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High Resolution Velocity Model for Imaging Complex Structures

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SUMMARY

With the improvement of automatic CIG picking tool, the accuracy of tomography is mainly limited by the model representation (e.g. model grid size) and the regularization of the inversion solver. In practice, a dense model grid with the grid size less than 20 meters and a 100 meters’ smoothing are applied to achieve high resolution velocity updates in some well-conditioned areas (e.g. shallow sediment areas). The small grid size and small model smoothing may cause inversion artefacts in poorly conditioned areas (deep part) and increase the computational cost dramatically. In this abstract, we introduce a non uniform grid, which has a dense sampling in shallow and a sparse sampling in deep to reduce the computing cost. Also we propose a scheme for smoothing along geological structures to stabilize the inversion. We demonstrate with a production example in the Gulf of Mexico that our high resolution tomography is able to improve the subsurface images.
Introduction

In seismic data processing, the accuracy of velocity model is crucial for imaging the geological structures beneath complex overburden. Since the earlier work of detecting velocity anomalies of permafrost (Bishop et al., 1985; Billette et al., 1998), traveltime tomography for velocity model building has been widely used in the industry. In the model building part of seismic prestack depth migration projects, tomography based on the analysis of the curvature of migrated common image gathers (CIG) was proposed by Stork (1992), and this migration-based velocity analysis (MVA) is broadly used. With the increasing challenge of imaging the structures under extremely complex geological bodies (e.g. salt, gas cloud, hydrates, carapace etc), seismic data with more and more folds and wide azimuth (WAZ) are acquired to enhance the quality of images (Etgen, 2006). In order to take advantage of WAZ data for better subsalt imaging, the high resolution velocity model building methods become a key component in seismic processing. In addition to a good tomographic inversion algorithm, the selection of CIGs, the reliable automatic CIG picking tools and the model representation techniques are also critical for a high resolution velocity update.

From Kirchhoff migration to one-way wave equation migration (OWEM) and then reverse time migration (RTM), the improvement of migration algorithms significantly enhances pre-stack imaging quality. However, because prestack Kirchhoff migration is more practical to produce CIGs in offset domain, it has been used for velocity model building during the last two decades. The CIGs in offset domain not only contain the migration artefacts in complex velocity model (Nolan and Symes, 1996), but also are proven more difficult to be used for tomography (Xu and Huang, 2007). The CIGs in angle domain can be produced by Kirchhoff as well (Xu et al., 2001), and they give a better chance for tomography to update the complex velocity model (Chauris, 2000; Lambaré, 2008). To image complex structures, the wave-equation based migration algorithms, especially RTM (Zhang et. al, 2009), provide superior images in the subsalt area than Kirchhoff migration does. The demand to output CIGs in angle domain (ADCIGs), especially for WAZ data, has been intensively increased. The 3D ADCIGs, which are indexed by subsurface azimuth angle and subsurface reflection angle (Xu et al. 2011), are necessary for velocity update, reservoir attribute interpretation and anisotropic parameter inversion. They maintain local azimuth information, and provide more information for high resolution model update. An automatic picking algorithm has been developed for 3D ADCIGs (Liu et al., 2010).

When tomography is applied to the WAZ data, the resolution analysis demonstrates that the lateral resolution of the velocity is comparable to the sampling rate of CDPs as long as the automatic event picking is performed on the same CDP grid. This is due to the fact that there are sufficient vertical wave propagations (vertical ray-path) for tomography inversion algorithm to distinguish laterally travel times. However, the vertical resolution, which mainly depends on horizontal wave propagation, can only achieve high resolution at shallow depth, where the maximum reflection angle is large. As the depth increases, the maximum reflection angle reduces, and hence the vertical resolution of tomography decreases.

Conventional grid based velocity models use uniform grids, which simplify the implementation of the inversion algorithms. These grids need to be dense enough, usually with the grid size less than 20 meters, to achieve high resolution in tomography. Usually the high resolution can be achieved only in the shallow part of the model, characterized by wider reflection angles. At the deep part, the tomographic inversion is more ill-conditioned and requires a stronger regularization (big smoothing) to stabilize the inversion, which reduces the resolution. For a big WAZ project, using such a uniform dense grid for the entire survey significantly increases the computational cost.

In order to achieve a high resolution model from tomography, we propose an adaptive velocity model parameterization, which retains high vertical resolution in the shallow part and lower resolution in the deep part. In additional, we propose a depth dependent regularization scheme which applies different regularizations in the directions parallel and perpendicular to the geological structures with user specified depth dependencies.
Tomography based on residual curvature analysis

The MVA using residual curvature analysis (RCA) of migrated CIGs is based on the principle that all the events from the same reflector focus on the same depth in a pre-stack migration with the correct velocity (Al-Yahya, 1989). The depth difference (moveout) in different offsets (offset domain) or angles (angle domain) provides the information for velocity model updates. This procedure can be formulated as a least-squared inverse problem and a good velocity model is approached by an iterative inversion method. Conventionally, the velocity model is parameterized on a uniform grid. Each value of the velocity on the grid is an unknown of the inverse problem. It is updated per iteration. The grid size determines the number of unknowns in the inversion and a large number of unknowns lead to a high computational cost.

For each point of an event in an offset (offset domain) or angle (angle domain) CIG, we can trace the tomographic rays in the initial migration velocity model. Then following the principle of traveltine invariance (the travel time of the event should be the same in the initial and updated velocity model), we have

\[
\int_{y} (\frac{\partial z}{\partial t} \frac{\partial s}{\partial m}) \Delta m_i dl = z_{updated} - z_i,
\]  

(1)

where \(i\) is the grid index, \(s_i\) is the phase slowness in the corresponding grid, which is a function of TTI model parameters \((v_p, \varepsilon, \delta, \theta, \phi)\) and of the ray direction inside the grid, \(m\) is the velocity parameter to be updated; \(\Delta m_i\) is the model perturbation; \(z_{updated}\) is also an unknown, denoting the focusing depth with the updated velocity model, and \(z\) is the picked event depth. In practice, two adjacent equations of formula 1 from the same event could be used to eliminate \(z_{updated}\), resulting in a tomographic scheme with floating reflectors based on minimizing misfit (Zhou et al., 2003).

\[
\int_{y} (\frac{\partial z}{\partial t} \frac{\partial s}{\partial m}) \Delta m_i dl - \int_{y2} (\frac{\partial z}{\partial t} \frac{\partial s}{\partial m}) \Delta m_j dl = z_2 - z_1,
\]  

(2)

The minimization of the linear system of equations 2 with some regularization constraints can be formulated as a least-squared inversion problem

\[
f(\Delta m) = \|W(A\Delta m - d)\|_p^p + \sigma\|\Delta m\|_p^p,
\]  

(3)

where \(W\) is the data space regularization matrix, \(A\) is the derivative matrix, \(\Delta m\) stands for the model perturbation, \(d\) is the CIG move out, \(\sigma\) is the model space regularization matrix, and \(\|\|_p^p\) denotes \(L^p\) norm. In practice, the perturbation \(\Delta m\) needs strong regularization in the model space to stabilize the inversion and to obtain a geologically reasonable model.

High resolution tomography for WAZ data

To achieve high resolution tomography, a dense velocity grid needs to be used. Unfortunately, such dense uniform grid significantly increases the computing complexity and the memory usage of computers, and makes the inverse problem impossible to be solved for big WAZ surveys. Considering the fact that high vertical resolution for WAZ data only exists in the shallow part, non-uniform grids,
dense shallow and sparse deep, are designed to reduce the computational cost to an affordable level. As shown in Figure 1, a simple depth-varying grid can achieve the purpose. The non-uniform gridding is only introduced in the z direction, where a scaling factor \( a_z \) is introduced to stretch the \( z \) grid. This non-uniform \( z \) grid allows for a dense sampling shallow, typically 10m near the surface; and for a sparse sampling deep, typically 200m at 15km. In between, the grid interval in \( z \) direction increases linearly. Solving the tomographic inverse problem on the non-uniform grid does not require lot of changes in the algorithm, but the model size is significantly reduced.

It is necessary to regularize the model perturbation \( \Delta m \) in equation 3 to stabilize the inverse problem. A dedicated regularization is the key to achieve high resolution velocity update. For sediments, the velocity changes more rapidly in the sediment bedding direction, which requires higher resolution. On the contrary the velocity is much smoother along the perpendicular direction. We propose a regularization scheme, which allows a large regularization radius along the formation direction, and a smaller regularization radius along the bedding direction. The structural consistency in the regularization scheme allows a stabilized numerical inversion. The structural bedding direction comes from the interpretation of the migrated stack images. In the meantime, the regularizations are also adaptable to the depth, i.e. smaller in the shallow part of the model and larger in deep part. Figure 2 gives a simple example of the directions and radii involved in our structural regularization.

**Figure 3:** a: the CIGs from the initial velocity model; b: the CIGs from the velocity model after a high resolution tomography update.

Numerical Examples

We applied our high resolution tomography scheme to a narrow azimuth project in Alaminos Canyon area in the Gulf of Mexico. It is an example of gas hydrate saturated sand in the shallow sedimentary layers. In this area, the water is about 8000 feet deep and the gas hydrates are about 900 feet below the water bottom. Since the gas hydrates are buried under deep water with relatively low temperature and high pressure, a strong reflector in the seismic data is expected in the shallow zone, which indicates the gas hydrate pocket in general with low velocity anomalies. In Figure 3a, the CIGs in offset domain are generated by a Kirchhoff prestack migration using the initial velocity model. The poor flatness of CIGs and the amplitude dimming zone under the gas hydrates structure in the stacked section (Figure 4c) indicate that the initial migration velocity is not accurate and the focusing of the reflectors needs to be improved. Here the initial velocity model was obtained by several conventional migration/tomography iterations. After a high resolution tomography update, the migrated CIGs are flatter (Figure 3b), and the focusing of the stack section is improved (Figure 4d). As shown in Figure

**Figure 4:** a: the initial velocity model. b: the updated velocity model. c: the image from the initial model. d: the image from the updated velocity model.
4a, the velocity trend in the initial model is quite smooth. After a high resolution tomography, it is easy to identify the zone of gas hydrate with low velocity anomalies, and the resolution of velocity model is improved (Figure 4b).

**Conclusion**

A high resolution tomography can be achieved by using a non-uniform inversion grid and a depth dependent and structural conformable regularization in the tomography algorithm. With such a high resolution tomography, shallow velocity anomalies can be identified automatically. The updated velocity model provides better a focusing of the reflectors beneath the velocity anomalies.

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**References**

Xu, S., Y. Zhang and B. Tang, 2011, 3D angle gathers from reverse time migration: Geophysics in press