Fast, High Resolution Beam Tomography and Velocity Model Building

N.M. Tanushev, A.M. Popovici, S.S. Hardesty

October 2016

Abstract

We present a wide azimuth beam tomography based on Fast Beam Migration and a method for automatically estimating the RMS velocity. This combination allows us to have a direct input data to velocity model work-flow that does not involve laborious manual user interaction other than QC. The estimated RMS velocity model serves as an inital model for tomography. A 3D RMO estimation enables a very rapid estimation of the depth or time delays along each ray, which represent the direct input to a tomographic update, without the time-consuming steps required for traditional tomography, including preparing the gathers for semblance analysis, semblance picking and back-projection picks QC. A 2,000 sq km velocity model can be updated using 400 CPUs in less than 5 minutes on a 20 by 20 by 20 m velocity model grid. In addition, Beam Tomography retains the true azimuthal information. This allows the tomographic update to go beyond the current limitation of limited wide azimuth velocity updates. 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 a single-parameter update (one time delay or residual velocity value for each image point), and multiple-parameter update (time delay depends on offset), we now have a wide azimuth and offset update (time delay depends on offset and azimuth).

1 Introduction

Fast Beam Migration (FBM) is a super-efficient algorithm that is two orders of magnitude faster than the standard Kirchhoff depth migration, and at the same time images multi-pathing energy and handles abrupt lateral amplitude changes, properties that are typically associated with wave-equation migration algorithms. The faster imaging software allows for more iterations of velocity model building, which enable the processing team to enhance the seismic resolution and imaging of complex geologic structures, and allows for deeper data penetration, steeper dip and sub-salt structure imaging. Improved velocity models in combination with wave-equation imaging provide much greater resolution and accuracy than what can be accomplished today with standard imaging technology.

Fast Beam Migration and all beam methods pivot on a preliminary step in which the seismic input data has to be decomposed into beams. A beam (Fomel and Tanushev, 2009) is a seismic event characterized by an arrival time, source and receiver location, amplitude, source and receiver dip orientation, curvature, and extent. The extent of a beam is controlled by an amplitude taper. This is done by analyzing the data for locally coherent events. The slope of these events is identified and the associated wavelet is recorded as a beam. This a preparation step that needs to be done only once since it is independent of velocity.

The beam forming stage is computationally expensive, however, each beam lets us make following strong statement about the subsurface of the earth: If we inject a packet of coherent waves at the source location with orientation given by the source dip and we wait a precise amount of time, we will record a packet of coherent waves at the receiver location with orientation given by the receiver dip. This provides us with a trove of information about the subsurface, including a way of estimating the RMS velocity. A natural next step is to convert this velocity to an interval velocity in depth using Dix formula and use it as the starting model for beam tomography.

We will begin with a short review of traditional tomography and Fast Beam Migration, since they are at the core of the velocity-building method that we propose. Next, we explain how components of traditional tomography and Fast Beam Migration can be put together for make a fast velocity building tool. Additionally, we describe how to automatically extract an RMS velocity model from beams. Finally, we show an example of the velocity-building method in practice and RMS velocity extraction.

2 Traditional Tomography

Migration velocity analysis 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.

Ray-based reflection tomography is an iterative inversion method that updates the velocity model and minimizes the deviation in the common image gathers from a flat event. Through semblance analysis, these gathers are analyzed to produce velocity residual values that would flatten the gathers. Additionally, special image points are selected based on dip and event coherency called back-projection points, from which rays are traced back to the surface in order to distribute the velocity residual values throughout the velocity model. Mathematically, the problem can be formulated as

$$L\Delta s \quad = \quad \Delta\tau \ , \tag{1}$$

where L is the tomography matrix assembled from the rays, $\Delta\tau$ is a vector containing the residual time delays computed from the velocity residual values associated with each rays, and Δs is the desired update to the slowness (reciprocal of the velocity).

Intuitively speaking, rays from different back-projection points illuminate parts of the same areas of the velocity model, and an appropriate compromise between velocity residuals coming from different rays is made by solving equation (1) in a least-squares sense.

A typical work-flow for tomography includes the following steps:

- **Migration:** A migration method is used to migrate the input seismic data and produce common image gathers.
- **Data Preparation:** The gathers are cleaned and pre-processed to facilitate better semblance analysis.
- **Pick Generation:** Points are picked manually or automatically in the subsurface of the earth that will be used for velocity analysis.
- **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.
- **Ray Tracing:** Fans of rays are traced back to the surface from each of the subsurface picks.
- **Velocity Update:** The velocity is updated along each of the rays with certain constraints (since many rays can pass through the same velocity sample) so that the subsurface images are better focused when imaged with the new velocity.

We point out that this procedure is based on the assumption that the update to the velocity is small and that if we were to re-trace the rays in the updated velocity model, their paths would not move by an appreciable amount, which can be ensured by constraining the update to be small and smooth. However, this presents us with a dichotomy, since we would like the image to change and be improved significantly, but at the same time this method relies on changing the velocity only slightly. The correct approach would be to iterate this method many times so that the individual updates can be small, but the final velocity can differ significantly form the starting velocity. Unfortunately, due to the time demands from the migration and the need for user input and QC in the data preparation, pick generation and semblance analysis, it is often difficult to afford more than a handful of iterations. Thus, we are forced to violate this assumption and rely on the intuition and ability of the user to manipulate the resulting velocity update to produce a physically plausible velocity model through smoothing, clipping, and manual editing.

3 Fast Beam Migration

As previously described, a Gaussian beam as a seismic event characterized by an arrival time, source and receiver location, amplitude, source and receiver dip orientation, curvature, and extent. The extent of a beam is controlled by an amplitude taper. In the process of seismic imaging, the beam changes its position in time and space, as well as its amplitude, orientation, curvature and extent. For all intents and purposes, we can think of a Gaussian beam as a packet of coherent waves. Neglecting higher-order effects, a Gaussian beam representation is a powerful asymptotic approximation for describing different wave propagation phenomena ([5, 1, 2, 4]). Since at the core of all seismic migrations sits a method for propagating waves, we can design migration methods based on Gaussian beams. One such method is Fast Beam Migration. The algorithm's speed relies on two observations:

1. A factor of 10-100 in speedup is achieved via beam forming, or beam decomposition of the input data, where the input data traces are converted to a relatively small number of beams.

2. Since beams have a localized extent, the beam wavelet is spread over a small patch.

A typical Fast Beam Migration work-flow contains the following steps:

- **Beam Forming:** The seismic input data is analyzed for locally coherent events. The slope of these events is identified and the associated event wavelet is stored. Beams are multidimensional objects associated with each seismic event 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 and it is independent of velocity.

- **Beam Propagation:** This stage determines the migration point 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 extracted in the beam forming stage. Next a beam correlation (imaging) point is determined as the closest point to the source and receiver rays satisfying the condition that the time from the source to beam correlation point plus the time from it to the receiver equals the recording time of the event. Barring pathological examples, the imaging point for each beam is unique. All of the beam parameters are propagated to this point. We note that these parameters provide information on how to locally reconstruct the source and receiver wave fields.

- **Image Forming:** The final stage is to form the seismic image using the propagated parameters from beam propagation. This involves spreading the seismic wavelet locally near the beam correlation point. We note that at this stage, we can produce a stacked image or several types of image gathers, including binning by surface offset, surface offset and azimuth, reflection angle, reflection angle and subsurface azimuth, and many others.

At this point, we can produce image gathers with FBM and carry out the traditional tomography work-flow. However, doing so discards the vast amounts of information that is associated with each beam. The two most important pieces of information that are available for each beam are, first, that we know what path the seismic waves took to image the reflector since we have the source and receiver rays, and, second, that for each beam we have the associated seismic event wavelet.

As the reader has naturally concluded, the source and receiver rays are none other than precisely what is needed to form the tomography ray matrix, which is what we intend to do. It is less immediately obvious how the seismic wavelet is useful for tomography, but this will become evident in the following section. We only mention that the missing pieces of information necessary to update the velocity are the time residuals associated with each ray.

4 3D Residual Move-Out

In the imaging stage of fast beam migration, the beam wavelet is spread locally near the beam imaging point in the image space. Since this procedure involves the ray-traced beam parameters, we can consider how the beam wavelet would have been spread in the image if the travel time along the source and receiver rays were longer or shorter. This essentially amounts to shifting the beam image in the direction perpendicular to the reflector that the beam is imaging; see figure 1. By correlating the shifted beam image and the image stack, we can find the perturbation at which the beam image best matches the stack. Additionally, we can convert this spatial shift into a time shift using the local velocity. Shifting the beam image and correlating it with the image stack is prone to the infamous "cycle-skipping" problem. It is evident in the correlation curve in figure 1. However, the global maximum of the correlation curve is often unique, in part because the beam wavelet contains the signature of the reflector and the wavelet. Furthermore, for each beam, the problem of identifying the maximum is small and we can afford to solve it without using an iterative method that can get trapped by the local maximums. Thus, in most cases, we estimate the correct shift, and "cycle-skipping" does not pollute the measured residuals.

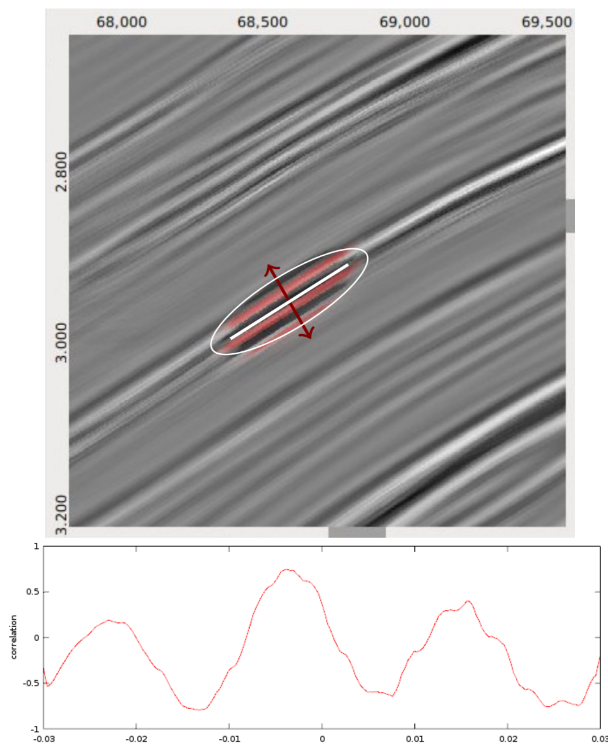

Figure 1: 3D RMO. Above: Each beam image is shifted perpendicular to the reflector it is imaging to find the best correlation with the image stack. Below: The correlation as a function of time shift. As can be seen from the graph, the best correlation when the beam is shifted by -0.003 seconds.

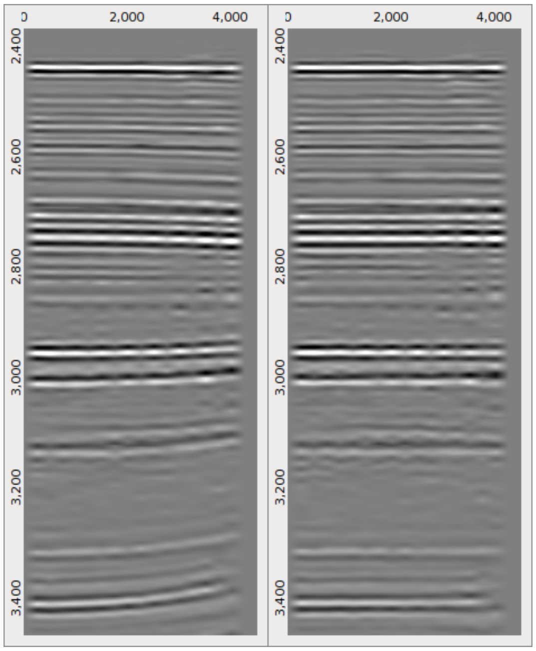

Figure 2: Common image gathers without (left) and with (right) RMO correction.

As a point of QC, we apply the time shift computed for each beam and re-form the seismic image. Figure 2 shows the common image gather binned by offset with and without the 3D RMO correction.

The 3D RMO time shift computed by this method becomes a component of the $\Delta\tau$ vector in the tomography equation (1). This shift contains truly three dimensional information, since it is associated with the unique source and receiver rays for the beam (see figure 3). There is also no assumption about the shape of the move-out curve.

5 Fast Beam Tomography

As alluded to in previous sections, during the beam propagation stage of FBM, for each beam we trace a source and receiver ray that meet at the reflector that the beam is imaging. If the image produced by a particular beam is not in agreement with the images produced by other beams of this reflector, we need to update the velocity. Now, the only part of the velocity that will affect the beam is concentrated near the beam rays. Thus, for each beam, we form a row of the tomography matrix L that contains the paths of the source and receiver rays. We use the 3D RMO time shift for each beam to form the right-hand side $\Delta\tau$ of the tomography equation (1).

A critical point to note is that the time shift for each beam is not an absolute residual. It is a relative residual computed in relation to the stacked image. The 3D RMO time shift answers the question of how much should this beam shift in order to match the reflector, while the tomography equation (1) finds a Δs such that the beam is shifted a total amount. Since the tomographic update can potentially change the location of the reflector, we must account for this change when using the 3D RMO shift. Consequently, we cannot simply solve tomography equation (1). To account for the relative nature of the residuals, we need to apply a matrix to the left hand side. The job of this matrix is to calculate the average new position of the reflector and subtract it from the total shift of each beam. On a matrix level, this amounts to the following procedure: For each row, take all of the other rows that belong to beams that image the same local piece of the reflector, multiply them by scaling values and subtract them from the original row. This process can be encoded with a matrix and, thus, the beam tomography equation becomes,

$$SL\Delta s \quad = \quad \Delta\tau \ , \qquad (2)$$

where the matrix S is a sparse adjacency matrix that contains the appropriate coupling between the row of L so that adjustment of the reflectors due to the velocity update is correctly accounted for. In a sense, the effect of this matrix is already encoded in the right hand side and we must multiply the left hand side by it to make the tomography equation consistent. The necessity for such a matrix was first noted in [7].

A typical beam tomography work-flow contains the following steps:

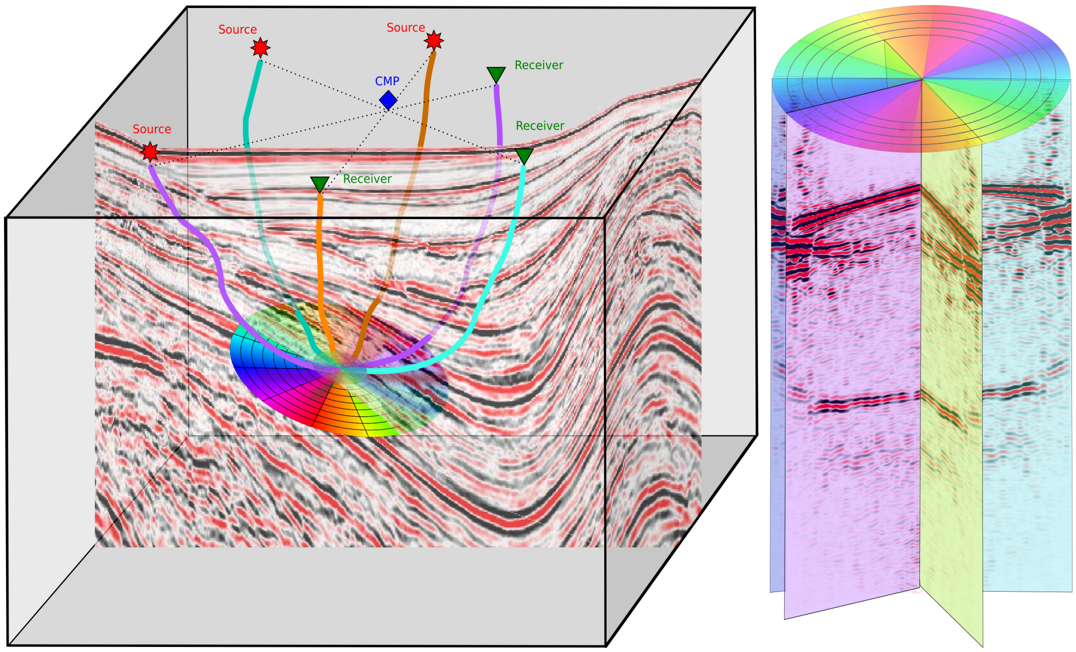

Figure 3: Pictorial representation of the information contained in 3D RMO. The image at every point is obtained from summing the contributions of many beams. Each of these beams has its own unique combination of offset and azimuth (or equivalently reflection angle and subsurface azimuth). Thus the RMO values that flatten the gather depend on offset and azimuth.

- **Beam Propagation:** This stage is identical to the "Beam Propagation" step in FBM, with the additional output of the tomography matrix, which is formed using the source and receiver rays. Each source and receiver ray pair generate a matrix row.
- **Image Forming:** Using the propagated beam we form a raw stacked volume. In general the stack is small and formed much faster than gathers simply because the size of the data is much smaller.
- **3D RMO Computation:** Using the stacked image, we locally shift the beams at their imaging location so that they better align with the stack. This relative residual is used to produce the right hand side of the velocity update equation.
- **Adjacency Matrix Computation:** For each beam, we determine which other beams were used to produce the stacked image with which the beam was aligned in the "3D RMO" step.
- **Velocity Update:** The velocity is updated along each of the rays with certain constraints (since many rays can pass through the same velocity sample) so that the subsurface images are better focused when imaged with the new velocity.

This flow can be automatically iterated to produce velocity updates, since there are no steps that require user intervention. The user can QC the velocity and the raw stack for each iteration. The beams produced in the "Beam Propagation" stage can be used to from image gather for some of the iteration to provide additional QC. An example of a velocity built using automatically iterated beam tomography is shown in figure 4.

Another key feature of Beam Tomography is that for each beam, which is associated with a particular row in the tomography matrix, we

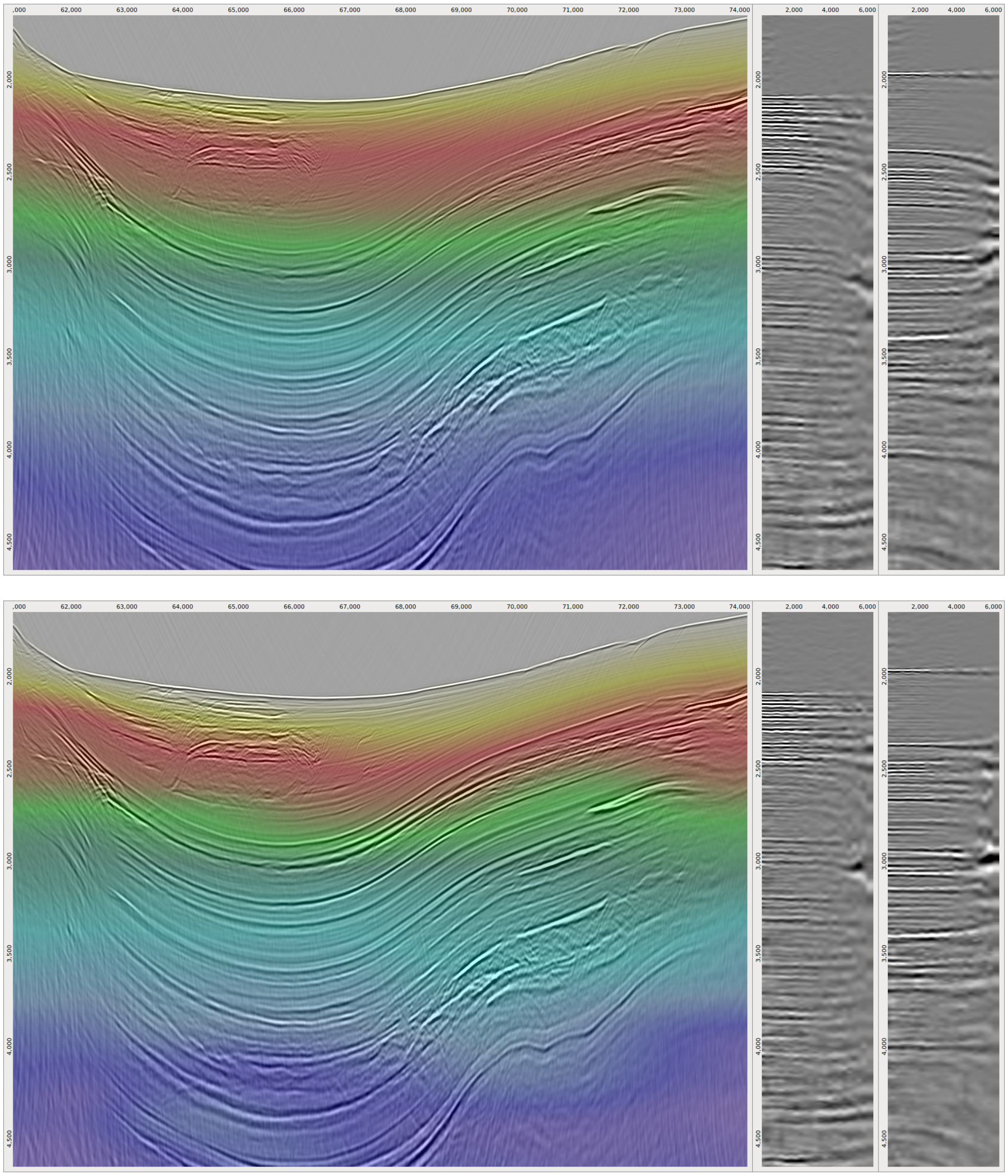

Figure 4: QC of updated velocity: The velocity overlaid with the stack, followed by the common image gathers binned by offset for two location: The figure on the top was produced using the initial velocity, while the figure on the bottom was produced using the updated velocity. The updated velocity was obtained through 40 automatic iterations of beam tomography.

have a multitude of auxiliary information, including the beam decomposition residual, the beam correlation distance, the incidence and reflection angles, the level of 3D RMO match, and much more. All of this information can be used to assign weights to the individual matrix rows that reflect the confidence in the computed time delay. This is particularly helpful in the case of a poor starting model. In that case, we can inhibit the contributions from beams with large time delays and thus lessen the effects of cycle skipping. As the model is refined, more and more of the beams will have a small time residual and thus their contributions will be included in later iterations of Beam Tomography. We also note that we can identify beams belonging to multiples by considering the additional beam information.

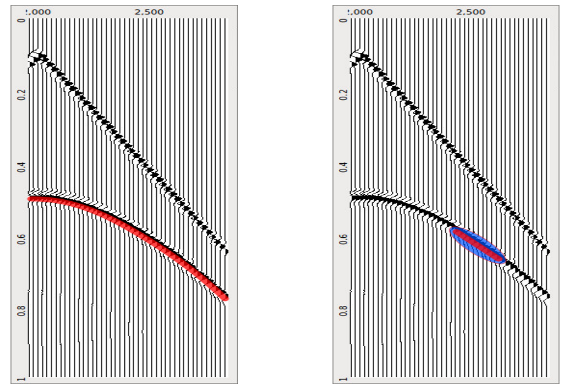

Figure 5: Synthetic common midpoint gather binned by offset. The figure on the left shows a normal (hyperbolic) move-out curve. The figure on the right shows a beam that formed from this gather. Note that the beam dip is a local linear approximation of the move-out curve.

6 RMS Velocity Estimation

One other piece of information that each beam contains is an estimate of the RMS velocity. This estimate is available immediately after beam forming, before any migration has taken place. To see how this can be achieved, consider the standard normal move-out curve:

$$t^2 = t_0^2 + \frac{h^2}{v^2} . \tag{3}$$

The NMO curve relates offset (h), RMS velocity (v), event time (t), and event time at zero offset (t_0). The RMS velocity v depends on t_0 and the common midpoint m of the gather.

Using implicit differentiation, we can obtain an expression for the change (slope) of the move-out curve

$$\frac{dt}{dh} = \frac{h}{v^2 t} . \tag{4}$$

Typically, we are not concerned the the slope equation (4), since we manually pick the RMS velocity so that this curve best follows the observed move-out in the gather. However, after beam forming, for each beam we have the offset h, the midpoint m, and a measured slope dt/dh (see figure 5). These quantities allow us to solve the two equations (3) and (4) for the remaining two unknowns t_0 and v. Thus, this simple algebraic manipulation allows us to get an estimate of the RMS velocity in a local neighborhood of t_0 and m.

Repeating this procedure for all of the formed beams for the data set, we can obtain an RMS velocity volume: in overlapping areas, the estimated velocities from different beams are averaged and gaps are filled by interpolation. Finally, we can smooth the model and an enforce any special conditions (water velocity, water bottom horizon, velocity increasing in time, etc.).

There are other more accurate methods to extract the RMS velocity from a formed beam. For example, the beam can first be time-migrated without a velocity [3] and the beam RMS velocity can be used as estimate of the RMS velocity near the time-migrated beam location instead of the beam CMP. A comparison between the extracted velocity and the picked velocity is shown in figure 6.

7 Conclusion

We presented a wide azimuth beam tomography based on Fast Beam Migration and a method for automatically estimating the RMS velocity. This combination allows us to have a direct input data to velocity model work-flow that does not involve laborious manual components other than QC from the user. The update method enables a rapid estimation of the time delays along each ray, which represent the direct input to a tomographic update, without the time-consuming steps required for traditional tomography, including preparing the gathers for semblance analysis, semblance picking and back-projection picks QC.

Acknowledgment

We would like to thank MultiClient Geophysical for the data used in the examples.

References

[1] Babich, V. M. and M. M. Popov, *Gaussian beam summation method: Radiophysics and Quantum Electronics*, 1990, pp. 1063-1081.

[2] Bleistein, N. and S. H. Gray, *Modeling, migration and inversion with Gaussian beams, revisited*, 77th Annual International Meeting, Soc. of Expl. Geophys., 2007, pp. 1835-1839.

[3] Fomel, S. and Tanushev, N., *Time-domain seismic imaging using beams* 79th Ann. Internat. Mtg., Soc. of Expl. Geophys. 2009.

[4] Kravtsov, Y. A. and P. Berczynski, *Gaussian beams in inhomogeneous media: A review*, Studia Geophysica et Geodaetica, 51, 2007, pp. 1-36.

[5] Popov, M. M., *New method of computation of wave fields using Gaussian beams*, Wave Motion, 1982, pp.85-95.

[6] Popovici, A. M., Tanushev, N., Sturzu, I., Musat, I., Tsingas, C., Fomel, S., *Fast Beam Migration using Plane Wave Destructor (PWD) Beam Forming*, EAGE 75th Conference, Expanded Abstracts, 2013.

[7] Sherwood, J.W.C., Sherwood, K., Tieman, H., Mager, R., Zhou, C., *Efficient Beam Velocity Model Building with Tomography Designed to Accept 3D Residuals Aligning Depth Offset Gathers*, 76th EAGE Conference & Exhibition 2014.

[8] Stork, C., *Reflection Tomography in the Post-migrated Domain* Geophysics, 57(5), 1992, pp. 680-692.

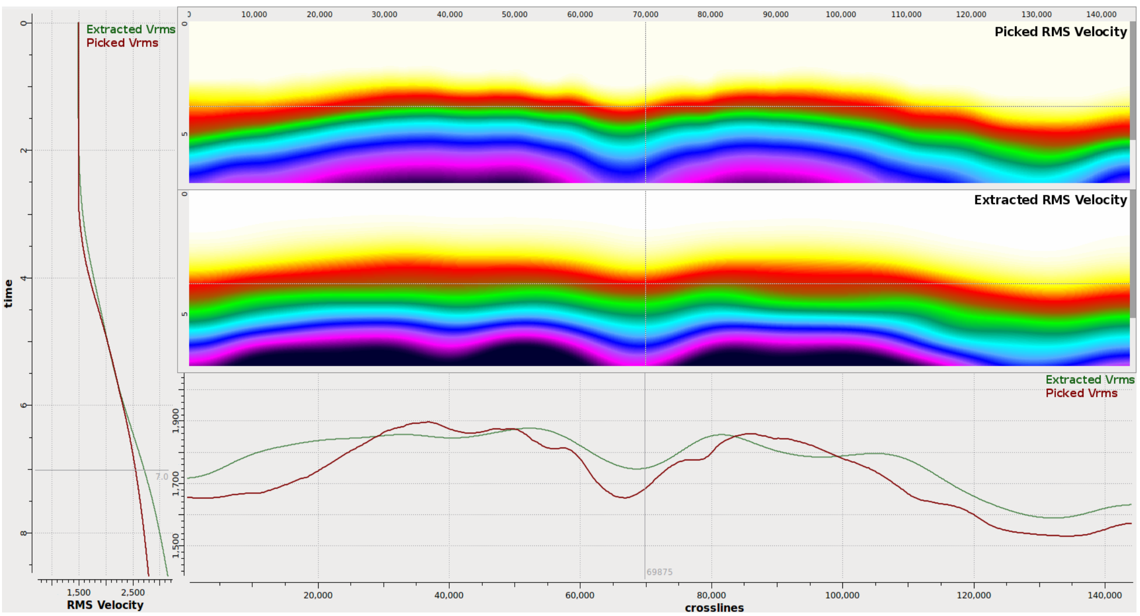

Figure 6: Comparison between the user picked RMS velocity model and the automatically extracted model.