Acquisition geometry regularization for multicomponent data

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SUMMARY

Acquisition geometry regularization is a key process for obtaining reliable subsurface images with 3D seismic data. 3D geometry regularization is, so far, a technique mainly used on *PP* land data. Multicomponent ocean bottom cable (OBC) technology simulates 3D land acquisition for multicomponent geophones at the ocean bottom. In order to obtain reliable subsurface *PS* images, that provide amplitude information, we should perform an acquisition geometry regularization process on both *PP* and *PS* data. We propose an acquisition geometry regularization methodology in the least-squares sense that uses a converted waves Azimuth Moveout (*PS*AMO) operator as a regularization term in the model space.

INTRODUCTION

Multicomponent ocean bottom seismic reestablishes the use and importance of converted waves (*PS*) data, yet opens the door for a series of new and existing problems with *PS* data. Irregular acquisition geometries are a serious impediment for accurate subsurface imaging. Irregularly sampled data affects the image with amplitude artifacts and phase distortions. Irregular geometry problems are more evident in cases for which the amplitude information is one of the main goals of study. For *PS* data, this problem is crucial since most of the *PS* processing focuses on the estimation of rock properties from seismic amplitudes.

The application of inverse theory satisfactorily regularizes acquisition geometries of 3D prestack seismic data (Audebert, 2000; Chemingui, 1999; Duijndam et al., 2000; Rousseau et al., 2000; Albertin et al., 1999; Bloor et al., 1999; Nemeth et al., 1999; Duquet et al., 1998). For *PP* data, there are two distinct approaches to apply: 1) data regularization before migration and 2) irregular geometries correction during migration. Biondi and Vlad (2002) combine the advantages of the previous two approaches. Their methodology regularizes the data geometry before migration, filling in the acquisition gaps with a partial prestack migration operator. This operator exploits the intrinsic correlation between prestack seismic traces. The partial prestack migration operator used is Azimuth Moveout.

This paper address irregularities in the acquisition geometry for *PS* data. We follow Biondi and Vlad's (2002) work, solving for geometry irregularities using a preconditioned-regularized least-squares scheme. In order to do that, we develop an azimuth moveout operator for converted waves (*PS*AMO). This operator acts as a regularization term in the model space while solving the least-squares problem. Moreover, the *PS*AMO operator ensures the preservation of dipping events and correct for the lateral shift of the common conversion point.

Our methodology depends on the ratio between the *P* and the *S* velocities (γ), since the *PS*AMO operator depends on this ratio. This situation makes our methodology an iterative procedure that focuses on minimizing the difference for γ before and after the geometry regularization procedure. The development of *PS*AMO and its implementation as a roughener operator in a least-squares scheme satisfactorily compensates for acquisition gaps in converted waves data.

First, we present the development of the *PS*AMO operator. We discuss a regularized least-squares scheme, that includes the *PS*AMO operator, in order to solve for acquisition geometry irregularities. Finally, we present the results of applying our methodology over a portion of the 3D OBC data set acquired above the Alba reservoir in the North Sea.

PS AZIMUTH MOVEOUT

Azimuth moveout (AMO) is a partial prestack migration operator that transforms prestack data into equivalent data with a different offset and azimuth position (Biondi et al., 1998; Chemingui and Biondi, 1997; Chemingui, 1999). AMO has the advantage of transforming prestack data into equivalent data with arbitrary offset and azimuth, moving events across midpoints according to their dip.

AMO is not a single trace to trace transformation. It is a partial prestack migration operator that moves events across midpoints according to their dip. Due to the nature of *PS*-data, where multiple coverage is obtained through common conversion point gathers (CCP), the *PS*AMO operator moves events across common conversion points according to their geological dip.

The cascade operation of *PS*DMO and inverse *PS*DMO yields to the *PS*AMO operator. We use the *PS*DMO operator in the log-stretch frequency-wavenumber domain (Xu et al., 2001). Performing the cascade operation of this *PS*DMO operator with its inverse, we obtain the *PS*AMO operator. This *PS*AMO operator consists of two main operations:

1. The input data ($P(t, \mathbf{x}, \mathbf{h_1})$) is transformed to the wavenumber domain ($P(t, \mathbf{k}, \mathbf{h_1})$) using FFT. Then, a lateral shift correction is applied as:

$$\widetilde{P}(t, \mathbf{k}, \mathbf{h_1}) = P(t, \mathbf{k}, \mathbf{h_1}) e^{i\mathbf{k}\cdot(\mathbf{D_1}-\mathbf{D_2})}. \qquad (1)$$

   Then, we apply a log-stretch along the time axis ($\tau = \ln(t/t_c)$).

2. The log-stretched time domain (τ) axis is transformed into the log-stretched frequency domain (Ω) by FFT. Then, the filters $F(\Omega, \mathbf{k}, \mathbf{h_1})$ and $F(\Omega, \mathbf{k}, \mathbf{h_2})$ are applied as follow:

$$P(\Omega, \mathbf{k}, \mathbf{h_2}) = \widetilde{P}(\Omega, \mathbf{k}, \mathbf{h_1}) \frac{F(\Omega, \mathbf{k}, \mathbf{h_1})}{F(\Omega, \mathbf{k}, \mathbf{h_2})}. \qquad (2)$$

   The filter $F(\Omega, \mathbf{k}, \mathbf{h_i})$ is

$$\begin{cases} 0 & \text{for } \mathbf{k}\cdot\mathbf{h_i} = 0 \\ \mathbf{k}\cdot\mathbf{H_i} & \text{for } \Omega = 0 \\ e^{\frac{i}{2}\Omega\left\{\sqrt{1+\left(\frac{2\mathbf{k}\cdot\mathbf{H_i}}{\Omega}\right)^2}-1-\ln\frac{1}{2}\left[\sqrt{\left(\frac{2\mathbf{k}\cdot\mathbf{H_i}}{\Omega}\right)^2+1}+1\right]\right\}} & \text{else.} \end{cases} \qquad (3)$$

The vectors $\mathbf{H_i}$ are a modified expression of the offset vectors ($\mathbf{H_i} = (2\sqrt{\gamma}/1+\gamma)\mathbf{h_i}$). The vectors $\mathbf{D_i}$ represent a lateral shift correction given by:

$$\mathbf{D_i} = \left[1 + \frac{4\gamma||\mathbf{h_i}||^2}{v_p^2 t_n^2 + 2\gamma(1-\gamma)||\mathbf{h_i}||^2}\right] \frac{1-\gamma}{1+\gamma}\mathbf{h_i}. \quad (4)$$

DATA REGULARIZATION

Regularized least-squares theory is the fundamental basis for solving the acquisition geometry regularization problem in this work. To preserve the resolution of dipping events in the final image, the regularization term includes a transformation by Azimuth Moveout (Biondi and Vlad, 2002). Additionally, Biondi and Vlad's method is computationally efficient because it applies the AMO operator in the Fourier domain and preconditions the regularized least-squares problem.

Using the *PS*AMO operator [equations (1) and (2)] as the regularization term in the model space allows to: 1) preserve the resolution of the dipping events, 2) correct for the spatial lateral shift of the common conversion point.

We discuss the concerns of handling *PS* data due to the dependency of the *PS*AMO operator on the ratio between the *P* and the *S* velocities.

*PS*AMO regularization

Partial stacking of the data recorded with irregular geometries within offset and azimuth ranges yields uniformly sampled common offset/azimuth cubes. In order to enhance the signal and reduce the noise, the reflections should be coherent among the traces that are stacked. Normal Moveout (NMO) is a common method used to create this coherency among the traces.

Let's define a simple linear model that links the recorded traces (at arbitrary midpoint locations) to the stacked volume (defined on a regular grid). Each data trace is the result of interpolating the stacked traces and equal to the weighted sum of the neighboring stacked traces. In matrix notation, this transforms to:

$$\mathbf{d} = \mathbf{A}\mathbf{m}, \quad (5)$$

where $\mathbf{d}$ is the data space, $\mathbf{m}$ is the model space and $\mathbf{A}$ is the linear interpolation operator. Formulating problem (5) in the least-squares sense, we have:

$$\min_{\mathbf{m}} \quad ||\mathbf{A}\mathbf{m} - \mathbf{d}||^2. \quad (6)$$

In general, the operator $\mathbf{A}$ is not square, and its inverse is not defined; therefore, we use its least-squares inverse. The least-squares solution to this overdetermined problem is given by

$$\mathbf{m} = \left(\mathbf{A}'\mathbf{A}\right)^{-1} \mathbf{A}'\mathbf{d}. \quad (7)$$

The least-squares solution is equivalent to applying the adjoint operator, $\mathbf{A}'$, followed by a spatial filtering of the model space. The inverse of $\mathbf{A}'\mathbf{A}$ represents this spatial filtering. Note that a fold normalization, acting as a diagonal operator $\mathbf{W}_m$, can be seen as a particular approximation of the inverse of $\mathbf{A}'\mathbf{A}$.

With the knowledge of model regularization in the least-squares inverse theory, it is possible to introduce smoothing along offset/azimuth in the model space. The regularized least-squares problem becomes:

$$\min_{\mathbf{m}} \quad \left\{||\mathbf{A}\mathbf{m} - \mathbf{d}||^2 \quad + \quad ||\epsilon_D \mathbf{D_h}'\mathbf{D_h}\mathbf{m}||^2\right\}, \quad (8)$$

where the roughener operator $\mathbf{D}_h$ can be an integration operator. However, the use of an integration operator may yield to the loss of resolution when geological dips are present. The substitution of the identity matrix in the lower diagonal of $\mathbf{D}_h$ with the *PS*AMO operator correctly transforms a common offset azimuth cube into an equivalent cube with a different offset and azimuth. This transformation also preserves the geological dip.

Partial stacking requires the data to be coherent among the traces. NMO obtains this coherency well for *PP* data. However, for converted waves we know that the moveout is not a perfect hyperbola, even in constant velocity media.

On conventional *PP* processing, the AMO operator is velocity independent. However, for converted waves the *PS*AMO operator depends on the ratio between the *P* and the *S* velocities (γ). Therefore, we need *a priori* velocity estimation. This suggests that for different γ values we will have different results.

Traditional *PS* processing attempts to first sort the data in the common conversion point (CCP) domain. This process has always been dependent on the value of γ; therefore, the *PS* processing community performs iterative processing (CCP binning, velocity analysis) until obtaining a satisfactory result.

After performing NMO on the *PS* data and the *PP* data, the value of γ is (Huub Den Rooijen, 1991):

$$\gamma = \frac{v_p^2}{v_{eff}^2}, \quad (9)$$

where v_{eff} is the NMO velocity of the *PS* section.

In order to proceed with the *PS* data regularization, a process that depends on the value of γ, we need to apply a *PS*NMO operator and obtain both an RMS velocity model and a γ value. We proceed with the following algorithm:

1. Sort the data in the CMP domain.
2. Estimate velocity model on the *PS* section.
3. Estimate the γ value with equation (9).
4. If it is not the first iteration, compare the previous and the actual γ values and:
   (a) if they are the same, finish the process.
   (b) if they are not, continue.
5. Apply NMO on the *PS* section.
6. Apply *PS*AMO acquisition geometry regularization.
7. Apply inverse NMO.
8. Go back to step 2.

RESULTS

We apply AMO regularization to a portion of a real OBC data set, the Alba field. The Alba oil field is located in the UK North Sea and elongates along a NW-SE axis. The oil reservoir is 9km long, 1.5km wide, and up to 90m thick at a depth of $1,900$m subsea (Newton and Flanagan, 1993).

A multicomponent OBC data set consists of both a *PP* and a *PS* section. Since the literature already presents extended work on *PP* regularization, we will present compact but complete regularization results for the *PP* portion. However, we will present more results and extended analysis for the *PS* section.

We use a portion of the entire 3D cube. This subsection consists of 17 crosslines with 719 cmps each. The *PP* section uses only the absolute value of the offset, for a total of 121 offsets. The *PS* section uses the full offset, the maximum offset extension is 4000m.

PP regularization

Figure 1 (top) presents the *PP* data for one crossline of the data set in our study. Observe the holes in the data due to irregularities in the geometry acquisition.

Biondi and Vlad (2002) examine the differences among regularizing the data with normalization, regularization with the integration operator and regularization with the AMO operator. They conclude that the precondition of the regularized least-squares problem with the AMO operator yields more continuous results.

On this part of the problem, we present the interpolation results using AMO regularization, bottom of Figure 1.

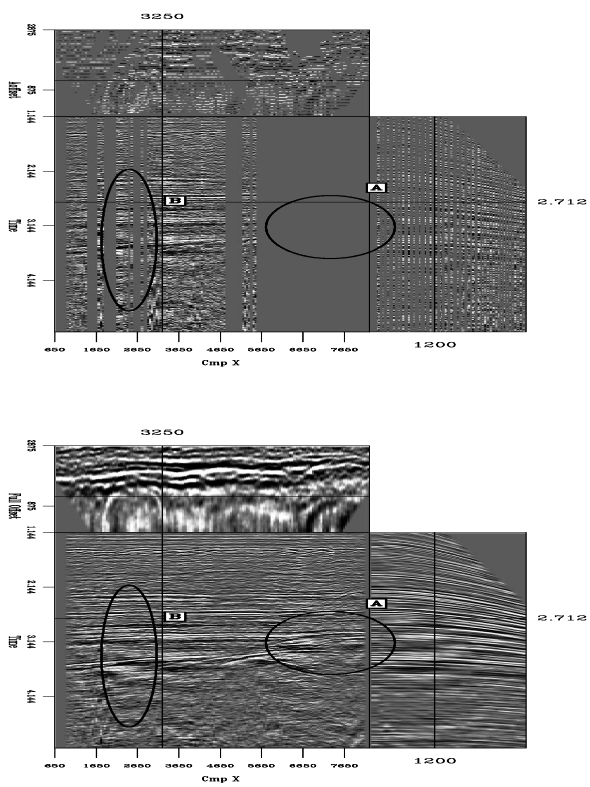

Figure 1: Acquisition geometries regularization results, original data (top) and AMO geometry regularization (bottom).

PS regularization

Figure 2 (top) depicts a *PS* line from the 3D data set. Again, observe the holes in the data, as well as the presence of more offset.

The data is sorted into CMP gathers. The *PS*AMO operator internally performs the correction from CMP point to CCP point based on the γ value.

Figure 2 (bottom) exhibits the geometry regularization result with the *PS*AMO as the roughener operator. Note that the moveout of the events is not a perfect hyperbola. This characteristic corresponds to the nature of propagation of *PS* waves.

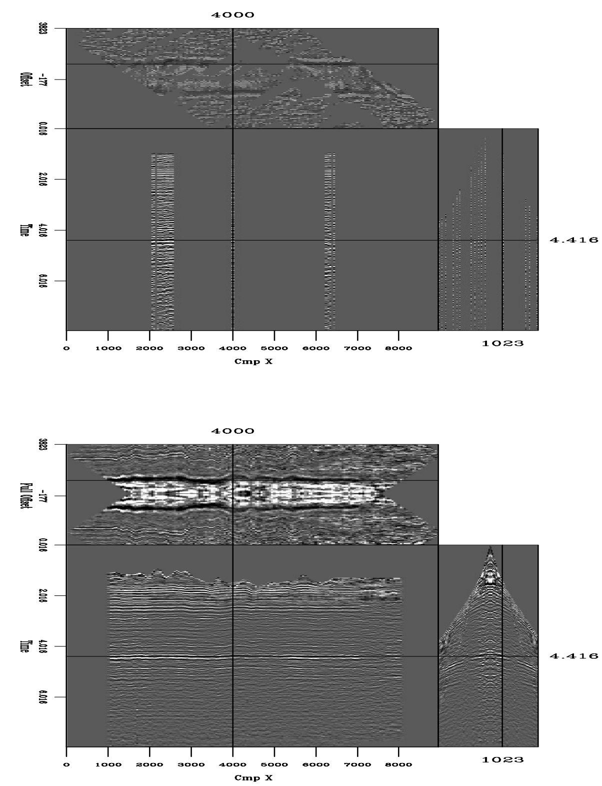

Figure 2: 2D line from the 3D OBC data set in process (top). *PS* regularization results using the *PS*AMO operator (bottom).

Figure 3 presents, from top to bottom, a detailed view of: 1) data set, 2) first iteration result of the PS geometry regularization process and 3) second iteration result. It is easy to observe that both results fit the data equally well. However, the second iteration is more realistic since it better follows the information of the surrounding traces.

CONCLUSIONS

We introduced a partial prestack migration operator for converted waves (*PS*AMO), this operator performs in the frequency wavenumber domain, it depends on γ and internally transforms a CMP into CCP.

We presented a regularized least-squares inverse theory that uses this *PS*AMO operator as the regularization term. This method satisfactorily interpolates the *PP* portion for the 3D OBC Alba data set. For the *PS* section, we follow an iterative scheme updating the P to S velocity ratio.

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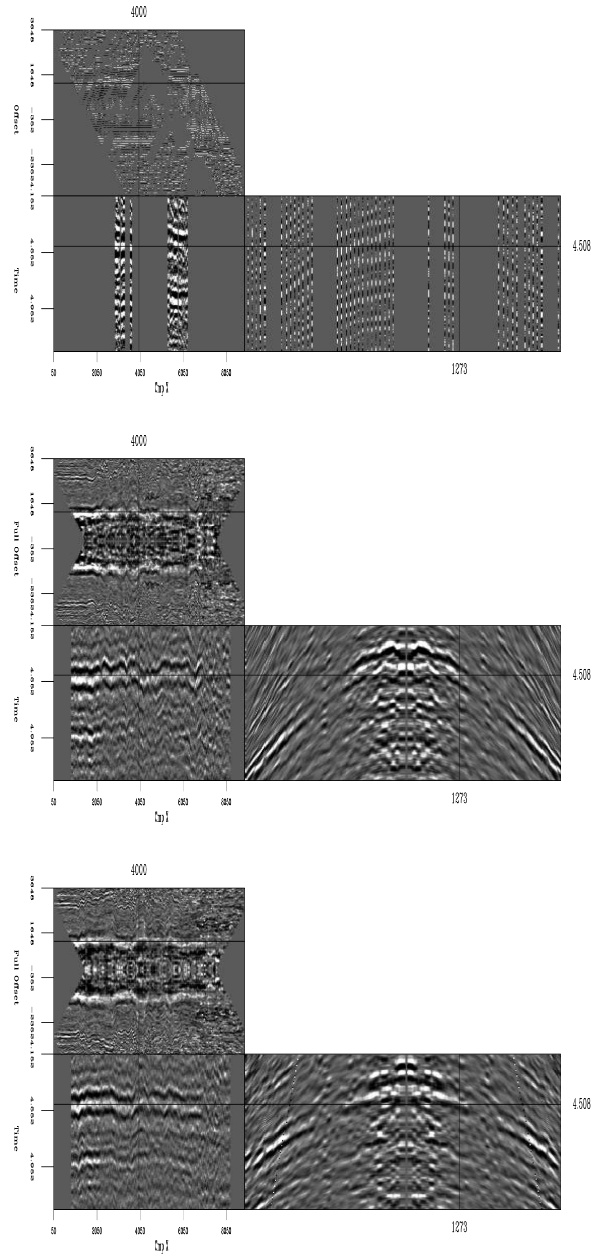

Figure 3: Detailed view of: the original data (top), the first (center) and the second (bottom) iterations.

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