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High Resolution, Super Efficient Wide Azimuth Beam Tomography for Velocity Model Building

A.M. Popovici* (Z-Terra Inc.), N. Tanushev (Z-Terra Inc.) & S. Hardesty (Z-Terra Inc.)

SUMMARY

We present a novel high resolution, wide azimuth Beam Tomography based on the Fast Beam Migration algorithm. The Beam Tomography uses Fast Beam Migration to directly output a set of image points (x,y, z) with velocity update values, which bypasses the time consuming steps required for traditional tomography, including preparing the gathers for semblance analysis, semblance picking and back-projection picks QC. The method enables a very rapid estimation of the depth or time delays along each ray that can be used to produce a high quality alignment of the common-image angle or offset gathers. In addition, Beam Tomography output contains image point azimuth information and this allows the tomographic update to go beyond the current limitation of limited wide azimuth velocity updates. In summary, Beam Tomography allows for faster turnaround time for large 3-D seismic projects and at the same time increases the accuracy of the velocity model by using wide azimuth information that is typically unavailable in traditional tomography.

Introduction

We present a novel high resolution, wide azimuth **Beam Tomography** (BT) based on the Fast Beam Migration (FBM) algorithm. The Beam Tomography uses Fast Beam Migration to directly output a set of image points (x,y,z) with velocity update values, which bypasses the time consuming steps required for traditional tomography, including preparing the gathers for semblance analysis, semblance picking and back-projection picks QC. The method enables a very rapid estimation of the depth or time delays along each ray that can be used to produce a high quality alignment of the common-image angle or offset gathers. A 2000 sq km velocity model can be updated using 400 CPUs in less than 5 minutes. In addition, Beam Tomography output contains image point azimuth information and this allows the tomographic update to go beyond the current limitation of limited wide azimuth velocity updates. In summary, Beam Tomography allows for faster turnaround time for large 3-D seismic projects and at the same time increases the accuracy of the velocity model by using wide azimuth information that is typically unavailable in traditional tomography. In addition to single parameter update (one time delay or residual velocity value for each image point), multiple parameter update (time delays for each offset value), we now have a wide azimuth and offset update (time delays for each incidence-reflection angle pair, for each azimuth and offset).

Short Review of Tomography Theory

Reflection Tomography is an iterative inversion method that updates the velocity model and minimizes the deviation in the Common Image Gathers (CIG) from a flat event. In Z-Terra's implementation, we select special image points based on dip and event coherency called back-projection points, from which the tomography traces rays back to the surface in order to distribute the velocity residual values throughout the velocity model. Rays from different back-projection points illuminate parts of the overburden (see Figure 1), and an appropriate compromise between velocity residuals coming from different rays is made by solving a least-squares problem.

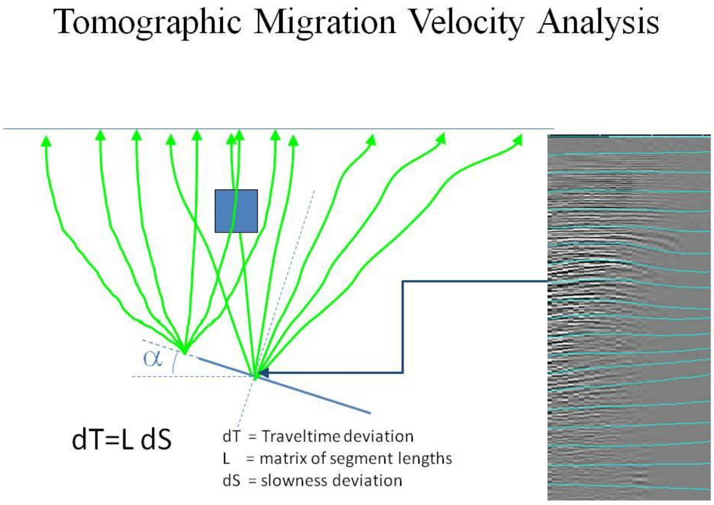

Figure 1 *Traditional tomography velocity update. Each MVA image point is used to trace a fan of rays to the surface. Information from the image gathers is then combined with the ray paths to update the velocity*

After the seismic data has been migrated using the current interval velocity model, consistency of the model with the data is assessed by examination of the move-out in the Common Image Gathers, representing variation over different wave paths in the predicted depth of subsurface reflection events. In the single-parameter update, the move-out is quantified through Semblance Analysis, which associates with each image point one or more velocity residual values, indicating whether the velocity in parts of the overburden visible to that image point is too high or too low. In the multiple-parameter update, the move-out or time-delays for a given event and all the offsets associated with that event in a CIG, is quantified through curve-fitting, using Plane Wave Destructor (PWD) filters to evaluate the dip and move-out of specific back-projection points from the stack.

The travel-time along a ray path γ is

$$\tau(\gamma) = \int_{\gamma} s(x)dx \,, \tag{1}$$

where s(x) is the slowness (the reciprocal of velocity). Once the slowness is discretized, the travel time can be expressed via the matrix equation

$$\tau = \gamma(s)s \,, \tag{2}$$

where $\tau \in R^m$ is a vector of travel-times over *m* ray paths, $s \in R^m$ is a vector of discrete slowness values, and $\tau[.] : R^m \to R^{m\times n}$ maps the slowness vector *s* to a matrix of arc lengths along the *m* ray paths. The dependence of γ on *s* is introduced because the ray paths themselves depend on the slowness field, and hence, (2) is non-linear. It can be linearized by considering deviations $\Delta\tau \in R^m$ and $\Delta s \in R^m$ with respect to a reference model s_0:

$$\Delta\tau = L\Delta s \,, \tag{3}$$

where $L \in R^{m\times n}$ is a matrix of arc lengths along the *m* ray paths as traced through s_0. The equation (3) is now linear. Given a travel-time deviation vector $\Delta\tau$, tomographic updating of the slowness model involves two steps:

1. The Forward Problem: Construct the matrix *L* by tracing rays from back-projection points through the current slowness model.
2. The Inverse Problem: Find an approximate solution Δs to the least-squares problem

$$\min_{\Delta s \in R^m} \left\| \Delta\tau - L\Delta s \right\| \tag{4}$$

The resulting slowness model is $s_{new} = s_0 + \Delta s$. An approximate solution to (3) is obtained by repeating this process until the updates become small.

There are several ways to estimate $\Delta\tau$ from seismic image gathers, including multi-parameter tomography based on differences in the move-out between normal and oblique incidence rays and single parameter tomography which fits a hyperbolic curve to the residual move-out.

The reflection tomography performed in the post-migrated domain has many advantages over standard tomography performed on prestack data (Stork, 1992). In general, post-migrated events are much easier to pick, the data volume is more manageable, and the whole process is more robust. The procedure converts common image gather residual picks to velocity changes using 3D tomographic back-projection. In tomographic MVA, fans of rays with the correct wave propagation geometry are used to back-project residual velocities to the places where the velocities errors originated. The extent of deviation at every offset corresponds to a residual traveltime associated with a ray pair from a source point to an image point and back to a receiver point. Tubes of ray pairs from an analysis image point illuminate part of the overburden velocity, and several overlapping ray tubes can be used to reconstruct the overburden velocity properties in a tomographic way. The resolving power of the tomographic method derives from illumination of velocity model cells under different angles with rays from different image points. In the tomographic reconstruction part, ray paths, computed residual traveltimes, and the unknown residual slowness field comprise a linear optimization system, which is solved by the method of conjugate gradients.

Fast Velocity Iterations

One key component of the fast velocity iteration workflow is the fact that the Fast Beam Migration allows the output of auxiliary velocity update information. We note that in traditional tomography, the gathers are scanned for an appropriate velocity perturbation at each analysis point and ray tracing is used to correctly spread this velocity perturbation into the velocity model. Since FBM is a ray based method, the information need by tomography to spread the velocity perturbation is readily available. Furthermore, since beams represent coherent events, the necessary velocity perturbation can be computed by comparing individual beams to the stacked beam image. Combining these two pieces allows us to replace the time consuming sequence of generating image gathers, post-processing and conditioning them, scanning them for single parameter (hyperbolic moveout) or multi-parameter residual curvature (non-hyperbolic moveout), picking residual semblance and QC-ing, and ray-tracing. Thus, the auxiliary veloicty update information from FBM can be immediately used as input for the velocity update stage of tomography, greatly reducing the velocity update iteration time.

Short Review of Gaussian Beam Raytracing and Tomography

We define a Gaussian beam (Fomel and Tanushev, 2009) as a seismic event characterized by a particular arrival time, location, amplitude, orientation, curvature, and extent. The extent of a beam is controlled by an amplitude taper, which can be understood as the imaginary part of a complex-valued event curvature. In the process of seismic imaging, the beam changes its position in time and space, as well as its amplitude, orientation, and complex curvature. Neglecting higher-order effects, a Gaussian beam representation is a powerful asymptotic approximation for describing different wave propagation phenomena (Popov, 1982; Babich and Popov, 1990; Bleistein and Gray, 2007; Kravtsov and Berczynski, 2007).

Fast Beam Migration (FBM) is a fast method for producing seismic images. It takes the recorded seismic data and a velocity model and produces an image of the subsurface. A typical beam migration workflow contains the following steps:

1. *Beam Forming* – The seismic input data is analyzed for locally coherent events. The slope of these events is identified and the associated wavelet is recorded as a beam. Beams are multidimensional objects that contain the recording time, the position of the source and receiver, the incident wave angles at the source and the receiver, and the associated seismic wavelet. This step needs to be done only once since it is independent of velocity.
2. *Beam Propagation* – This stage finds the migration time for each beam using ray tracing. For each beam, two rays are traced – one from the source and one from the receiver using the slopes identified in the beam forming stage. The time at which the rays meet in the subsurface is the migration time. All of the beam parameters are propagated to this time. These parameters provide information on how to reconstruct the wave field in the subsurface to form the image.
3. *Image Forming* – The final stage is to form the seismic image using the propagated parameters from beam propagation. At this stage, we can output an offset gather seismic volume that can be used as the input for traditional tomography or a stacked image. We note that due to the parsimonious nature of fast beam, the raw stack is computed quickly and does not usually require any post-processing in order to be used for the analysis outlined below.

Migration Velocity Analysis (MVA) improves the velocity model associated with a survey in order to create an accurate image of subsurface structures. This is done by carefully analyzing the data and exploiting the fact that subsurface reflectors are evident in the data at different source and receiver configurations. Typically, traditional tomography takes as input a seismic image volume comprised of image gathers. This volume contains many images of the subsurface, each resulting from different pairs of sources and receivers (offset); however, tomography can use images separated by an attribute other than offset as well, such as angle or p value. A typical workflow for tomography includes the following steps:

1. *Data Preparation* – The gathers generated from migration are cleaned and preprocessed to facilitate better semblance analysis.
2. *Generating Picks* – points are picked manually or automatically in the subsurface of the earth that will be used for velocity analysis.
3. *Semblance Analysis* – the seismic gathers are analyzed at the generated picks to quantify the mismatch between subsurface images, and measure time delays along rays due to velocity errors in the model.
4. *Ray Tracing* – fans of rays are traced back to the surface from each of the subsurface picks.
5. *Velocity Update* – the velocity is updated along each of the rays with certain constrains (since many rays can pass through the same velocity sample) so that the subsurface images are better focused when imaged with the new velocity.

3D Residual Beam Traveltime

Examining the algorithm used in the Beam Propagation stage of FBM, we note that a small increase or decrease in the traveltime along the source and receiver rays will shift the beam imaging location in the direction normal to the reflector that the beam is imaging. Thinking of this procedure in reverse, we can determine a residual traveltime shift along the rays that will align the beam with the reflector that it is imaging. This, of course, is well known and used in traditional tomography during the semblance scanning of the gathers. However, in beam migration, this analysis can be carried out in a much more efficient manner: Each migrated beam represents a localized portion of the seismic image with limited extent and can be easily compared and synchronized to the stacked image, which is produced by all beams. This is simply done by cross-correlating the beam with the stack. We emphasize that the alignment procedure is done with a stack and image gathers (common image, angle, etc) are not required. Furthermore, we note that since the beam can arrive at the reflector at any azimuth and reflection angle, the information obtained with this method is truly 3D and along with the beam source and receiver rays is all of the information required to update the velocity in the last step of traditional tomography. The procedure for determining the traveltime residual shift in the context of beams was first introduced by Sherwood, et al (2014), where the authors refer to it as "3DRMO".

Beam Tomography

By combining Fast Beam Migration and reflection tomography, we can eliminate the first four steps of reflection tomography and replace them with an automated 3D residual beam traveltime shift calculation. Since the beam forming step of beam migration needs to be done only once for a given seismic data set, the entire iterative procedure of velocity building using beam tomography is reduced to: beam propagation, residual calculation and velocity update. These steps require no input from the user and can be iterated several times before the user QCs the results. This significantly shortens the computation time between successive velocity updates. In addition, there are other significant time savings as the traditional imaging workflow needs to preprocess the image gathers before tomography. One of the features of FBM that sets it apart from other types of migration such as reverse time migration or wave equation migration is that beam migration contains direct information about the connection between events in the seismic image and events in the seismic data.

Conclusions

We present a high resolution, wide azimuth velocity model building algorithm based on the Fast Beam Migration algorithm. Beam Tomography allows for faster turnaround time for large 3-D seismic projects and at the same time increases the accuracy of the velocity model by using wide azimuth information for tomographic updates.

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