Application of turning-ray tomography to Hussar 2D seismic line from central Alberta
Babatunde Arenrin *, Gary Margrave and John Bancroft, CREWES, Dept. of Geoscience, University of Calgary

SUMMARY

Turning-ray tomography is a good tool for estimating near surface velocity structure, especially in areas where conventional refraction statics fail such as the case of a hidden layer. The velocity model from turning-ray tomography can be used for static correction, as a starting model for Full Waveform Inversion (FWI), and for wave equation datuming or prestack depth migration. In the work presented here, we apply turning-ray tomography to the statics problem of the Hussar 2D seismic line from central Alberta. In literature, the application of turning-ray tomography to the statics problem is commonly referred to as tomostatics. The traveltimes tomography approach used in this study is similar to the constrained, damped, simultaneous, iterative reconstruction technique (CDSIRT) of Zhu et al, (1992). To verify results from tomostatics, we compare datasets after tomostatics with datasets using the delay-time method of conventional refraction statics. Our result shows that the velocity model from turning-ray tomography reveals a hidden, low-velocity layer (LVL) between two fast-velocity layers that conventional refraction statics would not detect. The hidden layer is in agreement with the interval velocities from well logs. The stacked section, after applying tomostatics, shows better continuity of events compared to the stacked section from conventional refraction statics.

INTRODUCTION

Seismic tomography exists in two forms: traveltime tomography and diffraction tomography. Traveltime tomography is applicable when the target’s size is much larger than the seismic wavelength. This approach is based on the high frequency assumption of ray theory (Woodward, 1989) and can be implemented using reflection traveltimes or first arrivals (refraction) traveltimes. Diffraction tomography on the other hand should be chosen if the size of target is comparable to the seismic wavelength because the propagation of seismic waves is modelled as scattered energy using diffraction theory (Lo and Inderwiesen, 1994). In diffraction tomography, the wavefields are back propagated through the medium similar by reverse time migration.

Turning-ray tomography can be applied to seismic data in order to estimate near-surface velocity structure in areas where refraction statics techniques fail due to poor data or the absence of a smooth refractor structure. Stefani (1995) applied the concept of turning-ray tomography to seismic data from the Timbalier Trench in the Gulf of Mexico which is filled with low velocity sediments. Epili et al (2001) applied turning-ray tomography and delay time methods for constructing near surface velocity structure for a 2D dataset from Eastern Colorado. Bell et al (1994) applied turning-ray tomography to offshore Mississippi delta. In the cases mentioned above, turning-ray tomography proved to be successful and the cases above have similar stratigraphic features; the presence of a LVL (low-velocity layer).

In this report we apply the concept turning-ray tomography to real data. The first step in turning-ray tomography is to provide a good starting model for the inversion. Our starting model was derived from the analysis of the firstbreaks observed on the shot records. The final tomographic velocity model is used for statics correction.

METHODS IN TRAVELTIME TOMOGRAPHY

Traveltime tomography involves the integrals of reflection or first arrival traveltimes over their raypaths. Approximating the continuous earth by a system of discrete cells, the traveltimes can be written as:

\[ t_i = \sum_j d_{ij} / v_j = \sum_j d_{ij} s_j, \] (1)

where \( t_i \) is the total traveltime along the ith ray-path, \( d_{ij} \) is the path length in the jth cell of the velocity model for the ith ray, \( v_j \) is the velocity in the jth cell and \( s_j = v_j^{-1} \) is the slowness in the jth cell.

Generally there are two types of image reconstruction techniques in traveltime tomography. These are the series expansion methods and the transform methods (Lo and Inderwiesen, 1994). The series expansion methods allow for curved raypath trajectories through the target area and are well suited for traveltime tomography. The transform methods on the other hand allow only straight raypath trajectories through the target medium and are used in the field of medical sciences. In this paper we will limit our discussions to the series expansion methods of traveltime tomography.

Similar to inversion procedures, the series expansion method begins with an initial or starting model. The starting model is updated at each iteration step until it converges to the best solution. The forward modelling engine can be a finite difference algorithm or a ray tracing algorithm for predicting traveltimes. A ray tracing
algorithm traces rays through a starting model and computes predicted traveltimes using (1). The tomography must then iterate to converge to the best estimate of the true model by minimizing the differences between the observed and predicted traveltimes.

Kaczmarz’ approach to traveltime tomography

The Kaczmarz’ approach is a series expansion method that can be implemented in two ways: the algebraic reconstruction technique (ART) and the simultaneous iterative reconstruction technique (SIRT) (Lo and Inderwiesen, 1994).

The two ways are quite similar; however one major difference between ART and SIRT technique is that in ART the ray-tracer shoots one ray at a time out of the total number of rays through an initial or starting model. In SIRT the ray-tracer shoots all rays through the starting model. The SIRT process is equivalent to tracing all rays through the initial model so that all model updates for all the rays are known.

The jth model update for the ith ray in the ART technique can be expressed as:

$$
\Delta s_j = d_0 \frac{t_{\text{observed}} - t_{\text{predicted}}}{\sum_j (d_{ij})^2},
$$

and the jth model update for the SIRT technique can be expressed as:

$$
\Delta s_j = \frac{1}{W_j} \sum_i d_{ij} \frac{t_{\text{observed}} - t_{\text{predicted}}}{\sum_j (d_{ij})^2},
$$

where $t_{\text{observed}}$ is the observed traveltimes, $t_{\text{predicted}}$ is the predicted traveltimes, $i$ is the total number of rays, $W_j$ is the number of rays intersecting the jth cell and $\Delta s_j$ is the model update in the jth cell.

The algorithm for the turning-ray tomography used in this work is a variant of the SIRT similar to the constrained, damped, simultaneous, iterative reconstruction technique (CDSIRT). We used ProMAX software for this purpose.

**TURNING-RAY TOMOGRAPHY**

Turning-ray tomography falls under the category of series expansion methods. It is an inversion technique that employs turning rays from conventional surface acquisition geometry to iteratively solve for velocity in the near surface

between sources and receivers (Stefani, 1995). The maximum depth of penetration of turning rays is on the order of one-fifth the source-receiver offset provided the overall velocity field allows sufficient ray bending to return to the surface (Zhu et al, 1992). Applications of turning-ray tomography and tomostatics range from statics correction to wave-equation datuming or prestack depth migration (Zhu, 2002). Tomostatics have advantages when compared to refraction statics especially in regions where no refractors can be easily identified, in regions where high velocity materials overlay low velocity sediments, or the lack of smooth velocity structure such that conventional refraction statics usually fail due to continuously refracted rays (Stefani, 1993).

It is worth mentioning that one of the advantages of turning-ray tomography over reflection traveltime tomography is that the ambiguities between reflection depth and velocity in reflection traveltime tomography are absent in turning-ray tomography.

**Forward modelling/ray tracing and inversion**

The initial model for turning-ray tomography is a smooth version of the velocities derived from the slopes of the observed first arrivals as shown in Figure 1. The initial model is 4480 meters wide and 750 meters deep and is digitized into rectangular cells of 10m by 10m. Rays are traced through the model to obtain predicted traveltimes. The traveltimes residuals were used to derive velocity updates till the stopping criterion was reached. Stopping criteria are defined by Dennis and Schnabel (1983). Our stopping criterion was the point at which the change in the traveltimes residual was negligible. This occurred at the 50th iteration.

![Figure 1: Initial velocity model.](image-url)
Application of turning-ray tomography to Hussar 2D seismic line from central Alberta

The inverse problem solves Equation (3) directly. The model update in Equation (3) is an average correction applied to the cell being updated. In an approach similar to the constrained damped SIRT (CDSIRT) described by Zhu et al., (1992), the inversion scheme is constrained by choosing the minimum eigenvalue to invert and by choosing the maximum residual traveltime to include in the inversion. These constrains help the inversion to converge more quickly.

FIELD DATA EXAMPLES

The data for this work is a 2D seismic line from Hussar, central Alberta and it is about 4.5km long running from Southwest to Northeast (Margrave et al, 2012). The seismic source is dynamite with shot spacing of 20m and a total of 269 shot points. The number of receivers is 448 with receiver spacing of 10m. Three wells intersect the area of study, one of the wells is close to the beginning of the 2D line and another well is close to the end of the line.

Some key steps and quality control methods to run tomostatics in order to ensure the stability of the solution have been described by Zhu (2002). We applied some of these quality control methods such as picking the first arrivals consistently for turning-ray tomography, removing any previously applied elevation and velocity statics before tomostatics. One significant quality control used is observing the continuity of reflectors on cmp stacked sections. Well logs studies in the area reveal that the area of study is made up of horizontal reflectors within the logged intervals.

Firstbreak traveltimes were picked on the 269 shot gathers, with the assumption that the firstbreaks observed on the seismic data are as a result of turning or continuously refracted arrivals.

Figure 2 shows a raw shot record showing the firstbreaks picks in red.

Figure 3 shows the final velocity model after 50 iterations. This velocity model was used as static correction for the shot record. Figure 4 is a smoothed well log velocities, with the length of smoother set to be equal to the mean velocity divided by the dominant frequency in the seismic record which was about 25 hertz.

The velocity model in Figure 3 can be used as a starting model for full waveform inversion (FWI). The success of full waveform inversion is dependent on how close the starting model is to the global solution. A way of obtaining such starting model is by traveltime tomography (Pratt and Shipp, 1999).
Application of turning-ray tomography to Hussar 2D seismic line from central Alberta

Figure 4: Smoothed well velocities. Smoother Length is 200 meters.

The final velocity model from turning-ray tomography and the smoothed well velocities reveal a hidden layer. The hidden layer from the tomogram is between 350 and 450 meters, and between 350 and 400 meters from the smoothed well velocities. As observed from the logs, the hidden layer could explain why conventional refraction statics fail to produce a good stack response.

Figure 5 shows the stacked section after statics correction using conventional refraction statics. Figure 6 shows the stacked section after tomostatics. From Figure 5, it is evident that conventional refraction statics solution does not produce a good stacked response because the reflection events are not flat as observed from well logs. The reflection event at about 1200 milliseconds (red box) on the stacked section after tomostatics has been improved in terms of continuity and the structure of the event. The improvement is of great value to seismic interpreters.

CONCLUSIONS

The velocity model from turning-ray tomography can be used in depth conversion, wave equation datuming, prestack depth migration and as a starting model for Full Waveform Inversion (FWI). Turning-ray tomography is a viable technique for statics correction as observed on Hussar 2D seismic line from central Alberta. Our results show that the application of tomostatics has improved reflector continuity and corrected the structure of events. The final velocity model from tomography is also comparable to well logs velocities in the area although it has lower resolution, however the quality of the stack response suggests that it is a good candidate for use as a starting model for FWI.

ACKNOWLEDGMENTS

The authors would like to thank CREWES sponsors for the financial support. We thank Helen Isaac for her contribution. We also acknowledge the use of ProMAX and thank Landmark (a division of Halliburton) for making it available to us.

Figure 5: Stacked section after conventional refraction statics. The structure at 1200ms (red box) is not real and it is due to unresolved statics.

Figure 6: Stacked section after tomostatics. The structure at 1200ms (red box) has been resolved and the continuity of the event has improved.