

RESOLVING SMALL SCALE LATERAL VELOCITY ANOMALIES WITHOUT FWI OR STOCHASTIC APPROACHES

M. Reinier¹, T. Allemand¹, N. Salaun¹, Z. Yu¹, M. Pouget¹, A. Henry-Baudot¹, B. Chaintreuil¹, M. Mihoub¹, G. Gigou¹, I. Espin¹

¹ CGG

Summary

Small-scale heterogeneities create distortions in the wavefield that are usually resolved by Full Waveform Inversion (FWI). When FWI fails (for lack of diving waves or low frequencies), recent works promote the use of targeted stochastic approaches maximizing the stack power. We instead revisit here ray-based tomography and propose an innovative approach for a high definition tomography which can recover small-scale anomalies without any a priori information on their localization. While previously proposed tomographic approaches aimed at vertical resolution and structural conformity, our new approach focuses on enhancing lateral heterogeneities. The first key component is an accurate RMO picking with structural dip information honoring the variation of dip with offset. Second, is an efficient nonlinear slope tomography employing small grids and a minimum level of constraints. Our approach is demonstrated on a 2D synthetic dataset with small-scale lateral variations and confirmed on a 3D streamer dataset from the Barents Sea.

Resolving small scale lateral velocity anomalies without FWI or stochastic approaches

Introduction

Complex subsurface geology leads to distortions in the seismic wavefield. Only a detailed and accurate velocity model can undo these distortions and correctly image the Earth's structures. Modern velocity model building workflows employ Full Waveform Inversion (FWI) to recover a high-resolution, structurally consistent velocity model. However, FWI can fail in areas not illuminated by the recorded diving waves or when the data lacks low frequencies. In this context recent works have promoted the use of stochastic optimization of the stack power computed with one-way wave equation migration, bypassing the limitations of ray-based approaches and the picking (Shen et al, 2020, Ahmed et al, 2020). Even if producing interesting results, these methods remain computationally very expensive, requiring hundreds of migrations, thus currently limited them to targeted areas.

Whilst FWI grabs most of the headlines, ray-based tomography still plays an important role in most complex velocity model builds. We revisit here the estimation of small-scale lateral velocity perturbations by ray-based tomography (Woodward et al, 2008, Guillaume et al, 2008). The resolution of tomography highly depends on the density and accuracy of dip and residual moveout (RMO) picks, and also on the constraints introduced on the velocity model. Recent advances have improved the resolution of inverted models (Sioni et al, 2012, Hardy, 2013, Hilburn et al, 2014) leading to structurally conformable updates. Imposing a structurally conformable velocity perturbation can deteriorate the lateral resolution of the model, which may not be effective in case of a highly laterally heterogeneous velocity.

Our approach is based both on improving the RMO picking and on a dedicated conditioning of the tomographic inverse problem. When complex RMO shapes can be accurately picked on the Common Image Gathers (CIGs), we show that tomography can recover small-scale lateral heterogeneities in the velocity model. For the picking step we use a novel picking method that not only captures distorted RMO curves, but also accounts for the dip variation with the offset. For the velocity update we use nonlinear slope tomography, with a minimum level of a priori information, in order to let the data express themselves. Our approach builds on high definition tomography (Sioni et al., 2012): we call it Enhanced High Definition (EHD) tomography. It is demonstrated on a 2D synthetic line with strong lateral variations, as well as on a 3D streamer dataset from the Barents Sea.

High-resolution picking with offset-dependent dip

Small-scale lateral velocity variations not honoured in the migration model will impose complex shapes upon the RMO curves as well as variation of the structural dip of the migrated seismic from near to far offsets (Figure 1). All this needs to be preserved by the preconditioning of CIGs and accurately picked. For the RMO it means using non-parametric picking methods (Luo et al, 2014). Conventional practice is to take the structural dip from the stack and use the same dip for all the offsets. Traonmilin et al (2009) proposed to use a multi-dip estimation in several dimensions. We compute offset-dependent structural dip information with a more practical tau-p approach (Hermann et al, 2000) in local 4D windows (inline, crossline, depth, offset).

The impact of correctly accounting for the dip variation with the offset is highlighted on a 2D synthetic example (Figure 1). CIGs migrated in the smooth background model have complex curvatures. They were picked and inverted in two cases: using the same dip for all offsets or using multi-dip picks. Flattening of CIGs after tomography is clearly improved in the multi-dip case (Figure 1). The corresponding velocity model is less noisy and lateral variations are well recovered.

We illustrate our method on a 1500 km² 3D dataset from the Barents Sea, extracted from the Greater Castberg a 5000 km² source over streamer acquisition from summer 2019 (Salaun et al, 2020). The acquisition design was implemented to overcome the regional imaging challenges caused by the hard, rugose water bottom (400m), numerous gas pockets and shallow reservoirs (800m and 1400m), similar to the type of small-scale shallow heterogeneities mimicked in our synthetic example. The Loppa High faulted structure is also present to the East, containing recent discoveries visible as flat spots. Shooting above the deep tow streamers allows the full incidence angle from the water bottom reflection to be picked. This, combined with the dual azimuth information, leads to robust RMO curvature information. The main idea of the CIG pre-conditioning before RMO picking is to accurately preserve even the most

complex curvatures on the CIG gathers, by rigorous attenuation of the residual multiples using passes of Radon combined with trim statics. The depth shift volume between two consecutive offset classes illustrates the impressive level of details that can be extracted from the data, in agreement with the co-rendered migrated image (Figure 2). The depth shift is also overlaid on the preconditioned CIGs, showing the variability with depth and offset needed to recover a high-resolution velocity.

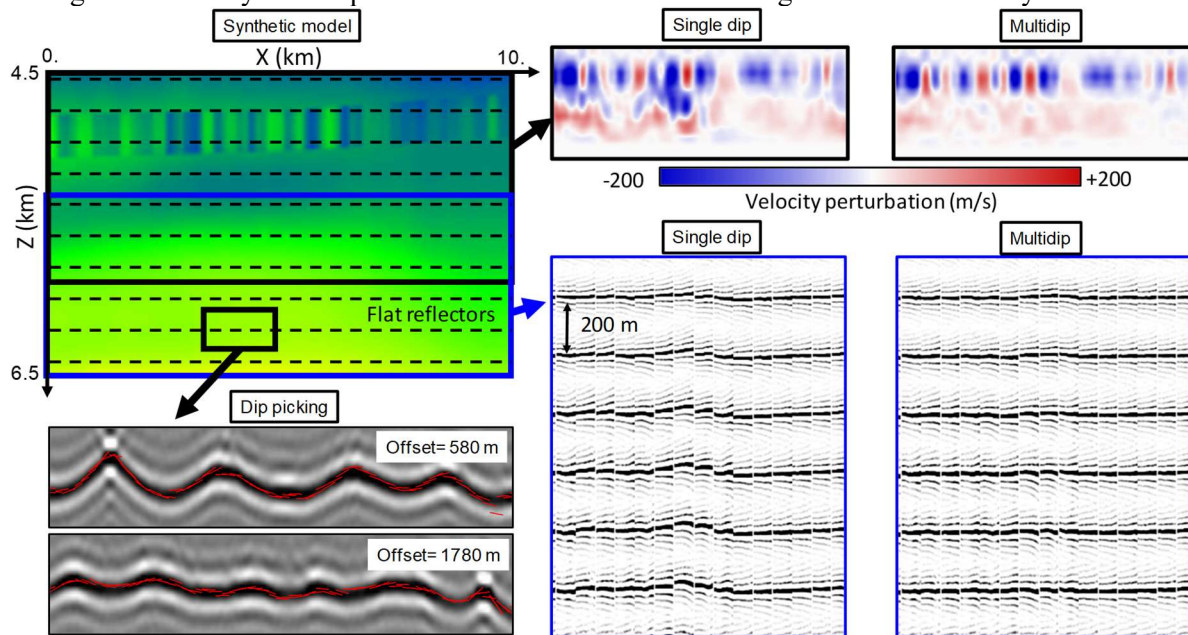


Figure 1: Importance of structural dip variation with offset. Left: synthetic test model with the added true perturbation (top), one horizon migrated in the background model for two different offset classes (bottom). Right: perturbations recovered by tomography with the remigrated CIGs, in two cases: using a single dip from stack or using offset-dependent dips (multidip).

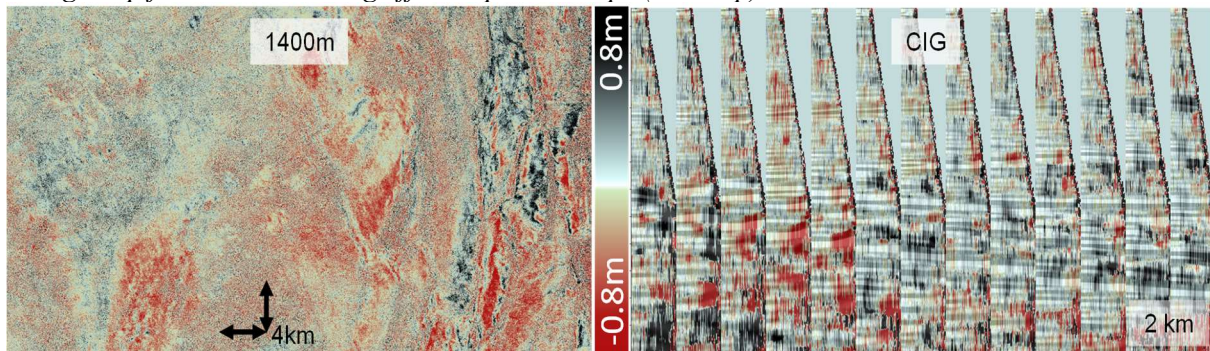


Figure 2: Left: Depth slice of depth shift computed at mid offset. **Right:** Kirchhoff preconditioned Common Imaged Gathers overlaid with depth shifts. Lateral variations are well captured.

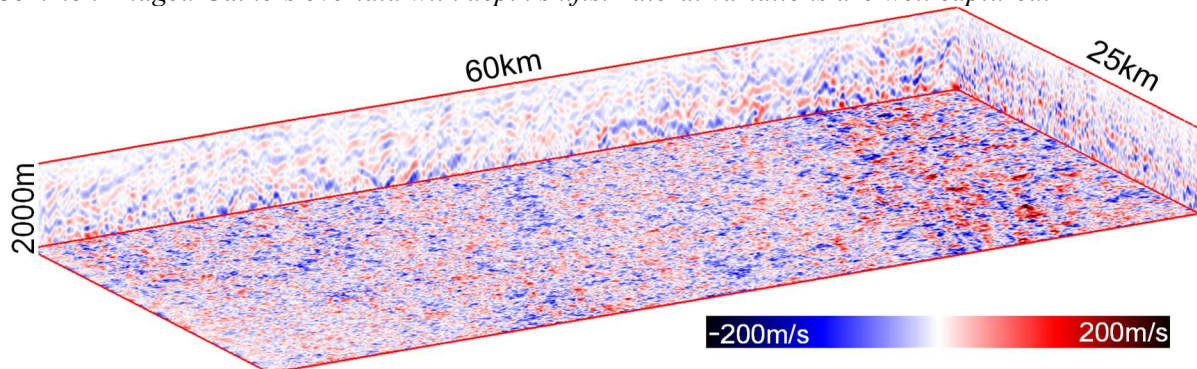


Figure 3: Effect of multi-dip picking on the velocity perturbation. The difference between the velocity models recovered by tomography with and without using multidip picks.

To demonstrate the importance of accounting for dip variation with offset on this dataset, Figure 3 shows one depth slice and two sections from the difference between the output models generated by EHD

tomography (see next section) using a single dip for all the offsets, versus an offset-dependent dip (multi-dip RMO). This difference manifests mainly as noise without structures, contaminating the output velocity model when the same dip is used for all the offsets.

EHD tomography inversion

Our method is based on nonlinear slope tomography (Guillaume et al, 2008). The dip and RMO picks are demigrated to compute kinematic invariants. The model is then updated in a nonlinear loop where each iteration consists of: kinematic migration to relocate the events in the current model, Fréchet derivatives computation, and linear inversion. Nonlinear slope tomography is more flexible than linear tomography since only one step of migration and picking is needed, and the same invariants can be used with different initial models. The model is parameterized by horizons and 3D B-Spline grids between horizons (Guillaume et al, 2013). We use smaller grids than conventional tomography, with the same cell size in all directions. We also use very low levels of damping and regularization in order to avoid artificially imposing a solution on the velocity update. We do not include any a priori information on the position of the heterogeneities; the resulting velocity is purely driven by the data.

Figure 4 shows the classic and EHD tomography results on two depth slices, with better lateral resolution with EHD tomography. The bottom panel of Figure 4 shows the tomography result with mono-dip RMOs. When compared to the EHD results, the noise (seen in Figure 3 above) is evident, demonstrating the importance of considering the dip variation with offset. Figure 5 shows one inline and one crossline of the velocity model overlaid on the migrated seismic image. EHD tomography is able to recover some Gas-Oil and Oil-Water contacts, and better delineates the faults, without any a priori information.

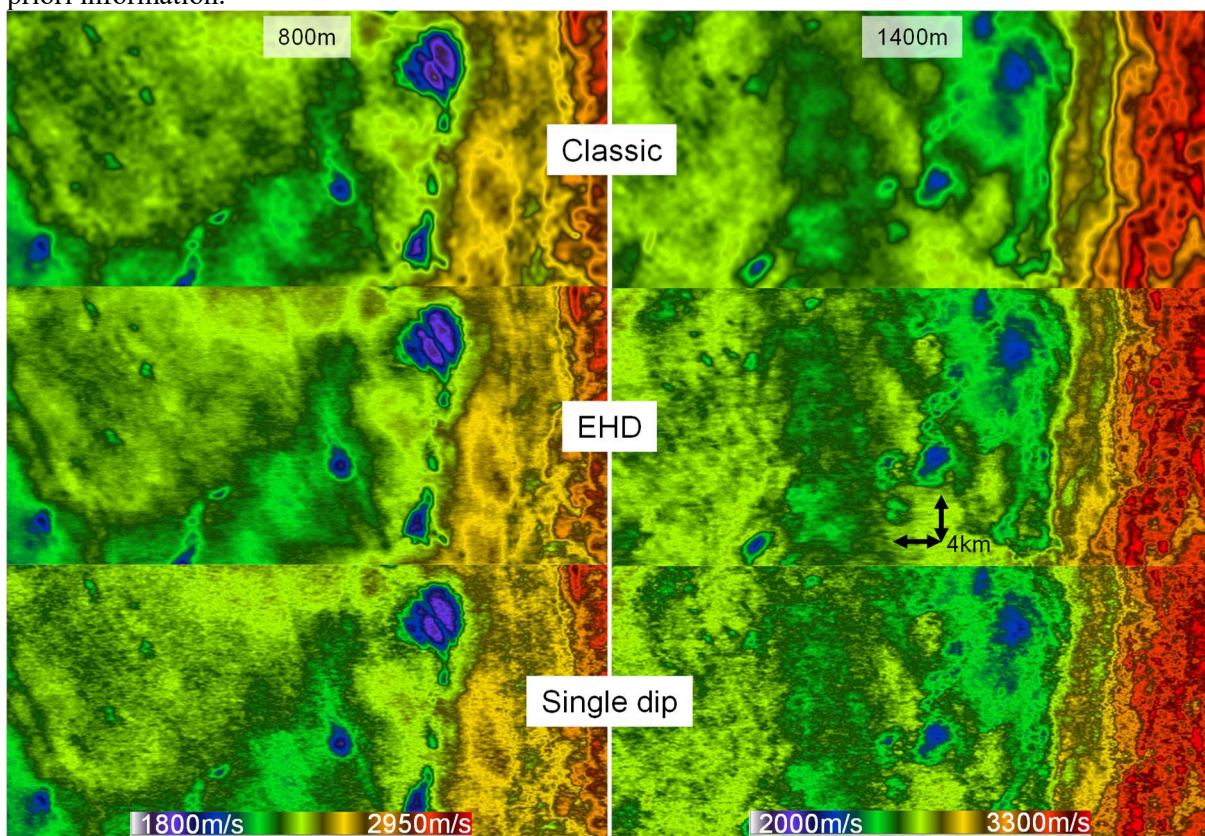


Figure 4: Velocity models obtained by tomography, depth slice at 800m (Left) and 1400m (Right). Top: result of classic tomography, Center: result of EHD tomography (multidip), and Bottom: same “EHD” tomography but with picks using the same dip for all offsets.

Conclusion

Modern complex model building workflows rely both on FWI and ray-based tomography. We propose and illustrate a new Enhanced High Definition Tomography, a fully data-driven process combining

several improvements in picking and inversion. It provides accurate velocity models with high lateral resolution, beyond that previously obtained using tomography. As long as events can be picked on CIGs, it can resolve small-scale lateral velocity anomalies, for a much smaller computational cost than stochastic methods employing hundreds of migrations, and without any a priori on the localisation of the anomalies.

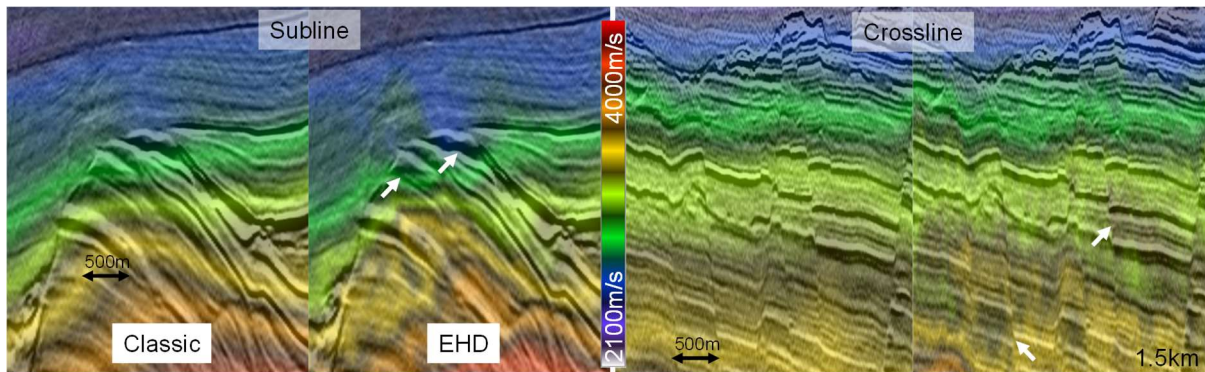


Figure 5: Velocity models overlaid on seismic, one subline and one crossline for classic and EHD tomography. The EHD velocity better defines the velocity variations at both flat spot locations (subline) and catches small-scale lateral velocity variations between the faulted blocks (crossline).

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