Dip-constrained non-linear slope tomography: an application to shallow channel characterization

Patrice Guillaume*, Mathieu Reinier, Gilles Lambaré, Alexandre Cavalié (CGGVeritas), Monica Iren Adamsen and Benny Munch Bruun (DONG Energy)

Summary

Ray based migration velocity analysis from pre-stack seismic reflection data is based on the characterization of the migrated reflected events by their position, dips and residual move-out. Such approaches update the depth velocity model through an optimization process, where the residual move-out of the picked migrated events is minimized while obeying some regularization constraints related to the depth or to the shape of some horizons or to the smoothness or structural conformity of the velocity field. We propose to introduce an additional term in the cost function involving the dip of kinematically migrated locally coherent events. The velocity is then updated to match the expected dip of the re-migrated offset-dependent events. We develop here the conceptual aspects of this approach within the frame of non-linear slope tomography and present a first application, on a North Sea dataset, to the characterization of very shallow channels creating pull-up and pull-down effects in deeper parts of the migrated image. Due to the very limited offset range of the residual move-out picks in shallow subsurface, these effects could not be solved by residual move-out based tomography. We demonstrate that the introduction of the dip-constrained inversion allows the correction of these pull-up and pull-down effects, resulting in improved depth imaging.
Introduction

Velocity model building aims at computing an accurate velocity model for seismic imaging. As the inverse problem is non-linear and ill-posed it requires both a non-linear optimization process and the introduction of relevant constraints. Among the non-linear tomography tools those based on non-linear slope tomography (Lambaré, 2008) have proven to be the basis of efficient industrial solutions able to cope with dense volumetric picking (Guillaume et al., 2008; Tieman et al., 2009). We will focus on them here. A wide diversity of constraints have been proposed, involving smoothness or structural constraints on the velocity model as well as positioning or structural constraints on the reflectors (Delprat-Jannaud and Lailly, 1993; Sinoquet, 1993; Jin, 1999, Adler et al., 2008). Structural constraints can be introduced as soon as we have some structural knowledge about the expected image. In particular, the imaging distortions associated with shallow heterogeneities, channels, faults, gas clouds or rough topography may all be corrected by proper structural constraints. The introduction of structural constraints on reflectors has been limited so far to horizons (Delprat-Jannaud and Lailly, 1993; Sexton and Williamson, 1998) and not extended to locally coherent events as considered in the non-linear slope tomography. We propose to introduce in the non-linear slope tomography (Guillaume et al., 2008) an additional structural constraint in the form of an offset-dependent dip constraint. An extra term is introduced in the cost function for minimizing the misfit between the offset-dependent dip of the re-migrated events and an expected dip (e.g. the average dip). We present this original spatial dip constraint making use of data picked volumetrically and insert it in the non-linear optimization scheme used by the non-linear slope tomography. We show a first application involving very shallow channels (Figure 1).

**Figure 1**: Pull-down and pull-up effects associated with very shallow channels as measured in PreSDM partial offset stacks. The colour indicates the dip error with respect to a smoothed dip model. The footprint of the shallow velocity anomaly gets wider with offset, showing the 3D nature of distortions. The black vertical arrows delineate the dip sub-volumes effectively inverted by the dip tomography.

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The input data used in the non-linear slope tomography consist of a set of offset-dependent locally coherent events defined in the un-migrated time domain by shot and receiver positions, two-way traveltime and time slopes in all the dimensions of the acquisition geometry (x, y and vector offset) (Lambaré et al., 2008) (Figure 2). These data are generally obtained by kinematic finite-offset de-migration and because they do not depend on the initial velocity model they are called kinematic invariants (Guillaume et al., 2001). Firstly, each locally coherent event is kinematically re-migrated in the velocity model. Then, for each event, we compute the derivative of the Residual Move-Out (RMO) curve with respect to offset $\delta RMO$ (Chauris et al, 2002) (Figure 2). The non-linear slope tomography finds a velocity model $m$ that minimizes the cost function $C(m)$:
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\[ C(m) = \sum_{i} \alpha_i \| \delta RMO_i \| + R(m) , \]

Where \( R(m) \) denotes some regularization term on the velocity model and \( \alpha_i \) denotes the weight associated with each picked RMO event. The non-linear slope tomography uses a non-linear iterative local optimization scheme for updating the velocity model. Fréchet derivatives of \( \delta RMO_i \) with respect to velocity model parameters can be computed thanks to paraxial ray theory (Chauris et al., 2002).

Figure 2: Kinematic invariants (left) and corresponding migrated facet (right) in 2D non-linear slope tomography (\( m \) denotes for mid-point position, and \( h \) for offset). Non-linear slope tomography aims at flattening gathers minimizing \( \delta RMO \). Our proposed dip constraint introduces an additional term in the cost function involving the misfit between the dip of the migrated facet and an expected dip model.

Let’s consider now that we have extra information on the common offset dip of some events (Figure 2). This information consists of an expected dip value \( dip_{\text{ref}} \). For example in the case of the pull-up and pull-down distortions observed in Figure 1 we expect the spatial dip to follow the general trend of the structure. The offset dependent spatial dip distortions that are measured below localised velocity anomalies can be introduced in the cost function for delineating and quantifying those velocity anomalies. We then propose the extended cost function:

\[ C(m) = \sum_{i} \alpha_i \| \delta RMO_i \| + \sum_{j} \beta_j \| dip_j - dip_{\text{ref}} \| + R(m) , \]

Where the additional term contains the misfit between migrated and expected dips (\( \beta_j \) denotes the weight associated with each dip event). Dip-constrained non-linear slope tomography consists in minimizing the new cost function (2) again using a non-linear iterative local optimization scheme, in which the Fréchet derivatives for the dip term are computed using the paraxial ray theory. Note that the dip constraint is structural and does not constrain the position of the seismic reflectors.

A shallow channel example

Migration velocity analysis usually fails to identify velocity variations caused by very shallow channels (Figure 1) because RMO picks are sparse in shallow parts and resolution (redundancy) is limited. Unresolved shallow velocity anomalies result in distortions after depth migration, e.g. pull-up or pull-down phenomena that affect in particular the shape and the position of the migrated seismic reflectors in the deeper parts of the subsurface. Several approaches have been proposed for removing these distortions. For example the geometry of the channels can be fixed while the best channel-fill interval velocity is determined either by a time consuming migration velocity scan (Jones, 2010) or by a constrained migration of horizons (Robein, 2003) with a lack of accuracy and flexibility due to the limited number of picked horizons.

Applying the dip constraint to volumetrically picked events can lead to more accurate and flexible workflows. We apply it here to a North Sea dataset. Figure 1 shows the pull-down and pull-up effects observed on various PreSDM partial offset stacks for a velocity model obtained by a conventional RMO tomography. The lack of RMO picks in the very shallow layers leads to a poorly resolved shallow section. The expected dip model is estimated from a smoothed version of the dip model. Figure 1 also shows the discrepancies between the measured offset-dependent dip and the expected dip model. A dense set of offset dependent dip events and a less dense set of RMO events are
volumetrically picked in the depth range 0-1250m. They are then inverted by dip-constrained slope
tomography for updating the shallow velocity layers in the depth range 0-300m. In a final step, a non-
linear slope tomography is performed while freezing the velocity in the shallow layers.

Figure 3: Shallow slice at 100 m depth of the PreSDM stack and of the corresponding velocity
model after dip-constrained tomography. Green indicates low velocity (1750m/s) and red indicates
high velocity (1850m/s).

Figure 4: Vertical section (indicated on Figure 3 by a yellow line) of the PreSDM stack and velocity
model across shallow channels (see arrows): Left) before tomography showing the anomaly footprint
getting wider with depth; Right) after dip-constrained non-linear slope tomography, the migrated
image is better focused and less distorted (see circled areas).
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Figure 3 shows a depth slice at 100 m depth where the localised shallow velocity structures have been revealed by the dip-constrained tomography. We see that it nicely conforms to the imaged structures. We see on Figure 4 that it removes pull-down and pull-up effects in deeper parts of the model and that the seismic amplitudes along main reflectors are more regular.

Conclusion

We have shown that introducing an offset-dependent dip constraint in the non-linear slope tomography can improve significantly the migrated image. Volumetric dip information can be automatically picked more densely, particularly in the shallower layers where RMO picks are sparse. Inverted together with the RMO it insures an optimal match of both structures and RMO. As such it can simultaneously correct imaging distortions and focus the image, in a quite automated way. We see a wide set of potential applications for this approach, as soon as offset dependent dip observations can be made, e.g. pull-up, pull-down effects or any distortions in imaging associated with shallow heterogeneities, channels, faults, gas clouds, rough topography or flat spots.

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References