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Non-linear Slope Tomography for Orthorhombic Pre-stack Time Imaging

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SUMMARY

For WAZ wide-azimuth data, the VTI hypothesis is not always sufficient for insuring focusing of time migration. We propose an extension of non-linear slope tomography for time imaging to the orthorhombic case. We use a model of orthorhombic anisotropy parameterized by five effective parameters, where the effective velocity and eta vary according to the azimuth of the migrated trace. In our approach the five parameters are updated jointly, allowing the extension to the orthorhombic case the advantages of non-linear slope tomography for time velocity model building, i.e. improved accuracy and turn-around.

Introduction

Velocity model building for time imaging is traditionally addressed by iterative workflows involving loops of pre-stack time migration (PreSTM) and picking steps with anisotropic velocity updates performed locally under zero dip and 1D assumptions (Siliqi *et al.*, 2003; Le Meur *et al.*, 2003). Taking advantage of approaches developed for velocity model building in depth (Guillaume *et al.*, 2008; Lambaré *et al.*, 2009) introduced non-linear slope tomography as an efficient and accurate solution for remedying pitfalls of the traditional time velocity model building workflow. In particular seismic dips and local variations of the effective velocity and η models are taken into account in a non-linear way, mitigating limitations of local zero dip 1D assumptions. This also results in improved accuracy and turnaround especially in the case of marine narrow azimuth data (Depagne *et al.*, 2012).

In the case of wide azimuth data (WAZ), VTI (Vertically transverse isotropic) velocity model building may result into residual "wobbling" effects in the azimuthal direction after PreSTM (Zimine *et al.*, 2010). This azimuthally dependent residual moveout (RMO) can be caused by velocity heterogeneities, dipping reflectors or azimuthal anisotropy not properly taken into account by VTI PreSTM. The azimuthal wobbling can be corrected by applying a post-migration azimuthal RMO correction to the PreSTM gathers, without updating the velocity model (Lecerf *et al.*, 2010) or azimuthal velocity correction based on a 1D assumption (Davison *et al.*, 2014), which can be used to feed an azimuthal migration (Wang *et al.*, 2013).

We propose here to extend the VTI non-linear slope tomography to the estimation of azimuthal effective velocity for time imaging. Our approach combines Horizontal Transverse Isotropy (HTI) and VTI modeling into "orthorhombic" anisotropy. With current long offset WAZ acquisitions (mainly onshore), this development is crucial for improving the quality of time imaging, in particular in the presence of fractured hard-rocks or subsurface stress.

Non-linear slope tomography

Non-linear slope tomography has been initially developed for velocity model building in depth (see Lambaré, 2008, for a review). As such it offers an industrial solution (Guillaume *et al.*, 2008) for an efficient and accurate velocity model building combining the advantages of dense volumetric picking and of a non-linear update of the velocity model (Lambaré *et al.*, 2014).

Its input consists of a set of "invariants", i.e. source and receiver positions, and time and slopes of locally coherent events that can be observed in the un-migrated time domain (Figure 1). They can be picked directly in the un-migrated time domain but much more frequently they are obtained by kinematic de-migration of "facets" picked in the pre-stack migrated image, i.e. local dips and associated RMO. They are called "invariants" because kinematic demigration removes the effect of the initial velocity model.

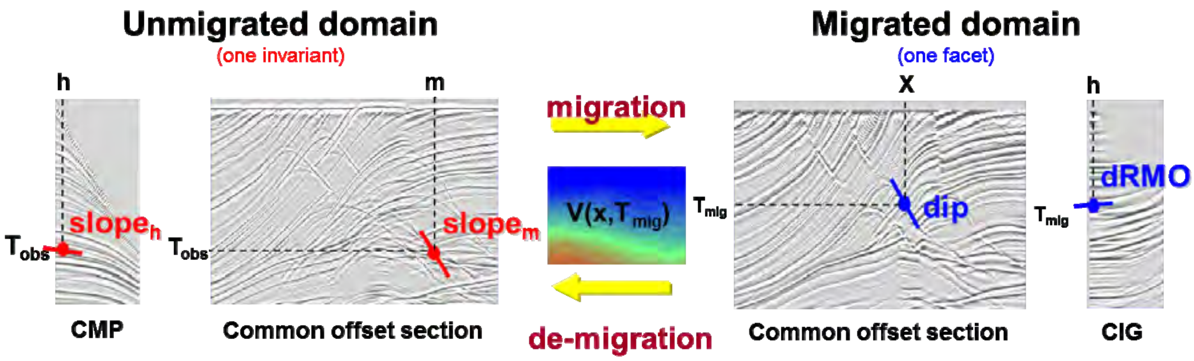

Figure 1 *A locally coherent event in the 2D case. Left) in the un-migrated domain, it is characterized by its position and slopes. Right) in the time migrated domain, the migrated facet is characterized by its central position, dip and derivative of residual move out dRMO in the common image gather (CIG) (from Lambaré et al., 2009).*

In time imaging the velocity model is described by effective velocity model parameters *(v_i)* (effective velocity and η in case of VTI time imaging (Lambaré *et al.*, 2009)). In non-linear slope tomography, the spatial variations of velocity parameters are defined by a 3D grid of cardinal cubic Bsplines functions. The velocity parameters are updated jointly through a local non-linear optimization scheme aiming at minimizing the dRMO of the remigrated facets,

$$\min_{v_i}\left(\left\|C_d^{-1/2}dRMO\right\|^2+\sum_i\left\|C_{v_i}^{-1/2}\left(v_i-v_i^{prior}\right)\right\|^2\right), \tag{1}$$

thus flattening the CIGs. C_d and C_{v_i} are covariance matrices on data and model parameters including for example a quality factor on the data and a damping factor on the model. In conjunction with Bsplines functions they greatly stabilize the inversion process.

Each iteration of the inversion solves a linearized problem first, performing kinematic migration of facets and computation of Fréchet derivatives in the current velocity model, and then updating the velocity perturbations by solving the linearized inverse system. At each iteration, the facets are remigrated according to the updated velocities, thus bringing in the non-linearity of the method.

VTI non-linear slope tomography for time imaging was presented by Lambaré *et al*. (2009) while applications to WAZ land data and marine NAZ data were presented by Zimine *et al*. (2010) and Depagne *et al*. (2012), respectively. We aim here at extending it to the orthorhombic case with applications to WAZ data.

Orthorhombic non-linear slope tomography

In Lambaré *et al*. (2009) the one-way travel time used in the time migration is based on the shifted hyperbola curve introduced by Castle (1994),

$$t\left(x_s,y_s;x,y,T_{mig}\right)=\frac{T_{mig}}{2}(1-S)+\sqrt{\left(\frac{T_{mig}}{2}S\right)^2+\frac{h_S^2}{V^2}S} \tag{2}$$

where (x,y,T_{mig}) is the migrated position, (x_s,y_s) is the source position at surface, $h_s(x_s,y_s;x,y)$ is the source-reflection point offset, and $V(x,y,T_{mig})$ and $S(x,y,T_{mig})$ are respectively the VTI RMS velocity and the anellipticity (fourth order) term (S is connected to anisotropic parameter η through $S=1/(1+8\eta)$).

The generalization to the orthorhombic case implies introducing a pertinent azimuth dependent behavior of the shifted-hyperbola formula (2). Equation (2) was rewritten by Siliqi (2007) introducing a dependency of the RMS velocity and anellipticity to the azimuth of the trace, β:

$$\begin{aligned}V\left(x,y,T_{mig};\beta\right)&=V_i\left(1-E_2+\cos\left(2\left(\beta-\beta_f\right)\right)+\frac{1}{4}E_2^2\right)^{-1/2}\\ S\left(x,y,T_{mig};\beta\right)&=S_i\left(\frac{1-E_2+\cos\left(2\left(\beta-\beta_f\right)\right)+\frac{1}{4}E_2^2}{1-E_4+\cos\left(2\left(\beta-\beta_f\right)\right)+\frac{1}{4}E_4^2}\right)^{-2}\end{aligned} \tag{3}$$

where $V_i(x,y,T_{mig})$ and $S_i(x,y,T_{mig})$ are the VTI velocity and anellipticity, $E_2(x,y,T_{mig})$ is a 2^{nd} order ellipticity parameter in the horizontal plane, and $\beta_f(x,y,T_{mig})$ is the azimuth of the fast RMS velocity axis, together parameterizing the elliptical azimuthal behavior of the effective velocity V (Figure 2). $E_4(x,y,T_{mig})$ is a 4^{th}-order horizontal ellipticity parameter characterizing the azimuth dependency of anellipticity (it parameterizes an elliptical azimuthal behavior for the "anelliptic velocity" $V_a=S^{-1/4}\times V$, that leads to the parameterization for S of the second line of eq. (3)). The proposed method combines anelliptic velocities in the vertical plane with elliptic variations in the horizontal plane and uses the same fast velocity axis for V and S quantities defined in equations (2) and (3). Other formulations of orthorhombic time processing exist. They slightly differ from each other in the parameterization of the 4^{th}-order term (e.g. Tsvankin, 2001).

Five velocity quantities are thus defined and estimated jointly by our orthorhombic non-linear slope tomography:

$$\left\{v_{i=[1,5]}\right\}=\left\{V_i,S_i,E_2,E_4,\beta_f\right\}. \tag{4}$$

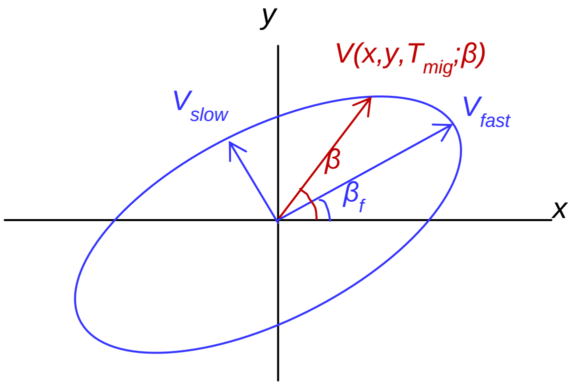

Figure 2 *Effective VI ellipse, at imaged position.*

Estimating jointly so many parameters in a non-linear inverse problem is a difficult challenge that we face in many velocity model building problems. For accuracy and efficiency we have chosen here to use a quasi-Newton optimization. It implies first the computation of the Fréchet derivatives for each model parameter. We have used an approach equivalent to paraxial ray tracing used in stereo-tomography (Billette and Lambaré, 1998), which requires the definition of appropriate regularizations leading to a stable iterative optimization. In this domain the key point has been the introduction of properly weighted damping and Laplacian regularization terms (time-domain velocity models must be smooth) for all the model parameters, v_i :

$$C_{v_i}^{-1} = \alpha_{vi}\, I_M + \delta_{vi}\, \Delta^{+}\Delta, \qquad (5)$$

where I_M is the identity matrix, Δ is the derivative operator, and α_{vi} and δ_{vi} are the weighting factors associated to the damping and Laplacian regularizations.

Another key stabilizer in case of azimuthal inversion is our choice of a cardinal cubic Bsplines description. Indeed, at least sampling on 3 azimuths are necessary to fit an ellipse, otherwise the inversion is unstable. The width of Bsplines basis function allows increasing azimuthal diversity that contributes to the update of each Bsplines weight. Combined with regularization, this leads to a very stable joint inversion of the five velocity parameters.

Results on field data

We test our algorithm on a WAZ land dataset with 5 km maximum in-line and cross-line offsets. Figure 3 shows a zoom at intermediary offset (between 2.5 and 3.5 km) on a CIG obtained from a time velocity model updated by VTI non-linear slope tomography (left) and for a time velocity model updated by orthorhombic non-linear slope tomography (right). Common Image Gathers (CIGs) are displayed as “snail” gathers (or “COCA” common-offset, common-azimuth), i.e. traces being sorted by increasing offset range and within each common offset range by increasing trace azimuth.

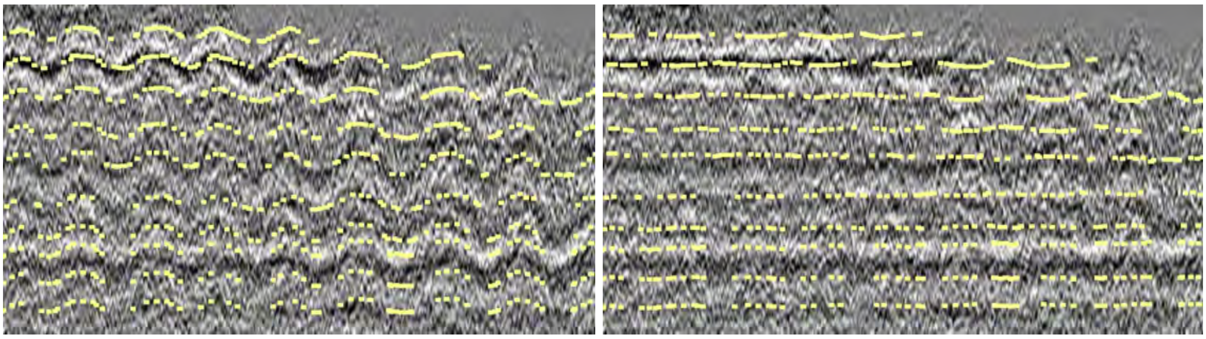

Figure 3 *Intermediate offset, [2.5,3.5] km, zoom on a “snail” time CIGs. Left) VTI time tomography and migration, Right) Orthorhombic time tomography and migration. Inverted facets are superimposed (They correspond to the same invariants).*

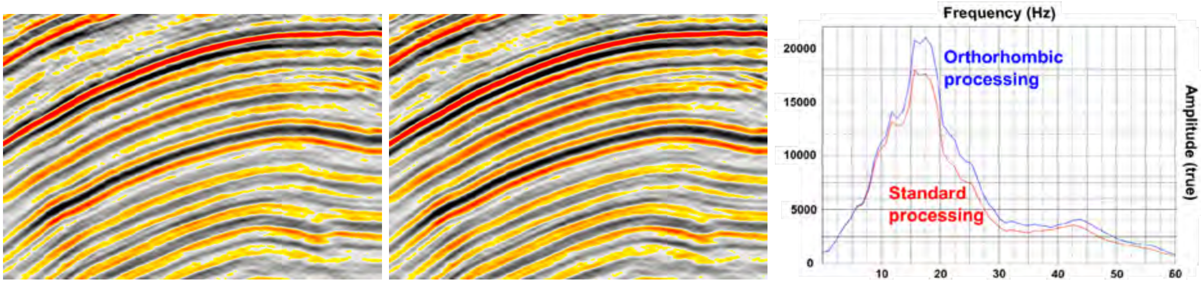

Figure 4 *Stack after time-migration. Left: VTI tomography and PreSTM. Center: orthorhombic tomography and PreSTM. Right: Spectra comparison.*

The left panel in Figure 3 shows, as in Zimine *et al*. (2010), a significant wobbling effect that could not be solved by the VTI velocity model building. The right panel shows the same CIG obtained after orthorhombic non-linear slope tomography. The wobbling effect has disappeared, greatly improving focusing and signal to noise ratio in the stack shown on Figure 4. The inverted facets are superimposed. For both panels they correspond to the same invariants kinematically demigrated from dips and RMO picked on an initial WAZ PreSTM (Lecerf *et al*., 2009). Not shown here, but the obtained fast velocity azimuth angle β_f is smooth and coherent with the angle that would have been picked on snail gathers.

Conclusion

We have presented the extension of non-linear slope tomography to orthorhombic time imaging. As such it offers an interesting solution for velocity model building in case of WAZ survey where the VTI assumption is rarely sufficient for insuring focusing. Our optimization scheme allows for a robust and accurate joint inversion of five velocity parameters, with all the advantages of non-linear slope tomography in terms of efficiency and accuracy.

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References

Billette, F. and Lambaré, G. [1998] Velocity macro-model estimation by stereotomography. *Geophysical Journal International*, **135**, 671-680.

Castle, R.J. [1994] A theory of normal moveout. *Geophysics*, **59**, 983.

Davison, C.M., Grimshaw, M.J., Murray, E.M., Kowalczyk-Kedzierska, M., Angio, S. and Ourabah, A. [2014] Orthorhombic Extension to HTI Velocity Analysis - Theory and Application to a High Density Aquisition. *76th EAGE Conference & Exhibition 2014*, Amsterdam.

Depagne, S., Wabara, K., Deladerrière, N., Guillaume, P., Lambaré, G., Touré, J.-P., Ayong-Mba, C., Zhang, X. and Lafet, Y. [2012] Revealing velocities: from time imaging to high definition tomography. *74th EAGE Conference & Exhibition*, Extended abstracts, W033.

Guillaume, P., Lambaré, G., Leblanc, O., Mitouard, P., Le Moigne, J., Montel, J.-P., Prescott, T., Siliqi, R., Vidal, N., Zhang, X. and Zimine, S. [2008] Kinematic invariants: an efficient and flexible approach for velocity model building. *78th Annual International Meeting, SEG*.

Lambaré, G. [2008] Stereotomography. *Geophysics*, **73**(5), VE25-VE34.

Lambaré, G., Deladerrière, N., Traonmilin, Y., Touré, J.P., Le Moigne, J. and Herrmann, P. [2009] Non-linear tomography for time imaging. *71st EAGE Conference & Exhibition*, Amsterdam.

Lambaré, G., Guillaume, P. and Montel, J.-P. [2014] Recent advances on ray based tomography. *76th EAGE Conference & Exhibition*, Amsterdam.

Lecerf, D., Navion, S., Boelle, J.-L., Belmokhtar, A. and Ladmek, A. [2009] Azimuthal Residual Velocity Analysis in Offset Vector for WAZ Imaging. *71st EAGE Meeting*, Amsterdam.

Le Meur, D., Siliqi, R., Gamar, F., Smith, L., Touré, J.P. and Herrmann, P. [2003] High density moveout parameter fields V and η. Part two: Simultaneous geostatistical filtering. *SEG Expanded Abstracts*, 2092-2095.

Siliqi, R. [2007] *WAZ PSTM*. Internal communication.

Siliqi, R., Le Meur, D., Gamar, F., Smith, L. and Touré, J.-P. [2003] High-density moveout parameter fields V and Eta, Part 1: Simultaneous automatic picking. *SEG Technical Program Expanded Abstracts*.

Tsvankin I. [2001] *Seismic Signatures and Analysis of Reflection Data in Anisotropic Media*. Pergamon.

Wang S., Wilkinson, D. [2013] Approach Enhances Seismic Imaging. *The American Oil & Gas Reporter*.

Zimine, S., Lambaré, G., Guillaume, P., Montel, J.-P., Touré, J.P., Deladerrière, N., Zhang, X., Prescott, A., Lecerf, D., Navion, S., Boelle, J.-L., Belmokhtar, and A. Ladmek, A. [2010] Azimuthal anisotropy? The time and depth imaging point of view: an imaging case history. *72nd EAGE Conference & Exhibition*, Barcelona.