Abstract

Ideal 3-D land seismic data processing requires a dense 5-D dataset, most current land acquisition has sparse line spacing for both shot and receiver lines. Limited by the field conditions, even sparsely sampled seismic data is not usually acquired on a regular grid. Therefore, an effective regularization scheme is crucial for optimum 3-D seismic data processing.

Seismic data regularization using the Fourier method estimates spatial frequency components of data, which is usually recorded on an irregularly sampled grid. After obtaining the Fourier coefficients, the data can then be reconstructed on any desired locations, as long as it is within the area covered by the input trace locations. However, difficulties arise from the non-orthogonality of the global Fourier basis functions on an irregular grid, they cause frequency leakage and spatial aliasing, which may alter the quality of regularization. The recently presented Anti-Leakage Fourier Transform (ALFT) technique aims to overcome these problems.

In this paper we present a high-dimensional version of the ALFT algorithm and adapt it to land acquisition geometries. We will show that the proposed technique can generate good quality, 5-D, seismic data from current land seismic acquisition geometries. We propose a two-pass strategy to achieve the 5-D data regularization: first we regularize for the receiver locations from common-shot data, then we regularize the shot locations from common-receiver data. In this paper, we show some promising results on land data from high-dimensional ALFT.

Introduction

Recent seismic data processing developments such as 3-D multiple attenuation (Lin et al., 2004), global velocity analysis (Zhou et al., 2003) and true amplitude common-angle wave equation migration (Zhang et al., 2004) are expected to dominate the next generation of seismic data processing. Theoretically, for a 3-D survey, these techniques require regularly and densely sampled input data in a five dimensional space: two dimensions for shot locations, two for receiver locations and one for time ($x_s,x_s,y_r,y_r,t$). Until such improvements are achieved in the field, we will need to regularize the data during pre-processing.

For 3-D land seismic surveys, the acquisition geometries may have wide azimuth distribution. However, the sampling between lines is very sparse. For instance, with typical land acquisition, the receiver locations are well sampled in inline direction, but poorly sampled in crossline direction, while the shot locations are well sampled in crossline direction but poorly sampled in inline direction. As a result, these acquisition geometries produce seismic data
with both inline and crossline direction aliasing of the dipping events even at low frequency.
In addition to this sparseness, land acquisition also suffers from environmental constraints
such as mountains, rivers, and culture etc., resulting in irregular data grid. Sparse sampling
and irregularities prevent applying wave equation based techniques (both migration and
multiple attenuation). Thus, data regularization is crucial for improving land data processing.

An efficient land data regularization scheme is necessary for handling both sparse data
sampling and strong acquisition irregularities, generating the ideal, dense and regular
acquisition geometry. The input land data is acquired in a five dimensional space (even if
sparse), so a dedicated, high-dimensional regularization/interpolation algorithm is required for
production processing. When complex structures are present, it is difficult to apply the
traditional land data regularization algorithms (Mazzucchelli and Rocca, 1999; Mazzucchelli
et al., 2000), which are based on NMO/DMO techniques and assume oversimplified
geological models. Though some high dimensional interpolation algorithms have already
been proposed to overcome spatial data aliasing (e.g Curry (2004), Liu et al. (2004)), The
ALFT algorithm shows it’s accuracy and efficiency with promising field data results (Xu et
al., 2004a). It allows randomly sampled data as input, and has shown good estimates of the
Fourier coefficients from an irregular grid (Xu et al., 2004b). Its first application, regularizing
marine seismic field data in the crossline direction, demonstrated the accuracy and efficiency
of the approach. In this paper, we generalize the ALFT algorithm to higher dimensions, and
apply it to land data. In land acquisition, the acquired dataset can be organized in either
common-shot gathers or common-receiver gathers. The common-receive or common-shot
gather of traces covers the 2-dimensional acquisition surface with an irregular sparse grid. To
reduce the high computational cost, we first regularize the receiver locations onto a regular
grid within the common-shot gathers, and then regularize the shot locations onto the same
regular grid within the common-receiver gathers. Therefore, the 5-D seismic data
regularization for land acquisition is decomposed into a two-pass 3-D data regularization.

Theory and Algorithm

As described in Xu et al. (2004a, 2004b), after transforming the seismic trace to the frequency
domain, ALFT transforms the seismic data from its irregular spatial coordinates to the wave-
number domain. The ALFT algorithm consists of the following three main steps:
1. Spatial forward Discrete Fourier Transform (DFT) the data on an irregular grid;
2. Spatial inverse DFT the most energetic Fourier component to the irregular grid;
3. Subtract this single component from the input data on the irregular grid to prepare the
   input for the next iteration and re-orthogonalize the Fourier basis.

In higher dimensions, the discrete input data positions and wave numbers are vectors and the
ALFT can be formulated as the following:

\[
\hat{f}(\mathbf{k}) = \frac{1}{\Delta x} \sum_{l \in N_p} \Delta x, f(x_i)e^{-2\pi \mathbf{k} \cdot x_i},
\]

\[
f^{k_m}(x_i) = \hat{f}(\mathbf{k}_m)e^{2\pi \mathbf{k}_m \cdot x_i},
\]

\[
f''(x_i) = f(x_i) - f^{k_m}(x_i).
\]

where \( \mathbf{k} \) denotes the wave-numbers, \( \mathbf{k}_m \) is the wave-number with the maximum energy in the
current iteration and \( f(x_i) \) denotes the input data for this iteration. \( f''(x_i) \) is the updated
input data for solving the next Fourier coefficient, which is sampled on the same irregular grid
as \( f(x_i) \). \( N_p \) is the total number of input trace locations \( x_i \) on an irregular grid. \( \Delta x_i \) are the
DFT summation weights, which can be represented as the sampling density function related
only to the input irregular grid in high dimensions; In our case, we have only two dimensional
irregularities, so the weights can be estimated by the method of Jousset et al. (2000). The $\Delta X$ is a global normalization parameter:

$$\Delta X = \sum_{l=N_p}^p \Delta x_l .$$  \hspace{1cm} (2)

Figure 1. ALFT data regularization for a common shot gather. Left: the acquired common shot gather; right: the common shot gather after ALFT regularization.

The theoretical computational cost of ALFT has order of $O(N_p \times N_k^2)$, with $N_k$ the total number of Fourier coefficients to be solved. An important advantage of the ALFT algorithm is that it can automatically handle aliased events with different amplitude scale (Gray and Desikachary, 1973), which is crucial for regularization on current land dataset.

**Application to a field dataset**

We have generalized the ALFT algorithm to work for land 3-D seismic data. The regularization algorithm is suitable for the common-shot gathers, where receivers irregularly cover the full 2D surface.

In Figure 1, an input shot gather is shown on the left; the receivers are on 8 receiver lines, with approximately 50m receiver spacing within the cables, but with approximately 200m between the cables. The shot position is at the center of the receiver patch. On the common-shot gather, the inline direction is well sampled and with no serious irregularities along it. The crossline direction is poorly sampled and is not suitable for common-shot wave equation migration. Therefore, data regularization is required to put the receivers on a 50x50m grid. The right hand side of Figure 1 shows the result from an ALFT regularization. With the now well-sampled common-shot data, a common-shot wave equation migration can be used.

**Conclusions**

We have developed a 3-D ALFT algorithm, regularizes/interpolates data located on an irregular 2-D surface. ALFT is a high fidelity interpolation algorithm, the DFT’s orthogonality on a irregular grid are improved by the subtraction step (Xu, et. al. 2004b). This technique can
be used to effectively regularize seismic data and to fill in some acquisition “holes”. Also it can be applied to correct for data aliasing problems. The proposed algorithm can overcome the “sparsely samples problem”, across both shot lines and receiver lines, hence it is quite suitable for land data pre-processing.

The application to field data is achieved by a two-pass strategy: regularizing the receiver locations in a common-shot gather and then regularizing within each common-receiver gather. When applied to field data, ALFT regularization can provide the “optimum” 5-D dataset required for further processing. This regularized 5-D data is crucial for prestack true-amplitude angle/azimuth migration, which provides not only good quality images, but also azimuthal anisotropy information for velocity model building and AVA analysis for reservoir characterization.

Acknowledgements

We thank Veritas DGC. for the permission of publishing this paper. We are also grateful to Yan Huang for helpful discussions and for providing the input field data. We thank Gareth Williams and Bruce Ver West for discussions and improvement of abstract writing.

References


Xu, S., Zhang, Y., Pham, D. and Lambaré, G., 2004a, Anti-leakage Fourier transform for seismic data regularization, accepted by Geophysics.

