Automatic nonhyperbolic velocity analysis in VTI media

Brahim Abbad*, IPT/NTNU,Norway, Bjørn Ursin, IPT/NTNU,Norway, and Didier Rappin, Total R&D, Pau, France.

Abstract

We present an automatic algorithm to implement nonhyperbolic velocity analysis in VTI media. The approach is based on the use of nonhyperbolic traveltime equations that are accurate at large offsets and in anisotropic media. This is combined with an efficient parameterization to allow appropriate search for the moveout parameters (zero-offset traveltime, moveout velocity, and effective anellipticity). The raw coherency curve obtained at each CMP gather is used to filter out noisy picks and detects automatically the reflected energy with the respective parameters which makes the procedure automatic avoiding thus the tedious task of interpreting velocity spectra and picking the moveout parameters. Dix-type inversion formulae are used to retrieve interval parameters from the picked values to be used for later processing.

Introduction

The assumption of isotropy in geological settings for seismic processing may seriously affect the results of several processing steps such as moveout corrections, accurate compensation for geometrical spreading effects, anisotropic DMO, and pre- and post-stack time migrations. With the increasing interest in anisotropic processing, parameters that describe deviations from isotropy are required to implement the abovementioned processes. Reflection moveout curves can be described more accurately at large offsets and in anisotropic media using several forms of high-order traveltime equations (de Bazelaire, 1988; Alkhalifah and Tsvankin, 1995; Ursin and Stovas, 2006). These are expressed in terms of the zero offset time t_0, the moveout velocity V_{nmo} and a parameter describing anisotropy called anellipticity and denoted by η. Nonhyperbolic velocity analysis can thus be implemented using a given traveltime approximation by performing a search for the parameters describing the reflection curve.

Method

Reflection moveouts are fitted using a set of curves described by tentative values of t_0, V_{nmo} and η. The fitting of a particular curve is measured via a coefficient that maximizes lateral coherency and semblance from trace to trace for a given curve. The procedure actually applies by scanning the whole CMP gather using a set of gates sufficiently narrow to estimate the fitting. A given reflection falls perfectly inside the time gate when the correct curve parameters are used in its construction. Thus, the wavelets of the considered reflection are in phase inside the gate and show maximum lateral coherency. Recently, Ursin and Stovas (2006) proposed a continued-fraction traveltime equation that simulates reflection curves with high accuracy at far offsets in VTI media. The equation depends on three parameters and is given by:

$$t_x^2 = t_0^2 + \frac{x^2}{V_{nmo}^2} - \frac{2\bar{\eta}x^4}{V_{nmo}^2\left[t_0^2 V_{nmo}^2 + 4\bar{\eta}x^2\right]} \qquad (1)$$

where x denotes the offset. To use this equation in nonhyperbolic velocity analysis, the parameters V_{nmo} and $\bar{\eta}$ are scanned within given limits $\left\{V_{min}, V_{max} \middle| \bar{\eta}_{min}, \bar{\eta}_{max}\right\}$ using a priori information about both parameters. For each t_0-value, a given $V_{nmo} - \bar{\eta}$ couple is used to construct a time gate using equation (1). To enhance accuracy and appropriate sampling in the estimated parameters, different parameterizations can be employed to make the search optimal (Alkhalifah and Tsvankin, 1995; Alkhalifah, 1997; Grechka and Tsvankin, 1998, Siliqi and Bousquié, 2000).

We propose instead a new parameterization defined by the parameters λ_1 and λ_2 as:

$$\begin{aligned} \lambda_1 &= \sqrt{t_0^2 + \frac{x_M^2}{V_{nmo}^2}} - t_0 \\ \lambda_2 &= \sqrt{t_0^2 + \left(1+\bar{\eta}\right)\frac{x_M^2}{V_{nmo}^2}} - t_0 \end{aligned} \qquad (2)$$

The parameter λ_1 represents the hyperbolic moveout at the maximum absolute offset x_M while λ_2 describes the moveout at the same offset using a similar equation involving the anellipticity. The search for the optimal parameters is performed using regular sampling in the λ_1 - λ_2 plane.

This parameterization is independent of the employed traveltime equation and results in simple relations to obtain the moveout parameters from (2) using:

$$V_{nmo}=\frac{x_M}{\sqrt{\lambda_1\left(\lambda_1+2t_0\right)}}$$

$$\bar{\eta}=\frac{\lambda_2\left(\lambda_2+2t_0\right)-\lambda_1\left(\lambda_1+2t_0\right)}{\lambda_1\left(\lambda_1+2t_0\right)} \tag{3}$$

The gate size used for the analysis should be sufficiently narrow to contain a single event at most and the fitting of a given gate is estimated by a bootstrapped differential semblance (BDS for brevity) estimator defined as:

$$BDS=\frac{\sum\limits_{\substack{i,j=1\\ i\neq j}}^{N}\sum\limits_{k=t_0-\frac{T}{2}}^{t_0+\frac{T}{2}}\left\{d\left(x_i,t_k\right)-d\left(x_j,t_k\right)\right\}^2}{2\sum\limits_{i=1}^{N}\sum\limits_{k=t_0-\frac{T}{2}}^{t_0+\frac{T}{2}}d^2\left(x_i,t_k\right)} \tag{4}$$

where N denotes the number of traces inside the gather and $d\left(x_i,t_k\right)$ denotes seismic data inside the gate of length T at offset x_i and traveltime t_k given by equation (1) for given values of t_0 , V_{nmo} and $\bar{\eta}$. Bootstrapping (Sacchi, 1998) is introduced here to increase the sensitivity to wavelet phasing inside the gate. In fact, the traces of the gate ordered in increasing offset are randomly re-ordered to compute the differential semblance. This has implications on increasing the resolution in the coherency slices λ_1 - λ_2 .Note that the notion of bootstrapping cannot be applied to the semblance coefficient, for instance, because permutation is allowed between the traces in the addition while subtraction (used in differential semblance, equation (4)) is not allowed and results in enhanced resolution. However, one should be aware of the fact that large amplitude changes with offset affects the accuracy the of BDS estimator while the conventional semblance is less affected by amplitude changes.

When a given gate fits perfectly the reflection moveout, the traces inside the gate are in good phasing and the BDS coefficient (4) is maximized.

This coefficient is calculated for each time slice t_0 by scanning the λ_1 - λ_2 domain by means of regular sampling along the two axes. Later, the maximum peak on each slice is taken and the corresponding parameters are considered to be the optimal for a possible reflection occurring at the corresponding zero-offset time t_0 . In practice, the whole CMP gather is scanned along the t_0 -axis by using overlapping time gates which produces a curve of maximum coherency (BDS curve in our case) in addition to two curves for moveout velocity and anellipticity for each gate central time. The three curves are computed at each CMP location. However, most of the values in the curves of moveout parameters (velocity and anellipticity) are not realistic because reflections occur at few time samples unknown a priori. The parameter curves are filtered according to the analysis of the coherency curve where only maxima above a given relative threshold are kept and are supposed to correspond to the reflections in the gather. An automatic derivative-based algorithm is applied to perform this and to produce the optimal parameters of the reflections inside the gather. This was applied with success to synthetic data corrupted with Gaussian noise and has shown remarkable efficiency on real datasets.

The optimal (apparent) parameters can be directly used for applying nonhyperbolic moveout corrections and for compensating geometrical spreading effects.

Although, recovering interval parameters is important for other processing steps related to imaging such as anisotropic dip moveout and time migration. While interval moveout velocities V can be deduced using the Dix (1955) standard equation as with plane isotropic layers, the interval anellipticity describing anisotropy, is inverted using:

$$\eta_k=\frac{1}{8}\left\{\frac{\left(1+8\bar{\eta}_k\right)t_{0,k}V^4_{nmo,k}-\left(1+8\bar{\eta}_{k-1}\right)t_{0,k-1}V^4_{nmo,k-1}}{\Delta t_{0,k}V_k^4}-1\right\} \tag{5}$$

where t_0, V_{nmo} and $\bar{\eta}$ are the parameters obtained from velocity analysis. Δt_k is the one- (or two-way) vertical time in layer k . Note that the apparent and interval parameters are the same for the first layer. Equation (5) was formulated by neglecting the effect of SV-wave on the propagation of the P-wave parameters and is valid only for qP-qP waves in VTI media. The interval anellipticity η replaces the anisotropies ε and δ (Thomsen, 1986):

$$\eta=\frac{\varepsilon-\delta}{1+2\delta} \tag{6}$$

It is important to note that the vertical P-wave velocities cannot be accessed with qPqP waves only and the interval velocity V is a moveout velocity related to the vertical qP-wave velocity V_{P0} as:

$$V=V_{P0}\sqrt{1+2\delta} \tag{7}$$

Any supplementary information about the anisotropy δ allows the determination of vertical velocities required for time-to-depth conversion.

Examples

To illustrate how bootstrapping enhances parameter estimation inside time gates, we consider an event with a stacking velocity equal to 2300 m/s recorded on a spread length equal to 4km. The time gate obtained using a tentative velocity of 2315 m/sec results in a gate containing an event with a slight dip with increasing offset as shown in (Fig1a.). By applying bootstrapping, the traces inside the gate are randomly rearranged and differences between adjacent traces become significant (Fig1b.) to increase the BDS coefficient given in (4) better than this is done using the original gate.

Seismic data contained in the CMP gather are truncated (muted) in offset to accurately estimate the moveout parameters. Synthetic examples show that applying a truncation at an offset-to-depth ratio from 1.8 to 2.2 recovers with high accuracy the moveout velocity while the anellipticity has an accepted resolution that depends on the strength of anisotropy in the model. Figure 2 shows the advantages gained using the parameterization defined in equation (2). Parameter tracking is easier in the $\lambda_1 - \lambda_2$ domain (Fig2c.) while estimating the optimal τ_0 for a given reflection in the $\tau_0 - dtn$ space (Siliqi and Bousquié, 2000) is difficult due to the large range of τ_0 -values with high BDS values as shown in (Fig2b.) resulting in poor anellipticity estimates. In addition, the $V_{\mathrm{nmo}} - V_{\mathrm{hor}}$ parameterization (Fig2a.) is also appropriate for accurate parameter estimation (Alkhalifah and Tsvankin, 1995; Alkhalifah, 1997; Grechka and Tsvankin, 1998), but has lower resolution than the proposed parameterization. To ensure the bijectivity in the transformations (2 and 3), the search techniques consider only a limited range inside the time slices. This is a requirement to obtain moveout parameters inside the velocity and anellipticity corridors initially used to guide the search.

The proposed algorithm has been tested with great success to synthetic datasets corrupted with Gaussian noise. A real data application was also performed on a seismic like in the Gulf of Mexico. The dataset consists of marine pure and converted waves, but we considered only qPqP waves for velocity analysis. The Mahogany area contains subhorizontal reflectors (valid for VTI assumption) and a salt dome beneath. The dataset was scanned using time gates of 20ms width with 40% overlapping. The BDS was computed at each CMP location from CDP 500 to the end of the line CDP 1713. The moveout velocity was scanned using corridors between 1500 to 3500 m/s while the anellipticity was scanned in the positive range 0-0.5. Fig3 shows the resulted raw stack section for qPqP waves in the area which illustrate most of the present reflectors in the area and shows the flanks of the salt dome which can be further enhanced using anisotropic time migration from the results of velocity analysis (moveout and anellipticity fields).

Conclusion

We presented an algorithm for automatic implementation of nonhyperbolic velocity analysis that allows the extraction of the moveout parameters from reflection curves in CMP gathers. This is done using a parameterization giving optimal parameter tracking. Bootstrapping is introduced to enhance the results of differential semblance estimator and is filtered using a derivative-based approach to keep maxima. The filtered parameters are directly used for nonhyperbolic NMO corrections. Interval parameters are deduced using Dix-type inversions, but caution must be considered for the inverted parameters which are sensitive to small interval times or important increase of effective parameters V_{nmo} and η. Resulted interval parameters can be enhanced using constrained Dix equations to provide parameters that are geologically plausible (Koren and Ravve, 2006).

Acknowledgments

BA and DR are grateful to Total R&D (Pau-France) for hospitality and financial support. BU thanks Statoil for financial support. We thank Jean-Luc Boelle and Jerome Guilbot from Total R&D for constructive discussions. We thank also WesternGeco for allowing the use of the Mahogany dataset.

References

Alkhalifah, T., 1997, Velocity analysis using nonhyperbolic moveout in transversely isotropic media: Geophysics, **62**, 1839-1854.

Alkhalifah, T., and Tsvankin, I., 1995, Velocity analysis for transversely isotropic media: Geophysics, **60**, 1550-1566.

de Bazelaire, E., 1988, Normal moveout revisited: inhomogeneous media and curved interfaces: Geophysics, **53**, 143-157.

Dix, C.H., 1955, Seismic velocities from surface measurements: Geophysics, **20**, 68-86.

Grechka, V., and Tsvankin, I., 1998, Feasibility of nonhyperbolic moveout inversion in transversely isotropic media: Geophysics, **63**, 957-969.

Koren, Z., and Ravve, I., 2006, Constrained Dix inversion: Geophysics, **71**, R113R130.

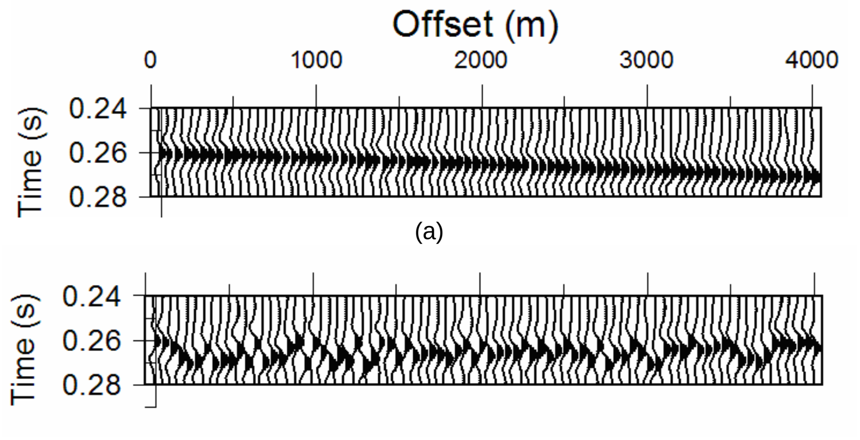
Sacchi,M.D.,1998, A bootstrap procedure for high-resolution velocity analysis: Geophysics, **63**, 1716-1725.

Siliqi, R., and Bousquié, 2000, Anelliptic time processing based on a shifted hyperbola approach: 70th Annual International Meeting, SEG, Expanded Abstracts.

Symes, W.W., and Carazzone, J.J., 1991, Velocity inversion by differential semblance optimization: Geophysics, **56**, 654-663.

Thomsen, L., 1986, Weak elastic anisotropy: Geophysics, **51**, 1954-1966.

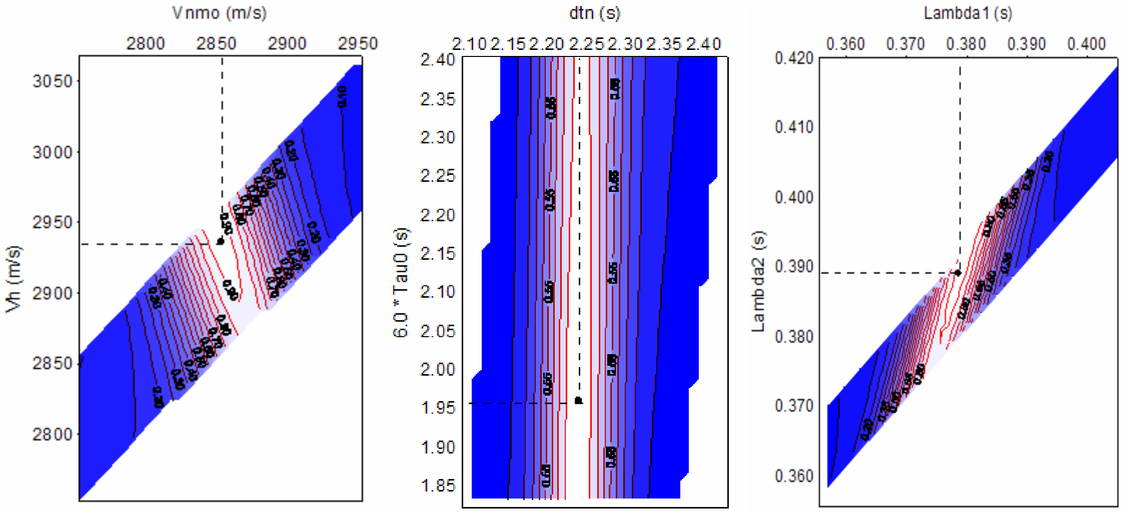
Ursin, B., and Stovas, A., 2006, Traveltime approximations for a layered transversely isotropic medium: Geophysics, **71**, D23-D33.



(a)

(b)

Fig1. A time gate containing a dipping event with increasing offset (a). Phase changes are clearly shown when bootstrapping is applied (b).



a) b) c)

Fig.2. Comparison of resolution in time slices using different parameterizations.
a) $V_{\text{nmo}} - V_{\text{hor}}$ parameterization, b) $\tau_0 - dtn$ parameterization, c) $\lambda_1 - \lambda_2$ parameterization

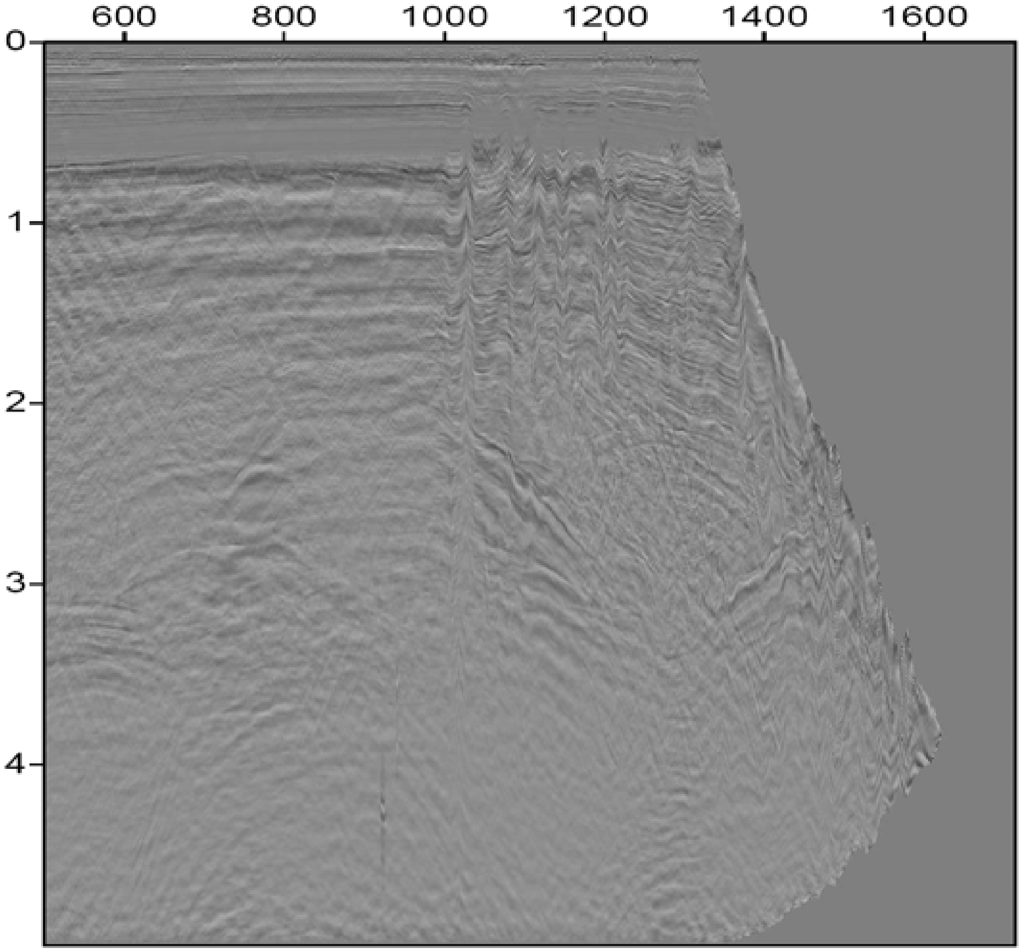


Fig3. The obtained stack of Mahogany offshore seismic line using automatic nonhyperbolic velocity analysis. Note in particular the focus of most reflectors and the top and bottom of the salt dome which requires time migration for a better focusing.