Two-Pass 3-D Prestack Time Migration

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Abstract

We describe a method to perform two-pass 3-D Kirchhoff prestack time migration whose computation time is nearly the square-root of that required for the one-pass algorithm. To better understand the conditions and restrictions associated with the application of the method we discuss the kinematical approximations involved in its derivation. A real data example shows that this approach can be applied with success in areas with moderate structural complexity.

INTRODUCTION

When dealing with geological settings subjected to complex three-dimensional structures, but under smooth horizontal velocity variation, 3-D prestack time migration may produce better focused images than the ones obtained with 3-D poststack time migration, while not losing quality when compared to the results from 3-D prestack depth migration (Liner, 1996, 1999). In such cases time migration has an advantage over depth migration because it has a lower cost both in terms of computation and interpretation efforts. Furthermore, even in cases where depth migration would be required, many methods for building the depth velocity model would benefit from a better reference time imaging obtained with prestack time migration. Kim et al. (1997) describe a hybrid method in which they prestack time migrate the data, stack, demigrate, and depth migrate the resulting zero-offset data.

In order to implement a cost-effective production code for prestack time migration of large 3-D datasets and to further reduce the computation cost one can use an operator separation procedure similar to the popular two-pass procedure of 3-D poststack time migration (Gibson et al.,1983). Some papers have already addressed this possibility and presented different two-pass algorithms. Berryhill (1991) presents the kinematics of a crossline migration method based on integration of common midpoint gathers along the crossline direction. The derivation assumes that the source-receiver line is parallel to the inline acquisition direction and the integration is not along a constant offset plane but instead maps data from different recorded offsets into a fixed output offset.

The method proposed by Canning and Gardner (1996) is not limited by the zero-azimuth constraint of the source-receiver offset and the crossline part of the migration is achieved by the successive application of the following velocity independent steps: 3-D dip-moveout (DMO), crossline 2-D prestack imaging (PSI), inline 2-D inverse dip-moveout (DMO^{-1}). After these steps, each subset of the data defined by a fixed inline direction is considered to have subsurface information arriving only from the vertical plane below that line, allowing any kind of 2-D prestack imaging method (either in time or in depth, including velocity analysis) to be applied. This process is more expensive than Berryhill's method because it includes the application of 3-D DMO and PSI requires a double integration (along the crossline and offset axes). In addition, to avoid undersampling during the integration along the offset axis, data volume reduction cannot be achieved by offset-range binning and, as in Berryhill's approach, offset-dependent information is affected by the process.

The method presented here operates in the common offset domain, and full 3-D migration is obtained by a single integration along the inline direction followed by a single integration along the crossline direction. Since the algorithm independently operates in each common offset cube, total data volume can be reduced by summing over ranges of offsets, memory requirements are quite limited, and offset-dependent information will be preserved during the process. The computation time for the proposed two-pass procedure is of the order of the square-root of the computation time for the one-pass migration. While no special preprocessing is required for data with small source-receiver azimuths, azimuth moveout (Biondi et al., 1998) should be applied to data in the presence of large azimuths at large offsets.

VALIDITY OF FULL OPERATOR SEPARATION

The kinematics of the constant offset 3-D Kirchhoff time migration operator is described by

$$t = \sqrt{\frac{t_0^2}{4} + \frac{(x_0 - x_m - h_x)^2}{v_0^2} + \frac{(y_0 - y_m - h_y)^2}{v_0^2}} + \sqrt{\frac{t_0^2}{4} + \frac{(x_0 - x_m + h_x)^2}{v_0^2} + \frac{(y_0 - y_m + h_y)^2}{v_0^2}}, \tag{1}$$

where x_0, y_0 and t_0 define the location of the migrated sample obtained by integration of the input samples with traveltime t lying on the surface described by equation (1). The integration covers all input traces with a common half-offset h, whose midpoint coordinates are x_m, and y_m. In the general case, the source-receiver line has a free orientation and the half-offset is defined by a vector $\mathbf{h} = (h_x, h_y)$. The velocity v_0 is a function of the migrated position $v_0 = v(t_0, x_0, y_0)$, thus constant for the integration.
For the special case of zero offset, equation (1) reduces to

$$t = \sqrt{t_0^2 + \frac{4\,(x_0 - x_m)^2}{v_0^2} + \frac{4\,(y_0 - y_m)^2}{v_0^2}}. \tag{2}$$

According to this equation, a sample at location (t, x_m, y_m) in the input cube will be multiplied by a factor and accumulated in the output location (t_0, x_0, y_0). A two-step procedure can be defined if we rewrite equation (2) as

$$t_x = \sqrt{t_0^2 + \frac{4\,(y_0 - y_m)^2}{v_0^2}} \tag{3}$$

$$t = \sqrt{t_x^2 + \frac{4\,(x_0 - x_m)^2}{v_0^2}} \equiv \sqrt{t_x^2 + \frac{4\,(x_0 - x_m)^2}{v^2(t_0, x_0, y_0)}}. \tag{4}$$

These equations represent one-pass 3-D migration splitted in two steps carried out along orthogonal directions (x and y). The first step accumulates the sample from (t, x_m, y_m) to position (t_x, x_0, y_m) of an intermediate data cube using equation (4), while the second step sums the resulting sample (t_x, x_0, y_m) from the intermediate cube into the final location (t_0, x_0, y_0) of the output cube as defined by equation (3). Unfortunately, equations (3) and (4) are not decoupled because equation (4) depends on (t_0, y_0), resulting in multiple partial paths leading to t_x, one for each final position of the diffractor. So, in principle, there would be no computational advantage in using this approach.
However, there is a way out if the geological conditions allow us some compromise. If $v(t_0, x_0, y_0) \approx v(t_x, x_0, y_m)$ is a reasonable approximation within a given range of y_0 around (t_x, x_0, y_m), then equation (2) will not be dependent on y_0 or t_0. The reasoning behind full separation of the 3-D operator is that a single 2-D x-integration will simultaneously perform all the partial integrations for all point diffractors located within that range from y_m. In short, for the zero offset case, two-pass migration replaces one-pass migration without significant loss of quality if lateral velocity variation in the crossline direction is small within the range covered by the crossline migration aperture.
For the case of a finite offset h, full splitting can still be accomplished, for the special case of $h_y = 0$, that is, when the source-receiver direction coincides with the inline direction x (offset azimuth equal to zero). In this case $h_x = h$ and equation (1) can be rewritten as

$$t_x = \sqrt{t_0^2 + \frac{4\,(y_0 - y_m)^2}{v_0^2}} \tag{5}$$

$$t = \sqrt{\frac{t_x^2}{4} + \frac{(x_0 - x_m - h)^2}{v_0^2}} + \sqrt{\frac{t_x^2}{4} + \frac{(x_0 - x_m + h)^2}{v_0^2}}, \tag{6}$$

which can also be described as a two-step procedure, first using equation (6) to transfer the input sample from position (t, x_m, y_m) to the intermediate position (t_x, x_0, y_m) and then equation (5) to reach the final location (t_0, x_0, y_0). The first step is responsible for both the NMO-DMO part and the inline zero-offset migration part of the full migration operator, while the crossline migration is the only part left for the second step.
The limitations concerning the velocity variation are the same ones already discussed for the zero-offset case while the influence of the acquisition geometry (offset azimuth) in the validity of using the two-pass approach will be discussed next. For typical marine surveys with multiple cables and moderate cable feathering the azimuths will be small and so will be the half-offset component h_y compared to h_x (except for small offsets). Using equation (6) for this case is equivalent to replace the 3-D dip-moveout operator by a inline 2-D operator. The NMO and the 3-D zero-offset migration parts of the process are not affected. At small offsets, when the azimuth becomes larger, the influence of the azimuth on the operator is less relevant and the approximation is still valid.
For data acquired with large azimuths at large offsets it is still possible to apply the method provided that a previous processing transforms the data into its zero-azimuth equivalent. This can be achieved by the azimuth moveout (AMO) operation, as described by Biondi et al. (1998).

REAL DATA RESULTS

Figure 1 shows part of a line acquired offshore Brazil after the application of 3-D poststack time migration. Figure 2 shows the result of applying one-pass 3-D prestack time migration. Figure 3 shows the same line after application of the described two-pass 3-D prestack time migration method. AGC has been applied to the three sessions. The prestack time migrated session has substantial improvements relative to the poststack time migrated session. The fault system located from position 300 to 450 and times 2 to 3 seconds, as well as the salt pillow in the bottom half of the session are much better defined in the prestack image. On the other hand, the differences between the one-pass and the two-pass prestack images are very small, and unlikely to affect the interpretation of the image. The better focusing of the amplitude anomalies in Figure 4-a over 4-b (no-gain windows of Figures 1 and 3) demonstrates that the improvements of prestack over poststack time migration are not constrained to structural information.

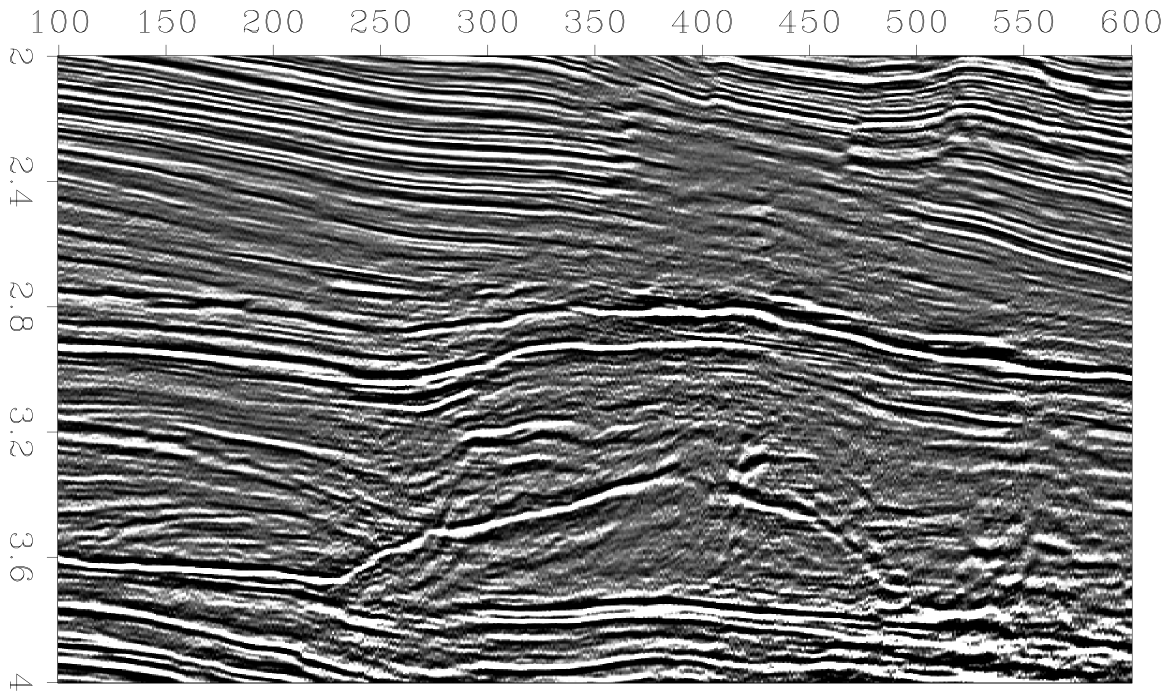

FIG. 1 Two-pass 3-D poststack time migration.

DISCUSSION

It can be proven that, whenever 3-D poststack time migration is applicable, so is two-pass migration. The reason for this is simply because both techniques are based on the same assumption: the lateral gradient of the velocity field is small. This concept may be extended to 3-D prestack migration provided that the crossline component of the source-receiver azimuth is neglectable. Moreover, because the second pass of the process is equivalent to zero offset migration, it could also be applied after stack, provided that AVO analysis is not required.

The real data results presented in Figures 1 to 4 may be considered as strong enough evidence for the validity of two-pass prestack time migration, not only because the images themselves, but also because, in all cases, the data were migrated with a conventional stacking velocity field, estimated after DMO. This means that there is still room for improvement, in the event of the application of time migration velocity analysis.

A final point to discuss is the amplitude treatment. Because of the inherent characteristics of two-pass prestack migration, the best amplitude treatment possible implies 2-D $v(z)$ geometrical spreading correction, applied during the first pass of the migration. This procedure leads to acceptable results in most cases and, more important, is fully consistent with the assumptions required for a successful time migration.

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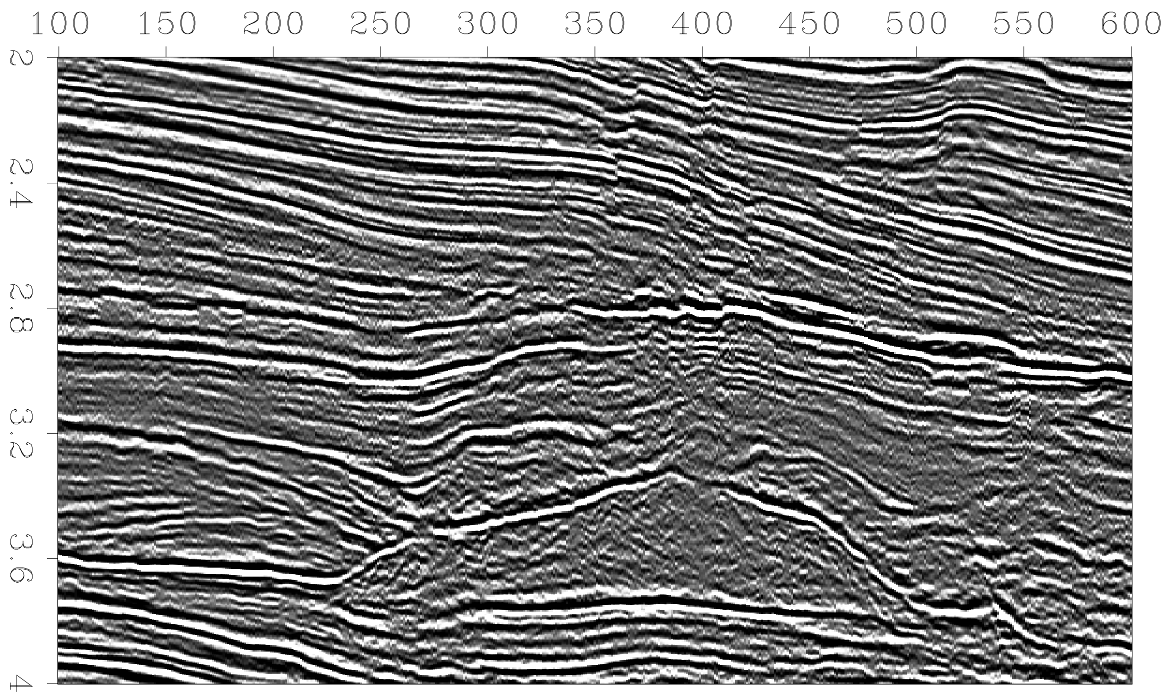


FIG. 2 One-pass 3-D prestack time migration.

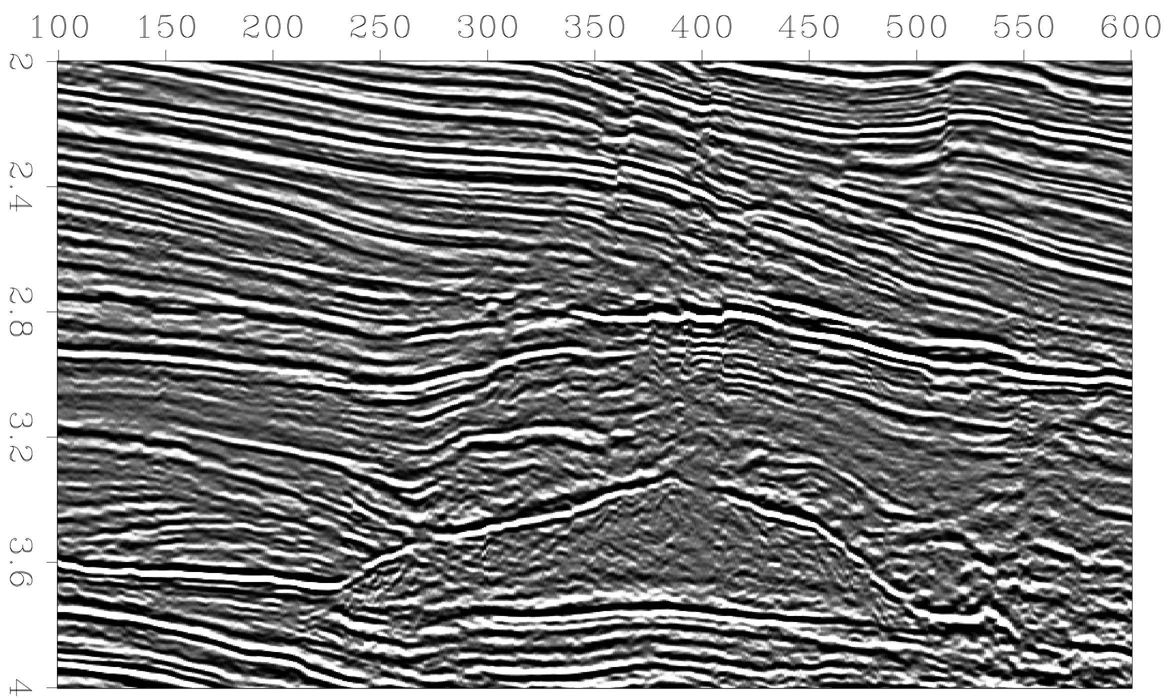
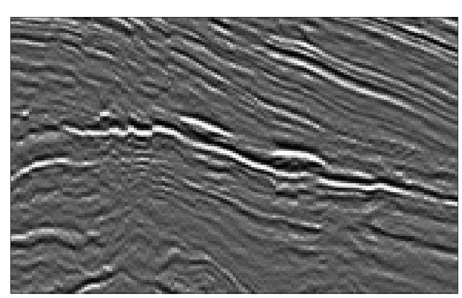


FIG. 3 Two-pass 3-D prestack time migration.


(b)