process can be expressed as a series of rotation plus time-shift operations depending on how many layers of HTI media are encountered.

Examples

A synthetic example is used to show how the radial-component based deconvolution may fail when a significant amount of energy is present on the transverse component and how vector deconvolution effectively solves the problem. Figure 1 shows a gather of trace vectors formed by radial and transverse component traces acquired on top of a flat HTI layer. A total of 72 traces are generated with source-receiver azimuths ranging from 5 to 360 degrees with a uniform 5-degree spacing between them. The possible amplitude differences between the split shear waves are ignored. This dataset is the input to our deconvolution tests. Figure 2 shows the result of the radial component based deconvolution. As expected, the deconvolution of both components is not optimal. The wavelets on the traces with significant energy present on the transverse component are not effectively ‘collapsed’. On the other hand, Figure 3 show that vector deconvolution effectively collapses the wavelets on all traces of both components. The differences between the results in Figure 2 and Figure 3 dramatically illustrate the shortcomings of the radial-component based deconvolution method, and the possible improvements that the vector deconvolution method can make.

Real data may not exhibit such obvious differences as this, even with large shear-wave splitting. The averaging effects of long design windows containing many reflections and the surface-consistent decomposition of the deconvolution operators can substantially ‘alleviate’ the inadequacy of the radial component based deconvolution method. Nevertheless, we believe that the vector deconvolution method is one step forward towards further improving the imaging quality of converted wave data.

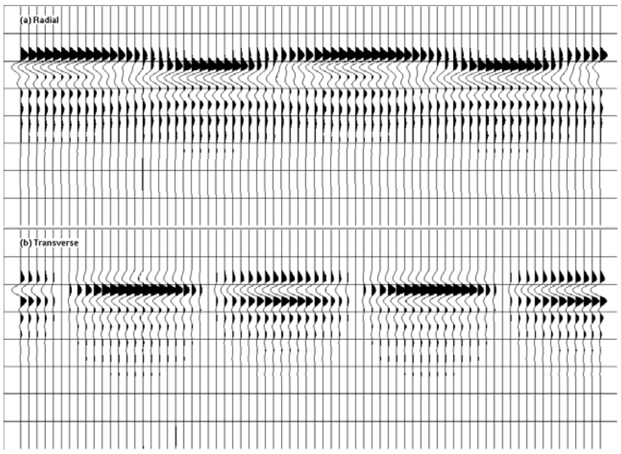

Figure 1: A synthetic gather of radial-transverse trace vectors exhibiting shear-wave splitting, shown before deconvolution. The synthetic assumes a shear wave wavelet polarized in the source-receiver radial direction vertically passing through an HTI layer. The transmission and attenuation differences between the fast and slow shear waves are ignored. The time delay between the fast and slow shear waves is 20 ms. The minimum phase wavelet has a bandwidth of 2-6-30-40 Hz. The display contains 72 trace vectors that have the same offset value and are 5 degrees apart in azimuth. The azimuth range is from 5 to 360 degrees. At the top are the radial component traces and at the bottom are the transverse component traces.

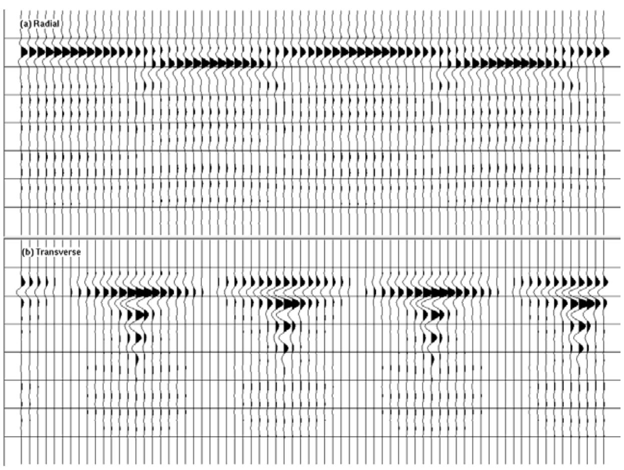

Figure 2: The deconvolution of the gather in Figure 1 using operators that are designed only on the radial component traces. The traces with significant energy on the transverse component are not effectively deconvolved.

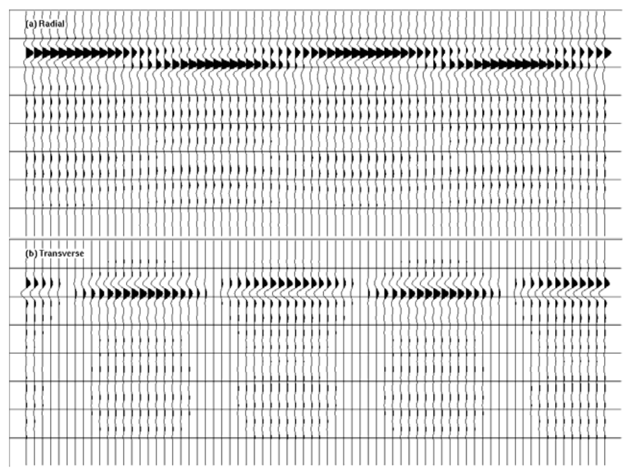

Figure 3: The deconvolution of the gather in Figure 1 using the vector deconvolution method. All traces are effectively deconvolved. The better vertical resolution of this result compared with the gather before deconvolution in Figure 1 and the better phase and amplitude fidelity compared to that of the gather in Figure 2, should provide superior birefringence analysis results.

Conclusions

Compared with the conventional radial component based deconvolution approach, the vector deconvolution method is more suitable for the deconvolution of multi-component horizontal components, especially for data with a significant amount of shear wave splitting. It can be a solution to the dilemma between good quality birefringence analysis and high resolution converted wave processing.

References

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