Final Laser-Beam Q-Migration

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Summary

We present a common offset multiarrival final laser-beam Q-migration (Q-beam) algorithm, which maintains high frequency and accuracy with improved performance over standard Gaussian beam migration. This is achieved by a laser beam method, which limits the beam spread similar to a laser. Such an approach handles large lateral velocity variations without imposing dip or multiarrival limitations for imaging. Furthermore, our method applies Q amplitude loss and phase-shift compensation in the Gaussian-beam multiarrival imaging condition, including interpolation in the inverse Q weighted travel time T* domain. Overhead cost for this approach when compared against standard Gaussian or Kirchhoff migration is negligible. Laser beam migration preserves broadband data frequency and is appropriate as a final imaging tool as presented by our broadband data example. The validity of our final laser beam Q-migration is demonstrated with our 2D synthetic data set and 3D field data set, compared against standard Gaussian beam and Q-Kirchhoff migration.

Introduction

Migration is a mapping operation, which involves the rearrangement of seismic elements so that the recorded wavefields are relocated to their true locations. Ray-based migrations use precalculated source and receiver traveltime measurements to map the surface seismic events back to their correct subsurface location. Production Kirchhoff migration applies a single-arrival approach, which mispositions other arrival energies and can introduce migration artifacts. Wave-equation based migration backward propagates the recorded wavefield and forward propagates the source wavelet, and includes some associated approximations (e.g., finite-difference) to the full wave equation. This migration accounts for multiarrivals, but substantially increases the computational cost over a standard Kirchhoff migration. Similarly, reverse time migration has added cost, increasing runtime exponentially with frequency, (i.e., N^4) making it impractical for broadband data.

Beam migration is a multiarrival ray-based migration algorithm which handles multivalued traveltime and raypath naturally (Hill, 1990, 2001; Gray et. al, 2009). Standard beam migrations use the "fat beam" approach, propagating the plane wave P_m within a relatively large neighborhood along the central ray (e.g., shaped with a Gaussian window), and the beam properties are then extrapolated with a Taylor expansion around the central ray. 3D production parameters spread the beams along time significantly, which introduce extrapolation errors that grow rapidly along the spread direction. Considering this, most production beam migrations focus on speed instead of quality, and was originally designed as a tomographic engine. Specifically, in regards to tomographic semblance analysis, beam migration isolates energy to a small number of seismic elements (Sherwood et. al, 2009). The algorithm has even been simplified for fast-beam migration (Gao et. al., 2006), which adopts a one-to-one mapping from the data domain elements to image domain. This may violate the multiarrivals assumption and sacrifice the migration quality, removing itself as final migration tool.

To maintain accuracy and efficiency, our "laser beam" migration is a controlled width beam migration, which strictly limits the seismic energy with a "thin beam", typically within a few wavelengths from the central ray. Similar to Kirchhoff beam migration (Liu and Palacharla, 2011), laser beam migration is also a generalized Gaussian beam migration. Ray tracing with laser beam migration uses a high-frequency approximation and does not require additional cost for broadband data processing. Constrained to a laser thin width, laser beam migration, approximates the propagation of the seismic wavefield with the accuracy level of the high frequency central rays, consequently performing well in the presence of caustics and beam spread. Thus the amplitude loss and phase shift, especially at high-frequency values can be correctly compensated inside a multiarrival beam migration. As the broadband acquisition and processing including Q-compensation becomes routine in production workflows, the capability for preserving high-frequency energy and accuracy is crucial for industry. After careful implementation, laser-beam migration can be several times faster than the production Kirchhoff migration and provides much higher frequency than the wave-equation based migration within the same turnaround time. This independent development is similar to the focused beam (Nowack, 2008) and frozen beam (Yang et. al, 2013) approach.

Theory

Laser-beam migration is a generalized Gaussian beam migration with a controlled beam width, which is predefined to a few wavelengths from the central ray. With a laser-thin beam, the extrapolation errors of beam property (ray amplitude, real and imaginary travel time, etc.) from the central ray are minimized to almost no influence on wavefield modeling and final image. This approach gives us the flexibility to choose either dynamic or kinematic ray tracing. This is extremely important to improve the accuracy and efficiency for shallow depths with high beam

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coverage, or beneath complex geology where low beam coverage is dominant.

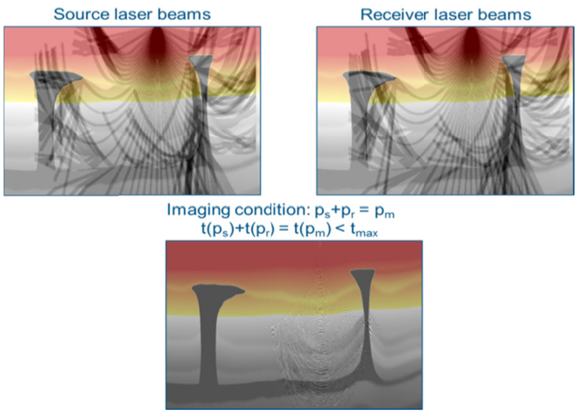

Figure 1: Laser-Beam theory scratch, computed using a source and receiver pairs in BP 2007 model.

Figure 1 shows the laser beam coverage for a source and receiver pair, which is computed using BP 2007 TTI model. Those high density laser beams are used to form the "timetable" and used for the subsequent beam stacking.

The efficiency of production-beam migration is memory and IO-bounded. With careful implementation, the laser

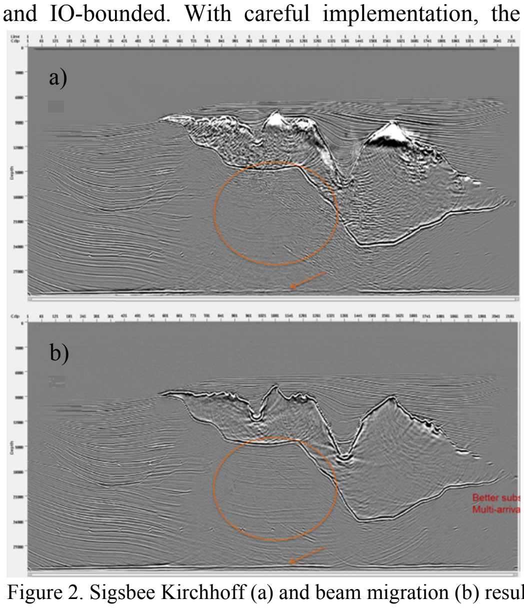

Figure 2. Sigsbee Kirchhoff (a) and beam migration (b) results.

beam Q-migration can have almost the same speed as the standard Beam migration. Implementation for the laser beam Q-migration is as follows:

Step 1. Decompose the tapered common offset data near a beam center into local plane waves by local slant stacking. If the data is regularized, fast FFT calculation can be used in tau-*p* transform to speed up the decomposition, rather than a slow version of irregular beam forming with X-T domain local slant stacking.

Step 2. Approximate the propagation of seismic wavefield using laser beams. First, ray trace the central rays for complex traveltime $T_c(\vec{x})$ at ray position $\vec{x}$ with Equation 1, and then extrapolate them using Taylor expansion to get the "timetable" $T(\vec{x})$ and $T^*(\vec{x})$, as shown in Figure 1. In production, we always prefer kinematic ray tracing (Červený, 2001), which is about two times faster than the dynamic ray tracing, and exhibits less extrapolation errors. The complex traveltime $T_c(\vec{x})$ is calculated as (Traynin et. al, 2008):

$$T_c(\vec{x}) = T(\vec{x}) - \frac{1}{2} i T^*(\vec{x}) - \frac{1}{\pi} T^*(\vec{x}) ln \frac{\omega}{\omega_0}, \quad (1)$$

Where $T^*(\vec{x}) = \int_{ray} 1/(c_0 Q) ds$, c_0 is the acoustic part of the complex velocity, Q is the quality factor, ω_0 is the reference frequency.

Step 3. Migrate the tau-*p* domain data using the Gaussian beam multiarrival imaging condition. First precompute the trace table indexed by different T* values, then the amplitude loss and phase shift are compensated by interpolating between different frequency band for T* values.

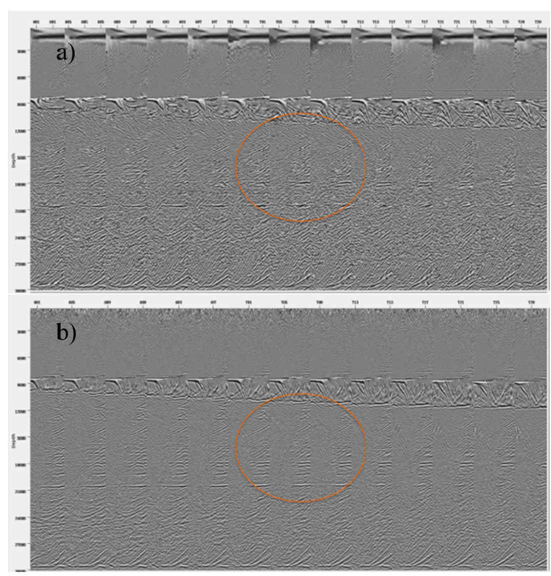

Figure 3: Sigsbee Kirchhoff (a) and beam migration gather (b).

Step 4. Stack the partial images from all offsets to the final image.

Numerical Examples

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2D Sigsbee data

We first applied the production laser beam migration on the original 2D Sigsbee dataset and compared it to the Kirchhoff migration. The single arrival (the most energetic arrival) Kirchhoff migration, as expected, provides poorly-defined faults, with weak and blurred point diffractors, including a discontinuous bottom reflector (Figure 2a). Strong artifacts due to incorrect interpolation between different arrivals are also present in the subsalt

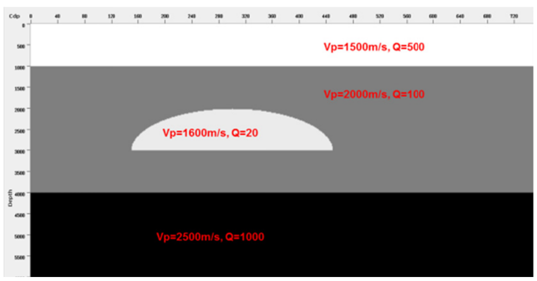

Figure 4: Vp and Q of 2D synthetic model.

area. Alternatively, laser beam migration properly handles the multiarrivals correctly, generating cleaner data with coherent subsalt imaging (Figure 2b). Laser beam gather in Figure 3, clearly shows much better events than the Kirchhoff migration.

2D Q synthetic data

We have validated the fidelity of laser-beam Q-migration

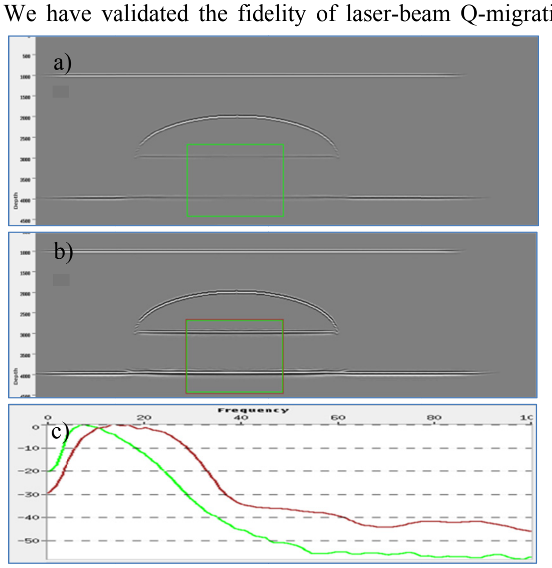

Figure 5: Standard beam migration (a), Q-Beam migration (b) and spectrum comparison (c), where beam spectrum is red and Kirchhoff one is green.

(Q-beam) using a 2D synthetic data. This simple 2D model consists of three horizontal layers and one gas pocket, the Vp and Q values are labeled in Figure 4. The migration

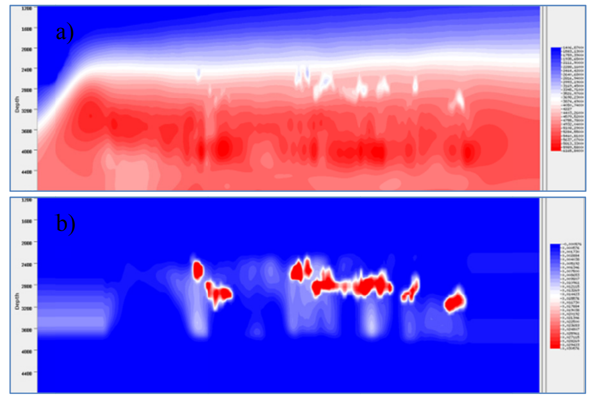

Figure 6: Hernando velocity (a) and Q model (b).

images in Figure 5 clearly demonstrate that the laser beam Q-migration correctly compensates the amplitude loss and phase shift. In addition, the spectrum after Q-migration is broadened as expected.

3D field data set

We also tested the Q-beam migration on the Hernando multi-client dataset, which is in the eastern Gulf of Mexico. Carbonate karst zones over the Florida escarpment have much lower velocity than the surrounding sediments (Figure 6a). Also, the zones are effected by high attenuation from fractures and unconsolidated rock. Those carbonate karst zones, with a size of several meters to several hundred meters, introduce multiarrivals as triplication while dimming the seismic amplitude beneath them. With the Q-model (Figure 6b) derived from the Q-tomography (He et. al, 2012), Q-beam migration handles the multiarrivals and compensates amplitude loss and phase shift (Figure 7). A field data gather comparison in Figure 8 shows that the Q-beam migration handles the amplitude, phase-shift compensation and multiarrivals better than the Q-Kirchhoff migration inside or beneath the low velocity target zones (Figure 8a).

Our Q-beam migration is capable of preserving data frequency from a TGS broadband dataset. After 3D migrations, the zoomed in view at shallow depth slice, and inline spectrum comparison (Figure 9), shows that both Q-Kirchhoff and Q-beam migration can go over one hundred hertz when dealing with broadband data.

Conclusions

We have developed a laser beam approach on standard Gaussian beam migration, which limits the beam energy

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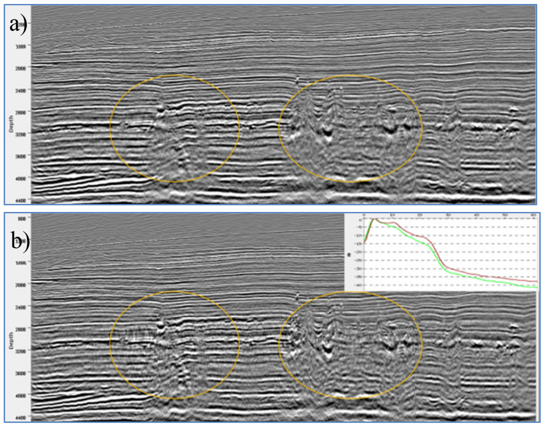

Figure 7: Hernando standard beam (a) and Q-Beam (b) results.

inside a laser-thin beam spread and reduces the computational cost. Furthermore, extrapolation errors from the central rays are minimized, producing trivial impacts on the final migration image. By a strict reduction of the extrapolation errors from high-velocity variations in the complex geologic setting, the laser-beam migration takes advantage of the high-frequency approximation of ray

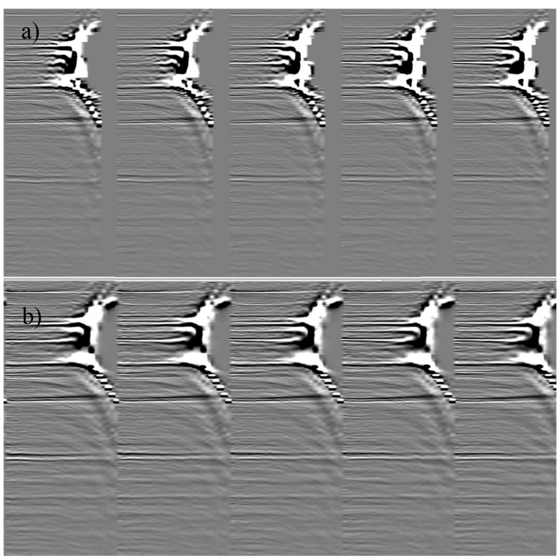

Figure 8: Field data Q-Kirchhoff (a) and Q-Beam gather (b) comparison.

theory. It can also preserve the broadband data spectrum and add no additional cost for a high-frequency broadband final-beam migration. Successfully, we applied the final laser-beam Q-migration on a 2D synthetic data set and a 3D field data example, resulting in final beam images that are superior to those of a single-arrival Kirchhoff or standard Gaussian beam migration with production parameters. The final image spectrum is broadened, and specifically the amplitude and phase of high-frequency values have been recovered using the Q laser-beam migration. In addition, this laser beam approach can be easily extended to common shot domain for future analysis.

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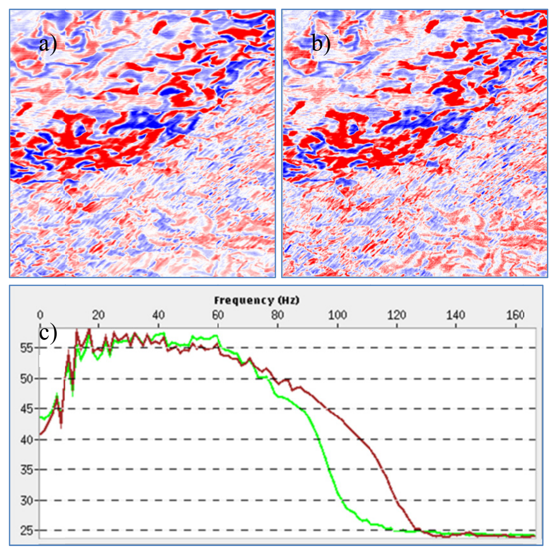

Figure 9: Q-Kirchhoff (a), Q-beam (b) depth slices at shallow depth, and inline spectra (c). The green curve is the Q-Kirchhoff spectrum, and the red curve is the Q-beam spectrum.

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EDITED REFERENCES

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