VELOCITY CALIBRATION AND WAVEFIELD DECOMPOSITION FOR WALKOVER VSP DATA

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ABSTRACT

Generalized stacking velocity analysis tools like the Common-Reflection-Surface stack method provide stacking parameters beyond the conventional stacking velocity. These parameters can be expressed in terms of useful geometrical wavefront properties. However, this requires a good estimation of the tuned velocities which are valid for imaging in the vicinity of source and/or receiver of the recorded data. Using the downgoing first arrivals, we introduce a simple and efficient method to determine the velocities at every receiver level in a walkover VSP experiment. The calibrated wavefront properties are subsequently used for the decomposition into upgoing waves arriving either as P- or S-waves at the receivers.

INTRODUCTION

The Common-Reflection-Surface (CRS) stack method and similar stacking approaches can be seen as generalized stacking velocity analysis tools. In contrast to conventional stacking velocity analysis, these methods provide entire sets of stacking parameters which carry useful information for a variety of applications like inversion. The generalized stacking parameters can be interpreted in several ways (see, e. g., Hertweck et al., 2007): in the data, they can be observed as the first and second spatial derivatives of traveltime. These can be expressed in terms of slowness components and imaging velocities, including the classic stacking velocity for the zero-offset case. Another attractive means of interpretation is to relate them to properties of (hypothetical) wavefronts, namely their propagation directions and curvatures at the source and the receiver, respectively. In particular the propagation direction, a usually quite stable parameter, can be employed for various purposes, e. g. topography handling, redatuming, and wavefield separation on multi-component data (see, e. g., Zhang, 2003; Boelsen and Mann, 2005).

In order to relate the traveltime derivatives to this geometrical interpretation, we need a good estimation of the *tuned* velocities in the vicinity of the respective source-receiver configuration for which the derivatives were calculated. For the application of the CRS stack, these velocities are usually assumed to be known and considered as virtually constant within the local stacking aperture.

As long as the geometrical interpretation is not explicitely used within the stacking process itself, the accuracy of the velocities is not crucial and a calibration of the wavefront properties with more accurate velocities can be applied later on. Usually, the geometrical interpretation enters only via extremal emergence angles which are convenient to constrain the search range for the first derivatives. If the velocity is underestimated, the search range will be larger and more coarsely sampled than intended. Too high velocities will have the opposite effect, in the worst case leading to the loss of steep events. Thus, with an —in case of doubt—underestimated velocity, there is no risk of failure due to an inaccuracy.

If the geometrical interpretation comes into turn, the accuracy becomes far more critical, especially in case of wavefront propagation directions being used to discriminate differently polarized wave types in multi-component data. As shown by Boelsen and Mann (2005) the CRS method can be extended to handle multi-component data by using the operator shape and orientation simultaneously with polarization directions. With inaccurate velocities the wavefront orientation and the polarization are wrongly estimated and the results are deteriorated. Another example for processes sensitive to the accuracy of the velocity is the handling of topography in surface seismics or deviated wells in VSP acquisition. Here, the propagation direction is used to implicitely redatum the data to local, planar reference levels.

CRS STACK FOR VSP GEOMETRIES

A typical survey method which features multi-component acquisition are VSP experiments. Here, the geometrical interpretation of stacking parameters is very convenient, e. g. for wavefield decomposition. Fortunately, VSP data allow to easily calibrate the velocities for all receiver levels from the kinematics of the wavefield. We will introduce this concept quite generally for the 3D case and a vertical borehole and furthermore provide an assessment with respect to deviated wells. We will present an application of this calibration method to a synthetic VSP walkover line with a vertical well and the application of the wavefield decomposition.

The CRS traveltime approximation is a variation of the CRS approach for *finite-offset* surface seismic data by Zhang et al. (2001) with an extension to general acquisition geometries (one possible solution can be found in Boelsen and Mann, 2005; Boelsen, 2005). We do not want to go into any details concerning the actual traveltime approximation being employed. In the context of this paper it is sufficient to know that source and receiver positions will, in general, not coincide. In this way, it depends on two components of the traveltime gradient on either side. Due to the nature of wells resembling spatial trajectories we can only determine one component on the receiver side from VSP data.

VELOCITY CALIBRATION

For isotropic media, the propagation direction of a wavefront is normal to the wavefront itself. Furthermore, body waves are polarized either in propagation direction or in the plane tangent to the wavefront. The slowness vector $\vec{p}$ fully characterizes all these directions in this case. However, from the first derivatives of traveltimes, we can only determine up to two components of this vector. For the more particular case of VSP data, we are looking for the velocities in the vicinity of the receivers. Due to the 1D nature of a well, the data only provides us with one component of the slowness vector, namely its component p_t tangent to the well.

For a given receiver at (x_G, y_G, z_G) the local velocity v_G is fixed. However, the waves from different source (and reflection) points will arrive there with different propagation directions, i. e. slowness vectors $\vec{p}$. Thus, the slowness component p_t tangent to the well will vary systematically: for a wave propagating normal to the well it will vanish, for a wave tangent to the well it will reach its maximum: $p_t = |\vec{p}| = v_G^{-1}$, the inverse of the true velocity, as p_t is the only non-vanishing component in this case. The latter case does not necessarily occur for the combination of given model and chosen acquisition geometry.

Let us now consider the direct downgoing wave in a walkover VSP configuration and a vertical well: here we can expect to have a large range of propagation directions available which are mainly distributed around the vertical orientation at each receiver. For a sufficiently dense source spacing and sufficiently large acquisition area, it is very likely that at least one of the associated rays will be virtually tangent to the vertical well. Therefore, we can expect that the maximum of the slowness component $p_{t,\text{max}}$ is actually the inverse of the sought-for true velocity v_G. We propose the following strategy:

- identification of the downgoing first arrivals
- for each source and each receiver combination contained in the data, determine the tangent slowness component by means of coherence analysis along these events
- for each constant receiver level, search for the source location $(x_S, y_S, 0)$ associated with the maximum tangent slowness component $p_{t,\text{max}}\,(x_S, y_S; x_G, y_G, z_G)$

In this way, we can determine the velocity $v_G\,(x_G, y_G, z_G)$ in the vicinity of each particular receiver. For the 2D case shown below, p_t reduces to a function of one source coordinate. Note that in the 3D case, the slowness vector can only be decomposed into a horizontal and a vertical component. The orientation of the horizontal component can only be deduced from hodograms rather than from wavefront properties, only.

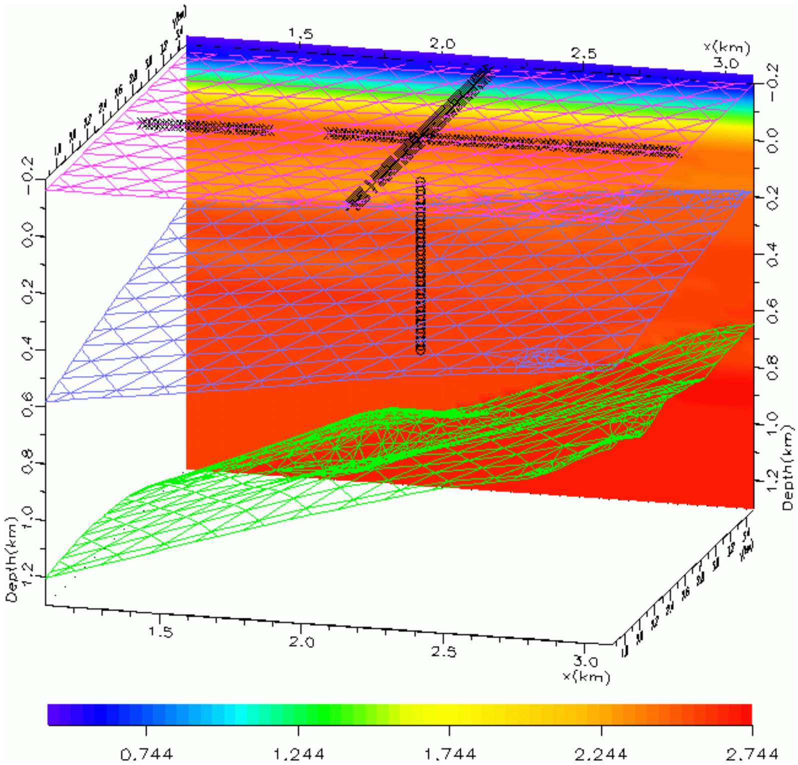

Figure 1: Geometry of receiver levels in the well, source lines, and reflectors. A vertical slice through the P-wave velocity model [km/s] is shown in the back.

DATA EXAMPLE

Figure 1 shows a 3D plot of two walkover lines crossing a vertical borehole in N-S and E-W direction. The acquisition surface is almost planar with a slight dip towards the west. The two reflectors are both strongly dipping and the second reflector has a very irregular shape. The inhomogeneous elastic background model contains a steep velocity gradient for the first 300 m, which cannot be observed in the figure because it is clipped out of the displayed range. Downgoing P waves as well as reflected PP, SS, and PS waves have been forward-calculated by means a wavefront construction method.

In the following, we consider the N-S line, only. For this 2D walkover line, it is more convenient to display the emergence angle β_G with respect to the well rather than the tangent slowness p_t. The first available interval velocity curve was obtained by checkshot inversion (see Figure 2). It served to calculate β_G from the slowness values p_t after coherence analysis. The respective results provided in Figure 3 show that for most receiver levels either a largely under- or over-estimated velocity was chosen. Angle ranges for near-offsets which either reach a minimum value far from being $0°$ or remain at $0°$ for a wide range point towards either case. By picking the velocities at locations where a reasonably small distinct minimum still can be observed we can estimate a preliminary, generally slightly underestimated, depth-velocity curve. The calibration based on this model already results in more consistent emergence angles.

Now we perform the calibration as proposed above which provides us with the estimation of the tuned depth-velocity curve (see Figure 2). The angles calculated with these velocities are in good agreement with the forward-calculated values of β_G. The tuned velocity curve for S-wave arrivals was found by applying $v_P/v_S = \sqrt{3}$ as used for the modeling of the data.

From this point we can employ the calibration velocities for subsequent imaging steps to calculate the emergence angles from CRS attributes for all kinds of reflection events. As an example for the application of these emergence angles we performed a wavefield decomposition of the multicomponent data into arriving P- and S-waves. Figure 4 demonstrates the accuracy of the angles: they are very close to the actual polarization direction such that the decomposition works almost perfectly.

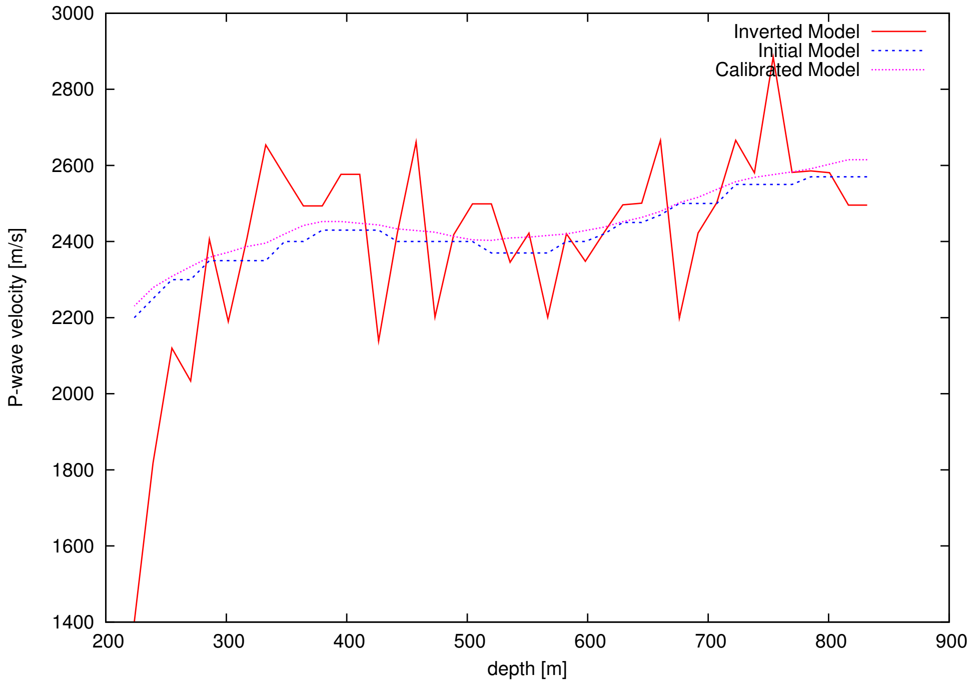

Figure 2: Interval velocities along the well from checkshot inversion (red), underestimated initial model for calibration (blue), and calibrated velocities (magenta).

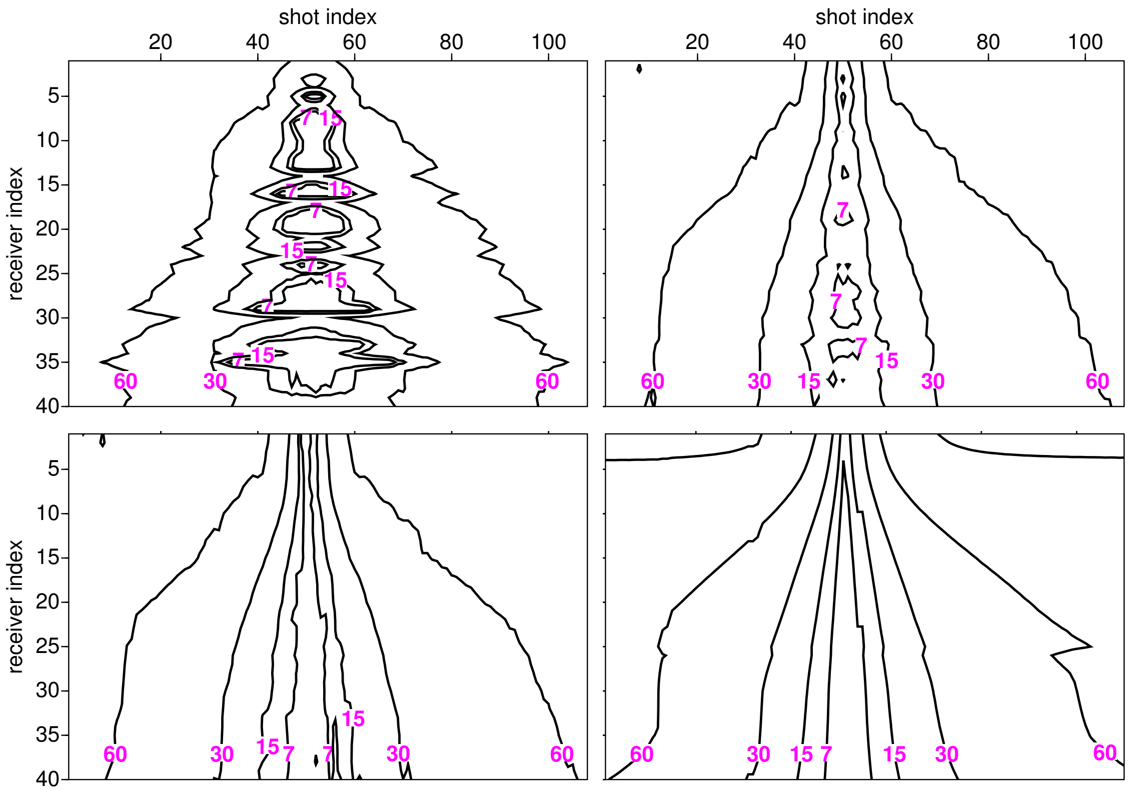

Figure 3: Receiver emergence angles [°] for every shot/receiver pair computed with interval velocities from check shot inversion (top left), underestimated interval velocities (top right), and calibrated velocities (bottom left). Corresponding ray tracing results (bottom right).

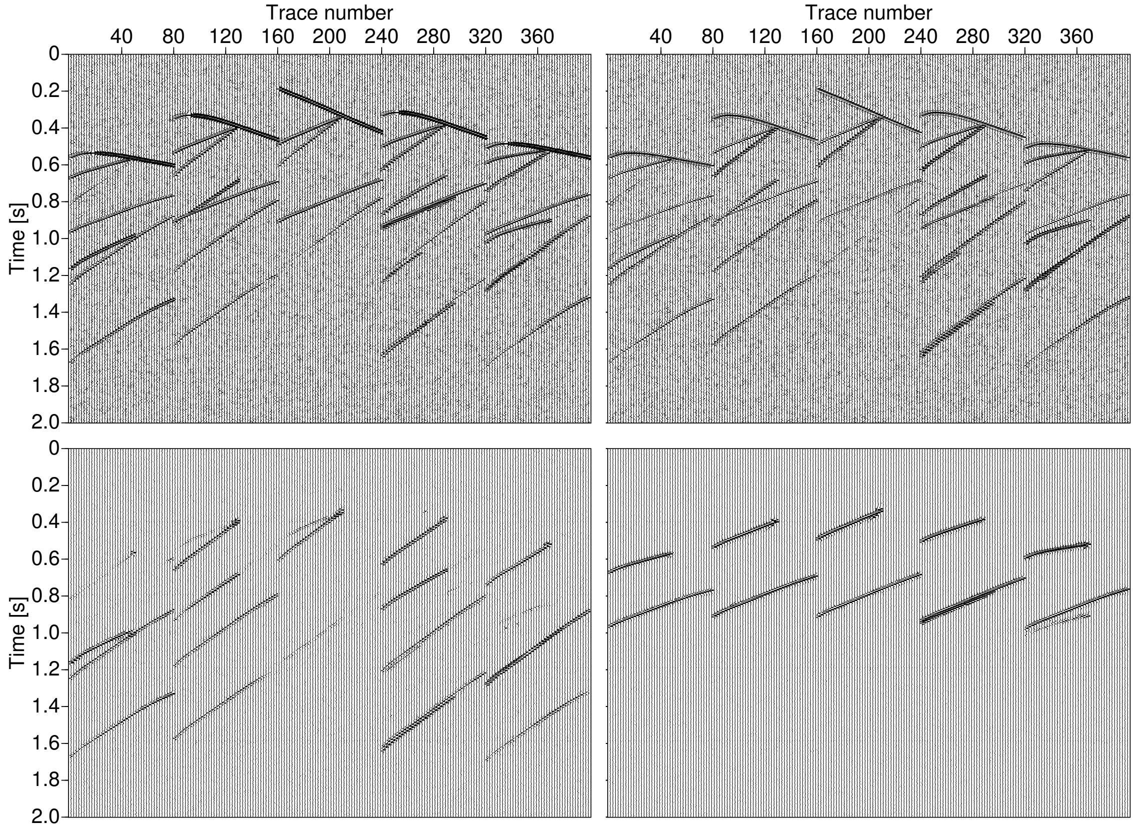

Figure 4: Top: vertical (left) and inline horizontal (right) component of the recorded wavefield. Bottom: transversal (left) and radial (right) component after wavefield decomposition.

DEVIATED WELLS

Although presented for a vertical well in this paper, the approach can be applied to deviated wells as well. We simply have to introduce a well-centered coordinate system. Again, the ray tangent to the well is associated with the searched-for velocity. However, for strongly deviated wells, the calibration approach might fail: the acquisition geometry might not cover the source position associated with the searched-for ray which reaches the receiver tangent to the well. In other words, the global slowness maximum cannot be found in the data. If we can only detect a supremum rather than a maximum, this clearly indicates such a situation where a calibration is impossible without a risk of misinterpretation. For complex models, local maxima might occur. A misinterpretation and, thus, wrong calibration will be the consequence when such a local maximum happens to coincide with the slowness supremum.

CONCLUSIONS

We discussed an approach to calibrate the tuned velocities for downhole receivers by means of an analysis of the slowness component tangent to the well. We used the downgoing direct waves of walkover VSP experiments to determine the modulus of the slowness vector and, thus, the velocity. Integrated into the CRS imaging workflow, we demonstrated the application of the calibrated velocities for wavefield decomposition in synthetic 2D VSP data.

ACKNOWLEDGMENTS

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