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Fast Beam Migration Using Plane Wave Destructor (PWD) Beam Forming

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SUMMARY

Fast Beam Migration is a super-efficient algorithm that is two orders of magnitude faster than the industry standard Kirchhoff depth migration, and at the same time images multi-pathing energy, a property that is typically associated with wave-equation migration algorithms. The faster and more accurate imaging step allows for more iterations of velocity model building (50-100 iterations, instead of the current 5-10), which enable the processing team to enhance the seismic resolution and imaging of complex geologic structures. Improved velocity models in combination with FBM or wave-equation imaging can provide much greater resolution and accuracy than what can be accomplished today with standard imaging technology.

Introduction

Fast Beam Migration (FBM) is a super-efficient algorithm that is two orders of magnitude faster than the standard Kirchhoff depth migration. The faster imaging step allows for more iterations of velocity model building (50-100 iterations, instead of the current 7-10), which enable the processing team to enhance the seismic resolution and imaging of complex geologic structures.

The idea of beam-based seismic imaging algorithms is not new. Hill (1990, 2001) developed a rigorous and powerful method of depth imaging following the classical Gaussian beam construction. This work has been extended in different ways by a number of researchers (da Costa et al., 1989; Nowack et al., 2003; Gray, 2005). The idea of fast beam migration was also explored by Gao et al. (2006) and found perhaps the most successful commercial implementation at Applied Geophysical Services (Masters and Sherwood, 2005; Sherwood et al., 2009). While building on top of the previous knowledge, we developed a principally new implementation of fast beam-based seismic imaging. Our approach is based on the following novel ideas:

1. An innovative method of beam forming by using automatic plane-wave destruction (Fomel, 2002). This method is the working engine in the Data Decomposition via Beam Forming part of the algorithm.
2. An innovative method of beam extrapolation and imaging. The method derives from ideas employed previously in wavepath and parsimonious migration (Sun and Schuster, 2003; Hua and McMechan, 2005) and oriented imaging (Fomel, 2003, 2007b).

In practice, the Fast Beam algorithm achieves its speed by using the dip information pre-computed from pre-stack data, in two steps: (1) a factor of 10-100 in speedup is achieved via beam forming, or beam decomposition of the input data, where the number of input data traces is reduced by a factor of 10-100; (2) a factor of 10-100 in speedup is obtained by spreading each input trace, or beam over a beam patch instead of a full aperture-volume, by using the approximate dip information. Thus a single sample is spread over a beam patch instead of a full ellipsoid surface. The combined speed up gives a factor of 100-1,000 in decreased run-time. The performance of the FBM algorithm allows us to migrate a 3000 square kilometers dataset on 1000 CPUs in 20-30 minutes, enabling a truly interactive migration for velocity model building definition and refinement

Theory of Data Decomposition using PWD filters

Plane-wave destruction (PWD) filters, introduced by Claerbout (1992), characterize seismic data by a superposition of local plane waves. They are constructed as finite-difference stencils for the plane-wave differential equation. In many cases, a local plane-wave model is a very convenient representation of seismic data. We can define the basis of the plane-wave destruction filters as the local plane differential equation:

$$\frac{\partial P}{\partial x} + \sigma \frac{\partial P}{\partial t} = 0 \qquad (1)$$

where P(t,x) is the wave field, and σ is the local slope, which may also depend on t and x. In the case of a constant slope, equation (1) has the simple general solution

$$P(t,x) = f(t - \sigma x), \qquad (2)$$

where f(t)is an arbitrary waveform. Equation (2) is the mathematical description of a plane wave. If we assume that the slope σ does not depend on t, we can transform equation (1) to the frequency domain, where it takes the form of the ordinary differential equation

$$\frac{\partial \bar{P}}{\partial x} + i\omega\sigma \bar{P} = 0 \qquad (3)$$

And has the general solution:

$$\bar{P}(x) = \bar{P}(0)e^{i\omega\sigma x}, \qquad (4)$$

The goal of predicting several plane waves can be accomplished by cascading several two-term filters. In fact, any F-X prediction-error filter represented in the Z-transform notation as

$$A(Z_x) = 1 + a_1 Z_x + a_2 Z_x^2 + \ldots + a_N Z_x^N \qquad (5)$$

can be factored into a product of two-term filters:

$$A(Z_x) = (1 - \frac{Z_x}{Z_1})(1 - \frac{Z_x}{Z_2})...(1 - \frac{Z_x}{Z_N}) \quad (6)$$

where $Z_1, Z_2, ..., Z_N$ are the zeroes of polynomial (5). Thus we can fit an infinite number of dips in our input data. In practice, the user sets the maximum number of dips at a single location, and typically that is a number less than 5.

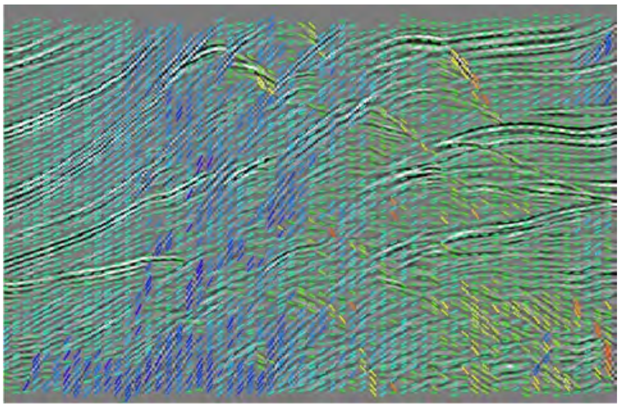

Figure 1 *Prestack data decomposition in locally coherent events using PWD filters.*

The first step of the FBM migration is the decomposition of the seismic data in seismic wavelets, 100-200 ms in time duration (Masters and Sherwood, 2005). The beam formation is performed directly in D(t,Sx,Sy,Gx,Gy) coordinates, where (Sx,Sy,Gx,Gy) are shot and receiver X,Y coordinates. Beams are formed on a uniform grid with interals around 200-250 meters from traces that are collected in super-bins that are 200-500 meters wide in each of the spatial axes. Such a decomposition has additional regularization benefits, compensating for acquisition footprint and also control anti-aliasing even for very steep dips (Masters and Sherwood, 2005), thus FBM does not suffer from the aliasing effects typically encountered in the standard Kirchhoff migration.

Gaussian Beam Forming

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).

The first step of a beam-based processing strategy is decomposing the input data into Gaussian beams. The input data for many time-domain imaging steps are defined in *t*-*x* coordinates, where *t* is time and *x* is distance. The local traveltime curve at any given input location (t0, x0) can be expressed as the truncated series expansion:

$$T(x) = t_0 + p_0(x - x_0) + \frac{c}{2}(x - x_0)^2. \quad (7)$$

The local linear slope of the curve is determined by p_0, while *c* is a measure of the local parabolic curvature. A Gaussian beam centered at (t_0, x_0) can be constructed simply by allowing the curvature to be complex-valued $(c = c_r + ic_i)$:

$$T(x) = t_0 + p_0(x - x_0) + \frac{c_r + ic_i}{2}(x - x_0)^2 \quad (8)$$

The curvature of the beam is still controlled by the real part of *c*, while the extent of the beam from the center is controlled by the imaginary part of *c*. Equation (8) also suggests there will be a real and an imaginary part of the traveltime itself (i.e., T = Tr +iTi).

FBM Image Reconstruction

The beam wavelet with its auxiliary attributes is used to form a limited wavefront Kirchhoff migration for each pre-stack depth volume. Each beam wavelet is migrated separately, and by combining the effect from multiple beams to form the migration impulse response, we can observe local multi-pathing propagation. In addition, FBM does not suffer from the aperture limitations of the standard Kirchhoff implementation, allowing the imaging of very steep dips and overturning ray-paths while maintaining the complete aperture of the input data. This procedure allows for a higher signal to noise image compared to the standard Kirchhoff, where data from millions of traces may not have the necessary amplitude to cancel the migration swings in complex areas such as sub-salt. The true amplitude necessary for AVO friendly processing is also better preserved. Input wavelets can be excluded from the output image at this stage, for example by estimating the focusing quality factor, providing the means for reducing the coherent noise typically present in the deeper migrated areas. Finally, residual moveout can be applied to the migrated gathers for better final stacking, or used in successive tomography iterations for improving the velocity model.

Data Examples

Figure 1 Show the results of estimating the local dip events. Figure 2 shows an FBM image of the Marmousi model. Figure 3 shows an impulse response using FBM in the Sigsbee velocity model. Triplications in the impulse response operator demonstrate the ability to image multi-pathing energy with FBM. Figures 4 and 5 shows a comparison between Kirchhoff and FBM depth migration of a real dataset**.**

Conclusions

We discuss the development details of Fast Beam Migration, an ultra-fast imaging algorithm based on the decomposition of the pre-stack data into locally coherent events, or beams, using PWD filters. FBM allows for very fast imaging iterations (order of minutes for imaging thousands of square kilometers), which combined with very fast migration velocity analysis tools, including wide-azimuth tomography provides much greater resolution and accuracy than what can be accomplished today with standard imaging technology. We show the application of the methodology with examples on synthetic and real data. FBM enables an order of magnitude more effective imaging of complex geologic structures.

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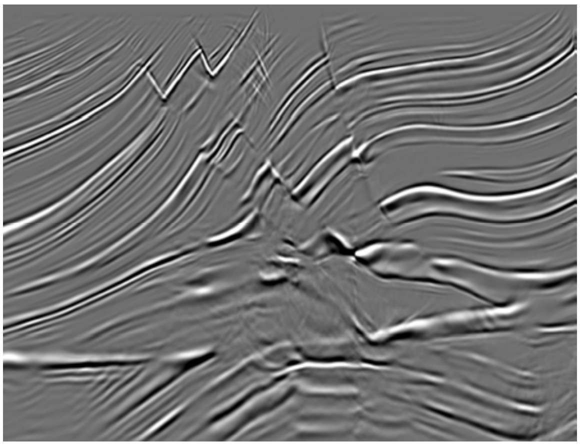

Figure 2 *FBM Marmousi Image.*

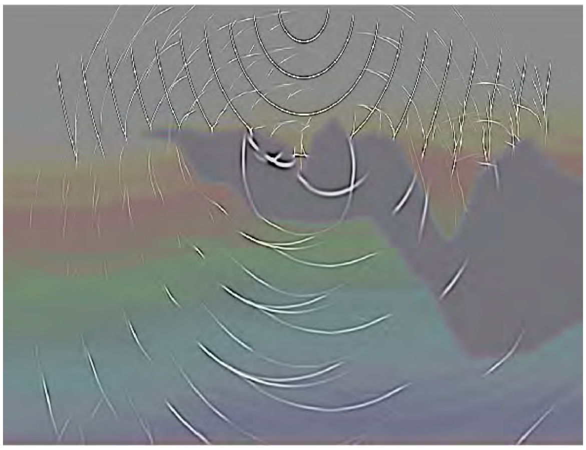

Figure 3 *Sigsbee FBM impulse response.*

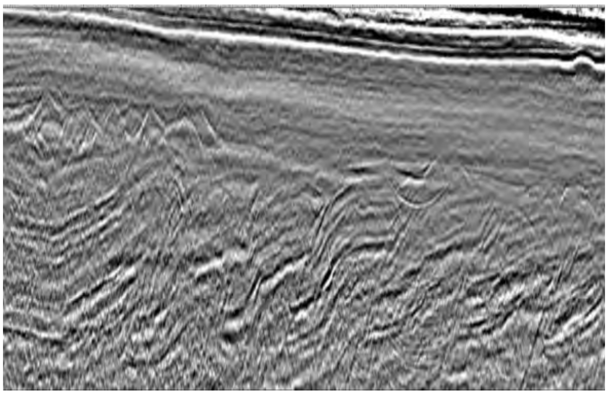

Figure 4 *Kirchhoff image of a real data set.*

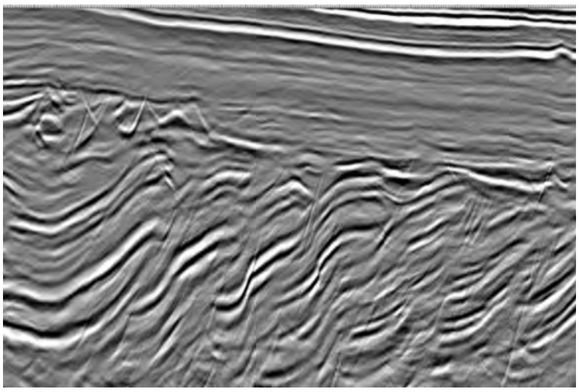

Figure 5 *FBM image of a real data set.*