Wide Azimuth Interpolation

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Abstract

Seismic processing techniques, such as migration, have strict requirements on information content in the input seismic data. Although not a substitute for well-sampled field data, interpolation can provide useful data preconditioning that allows migration to work better. Seismic data interpolation has been around for long time, but only recently have we been able to use complex multidimensional and global algorithms that have the capability to infill large gaps in wide azimuth 3D land surveys. This innovation offers great potential for improvement, but the success of this technology strongly depends on three decisions: 1) the best domains to interpolate, 2) the optimal size of operators and 3) whether the original data should be regularized or kept untouched. The best domains to interpolate are those where the data look simple enough that a simple model can be used to predict unavailable information. The optimal size of operators depends on the structural complexity for every case and the initial sampling. Using operators that are too large can smear the data but operators that are too small cannot extract enough information to infill big gaps. Regularizing the data can produce an ideal geometry for migration, but this implies discarding all the original measurements and replacing them with predictions. Staying close to the input geometry in order to minimize distortions is a more conservative approach that can still help migration algorithms. Obviously, this decision depends on our confidence in the model that the interpolator uses.

Additional considerations when sampling in multiple dimensions affect our traditional aliasing constraints, because in multi-dimensions there is less overlapping between signal and aliases of the signal, opening new directions for research. In this paper, we address all these issues and show some examples of wide azimuth land data interpolation.

Introduction

All currently used 3D geometries have poor sampling along one or more dimensions. Migration suffers from artifacts when applied to poorly sampled data, because migration algorithms are based on the principle of constructive and destructive interference. Amplitude variations along offset and azimuth (AVO, AVAz) are affected in the presence of gaps. There are many different approaches to attack this problem. The only perfect solution is to acquire well-sampled data; all the other approaches attack the symptoms of the problem rather than the problem itself, and there is no guarantee that they can really solve it. However, given that in the real world we cannot go back to the field and fix the actual problem, we need to address this issue using all the processing tools at our disposal. It is important to realize that most seismic algorithms implicitly apply some sort of interpolation because they assume correctly sampled data. Usually, missing samples are assumed to be zero or similar to neighboring values. The advantage of using a separate interpolation algorithm is that more intelligent assumptions can be made using a priori information. For example, since interpolation uses the very reasonable constraint that frequencies beyond Nyquist are zero. Interpolation algorithms can then be viewed as methods to precondition the data with intelligent constraints.

Interpolation of wide-azimuth land data presents many challenges, some of them quite different from those of interpolating narrow-azimuth marine data sets. The most familiar interpolation algorithms have been developed for marine streamer surveys. Marine data are usually well sampled in the inline direction and coarsely sampled in the crossline direction. Many algorithms have been quite successful in infilling the crossline direction, even in the presence of aliasing and complex structure (Xu et al., 2005, Hung et al., 2004, Zwartjes, and Hindriks, 2001). Land data interpolation, however, brings additional complications because of noise, topography and its wide azimuth nature. In particular, the azimuth distribution forces us to use information from several dimensions at the same time.

Multidimensional interpolation algorithms are becoming feasible, even for five dimensions (Liu et al., 2004). This new capability raises new possibilities but also new questions. The general principle is still the same: missing data can be assumed similar to recorded data in its neighborhood, but the term "neighborhood" can have different meanings in multi-dimensions. Furthermore, a multi-dimensional operator has efficiency issues. Finally, data are always very irregular and sparse when analyzed in multi-dimensions. Therefore, interpolation has two different aspects: the general interpolation strategy (where to put the new traces, operator size, grouping of data), and the mathematical engine that uses some kind of model to predict the new traces. A discussion of these two aspects follows.

Different Interpolation Strategies

Different interpolation methods differ in complexity and assumptions and, most importantly, in operator size. Local methods (e.g., triangulation, nearest neighbour, etc.) tend to be robust, fast, adaptable and easy to implement. They use a simple model to represent the data in small windows. Their shortcoming is an inability to interpolate very large gaps, because they need nonexistent local information (there are no data around the trace to interpolate). Global methods are slower, less adaptable and harder to implement, because they cannot assume simple models for the data at a large scale. However, they can, at least in a mathematical sense, interpolate large gaps by using information supplied from distant data.

Most practical methods fall between these two extremes, but the sparser the sampling, the larger the operator size needs to be. If the geology is complex, a large operator can smear the features and decrease resolution. Our approach to this problem is to work with medium to large operators, but in domains where the data look simple. Our best results have been obtained in the inline-crossline- azimuth-offset-frequency domain with NMO-corrected data.

A related distinction is the number of dimensions that the algorithm can handle simultaneously. Although 3D seismic data have four spatial dimensions, one-dimensional methods use data along one dimension only. If the method is cascaded through the different dimensions, the order of these operations becomes extremely important. Multidimensional methods can use information from a well-sampled dimension to infill a poorly sampled dimension. In our experience, the best practice has been the use of four dimensions simultaneously, only in particular cases using all the five dimensions.

The issue of which dimensions to interpolate (where to put the new traces) is critical. To precondition the data properly for Kirchhoff migration, we desire full, uniform coverage of offsets and azimuths. Unfortunately, this can increase the size of the survey by an order of magnitude, making migration very expensive. Furthermore, full coverage surveys have geometries that can be very different from what we have acquired; going from the acquisition geometry to the full coverage geometry opens the door for data distortion.

To avoid this risk, we normally adopt a different approach: to stay as close as possible to the original geometry ("keep it real"). In this case the problem is well constrained by the original data, and good quality control is possible. We do this by creating new shots and/or receivers while keeping the original traces unchanged. Often this means that we decrease shot and/or receiver spacing (reducing bin size), or decrease shot and/or receiver line spacing to improve the offset and azimuth coverage (fold). In all cases, we take care not to add too many artificial traces. A quality control parameter is essential for this, allowing us to discard some interpolated traces, reducing the impact of the artificial traces on the final result. Typically, the quality parameter is the distance between the new and the original traces.

A different strategy is to regularize the data; this is to move the traces to a regular grid. Antileakage Fourier Transform (Xu et. al, 2005) and the pyramid transform (Hung et. al, 2004) are two successful data regularization techniques. These techniques require more localized operators (three dimensions instead of four or five) because regularization is computationally more expensive than interpolation.

The Interpolation Engine

The second major component of the interpolation problem is the choice of mathematical algorithm to predict new information given a set of recorded traces. One method with the flexibility to adapt to our requirements for multidimensional global interpolation is *Minimum Norm Weighted Interpolation* (MWNI) (Liu and Sacchi, 2004). MWNI is a constrained inversion algorithm formulated as follows. The actual data, d, are the result of a picking matrix (sampling), *T*, acting on an unknown fully sampled data set, *m*. The unknown (interpolated) data are constrained to have the same multidimensional spectrum as the original data. Enforcing this constraint requires a multidimensional Fourier Transform F_{nd}. To solve for the unknown data, a cost function is defined and minimized using standard optimization techniques. The cost function *J* is defined as

$$J = \|\mathbf{d} - \mathbf{Tm}\|^2 + \lambda \|\mathbf{m}\|_{\mathbf{W}} \quad \text{with a norm calculated as} \quad \|\mathbf{m}\| = \mathbf{m}\, \mathrm{F}_{nd}^{-1} |p_k|^{-2}\, \mathrm{F}_{nd}\, \mathbf{m}$$

F_{nd} is the multi-dimensional Fourier transform and *nd* is the dimension of the data with *nd* =2, 3 or 4 for 2D data, common azimuth, or 3D data, respectively. p_k is the spectrum of the unknown data, obtained by bootstrapping or iterations. In spite of being global, this method is very fast because it uses FFTs. Its main drawback is that the original data sampling has to be an integer multiple of the required final sampling along each dimension. Although this implies binning the data along the chosen dimensions, the effect of this on the interpolation is not strong because the binning effect in small wave numbers is negligible, with influence only on the inversion constraint.

Example

We show an example of the benefits of data interpolation for migration in Figure 1. The land data set in this example was acquired over a structured area in Thailand using orthogonal shot and receiver lines. The objective of the interpolation was to obtain more information on steep dips by including moderate to high frequency energy that the migration antialias filter usually removes. For this purpose we decreased the shot spacing along lines to decrease the bin size and therefore to relax the antialias filter. First, a PSTM migration/stack was produced using the original acquired data, and then the stack was interpolated, as shown in figure 1a. In Figure 1b, the data were interpolated before migration. The prestack interpolation produced a data set for migration input that was better sampled than the uninterpolated data set, and this allowed the migration to operate with greater fidelity (in this case, less anti-aliasing) on the steep-dip events. As expected, the prestack interpolation did not add information to the 3-D data set, but it did allow the migration to make better use of the information that was already there. Figure 2 shows the shot locations after interpolation. Red dots are the locations of the original shots and blue dots are the locations of the new shots. To fully cover the gaps a very large extrapolation is required (close to 1000 meters) but we decided to extrapolate only to 300 meters from the borders of the gaps. In this case, beyond 300 meters the extrapolated traces lose credibility.

Conclusions

3D land geometries are usually under sampled along one or more dimensions. As seismic processing becomes more demanding in terms of analyzing prestack data in detail, interpolation has become a very useful tool to condition the data for migration, AVO and AVAz. There are several well-understood algorithms for predicting data, but the engine used to predict missing samples is only half of the problem. Given that 3D seismic data live in five dimensions, it is very important to decide the best domain in which to apply this engine and the optimal size for the interpolation operator.

The perfect input data set for migration may contain full CMP coverage for all offset ranges and uniform azimuth distribution, but this is very different from typical current land data. This situation leads to conflicting goals for processing: either obtaining perfect data for, say, migration or preserving as much original data as possible. We need to resolve this conflict by understanding how much data should be created, where to put it, and how much we can trust it for subsequent processing. These decisions are related to considerations of aliasing, complexity of the structure in different domains, efficiency, ability to manage large gaps, and regularity of the sampling. We are just scratching the surface of this difficult problem.

New interpolation algorithms allow us to look at several dimensions at once; this is of great benefit when we process irregular data sets that typically have large gaps. Infilling shot and receiver lines or constant offset/azimuth planes are two approaches we have successfully applied to mitigate acquisition artifacts. Better understanding of these processes will certainly push forward today's state of the art in seismic processing.

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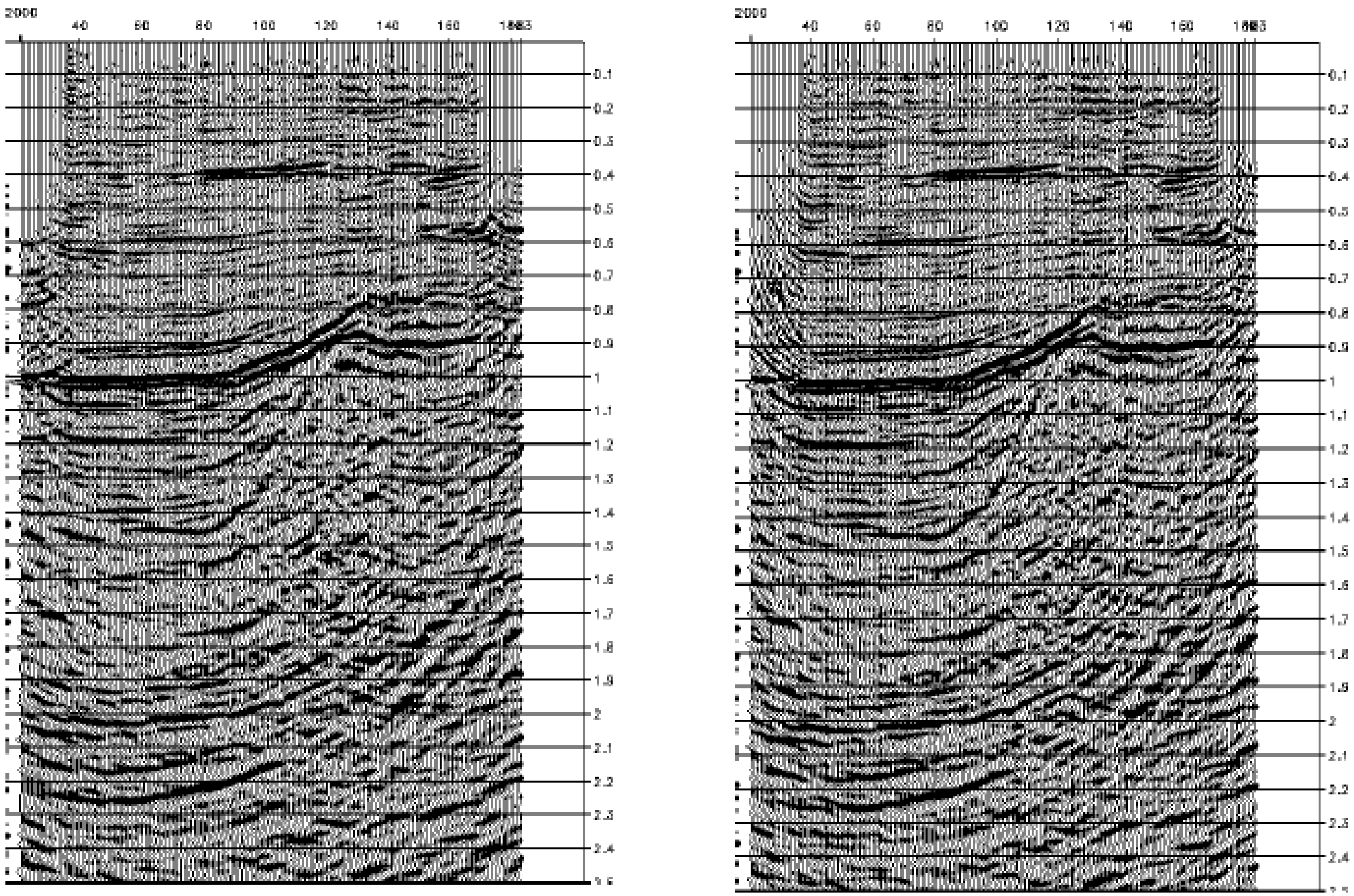

Figure 1. PSTM images from a land 3-D data set in Thailand. In (a) the interpolation was performed after stacking the migrated images; in (b) the interpolation was performed before the migration. The improved imaging of the steep-dip event in the center of the section is evident in (b). (Data courtesy of PTT Exploration and Production.)

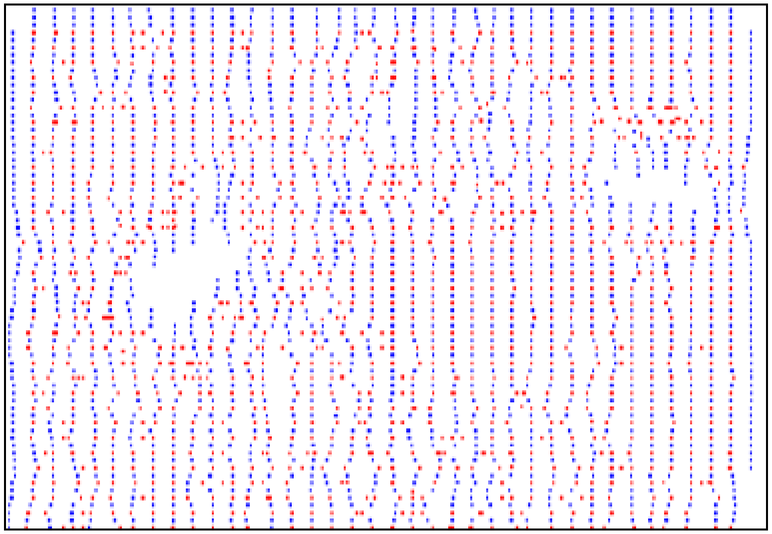

Figure 2. Shot locations after interpolation. Red dots are original shots. Blue dots are new (interpolated) shots. The two large gaps are between 1000 to 1500 meters in diameter (before interpolation). The shot spacing was decreased from 100 to 50 meters reducing the bin size by a factor of two along the vertical direction. The bins are now square as opposed to the original rectangular bins.