Azimuthal velocity uncertainty: estimation and application

Chris Davison*, Andrew Ratcliffe, Sergio Grion (CGGVeritas), Rodney Johnston, Carlos Duque, Jeremy Neep, Musa Maharramov (BP).

Summary

Azimuthal velocity models for HTI (Horizontal Transverse Isotropy) media are extensively and widely used for land seismic exploration in North America, North Africa and the Middle East. A surface fitting technique honouring all azimuths can invert for an HTI velocity model, which can then be used to perform azimuthally dependent NMO to flatten the CMP gathers. When performing the velocity inversion it is important to estimate the degree of confidence in the estimated velocity model. The main subject of this paper is velocity uncertainty estimation. Furthermore, we investigate the estimated errors in the model parameters with varying acquisition direction for various offset-azimuth distributions including azimuthal sectors and Common Offset Vector (COV) classes. The application of the technique to WAZ land data from Algeria illustrates the strength of the proposed technology.

Introduction

The methodology of inverting for velocities from travel-times calculates trim statics between CMP traces and a pilot stack using a cross-correlation technique. This also provides a set of correlation values which give the degree of confidence in any given trim static. The trim statics are then used to reconstruct azimuthally varying travel-times as a function of offset for the zero-offset times at which we wish to invert. Finally, the move-out curves are inverted for the velocity model parameters. An application example of this technique is shown in Todorovic-Marinic et al. (2005).

Theory

Modeling of HTI media by an azimuthal velocity model was proposed by Contreras et al. (1999). The NMO velocity has the form of an ellipse varying with the shot-receiver azimuth:

\[
\frac{1}{V_{nmo}^2} = \frac{\cos^2(\phi - \beta)}{V_{fast}^2} + \frac{\sin^2(\phi - \beta)}{V_{slow}^2}.
\]

Here, \(\phi\) is the shot-receiver azimuth and \(\beta\) the angle of orientation of the fast velocity axis. We invert for the velocity model parameters, \(m = (V_{fast}, V_{slow}, \beta)\), using a constrained, linearised, least-squares technique. As a constraint we use an a priori model \(m_0 = (V_{oef}, V_{oow}, 0)\), where \(V_{oef}\) is estimated from conventional isotropic velocity analysis. The a priori model co-variances \(\sigma_{Vf}, \sigma_{Vs}, \sigma_{Vb}\) must also be defined by the user and form the diagonal a priori co-variance matrix \(C_m\). The methodology of linearised least squares inversion with a priori constraints is described by Tarantola (1987). The a posteriori covariance matrix is defined by:

\[
C_m = \left( \frac{1}{\sigma_t^2} J^T W J + C_m^{-1} \right)^{-1} = \begin{bmatrix}
\sigma_{Vf}^2 & \sigma_{VfVf} & \sigma_{VfVb} \\
\sigma_{VfVf} & \sigma_{Vs}^2 & \sigma_{VsVb} \\
\sigma_{VfVb} & \sigma_{VsVb} & \sigma_{Vb}^2
\end{bmatrix}
\]

Here \(J\) is the Jacobian of the least squares inverse problem, and \(W\) a diagonal matrix containing weights corresponding to the degree of confidence in each of the data points. Each diagonal entry of \(W\) corresponds to a cross-correlation value from the calculation of the trim-statics for a particular data point. For the inversion, it is necessary to specify the data random noise level. We assume that the noise has a white Gaussian distribution with a zero mean and a standard deviation \(\sigma\). We estimate the noise standard deviation from the difference between the data move-out time \(t_{data}\) and the model move-out time \(t_{model}\). For \(N\) points in the move-out curve, we have:

\[
\sigma_i^2 = \frac{1}{N-1} \sum_{i=1}^{N} \left( t_{data}^i - t_{model}^i \right)^2,
\]

where the superscript ‘-’ refers to the \(i\)-th point in the move-out curve. We update the estimate of \(\sigma_i\) for each iteration of the inversion.

The diagonal terms of the a posteriori co-variance matrix are the variances of each of the model parameters, whereas the off-diagonal terms describe the degree of correlation between the estimated quantities. Correlation is sometimes ignored in uncertainty studies, but a complete characterization of uncertainty requires both. An accurate and realistic estimation of the data random noise level is not required for the inversion, although it can reduce the number of iterations required. However, because \(\sigma_i\) appears in the expression of the a posteriori co-variance matrix, an accurate and realistic estimate of this is necessary to calculate accurate and realistic errors in the velocity model parameters.

Uses of the velocity uncertainty estimates

Velocity uncertainty estimation is useful for survey design...
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purposes, to compare and evaluate the effect of various acquisition geometries and data binning. Grion et al. (1998) performed such a study for the case of isotropic, 3D velocity analysis. Here we compare the effect of binning the data into COV classes and azimuth sectors within the framework of azimuthal velocity analysis.

We consider an event with a zero offset time of 1.37 s, average velocity of 3890 m.s. and \( \sigma = 4.5 \) ms. This synthetic example relates to an event in the reservoir area of the real data set considered in the next section of this paper and is characterized by 5% anisotropy. Velocity is assumed to be known with an uncertainty of 100 m.s. and azimuth with an uncertainty of 180 degrees (i.e. unknown). It is well known that noise standard deviation decreases by the square root of fold. The predictions of errors and correlations are normalised with respect to a fold of 150 to allow a direct comparison of the different geometries independent from fold.

The polar plots illustrated in Figure 1 show how the results vary with acquisition direction, or equally the direction of the HTI isotropy plane. While results from many acquisition geometries have been studied, for reasons of space only two cases are shown here: case (a) relates to binning in COV classes (300x400m) and case (b) to azimuth sectors (sampled every 30 degrees in azimuth and 100m in offset). In both cases, the data has full azimuth coverage and a maximum offset of 2.4 km. Furthermore, it is regularized to the binning geometry of choice, so that there is one trace at the centre of each COV class and, for each offset, one trace at the centre of each of the azimuth sector.

It can be seen that for equal fold, the standard deviations of velocities and angles predicted for binning into COV classes are smaller than those observed in azimuth sectors. Our interpretation of this result is that, relative to the azimuth sectors, the COVs have a distribution containing more traces at larger offsets, and it is these traces that contain more discriminating power in the azimuthal velocity inversion, hence the reduced error. Correlations are small for both COVs and azimuth sectors. COV correlations do not exhibit circular symmetry because of the corresponding binning asymmetry. COV errors are only slightly asymmetrical: velocity errors are higher when the COV classes are oriented like the fracture system, while azimuth errors are higher at intermediate directions.

Velocity uncertainty estimation can also be useful in assessing the impact of pre-processing (e.g. noise attenuation) on the estimated velocity model, and to associate a confidence measure to subsequent interpretation work. These uses are best discussed via the real data example that follows.

Real data example

Velocity inversion was carried out on WAZ land data from the Tiguentourine 3D survey in Algeria. This ~950 km² area was covered by surveys carried out in 2004 and 2007 for the In Amenas Joint Venture (Sonatrach, BP and Statoil). For this work we concentrated on a 240 km² subset of this volume. The data were acquired with a shot line spacing of 150m and a shot spacing of 50m. The receiver line spacing is 200m, with a receiver spacing of 50m. The nominal bin size is 25x25m, and the fold is 200-240. The data is binned into COV classes of 300x400m.

Azimuthal velocity analysis is applied to the seismic data after a processing flow that honours azimuth information, including pre-stack time migration. Figure 2 shows the final velocity parameters after they are mapped to a horizon at the reservoir level: (a) the anisotropy, (b) the fast velocity azimuth, (c) the fast velocity, and (d) the fast velocity uncertainty. Joint evaluation of seismic images and attributes shows that anisotropy and fast velocity azimuth correlate with structural geology. The fast velocity azimuth can correspond to the strike direction of rock fractures, and hence is useful in interpretation. Note that the velocity errors are small because super-gathering was used in the inversion, resulting in an effective fold of approximately 6000 for each location. Super-gathering tests showed no evidence of resolution loss. We can clearly see the areas of higher uncertainty in the survey which correspond to regions where higher levels of noise in the data have been observed, for example, the known poor data area on the West caused by an escarpment.

Conclusions

We have discussed a method of calculating velocity uncertainty. While the velocity inversion method itself is not too sensitive to the accuracy of the random noise level estimation, an accurate noise level estimation is necessary for uncertainty calculations. This velocity uncertainty estimation can be used in survey design and to evaluate processing strategies. For example, we find that COV classes give smaller errors in the model parameters than azimuth sectors for the case of a real dataset acquisition geometry. Finally, we have successfully applied the method to real data from a 3D Algerian WAZ land survey.

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Figure 1 a) Errors and correlations for (300×400m) COV classes, b) Errors and correlations for (Δx=100m, Δφ=30°) azimuth sectors.
Figure 2  a) Anisotropy, b) azimuth of the fast velocity, c) fast velocity, d) fast velocity error on a horizon near the reservoir.
REFERENCES


