High definition tomography brings velocities to light
Saverio Sioni, Patrice Guillaume*, Gilles Lambaré, Anthony Prescott, Xiaoming Zhang, Gregory Culianez, and Jean-Philippe Montel (CGGVeritas)

Summary
Velocity model building remains a crucial step in seismic depth imaging. A general drawback of conventional tomographic approaches is that the estimated velocity models do not conform enough to the structures. We present several applications of an innovative high resolution tomography that inverts densely picked dip and residual move-out data to reveal detailed structurally conformable velocities. The application to the synthetic 2D Marmousi II dataset offers the possibility to carefully assess the method. It demonstrates its ability to produce structurally conformable velocity models with a level of detail that promotes velocity attributes as an aid to geological interpretation. As such it is complementary to full waveform inversion for the interpretation of reflected waves. Finally we show an application to 3D marine dataset where obtained higher resolution velocity model results in improved focusing of migrated images and improved match to well velocities.

Introduction
Successive step changes in tomography-based migration velocity analysis have resulted in much improved seismic imaging. As for any inversion-based method, these step changes fall in two categories: a first one concerns the data to invert and a second family relates to the model-space representation and the inversion algorithms. On the data side, recent high density rich azimuth acquisition geometries have greatly increased the angular redundancy / diversity of wave-paths that constitutes the main velocity discriminator. De-noising and signal enhancement techniques have also significantly contributed to improve reliability of dense automated picking tools (Siliqi et al., 2009).

On the model-space representation and tomographic inversion algorithm side, we have been able to solve bigger and bigger regularized linear systems and we can now QC enormous amount of data. First tomographic approaches involved iterative processes with several iterations of prestack depth migrations (PreSDM), residual move-out (RMO) picking and linear update of velocity (Liu, 1997). Non-linear tomography (Guillaume et al., 2001) and more recently non-linear slope tomography (Billette et al., 2003; Lambaré, 2008; Guillaume et al., 2008) uses a local focusing criterion with no assumptions about the shape of the reflectors or of the RMO curves. Moreover, the physics of wave propagation is more accurately taken into account with tilted transverse isotropy (TTI) velocity models. Despite these advances, velocity models updated with such approaches remain smooth and poorly conform to structures (Figure 1 right); this appears as a serious drawback considering velocity structures revealed by full waveform inversion (Plessix et al., 2010). This statement could be mitigated when looking at the RMO field picked by a dense automated picking (Figure 1 middle), which exhibits nice detailed features corresponding to geological structures. For example the rapid changes in RMO in the gently dipping thin beds and in the structured area do not translate into detailed velocities after conventional tomography. Can we do better?

Guillaume et al. (2011) recently proposed an innovative high definition (HD) tomography that can estimate detailed structurally conformable velocity models. In the present paper we present two applications of the approach. The capability of the method to reveal detailed spatial variations of velocity and to improve seismic imaging is first illustrated using the Marmousi II synthetic example. We then apply the high definition tomography to a marine dataset.

Figure 1: Limits of conventional tomography. Detailed RMO map (middle) picked on PreSDM results (left) do not translate into detailed velocities (right). The RMO map represents the second order polynomial coefficient of the RMO curve.
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High definition tomography

High definition tomography is applied starting from an accurate velocity model obtained by conventional tomography. We can have a multi-layer velocity model representation in which layer boundaries describing strong velocity contrasts can be introduced. Inside the layers the size of the velocity grid mesh is chosen according to the density of data and to the expected spatial wavelengths of velocity variations.

High definition tomography inverts densely picked RMO and dip data. RMO picking is performed in a continuous manner, thus gathering huge amounts of detailed RMO information obtained either tracking local coherency in multi-dimension (Traonmilin et al., 2009) or scanning parametric curves along common image gathers (CIG) (Siliqi et al., 2009). The multi-dimensional tracking approach is more accurate when the signal to noise ratio is sufficiently high, while the curve/surface picking methods can be preferred when signal to noise ratio is low.

Because tomography from surface seismics experiments tries to solve a quite ill-posed inversion problem in some kind of least squares sense, it is important to make it as well-conditioned as possible and to reject outliers in RMO picks as much as possible. The high definition tomography proposed by Guillaume et al. (2011) accurately translates the validated small spatial variations of RMO (as shown in figure 1) into localized perturbations of velocity.

Synthetic Marmousi II dataset

We consider an acoustic version of the well known Marmousi II synthetic model (Martin et al., 2006) with a water column of 460m. This model is interesting because it exhibits velocity discontinuities that we can expect to recover with our high definition tomography. Seismic data are computed by an acoustic wave equation finite differences scheme for a marine type acquisition with a maximum offset of 3 km.

We perform a first iteration of non-linear slope tomography that produces a relatively smooth velocity model (Figure 2 left). In a second iteration, a full data PreSDM is run with this updated velocity model. RMO is picked again on high density CIGs and is inverted using high definition tomography (Figure 2 middle). The obtained high definition model is compared to a slightly smoothed version of the exact model (Figure 2 right). In Figure 3 the high definition velocity model is superimposed with the corresponding depth migrated image and some logs are extracted for a comparison between the conventional tomography, high definition tomography and exact velocity models.

Even if the velocity model obtained by conventional tomography approach provides a good focusing it is quite smooth and poorly conforms to the geological structures. The high definition tomography slightly improves the focusing and the positioning but greatly improves the structural conformity of the velocity model which now nicely fit to the PreSDM image. Both in shallow and deeper parts of the velocity model thin velocity layers now appear and nicely match those of the exact model.

Figure 3 shows several logs allowing to compare the exact vertical velocity profile (in black, smoothed in order to fit with the resolution of the high definition tomographic result) the conventional tomography (red) and high definition tomography (yellow) velocity models. The variations of velocity are nicely detected and quantified, especially in the shallow part.

Figure 2: Synthetic Marmousi II dataset. left) Conventional tomographic velocity model; middle) High definition tomographic velocity model; right) Exact velocity model (slightly smoothed).
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Application to a marine dataset

High definition tomography is applied to a marine dataset. A conventional velocity model building (Guillaume et al., 2008) was first done allowing to image the complex structures and to fit to the wells thanks to the introduction of TTI isotropy. Here again high definition tomography was performed using dense dip and RMO picks. Figure 4 shows a comparison between the conventional approach and the high definition tomography, where both velocity models are superimposed with the corresponding depth migrated images. We can see again that the high definition velocity model nicely conforms to the geological structures but also nicely improves the structures in the PreSDM image (see the bottom flat reflector).

Figure 5 shows several common image gathers (CIGs) on another depth migrated section (see the corresponding high definition velocity model on Figure 6). We see that the flattening of the CIGs has been significantly improved as expected when performing tomography. Figure 6 shows the high definition velocity model superimposed with the final PreSDM stack. This Figure is very representative of what can be expected from a high definition tomography project as an aid to interpretation. It shows a clear and nice delineation of the velocity structures along the layers. The velocity definition appears suitable for pore pressure prediction. Compared to conventional pore pressure prediction done in time domain, our high definition tomography is part of a physically valid pure depth workflow, which improves the accuracy of estimated velocities and the focusing of final PreSDM.

Figure 3: Synthetic Marmousi II dataset. Left) High definition velocity model superimposed with the final PreSDM. Right) comparison at locations A, B, C and D of the velocity profiles for the conventional tomography (red), the high definition tomography (yellow) and the exact velocity model (slightly smoothed to match resolution of high definition tomography).

Figure 4: Marine case study. Left) Conventional tomographic velocity model superimposed with the initial PreSDM; Right) High definition tomographic velocity model superimposed with the final PreSDM.
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Conclusion

We have presented two applications of an innovative high definition tomography that inverts densely picked residual move-out data for revealing detailed structurally conformable velocities. The application to the synthetic 2D Marmousi II dataset demonstrates the ability to produce structurally conformable velocity models with a level of detail that promotes velocity attributes as an aid to geological interpretation. As such it can offer an alternative to full waveform inversion for the interpretation of reflected waves. The application to a 3D marine dataset further demonstrates the capability of the method in presence of noise. The obtained higher definition velocity model results in improved focusing as well as an improved match to the well velocities.

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Figure 5: Marine case study. Improvement of focusing: Top) localization of the CIGs. Bottom left) CIGs before high definition tomography; Bottom right) CIGs after high definition tomography.

Figure 6: Marine case study. Left) High definition velocity model superimposed with the final PreSDM stack. Right) comparison at a well location of the preconditioned well log (blue), conventional velocity model (black) and high definition velocity model (light blue).
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References