Gaussian beam depth migration of wavelet compressed seismic data

Lorenzo Casasanta (Shearwater GeoServices)*

Summary

We have investigated an implementation of Gaussian beam depth migration which images seismic data after being compressed by a digital wavelet transform. Conventional Gaussian beam migration consist of two main steps: (1) a local plane wave decomposition of the input seismic traces into directional components or beam traces; (2) mapping of each beam trace sample to its depth location through dynamic ray tracing into a given velocity model. Instead of migrating each beam time sample individually, we propose to migrate a selection of picked wavelets. These wavelets are associated with the largest coefficients of an appropriate digital wavelet transform of the beam traces. Coupling a Gaussian beam decomposition with a wavelet compression can lead to an improved signal-to-noise ratio and also a direct saving in computation at the cost of some reduction in imaging accuracy.

We have tested this approach on both synthetic and real data sets. By only imaging a small percentage (1% ÷ 3%) of the wavelet coefficients we have enhanced the signal-to-noise ratio of both stack images and pre-stack common image gathers.

Introduction

The ultimate goal of seismic processing is to render an image of the earth interior from the recorded seismic data and an estimated velocity model. The current state of the art in imaging is the routine use of depth migration for marine and land data, using one or more imaging algorithms (Etgen et al., 2009).

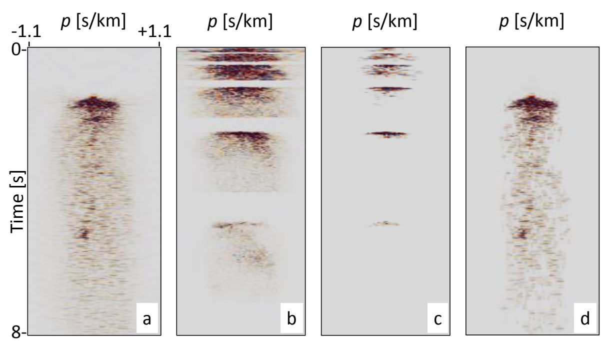

Figure 1: a) local slant stack for a given beam center location. The beam traces are sorted according to the emergence ray parameter *p*. b) wavelet transfrom of each beam trace sorted from the coarsest to the finest scale. c) 1% of the largest wavelet coeffiecients and d) associated time domain wavelets.

Kirchhoff migration is the most familiar and possibly still more used of the depth imaging-based methods. It can accommodate any acquisition geometry, it easily incorporates seismic anisotropy, it images steep dips and overturning events, and it can output broadband images and high fold pre-stack gathers thanks to its extreme scalability on modern high performance computing architectures (Teixeira et al, 2013). However, the majority of ray-based Kirchhoff implementations perform poorly in the presence of wavefront multi-pathing at the image point. Therefore, in regions of substantially complex geology with strong lateral velocity variation, more accurate but computationally intensive wave-equation migration methods are generally preferred. The Gaussian beam migration algorithm sits in the middle: in fact it overcomes the single-wavefront limitation of the majority of Kirchhoff implementations but still benefits from an efficient ray-based engine when compared to one-way or reverse time imaging algorithms.

In his seminal paper, Hill, 2001 provides the theoretical foundations of Pre-Stack Gaussian beam migration. Further developments from different authors have resulted in a variety of specializations of the original method: Vetle et al., 2008 proposed a controlled beam migration to enhance both signal-to-noise and steep-dips of images in complex geology area; Gao et al, 2006 and Sherwood et al, 2009 described similar parsimonious beam migrations to speed-up the turnaround of depth imaging and velocity model building. All these different imaging approaches share the fundamental idea that seismic data have redundant information that can be extracted using a compressive workflow.

Taking inspiration from these works, we investigate an alternative implementation of the Gaussian beam depth migration which images seismic data after being compressed by a digital wavelet transform. Gaussian beam migration consist of two main steps: (1) a local plane wave decomposition of the input seismic traces into directional components or beam traces; (2) mapping of each beam trace sample to its depth location through dynamic ray tracing into a given velocity model. Instead of migrating each beam time sample individually, we propose to migrate a selection of picked wavelets. These wavelets are associated with the largest coefficients of an appropriate digital wavelet transform of the beam traces. Coupling a Gaussian beam decomposition with a wavelet compression can lead to both an improved signal-to-noise ratio and a direct saving in computation at the cost of some reduction in imaging accuracy.

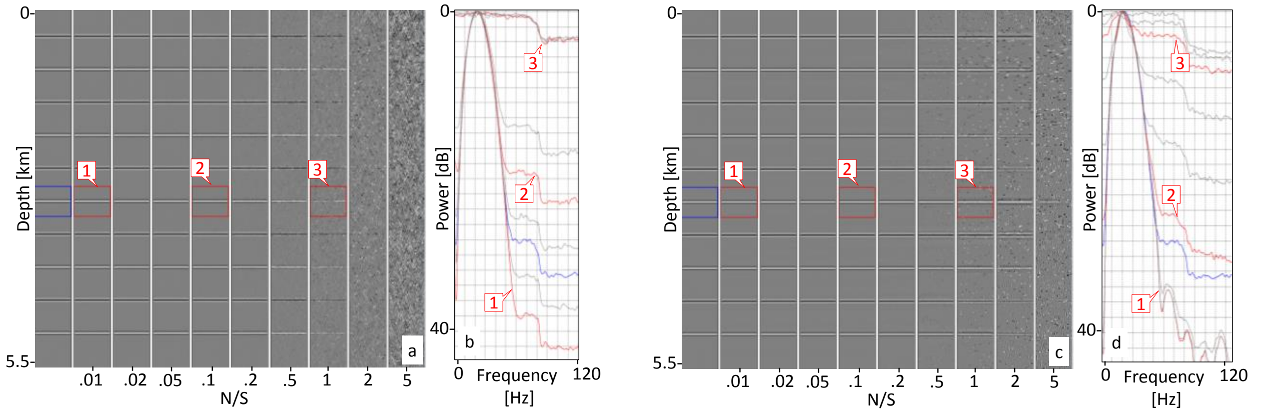

Figure 2: Gaussian beam migrations of a synthetic dataset comprising 10 flat horizons in a 2000m/s homogenous velocity model. A 20Hz Ricker wavelet is used to model the reflections. An increasing level of white Gaussian noise is added to the input data to assess the robusteness of the wavelet extraction based on ampltiude thresholding of the beam traces a) or of their digital wavelet trasform coefficients c) and b) and d) are the spectrum of the migrated wavelets and the level of migration noise using the described wavelet extraction approaches.

We have tested this approach on both synthetic and real data sets. By only imaging a small percentage (1% ÷ 3%) of the wavelet coefficients we have enhanced the signal-to-noise ratio of both stack images and pre-stack common image gathers.

Methodology

The idea of migration using wavelet compressed seismic data is not new. Dessing, 1995 used compact supported orthonormal wavelet functions to transform the seismic data into the wavelet domain, and numerically calculated the migration operator. Wang and Pann, 1996 briefly discussed an application of the wavelet transform for ray based migration but a matching pursuit approach using a dictionary of multi-frequency Ricker wavelets was instead preferred with the claim of a higher compression rate. However, Ricker wavelets are only adequate to represent zero-phase signal and relatively narrow band signal. Today's seismic acquisitions record wider band signals. Therefore, we believe the wavelet transform with the partition of the entire frequency spectrum into octaves is indeed more appealing.

Moreover, the digital wavelet transform is an efficient operation when implemented using a lifting scheme. Assuming that the prediction and update operators have a constant cost, the number of operations at the next scale is half those at the previous one for a total $O(2N-1)$ complexity, which is smaller than the $O(N\log N)$ cost of the Fourier transform, where N is the number of samples per trace (2006, Fomel).

In Figure 1 we show conceptually how the wavelet compression works within the Gaussian beam migration algorithm. A local slant stack for a given beam center location is calculated and the beam traces are sorted according to their surface ray parameter *p*. (Figure 1a) A wavelet transfrom of each beam trace is computed. Figure 2b shows the calculated wavelet coefficient sorted from the coarsest scale (long low frequency wavelets) to the finest scale (short high frequency wavelet). The wavelet transform performs a correlation anlysis and therefore we expect the coefficients to be largest and concentrated (sparse) when the input signal most resembles the mother wavelet used. Converserly any other signal or noise will have its energy spread over a large number of relatively small coefficients. With this in mind, we select a subset of the coefficients to represent the input beam traces with some degree of accuracy. A simple amplitude thresholding criterion keeps only 1% of the wavelet coefficients (Figure 1c). The reconstructed wavelets in Figure 1d retain most of the main features of the original slant stack thereby confirming that the wavelet transform has successefully compressed the seismic data with a small relative loss of information. Once selected, the wavelet coefficients can be stored in a database together with the timing and directional information of each wavelet. This procedure achieves large disk space saving and it can lead into direct improvement in migration computational cost when instead of migrating each beam time sample individually, each picked wavelet is mapped into depth domain as a whole (Gao et al. 2006, Sherwood et al. 2009).

By looking again at the local slant stack in Figure 1a one can think that it is already a sufficiently compressed representation of the input signal and therefore can be used to directly extract a set of wavelet to be mapped in depth.

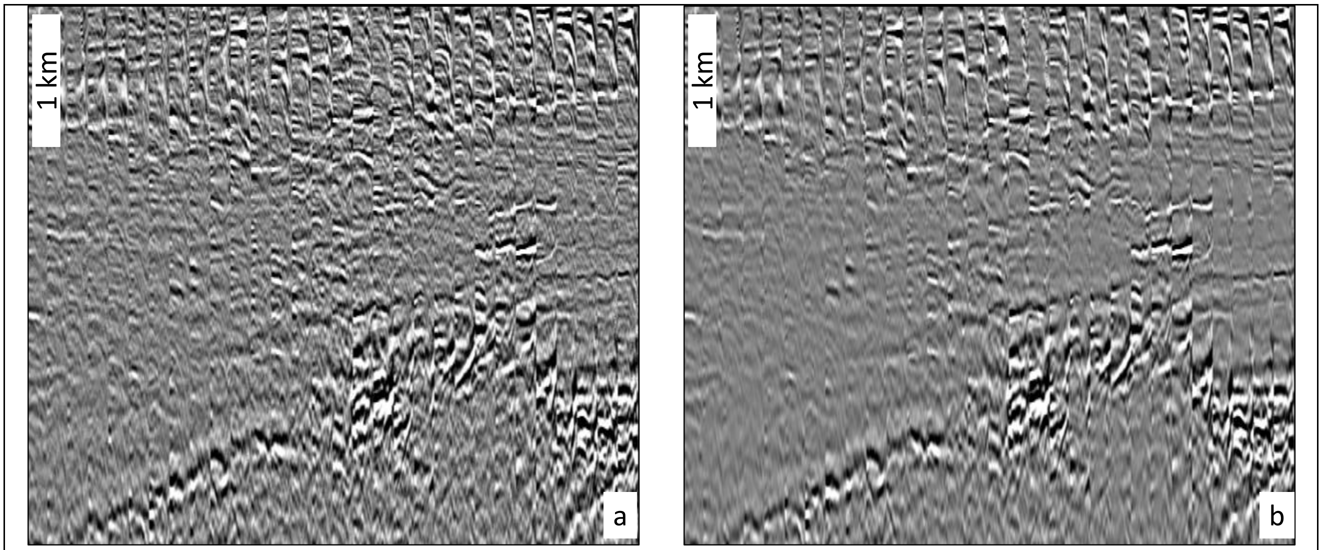

Figure 3: Gaussian depth migration of a 2D test line without (a) and with (b) wavelet compression of the slant-stack traces. Only 0.5% of the wavelet coeffiecients are selected: the pre-stack offset gathers (b) enhances the most coherent feature but still preserving the moveout curvature when compared to the standard migration results (a).

We employed a synthetic test to address this claim. Figure 2 shows an ensamble of Gaussian beam migrations of a synthetic dataset comprising 10 flat horizons with constant reflectivity in a 2000m/s homogenous velocity model. A 20Hz Ricker wavelet is used to model the reflections. An increasing level of white Gaussian noise is added to the input data. The noise-to-signal level (N/S) is measured as the ratio between the noise standard deviation and the signal peak reflectivity. Figure 2a shows the Gaussian beam migration results using a set of wavelets extracted directly from the slant stack using an amplitude threshold criterion on the samples of the beam traces (Sun and Schuster, 2001). Figure 2c show instead the migration results using the proposed wavelet selection using the largest coefficients of the wavelet transform of the input beam traces. Both approaches perform relatively well, although the wavelet transform route is able to enhance the signal and suppress the migration noise at a higher level of N/S thanks to its intrisinc correlative analysis. Figure 2b-d shows the spectra of the reconstructed migrated wavelet for both approaches agree well with that of the reference standard Gaussian beam migration (blue) with N/S=0.01 and no beam trace compression or wavelet extraction applied

Real data examples

We first applied our wavelet transform event selection approach to a 2D test line which was undergoing velocity updates (Figure 3). The tomographic velocity model building was at its later stages, so we would expect almost flat curvature in the pre-stack offset gathers. A conventional Gaussian beam migration and gathers (Figure 3a) were available and already delivered improved image and gather quality when compared to Kirchhoff migration. We tested different wavelet coefficient compression rates and we observed that with more than 5% of them there was little or no difference with the standard beam migration with no compression. We went as far as retaining only 0.5% of wavelet coefficients and the results are those depicted in Figure 3b. The wavelet compression approach retains the majority of the most coherent feature in the image. The enhanced signal-to-noise ratio gives to pre-stack offset (Figure 3b) a synthetic looking aspect, which however can help in structural interpretation and velocity analysis. The superior quality of these migrated offset gathers offer the opportunity of a far more accurate residual moveout (RMO) picking, which eventually can outperform tomographic updates based on Kirchhoff imaging (Vetle et al. 2008).

The second example is from a Multi-Client seismic survey acquired by Spectrum in 2017. comes from the Barents Sea where Permian Templefjorden carbonates are overlain by Triassic and Jurassic hydrocarbon-bearing sediments. The hard sea bed and Base Quaternary events give rise to strong linear noise. The seismic data have been acquired and processed with state-of-the art broadband technologies. At the time of our test the data were at the initial stages of depth velocity model building. Therefore we expect a not optimal migration result with some unfocused diffractions and mis-positioned reflections especially when the geological dips are steeper. Figure 4 shows the migration results for a single offset volume where we expect strong migration noise. Above the Top Jurassic the wavelet compression approach performs better than the standard Gaussian beam migration especially in removing the cross-cutting noise due to the uncancelled swing of the mgiration operators (Figure 4a and c). However deeper down below, where the signal-to-noise ratio is naturally poorer, we observe a much clearer improvement. By only keeping 1.5% of the wavelet coefficients we are able to successefully suppress both the incoherent and migration noise without degrading the main geological features as also confirmed by analysing the 2D Fourier spectra (Figure 5) in the red box on the depth slices in Figure 4b and 4d.

Conclusions

We have investigated an alternative implementation of the Gaussian beam depth migration which images seismic data after being compressed by a digital wavelet transform. Instead of migrating each beam time sample individually, we propose to migrate a selection of picked wavelets associated to the largest coefficients of an appropriate digital wavelet transform of the traces in the slant stack. Both synthetic and real data examples have showed that coupling a Gaussian beam migration with a wavelet compression can lead both into improved signal-to-noise ratio in both stack images and pre-stack offset gathers.

Acknowledgments

We are grateful to our colleagues for their support, suggestion and constructive critics. We thank Spectrum for the 2017 Barents Sea Multi-Client example.

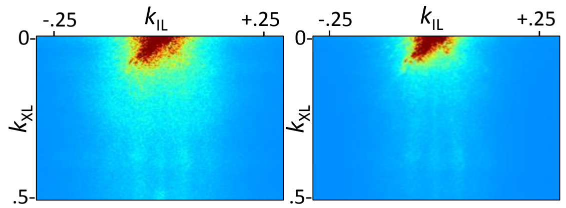

Figure 5: 2D Fourier spectra of the depth slices shown in Figure 4. Left, conventional beam migration. Right beam migration with wavelet transform compression.

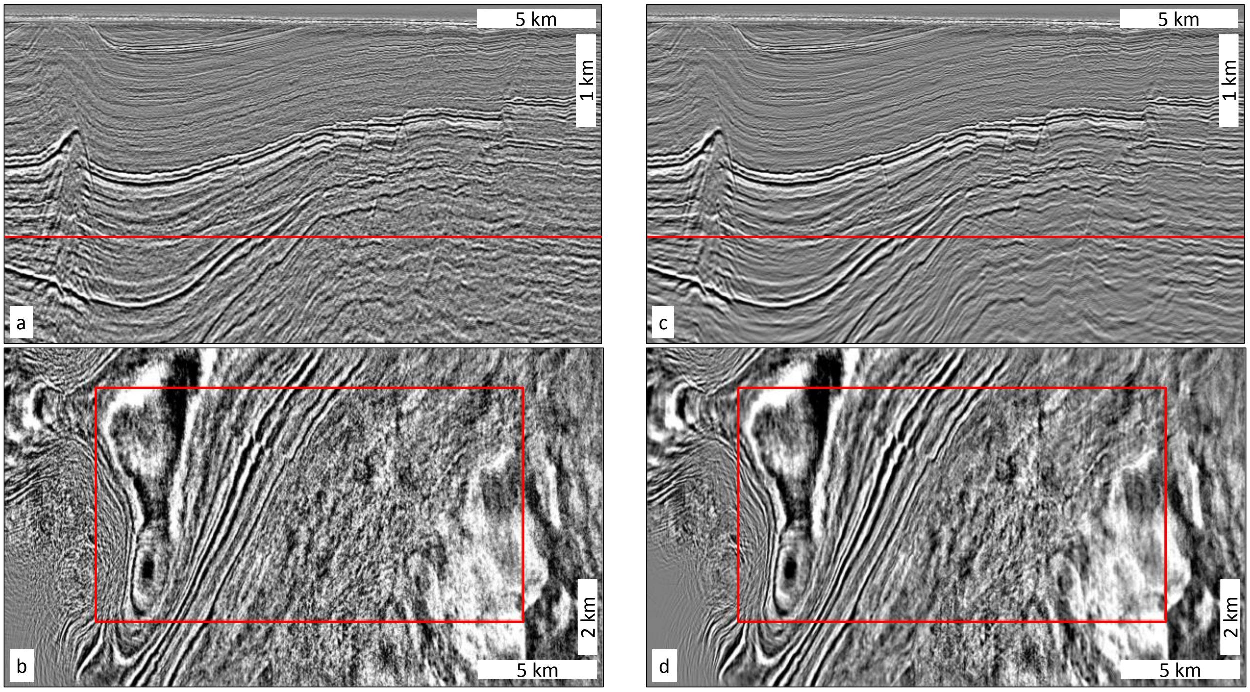

Figure 4: Gaussian beam migration of data from a 2017 Barents Sea Multi-Client dataset courtesy of Spectrum: Standard (a and b) and wavelet compressed (c and d) migration of a near offset volume. Central Inline views (a and c). The red line shows the depth location of the slices exctracted below the top Jurassic.

References

Etgen, J., Gray, S. H. and Zhang, Y., 2009 An overview of depth imaging in exploration geophysics: Geophysics, Vol. 74, No. 6

Teixeira, D., Yeh, A. and Gajawada, S., 2013, Implementation of Kirchhoff prestack depth migration on GPU: SEG Technical Program Expanded Abstracts 2013: pp. 3683-3686.

Hill, N. R., 2001, Prestack Gaussian-beam depth migration: Geophysics, 66, 1240–1250.

Vinje, V., G. Roberts, and R. Taylor, 2008, Controlled beam migration: A versatile structural imaging tool: First Break, 26, 109–113.

Gao, F., Zhang, P., Wang, Bin., and Dirks, V, 2006, Fast beam migration — A step toward interactive imaging. SEG Technical Program Expanded Abstracts 2006: pp. 2470-2474.

Sherwood J.W.C., Sherwood K., Tieman H. and Schleicher K., 2009, 3D beam prestack depth migration with examples from around the world: The Leading Edge, 28(9), 1120-1127.

Sun, H. and Schuster G., T., 2001, 2-D wavepath migration. Geophysics, Vol. 66, No. 5

Wang B., and Pann K., 1996 Kirchhoff migration of seismic data compressed by matching pursuit decomposition. SEG Technical Program Expanded Abstracts 1996: pp. 1642-1645.

Dessing, F., 1995, Seismic migration with one-way operators in the wavelet domain, DELPHI Research Consortium annual report.