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PS - Azimuth moveout: Real data application

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ABSTRACT

We present an application of the PS-AMO operator for partial-stacking 3-D multicomponent, ocean-bottom seismic data. The partial-stacking problem is defined as a regularized least-squares objective function. To preserve the resolution of dipping events, the regularization term uses the PS-AMO operator. Application of this methodology on a portion of the Alba 3-D, multicomponent, ocean-bottom seismic data set shows that we can satisfactorily obtain an interpolated data set that honors the physics of converted waves.

INTRODUCTION

PS Azimuth Moveout (PS-AMO) transforms the offset and azimuth of multicomponent data. To do this, we transform the data from the CMP domain to the CRP domain, where we compute the new offset and azimuth, and then transform back from the CRP domain to the CMP domain. Theoretically, the cascade operation of any 3-D prestack imaging operator with its inverse produces AMO (Rosales and Biondi, 2006)

PS-AMO has several potential applications for 3-D multicomponent processing. One is geometry regularization, through which PS-AMO helps to fill in the acquisition gaps using the information of surrounding traces. Another is data-reduction through partial stacking, which combines PS-AMO and partial stacking to reduce the computational cost of 3-D prestack depth imaging. A third application is the interpolation of unevenly sampled traces, which differs from the first application in the sense that PS-AMO is the main interpolation operator. In this paper, we will use PS-AMO to reduce the dimensionality of the 3-D prestack data, that is, to go from a five-dimensional prestack cube ($P(t,\mathbf{x},\mathbf{h})$) to a four-dimensional cube ($\widetilde{P}(t,\mathbf{x},h_x)$).

Multicomponent ocean-bottom seismometer (OBS) technology brings new problems to the table with converted-wave data. One of the main problems with OBS data is the irregularity in the acquisition geometry. Irregular geometries are a serious impediment to accurate subsurface imaging (Beasley, 1994; Gardner and Canning, 1994; Chemingui, 1996). Irregularly sampled data affect the image with amplitude artifacts and phase distortions if the missing data are assumed to be zero traces. Irregular geometry problems are more evident in cases in which the amplitude information is one of the main goals of study. Typical OBS seismic-data acquisition presents processing problems similar to those of land data. Gardner and Canning (1994) demonstrate some of the effects of irregular sampling on 3-D prestack migration, through synthetic examples using real 3-D land-acquisition geometry. For converted waves, the problem of irregular sampling is especially crucial, since most of the PS processing focuses on the estimation of rock properties from seismic amplitudes.

To solve the problem of reorganizing irregular geometries, there are two distinct approaches that can be applied: 1) data regularization before migration (Duijndam et al., 2000), and 2) irregular-geometry correction during migration (Duquet et al., 1998; Nemeth et al., 1999; Albertin et al., 1999; Bloor et al., 1999; Audebert, 2000; Rousseau et al., 2000; Prucha and Biondi, 2002). 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 an AMO operator that preserves the amplitudes in the frequency-wavenumber log-stretch domain.

A methodology that involves the PS-AMO operator can be used to solve for geometry irregularities of OBS PS data. Due to the asymmetry of ray trajectories in PS data, there are more elements to consider in PS-data regularization than in PP-data regularization. Our method for PS-data regularization uses the PS-AMO operator to preserve the resolution of dipping events and correct for the lateral shift between the common midpoint and the common reflection point.

The 3-D OBS data set acquired above the Alba reservoir in the North Sea serves as test data for our PS geometry-regularization methodology. We show how our methodology fills the acquisition gaps using information from neighboring traces and the physics of the converted-wave propagation phenomena, as we reduce the dimensionality of our data from five dimensions to four dimensions.

Throughout this paper, we will first describe the PS-AMO operator used for this experiment and its implementation; then we will describe its application to reduce the dimensionality of the data set in preparation for converted-wave common-azimuth migration of the 3-D OBS data set from the Alba oil field.

F-K LOG-STRETCH PS-AMO

The PS-AMO operator is conceived of as a cascade of forward and reverse PS-DMO; therefore, the accuracy and speed of the PS-DMO operator is important. The PS-DMO operator in the frequency-wavenumber domain (Alfaraj, 1992) is accurate and conceptually simple, but is computationally expensive because the operator is nonstationary in time.

The technique of logarithmic time-stretching, introduced by Bolondi et al. (1982), increases the computational efficiency, because the PP-DMO operator is stationary in the log-stretch domain. Fast Fourier Transforms (FFT) also can be used instead of the slower Discrete Fourier Transforms (DFT). Zhou et al. (1996) create a PP-DMO operator that considers variations of the traveltime as well as variations in the midpoint position before and after PP-DMO; therefore, the operator has the main properties of handling steeply dipping reflectors properly, and producing slightly stronger amplitudes for steep reflectors. Xu et al. (2001) introduce a log-stretch frequency-wavenumber PS-DMO operator that is computationally efficient and kinematically correct; moreover, their implementation performs a correction for the transformation from CMP to CRP. However, this implementation does not consider the variation along CMP as does the PP-DMO Zhou's et al. (1996) PP-DMO operator does. Rosales (2002) follows a procedure similar to the one Zhou et al. (1996) used for the derivation of PP-DMO to create a 3-D PS-DMO operator that that considers both time shift and spatial shift. This 3-D PS-DMO operator is computationally efficient and kinematically correct.

Rosales and Biondi (2002) introduces the PS-AMO operator that we use in this paper. This PS-AMO operator is computationally efficient because it performs in the frequency-wavenumber log-stretch domain. This PS-AMO operator consists of two main operations. In the first operation, 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 using the transformation vectors ($\mathbf{D_{10}}$ and $\mathbf{D_{02}}$) as follows:

$$\widetilde{P}(t,\mathbf{k},\mathbf{h_1}) = P(t,\mathbf{k},\mathbf{h_1}) e^{i\mathbf{k}\cdot(\mathbf{D_{10}}-\mathbf{D_{02}})}, \tag{1}$$

this lateral shift is responsible for the CMP to CRP correction, the transformation vectors, $\mathbf{D_{10}}$ and $\mathbf{D_{02}}$) are:

$$\mathbf{D_{10}} = \left[1+\frac{4\gamma\|\mathbf{h_1}\|^2}{v_p^2 t_1^2 + 2\gamma(1-\gamma)\|\mathbf{h_1}\|^2}\right]\frac{1-\gamma}{1+\gamma}\mathbf{h_1}, \tag{2}$$

$$\mathbf{D_{02}} = \left[1+\frac{4\gamma\|\mathbf{h_2}\|^2}{v_p^2 t_0^2 + 2\gamma(1-\gamma)\|\mathbf{h_2}\|^2}\right]\frac{1-\gamma}{1+\gamma}\mathbf{h_2}. \tag{3}$$

The final step of the first operation is to apply a log-stretch along the time axis with the following relation:

$$\tau = \ln\left(\frac{t}{t_c}\right), \tag{4}$$

where t_c is the minimum cutoff time, introduced to avoid taking the logarithm of zero. The data set after the first operation is $\widetilde{P}(\tau,\mathbf{k},\mathbf{h_1})$. In the second operation, the log-stretched time domain (τ) section is transformed into the frequency domain (Ω) using FFT. Then, the filters $F(\Omega,\mathbf{k},\mathbf{h_1})$ and $F(\Omega,\mathbf{k},\mathbf{h_2})$ are applied as follows:

$$P(\Omega,\mathbf{k},\mathbf{h_2}) = \widetilde{P}(\Omega,\mathbf{k},\mathbf{h_1})\frac{F(\Omega,\mathbf{k},\mathbf{h_1})}{F(\Omega,\mathbf{k},\mathbf{h_2})}. \tag{5}$$

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

$$F(\Omega,\mathbf{k},\mathbf{h_i}) = e^{i\Phi(\Omega,\mathbf{k},\mathbf{h_i})}, \tag{6}$$

with the phase function $\Phi(\Omega,\mathbf{k},\mathbf{h_i})$ defined by

$$\Phi(\Omega,\mathbf{k},\mathbf{h_i}) = \begin{cases} \alpha\mathbf{k}\cdot\mathbf{h_i} & \text{for } \Omega = 0 \\ \frac{1}{2}\Omega\left\{\sqrt{1+\left(\frac{2\alpha\mathbf{k}\cdot\mathbf{h_i}}{\Omega}\right)^2} - 1 - \ln\frac{1}{2}\left[\sqrt{\left(\frac{2\alpha\mathbf{k}\cdot\mathbf{h_i}}{\Omega}\right)^2+1}+1\right]\right\} & \text{for } \Omega \neq 0. \end{cases} \tag{7}$$

The set of equations 1-7 compose the *f-k* log-stretch PS-AMO operator. The next session describes the practical implementation of this operator in order to reduce the dimensionality of the data set.

IMPLEMETATION

The PS-AMO operator described above works on a regular sampled cube, our data is recorded on an irregular mesh. Following the methodology described in Clapp (2006) we first map our data to a regular 5-D mesh. For this problem we chose nearest neighbor interpolation, designated by the operator $\mathbf{L}'$. For migraion efficiency, and because the five-dimensional space is sparsely populated, we want to reduce the dimensionality of our dataset. A common goal, and the one we chose to implement, was to create common azimuth volume orriented along the inline direction. As a result we want to eliminate the h_y axis.

Our PS-AMO operator (diagramed in Figure 1) allows to transform between various vector offsets. We use it to transform data from $h_y \neq 0$ to $h_y = 0$. We can think of it in terms of an operator $\mathbf{Z}'$ which is a sumation over h_y. We can allow for some mixing between h_x by expanding our sumation to form $h_x = a\ h_y = 0$, by summing over all h_y and

$$\sum_{a-\Delta h_x}^{a+\Delta h_x}, \tag{8}$$

where Δh_x is small.

We can combine these two operators to estimate a 4-D model ($\mathbf{m}$) from a 5-D irregular dataset ($\mathbf{d}$) through,

$$\mathbf{m} = \mathbf{Z}'\mathbf{L}'\mathbf{d}. \tag{9}$$

Equation 9 amounts to just running the adjoint of the inversion implied by,

$$Q(\mathbf{m}) = ||\mathbf{d} - \mathbf{L}\mathbf{Z}||^2. \tag{10}$$

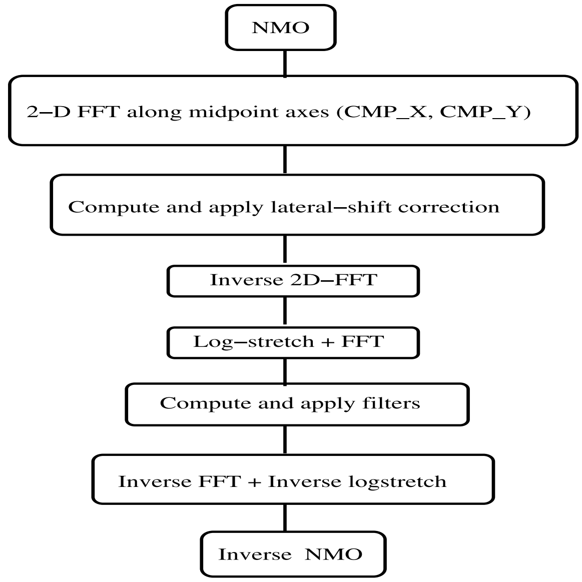

Figure 1: Diagram flow for the implementation of the PS-AMO operator. daniel2-flow [NR]

The adjoint solution is not ideal. The irregularity of our data can lead to artifical amplitude artifacts. A solution to this problem is to approximate the Hessian implied by equation 10 with a diagonal matrix based on a reference model (Rickett, 2001),

$$\mathbf{m} = \mathbf{H}\mathbf{Z}'\mathbf{L}', \tag{11}$$

where

$$\mathbf{H} = \mathrm{diag}\left[\frac{\mathbf{Z}'\mathbf{L}'\mathbf{L}\mathbf{Z}\mathbf{m}_{\mathrm{ref}}}{\mathbf{m}_{\mathrm{ref}}}\right]. \tag{12}$$

We set our reference model $\mathbf{m}_{\mathrm{ref}} = \mathbf{1}$.

PARALLEL IMPLEMENTATION

The methodology described above is not feasible on current archetecture. The computational requirements are onerous, but potentially managable. However, the memory requirements are not. A full 5-dimensional cube, that we are creating when applying $\mathbf{L}$, can easily achieve tens of gigabytes. This size of data makes it almost impossible to practically implement any algorithm for 3-D prestack seismic data-processing on a single machine.

Clapp (2004) introduces an efficient python library for handling parallel jobs. The library makes it easy for the user to take an already existing serial code and transform it into a parallel code. The library handles distribution, collection, and node monitoring, commonly onerous tasks in parallel processing.

The main prerequisite to using the python library is to build an efficient serial code, and to describe how the parallel job should be distributed on a cluster. For our problem we chose to split along the h_x axis. We create a series tasks, each assigned to produce a single (time, cmp_x, cmp_y) volume. Each task is passed a range of h_x's defined by equation 8. The resulting image volumes are then recombined to form the 4-D output space.

3-D RESULTS

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

The 3-D OBS data set has been already preprocessed and separated into a PP and a PS section. This paper focus on the PS section only. The subset of the data set consists of 250 inline CMPs, 50 crossline CMPs, 200 inline half-offset, and 40 crossline half-offset.

Figure 2 presents the spatial distribution for the shots on the left, and receivers on the right. Observe the gap in the shot distribution due to the platform. Additionally, Figure 3 shows the distribution of the CMPs on the left, and the offsets on the right. Note that the main goal of this experiment is to collapse the crossline offset into zero crossline offset. Figure 4 shows the data, for a particular inline offset, at zero crossline offset. Observe the sparsity of the data and the small number of live traces.

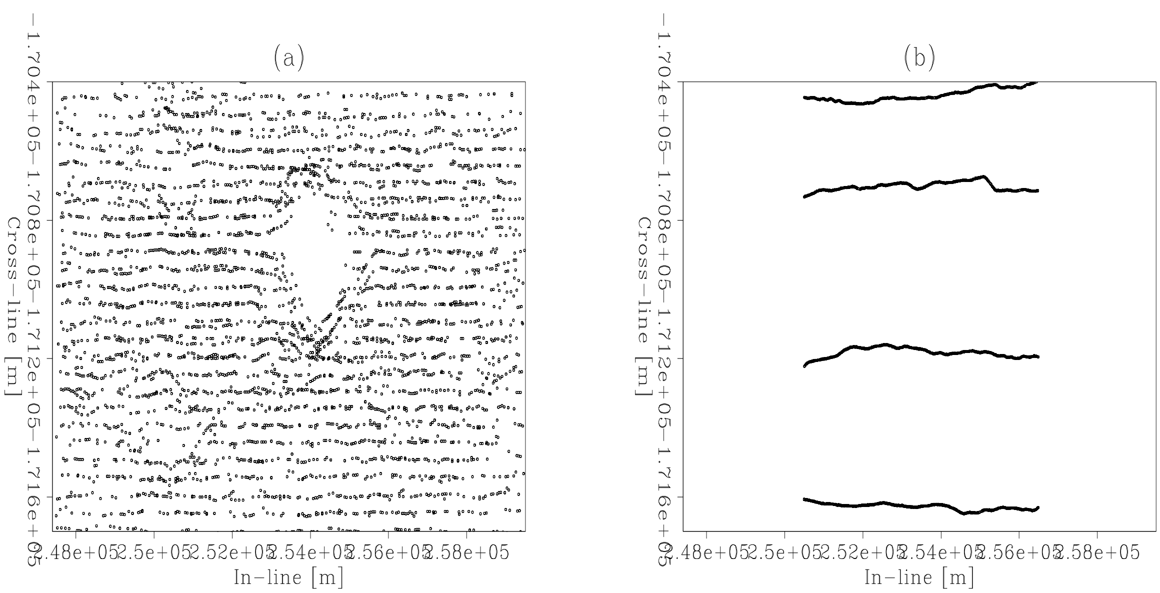

Figure 2: Source (a) and receiver (b) distribution for the fraction of OBS data set in study. daniel2-shot-rec [CR]

Figure 5 presents the main result of this paper. It compares the real data at zero crossline offset, the result of pure stacking all the crossline offsets, and the result of partial stacking the crossline offsets with the PS-AMO operator. The sections for all the cubes are taken at the

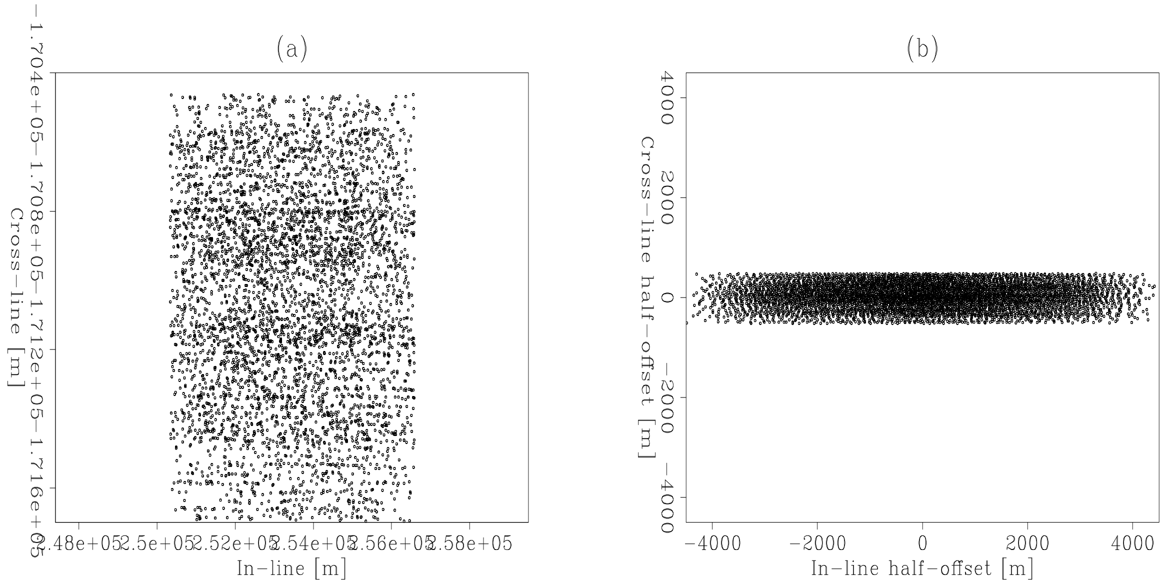

Figure 3: CMPs (a) and half-offset (b) distribution for the fraction of OBS data set in study. daniel2-cmp-off [CR]

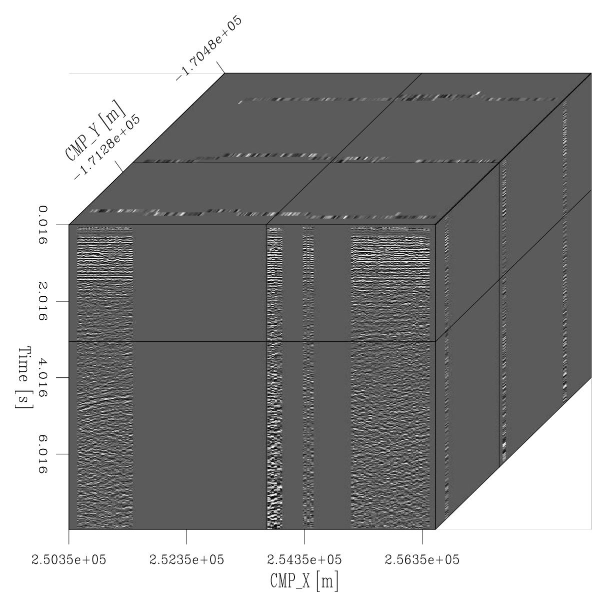

Figure 4: Real data problem, data for zero crossline offset, the missing data is obvious. daniel2-data [CR]

same position. Note that by just stacking there are still holes in the data. This is not the case after running partial stacking with the PS-AMO operator.

Additionally, Figure 6 presents the partial stacking with PS-AMO with and without the normalization. Note that by approximating the Hessian of the PS-AMO transformation using equation 12, we are able to balance the energy of the traces after normalization.

CONCLUSIONS

The PS-AMO operator that we used had the advantage of not demanding data in the CRP domain. This operator, as a cascade operation of PS-DMO and its inverse, internally performed the CMP to CRP lateral-shift correction, since the PS-DMO operator does it as well. Therefore, *a priori* CRP binning was not necessary before applying azimuth moveout to converted-wave data. The PS-AMO operator had two main characteristics: 1) it preserved the resolution of the dipping events, and 2) it corrected for the spatial lateral shift of the common reflection point.

PS-AMO has several applications. In this work, we tested the operator for the problem of irregular geometries; more specifically the converted-wave portion of OBS seismic data. In this case, the geometry-regularization problem was handled in the least-squares sense.

Our methodology gave promising results for the irregular-acquisition-geometry problem focused on converted-wave data. We were able to obtain an interpolated data set that honored the input data and the nonhyperbolic moveout of converted-wave data. Although we used a hyperbolic moveout equation, which is valid only for short offset and shallow depth, we still obtained satisfactory results.

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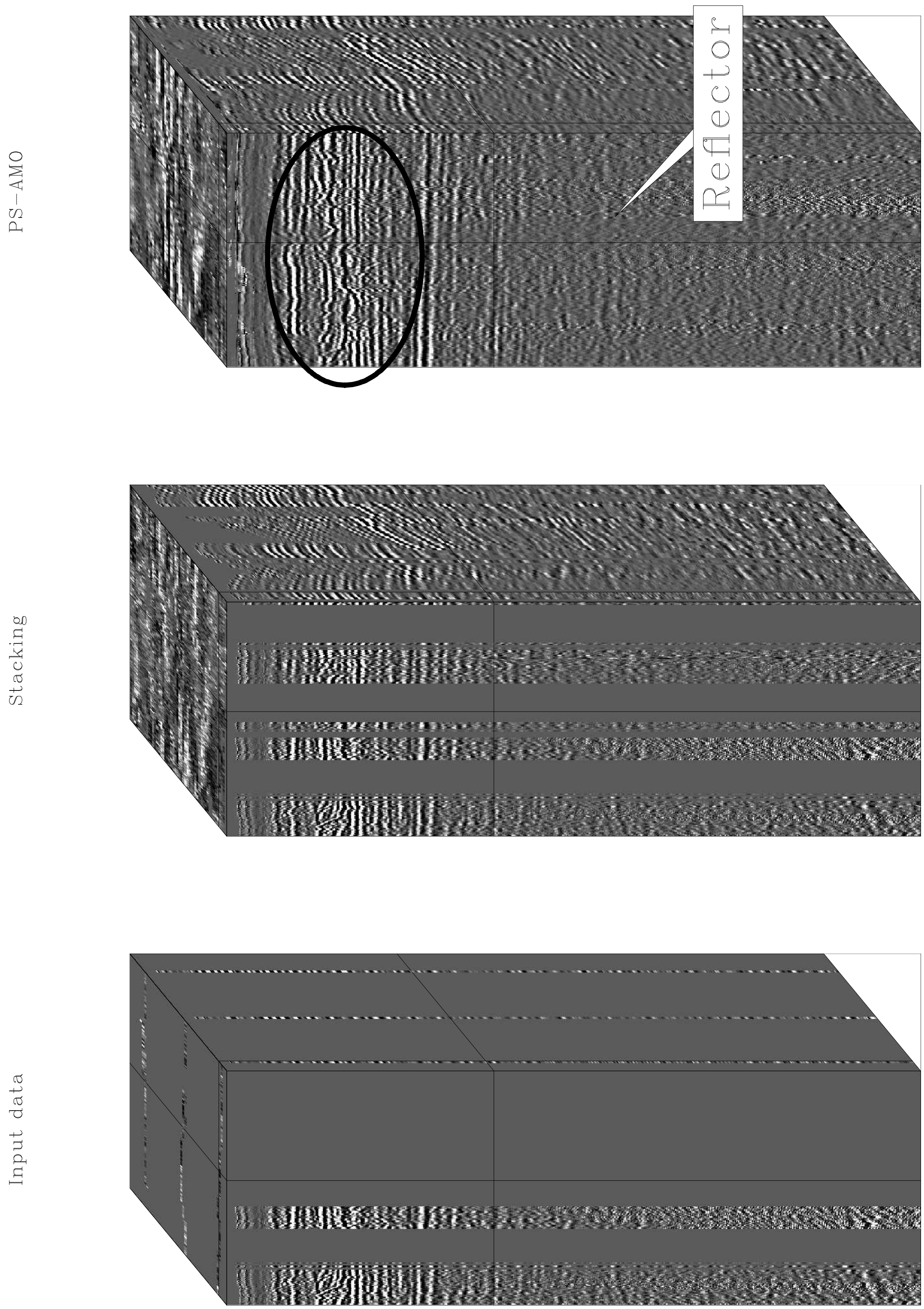

Figure 5: Result of partial stacking with PS-AMO. (a) Real data at zero crossline offset. (b) Result of simple stacking all the crossline offsets into zero crossline offset. (c) Result of running PS-AMO to collide all the crossline offsets into zero crossline offset. daniel2-data-psamo-comp [CR]

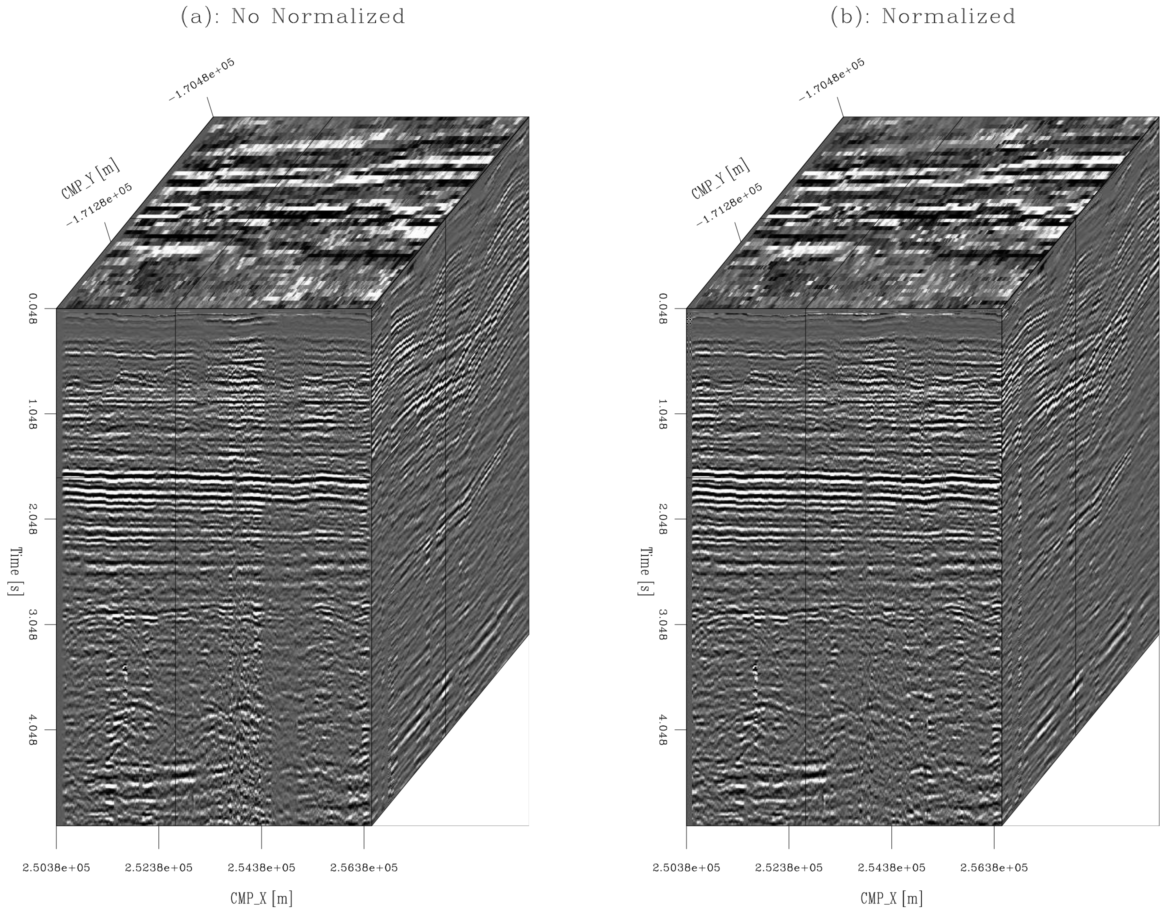

Figure 6: Result of PS-AMO reduction. (a) Unnormalized PS-AMO reduction. (b) Normalized PS-AMO reduction. daniel2-psamo-unor-nor [CR]

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