5D data regularization using enhanced antileakage Fourier transform

Wilfred Whiteside, Manhong Guo, Jun Sun, Bin Wang, TGS*

Summary

We have applied an improved computational methodology to 5D antileakage Fourier-based data regularization that is found to greatly increase the computational efficiency. This is important, as the computational cost of 5D antileakage hinders its widespread use on large surveys. Large land surveys and higher fold multiazimuth marine data can make the 5D antileakage method too costly to be practical without introducing shortcuts. We have implemented a spectral pattern-removal technique which speeds up the computation dramatically without sacrificing quality.

Introduction

Data regularization has recently come into widespread use in the seismic imaging industry for a variety of purposes such as in 4D imaging where removing the effects of acquisition geometry differences is required, and traces from different vintages must be sampled to a common grid for subtraction. Another primary driver, the creation of regularly sampled data, is to improve the quality of images formed in the migration step. Migration algorithms assume data regularity in order for the discreet computational mathematics to best approximate the underlying physics.

Seismic data, however, is always acquired in an irregular fashion, whether intended or not, and migrating such data results in noise artifacts and damage to imaging steeper dipping structures. Trace weighting schemes such as standard fold compensation or Vornoi weighting can help to partially mitigate these artifacts. However, these techniques break down rapidly as the distance between traces exceeds the natural line and cdp bin spacing. Additionally, spatial smearing is unavoidable using premigration weighting alone. Antileakage Fourier Transform (ALFT) based data regularization is a technique of choice currently used to address these shortcomings (Xu 2005, 2010).

Seismic data is typically processed in the five dimensions of lateral source, receiver coordinates and time, making 5D interpolation a requirement to account for amplitude and timing variations that are a function of all these dimensions. But for higher dimensionality ALFT, such as 5D or even 4D (where azimuth is not considered), computational cost can be prohibitive for large land surveys or multiazimuth marine surveys. To address the cost issue, we have implemented a spectral pattern removal technique which has resulted in significant reduction of the computational cost. The key to this technique is the fact that spectral leakage is only a function of the acquisition geometry. We show a real data example where 5D data regularization ran five times faster than the prior implementation.

Theory and Method

In order to regularize data, where holes in coverage exist, basis functions have been sought that can explain the measured data while spanning the gaps. Generally, the more appropriate the basis functions, the sparser the subset of basis functions needed to explain the measured data. Once a set of basis functions is determined and coefficients estimated by some means, the output data can be created at any desired location. Antileakage refers to the sparse-inversion technique used to estimate these coefficients. For computational purposes, the input data are divided into overlapping windows. Within each window, the basis function coefficients are estimated and used to reconstruct the input data at regular bin center locations. In this study we focus on the standard Fourier basis, although other more complex basis functions such as curvelets may, in principal, be used or combined with the Fourier basis to represent the data in an even sparser manner.

To understand ALFT and the pattern removal technique, we need to understand leakage which arises from the fact that the Fourier basis functions are no longer orthogonal when evaluated at spatially irregular sample locations. As a result, there is cross talk between them in the measured spectrum. This cross talk is referred to as leakage. A fundamental example of leakage would be a single plane-wave basis function which if sampled regularly would yield a spectrum with zero amplitude everywhere except for the spectral element corresponding to its wavenumber. This would be the model spectrum we desire because it would allow us to reconstruct the plane wave at any location we choose. However, the spectrum of the plane wave when sampled irregularly in space has additional non-zero spectral amplitudes corresponding to other plane wave basis functions. These extra terms in our spectrum are called leakage. Because the time dimension is sampled regularly, there is no leakage between frequency slices.

Leakage is illustrated in Figures 1 and 2. Figure 1 shows a trace binning map for a small analysis window from a common-offset cube being interpolated in common midpoint x,y. The inline direction is well sampled, but the crossline direction is missing approximately every other trace. Figure 2 shows a frequency slice measured from a single horizontal reflection event present on these traces. The central dot at $kx=ky=0$ is the true component we would like to model, and the two spots on either side are the

DOI http://dx.doi.org/10.1190/segam2014-0724.1

aliased dips. Much weaker leakage can be seen throughout the spectrum including the sinc function pattern introduced by our finite rectangular window.

Next we describe the standard ALFT process. The input data is processed in moving windows. ALFT begins by measuring the spectrum in all dimensions. Because the data is sampled regularly in time, it is initially converted to frequency-space domain via fast Fourier transform. The remaining spatial dimensions are irregularly sampled, requiring the computation of either very expensive discreet Fourier sums or a suitable faster approximation method such as the non uniform fast Fourier transform (NFFT) (Keiner, 2009).

Once the input spectrum is computed, a model spectrum is generated via the ALFT inversion process which proceeds by moving one plane wave at a time from the input to the output domain. The strongest event in each frequency slice is assumed to be a true plane wave component which we can move to our model output spectrum. The corresponding plane wave is then removed from the input data in time and space. The irregular spectrum of the remaining input data is then calculated. The strongest remaining event is selected, and the process repeats until the strongest amplitude in the residual input spectrum is below a certain threshold relative to the strongest event in the original input spectrum.

Again, because the time domain is regular, there is no leakage between frequency slices and the above process can be applied to each slice independently. However, at the slice level, it is often difficult to distinguish leakage energy from the true-event energy, creating results that are less than satisfactory due to poor event picking. Since a locally planar event maps to a straight line event in the spectrum pointing to the origin, and its leakage maps to parallel lines shifted away from the origin, many implementations make use of this by stacking through frequency slices along lines to the origin in order to determine a weighting factor to better distinguish the primary energy from the leakage (Schonewille, 2009). Typically, the weights are generated using a band of lower frequencies where dips are reliable and not aliased.

The above ALFT inversion process can be expensive for 4D and much more so for 5D due to the high computational cost of recomputing the input spectrum after each plane wave removal. The technique we originally used to reduce computation time was to pick the strongest few events and remove them in sequence, only updating the input spectrum at these particular locations. This required a small but significant number of discreet Fourier summation passes across the input data and resulted in significant computational speedup. The drawback of this approach is that the residual spectrum is only updated intermittently causing a small sacrifice in accuracy. We call this the DFT approach (Discreet Fourier Transform).

However, we have recently achieved much greater computational time savings using a different methodology. Here, we take advantage of the fact that every plane wave basis function has the same leakage pattern in *k*-space relative to its point location in the output model spectrum. This can be understood by thinking of our measured data as a continuous function sampled only at discreet irregular locations. In effect, our measured data is simply the product of delta functions at the measurement locations and the continuous amplitudes. Since a multiplication in space domain is a convolution in *k*-space, it follows that the measured spectrum of our data is the convolution of the desired but unknown model spectrum and the spectrum of the point locations that we measure (Grey, 1973). Recognizing this, we find that the leakage pattern is only a function of the sampling geometry and needs be computed only once. This serves as a lookup table where the leakage coefficient of any plane wave to another plane wave may be pulled based on their relative positions in k-space. This spectral template must be computed out to twice the desired k extents of the model spectrum. Figure 2 is, in fact, the leakage pattern created by the geometry in Figure 1.

The previous DFT approach to updating a spectral element involved computing trigonometric functions over all input data samples repeatedly and many calls to the NFFT routine for full spectrum updates. The pattern-removal approach involves only a single pass through the spectral samples performing only simple multiply and add operations. As a result, we have seen a factor of 20 speedup for 4D marine data and roughly a five-fold speedup on 5D marine data. The DFT cost scales in proportion to the number of input samples, whereas the pattern removal technique scales in proportion to number of output samples. Because data is sparser in 5D, the relative benefit of the pattern removal technique is decreased but still large.

Example

Figure 3a shows a crossline from a common offset cube from a 3D offshore Angola survey. There are many zig-zag patterns apparent which are caused by large amounts of feather combined with large azimuthal moveout effects. 5D data regularization is required to properly handle, or account for this.

Figure 3b shows the 5D interpolated result from the prior DFT technique which may be compared with the much more rapid pattern removal result shown in Figure 3c. There is no appreciable difference as can be seen in the difference section in Figure 3d.

DOI http://dx.doi.org/10.1190/segam2014-0724.1

Conclusions

ALFT may be sped up dramatically by taking advantage of the fact that the leakage pattern of plane waves is only a function of their relative positions in the spectrum. This pattern is simply the Fourier transform of the input trace coordinates and may be computed once at the beginning of the inversion process and used to quickly update the residual spectrum without going back to the time and space domain. This has led to much reduced computation times for 4D and 5D data regularization while improving accuracy relative to the prior DFT approach.

Acknowledgements

We would like to thank Chuck Mason, Himadri Pal, and Raheel Malik for their extensive testing and kind advice and to thank Connie VanSchuyver and Jeff Sposato for editing this paper. And we thank TGS management for permission to publish this work.

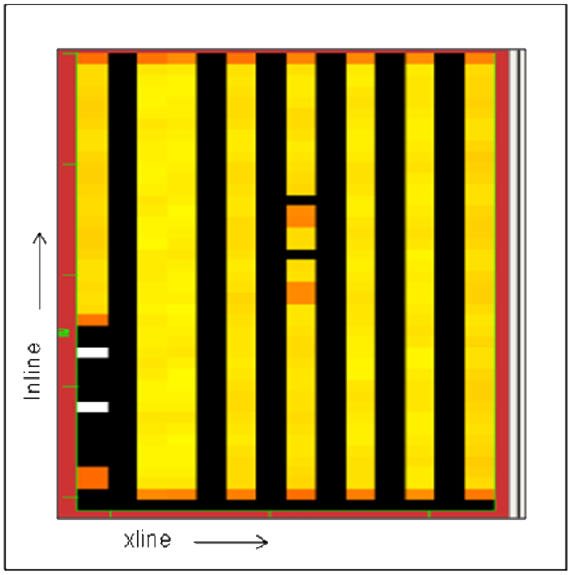

Figure 1. Map of input trace locations in inline and crossline. Each colored rectangle represents a line/cdp bin with one trace and black areas are where no trace exists. The colors (not labeled) represent trace weights based on Xu (2010) increasing from yellow to orange to white.

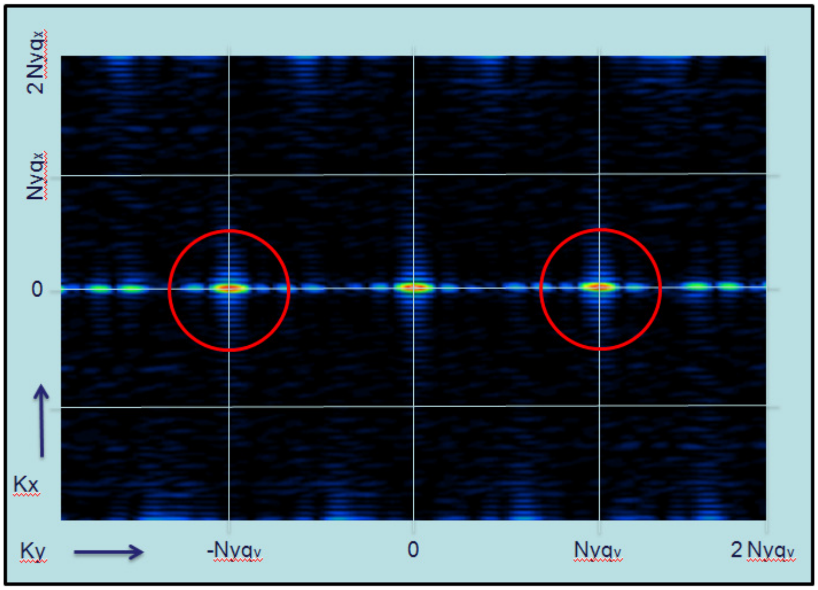

Figure 2. 20 Hz slice of leakage pattern from a flat reflector (*kx*=*ky*=0) on the traces in Figure 1. *Ky* corresponds to the crossline direction and aliased energy is circled in red.

DOI http://dx.doi.org/10.1190/segam2014-0724.1

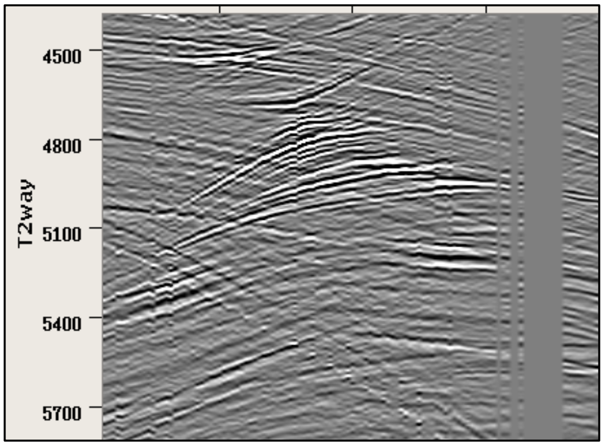

Figure 3a. Input crossline from 1500 m common offset bin. Zig-zags and discontinuities are due to source-to-receiver azimuth variations and strong azimuthal moveout effects.

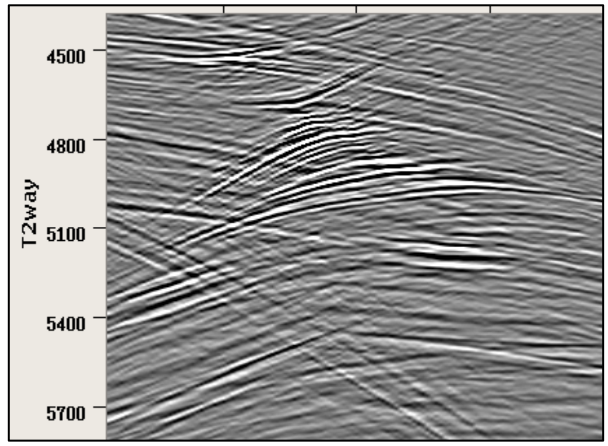

Figure 3b. 5D ALFT data regularization using DFT approach.

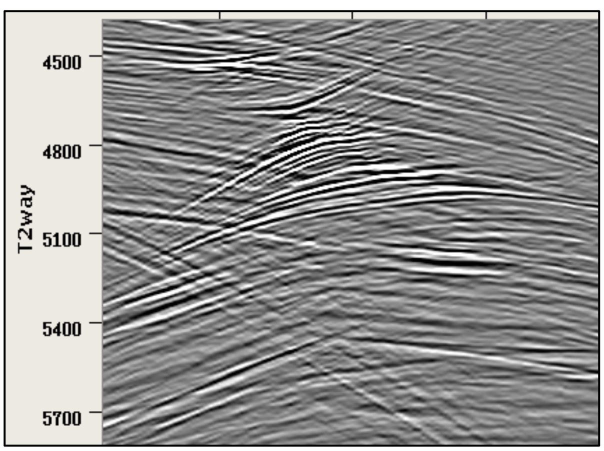

Figure 3c. 5D ALFT result using spectral pattern removal approach is computed 5x faster than DFT result in Figure 3b.

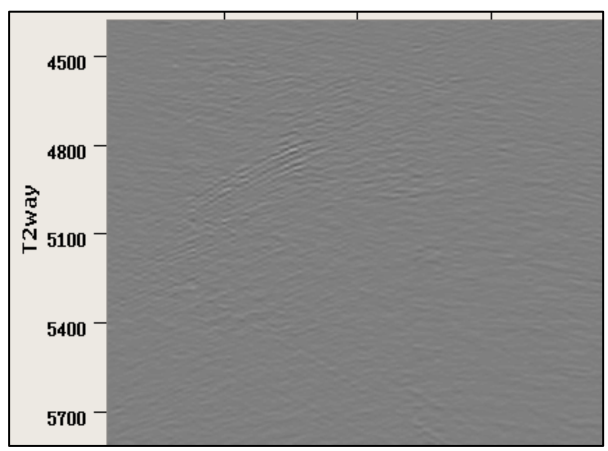

Figure 3d. Difference plot of DFT vs. pattern removal at same scale shows results are almost identical.

DOI http://dx.doi.org/10.1190/segam2014-0724.1

http://dx.doi.org/10.1190/segam2014-0724.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2014 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Gray, D. F., and K. Desikachary, 1973, A new approach to periodogram analyses: Astrophysical Journal, **181**, 523–530, http://dx.doi.org/10.1086/152068.

Keiner, J., S. Kunis, and D. Potts, 2009, Using NFFT 3 — A software library for various nonequispaced fast Fourier transforms: ACM Transactions in Mathematical Software, **36**, no. 4, http://dx.doi.org/10.1145/1555386.1555388.

Schonewille, M., K. Andreas, and V. Alan, 2009, Anti-alias anti-leakage Fourier transform: 79th Annual International Meeting, SEG, Expanded Abstracts, 3249–3253.

Xu, S., Y. Zhang, and G. Lambaré, 2010, Antileakage Fourier transform for seismic data regularization in higher dimensions: Geophysics, **75**, no. 6, WB113–WB120, http://dx.doi.org/10.1190/1.3507248.

Xu, S., Y. Zhang, D. Pham, and G. Lambaré, 2005, Antileakage Fourier transform for seismic data regularization: Geophysics, **70**, no. 4, V87–V95.