# Estimating interval shear-wave splitting from multicomponent virtual shear checkshots

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**Summary**

The classical approach to estimating shear wave splitting from VSP data is through layer stripping which can be difficult under complex overburden. We propose a new technique that is easy and accurate under any overburden and does not require knowledge of the overburden. The new approach is based on a multicomponent version of the virtual source method in which each 2C VSP receiver is turned into a 2C shear virtual source. The resulting 2C x 2C virtual dataset is affected only by the properties of the medium between the receivers. A simple Alford rotation transforms it into fast- and slow-shear virtual checkshots from which shear wave splitting can be measured with ease regardless of overburden complexity.

**Introduction**

Measuring shear-wave splitting from VSP data can benefit fracture and stress characterization. A well-established approach to measuring azimuthal anisotropy at depth is through layer-stripping of 2C x 2C VSP data (Winterstein and Meadows, 1991; Thomsen et al., 1999). It starts from the top layer and establishes its principal directions, or symmetry axes, by performing Alford rotations with trial angles until the diagonal components of the VSP are maximized (Alford, 1986). Then, the maximized diagonal components are analyzed for fast- and slow-shear wave velocities (shear-wave splitting) in the top layer. To proceed with the next layer, the anisotropy in the top layer is stripped off by undoing the time-lag between the fast and slow shear waves accumulated there. This technique is subject to the following limitations:

- it is applicable only to vertical propagation in horizontally layered media;
- it requires a well instrumented with receivers from top to bottom if the principal directions in the overburden vary with depth and are unknown;
- if there are uninstrumented anisotropic intervals, the principal directions in them would have to be inferred from other geological and geophysical information;
- due to the interpretative nature of the stripping process errors accumulate with depth;
- the presence of azimuthal anisotropy in the overlying layers does not allow reliable estimation of polarization directions at the beginning of each new layer or inside thin layers [so called "inertia" effect identified by Winterstein and Meadows, (1991)].

We introduce an alternative technique that is free of these limitations. It utilizes a multicomponent version of the virtual source method (Bakulin and Calvert, 2004, 2005).

**Multicomponent Virtual Checkshot with Shear Waves**

The virtual source method (VSM) was introduced by Bakulin and Calvert (2004, 2006) as a method to image below complex overburden. Placing downhole receivers below the most complex part of the overburden and cross-correlating the responses at two receivers allows reconstructing new data as if the first receiver acted as a virtual source (VS). In its simplest application, virtual checkshot (Bakulin and Calvert, 2005; Bakulin et al, 2007), this technique is used to reconstruct direct arrivals between receivers along the well and estimate interval velocities for P- or S-waves.  In isotropic media, a shear virtual checkshot can be created from a conventional P-source VSP by cross-correlating the in-line receiver components (Bakulin et al., 2007). But in azimuthally anisotropic media that is not enough; we need a 2C X 2C VSP to create fast- and slow-shear Virtual Checkshots.

For simplicity let us consider a vertical well in a horizontally layered medium. Each layer is azimuthally anisotropic (orthorhombic) and has vertical symmetry planes with arbitrary orientation.  The goal is to estimate the principal directions and shear-wave splitting between two depth stations. With two types of surface sources (orthogonal shear vibrators along X and Y directions) and two horizontal components per VSP receiver (X and Y), there are eight possible cross-correlations that could be made between traces from a common surface source to two depth stations: $XX_1*XX_2$, $YX_1*YX_2$, $XY_1*XY_2$, $YY_1*YY_2$, $XX_1*XY_2$, $YX_1*YY_2$, $XY_1*XX_2$, $YY_1*YX_2$, where the first letter denotes source polarization, the second letter denotes receiver component, and the subscript identifies the receiver location (1 or 2). Naive assumptions may suggest $XX_1*XX_2$ should correspond to an X-component recording from a virtual source at receiver 1 polarized in the X-direction. However physical intuition, as well as Wapenaar (2004), suggest that when principal directions in the overburden are unknown, all cross-correlations should be used on equal footing in order to obtain a 2C x 2C virtual source dataset. This is achievable with the following expressions:

$$\begin{aligned} XX_{VS} &= XX_1*XX_2 + YX_1*YX_2 \\ YY_{VS} &= XY_1*XY_2 + YY_1*YY_2 \\ XY_{VS} &= XX_1*XY_2 + YX_1*YY_2 \\ YX_{VS} &= XY_1*XX_2 + YY_1*YX_2 \end{aligned} \quad (1)$$

Here $XX_{VS}$ , $YY_{VS}$ , $XY_{VS}$ , and $YX_{VS}$ is the virtual 2C x 2C dataset obtained after redatuming so that the first receiver is turned into a shear virtual source. For brevity we omit summation over source locations along the surface in equations (1).

The so obtained virtual source dataset has correct ratios between amplitudes and can be diagonalized by Alford rotation so that the fast- and slow-shear modes are isolated. An example is shown in the next section. It is important to note that the orthogonal shear sources on the surface should have equal strengths to create proper 2C x 2C virtual data.

Finally, we should note that the simple equations (1) are also supported by the analysis of Wapenaar and Fokkema (2006) for a completely general case.

**Synthetic Example**

Let us apply the multicomponent virtual shear checkshot to the horizontally layered model shown in Figure 1.

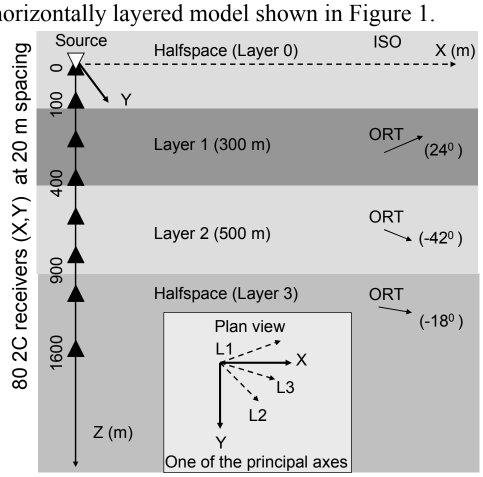


Figure 1: Model: the orientation of the "natural x" axis of each orthorhombic layer is marked by an arrow. Density and P-wave velocity are fixed (2500 kg/m$^3$, 2000 m/s). Shear wave velocities are $V_1$=$V_2$=1000 m/s in Layer 0 (isotropic half space), $V_1$=1000 m/s, $V_2$=846 m/s in layer 1 [($V_2$-$V_1$)/$V_1$=-15% splitting], $V_1$=900 m/s, $V_2$=1000 m/s in Layer 2 [11% splitting]; $V_1$=970 m/s, $V_2$=1000 m/s in Layer 3 [3% splitting].

Consider a zero-offset VSP with two orthogonal shear sources acting in a homogeneous isotropic half-space. The isotropic half-space is underlain by three orthorhombic layers with horizontal symmetry planes. Their vertical symmetry planes, however, have different azimuths. We used 3D dynamic ray tracing to generate synthetic data that contained only transmitted shear waves. Since the azimuth of the symmetry axes varies with depth, the number of the shear arrivals doubles with every additional layer. Thus, the wave field becomes progressively more and more complicated with depth (Figure 2); in the isotropic top layer each source (X, Y) excites a single component of displacement in the same direction but by the time waves reach the deepest layer, interfering arrivals show up on all receiver components with a similar strength.

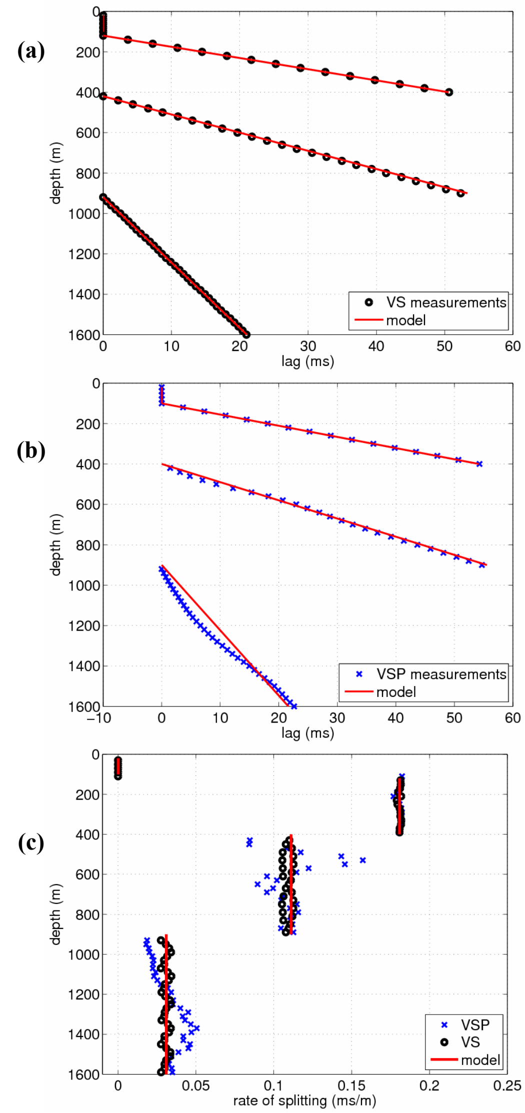


Figure 5: Estimated travel-time delays between fast and slow shear waves using: a) virtual source data; b) conventional layer-stripping technique applied to VSP data. Note the "inertia" effect in (b). The estimated shear-wave splitting (c), corresponding to the slope in (a) and (b), demonstrates the higher accuracy achieved by the VSM.

We apply equations (1) to construct a 2C x 2C virtual dataset from the synthetic VSP. For simplicity we do not perform any summation over surface shot locations as it is typically required in VSM - we consider only the stationary phase contribution coming from the pair of X, Y sources at the wellhead. Redatumed datasets with a virtual source at the top of each layer are shown in Figure 3. The number of arrivals inside each anisotropic layer is reduced to two (as opposed to $2^{(n+1)}$ where $n$ is the number of overburden layers). However these two interfering arrivals show up on all four components because the symmetry axes of the layers do not coincide with the X and Y receiver orientations. Performing Alford rotation with known principal axes angles produces the nearly diagonal datasets in Figure 4. Now fast and slow shear modes show up separately on the XX or YY component and exhibit remarkably clean and consistent waveforms starting from the first receiver located at the VS location. This repeatable character of the waveforms allows accurate estimation of shear-wave splitting using simple cross-correlation between XX and YY components at each receiver depth. The resulting time lags and shear-wave splitting are shown in Figure 5a and 5c. Note the lack of "inertia" near the top of each layer – the redatuming has simply removed the effect of the overburden. For comparison we estimated the same values from the original VSP using traditional layer-stripping (Figure 5b). Despite the fact that we used exact angles for the Alford rotation of the VSP, the results were substantially less accurate, clearly suffering from the "inertia" effect as well as struggling to pick up the small splitting in the bottom layer.

**Discussion and Conclusions**

While we considered a 1D model in the above, the virtual source method is applicable in any heterogeneous and anisotropic medium. Therefore the new technique gives us an opportunity to estimate interval shear-wave splitting of deep layers located beneath 3D, complex, and anisotropic overburden. Summation over a number of surface sources (i.e., walk-away or 3D VSP) would be required to achieve proper illumination along the well under complex overburden. For a vertical well, two *identical* shear vibrators operating in orthogonal directions are all we need on the source side. For strongly deviated wells, a vertical surface vibrator may also be needed.

Since the virtual source method does not require any knowledge of the overburden, we no longer need to instrument the entire well with receivers or possess *a priori* information about principal directions in the overburden in order to estimate shear wave splitting at depth.

A virtual source can be created at any receiver location and therefore, the new technique should not suffer from error accumulation with depth, unlike the VSP layer-stripping technique. Similarly, the new technique is free of "inertia" effects since the overburden influence is completely removed from the virtual source data.

All these reasons suggest that the new technique may deliver substantial improvements over the current layer-stripping approach. Moreover, the use of the so obtained 2C x 2C virtual dataset can be extended beyond Virtual Checkshots – it can be used for look-ahead imaging with fast and slow shear waves, unaffected by overburden complexities. That opens a whole new field of possibilities for fracture and stress detection at depth and may greatly facilitate the interpretation of multicomponent surface seismic data.

**Acknowledgements**

We are very grateful to our colleague Peter Bakker (Shell) for generating the synthetic VSP used in the example.

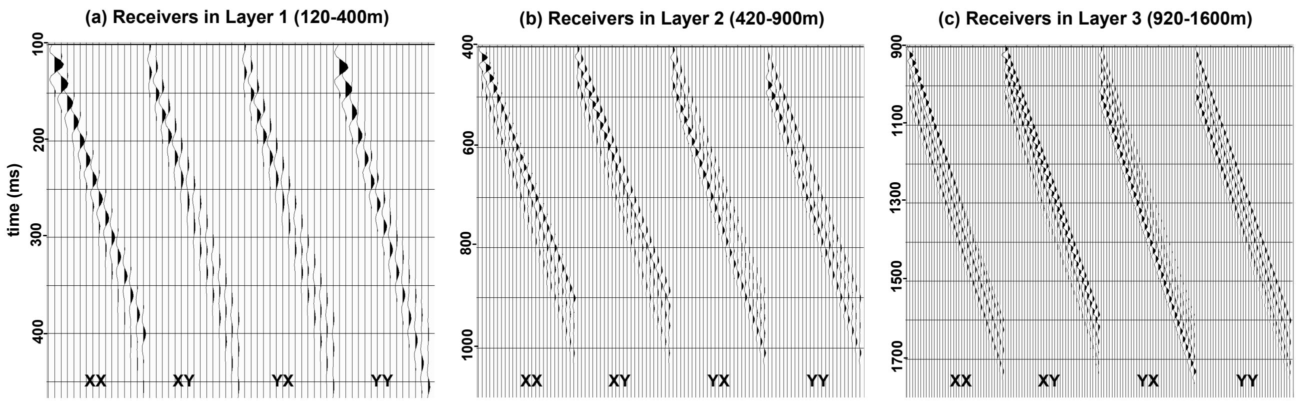


Figure 2: 2C X 2C synthetic VSP dataset containing only transmitted shear waves generated by dynamic ray tracing in the model of Figure 1. Note the escalating complexity of the wavefield with depth. Wavefield in isotropic layer 0 is not shown.

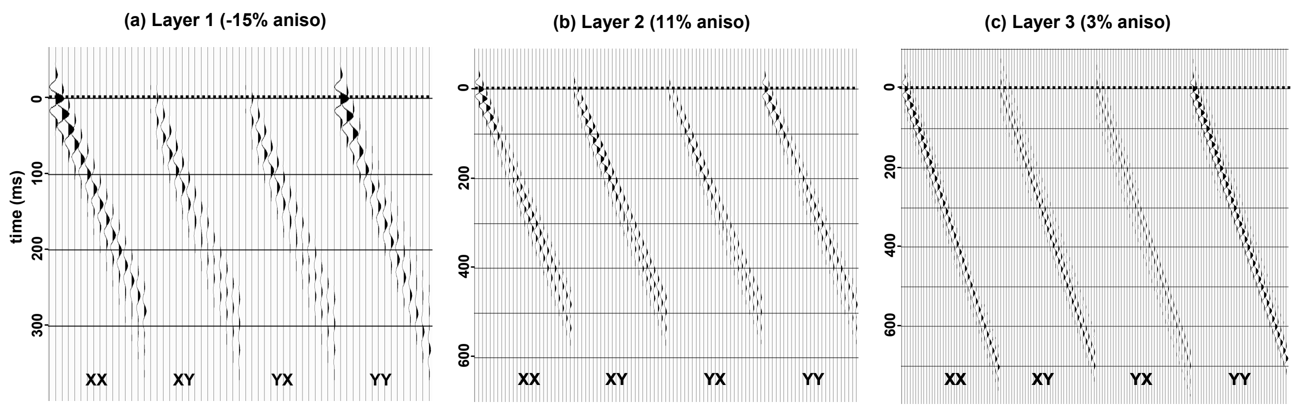


Figure 3: 2C X 2C Virtual Source dataset: top receiver was turned into a multicomponent (X and Y) virtual source in each layer. Note the simpler wavefield in the deep layers as compared to Figure 2. However all four components exhibit some energy because no rotation has been performed yet.

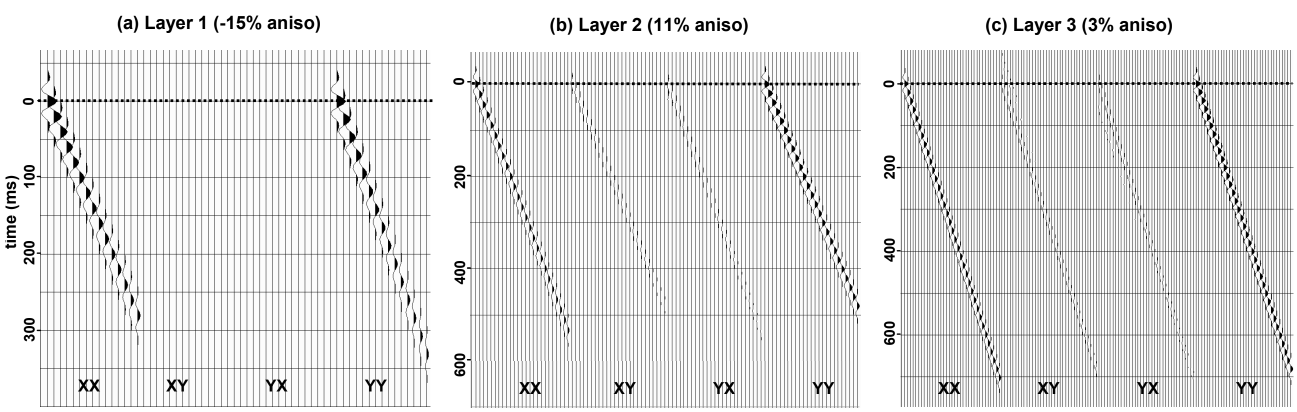


Figure 4: Same as Figure 3 but after Alford rotation performed inside each layer with the angles from Figure 1. Note that datasets in all layers are now diagonalized: fast and slow waves show up separately on diagonal components whereas only small amount of residual energy is present on a cross-components XY and YX. Fast and slow shear wave velocities measured from XX and YY overall moveout are in perfect agreement with the model.

## EDITED REFERENCES

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