Creating image gathers in the absence of proper common-offset gathers

Gijs J.O. Vermeer, 3DSymSam – Geophysical Advice, The Netherlands

Paper prepared for ASEG Conference, November 1998

ABSTRACT

Current velocity model building techniques have been developed specifically with parallel geometry in mind. In this geometry it is possible to create common-offset gathers, to migrate individual gathers, and then to analyse moveout in the image gathers directly as a function of offset. In practice, well-sampled 3D common-offset gathers with constant azimuth are not available, not in land data acquired with the orthogonal geometry or other crossed-array techniques, and not even in data acquired with the parallel geometry.

Therefore, alternative data gathers have to be sought which are suitable for migration and which still allow migration velocity analysis. The method proposed in this paper is based on an extension of the notion of a minimal data set, being a single-fold alias-free data set, suitable for migration. Examples of minimal data sets are common-offset gathers with constant azimuth and cross-spreads. However, proper minimal data sets cannot always be constructed, or, in other cases, minimal data sets do not extend across the entire survey area. This requires the construction of pseudo-minimal data sets. Each pseudo-minimal data set is an approximation of a minimal data set; their number should be equal to the fold count.

In parallel geometry the pseudo-minimal data sets are still close to common-offset gathers. These gathers can be used directly for velocity analysis. In other geometries, the pseudo-minimal data sets encompass a wide range of offsets. Then it is necessary to determine from all traces in a pseudo-minimal data set which trace is the imaging trace, and what is its offset. A possible technique to determine this offset is the vector-weighted diffraction stack.

The proposed data gathering and velocity-analysis technique needs further research and testing for the best results.

Key Words: prestack depth migration, velocity model, velocity analysis, image gather, minimal data set, parallel geometry, orthogonal geometry, method of stationary phase, vector-weighted diffraction stack.

Introduction

Current 3D velocity model building techniques tend to be extensions of the methods used in prestack migration of 2D seismic lines. Well-sampled 2D lines can be considered as a collection of common-offset gathers. Separate migration of those gathers provides as many output traces (called "image traces") in each output point as there are common-offset gathers. The collection of image traces in an output point is called "common-image gather" or CIG. If the velocity model is correct, the reflections in the CIG should be horizontal, and reinforce each other when stacked. Errors in the velocity model exist if the reflections show upward or downward curvature as a function of offset in the CIGs, and the velocity model is updated on basis of analysis of this behaviour as a function of offset (Deregowski, 1990, Liu and Bleistein, 1995).

Extending this 2D technique to 3D is straightforward, provided well-sampled 3D common-offset gathers are available which have constant azimuth. A constant (shot-receiver) azimuth of the gathers ensures a smooth behaviour of the reflection times in each gather, whereas variations in azimuth would lead to irregularities in the spatial behaviour of the reflection times. Unfortunately, in practice 3D common-offset gathers with constant azimuth (COA gathers) are never acquired. Yet, data acquired with parallel geometry (source tracks parallel to each other and parallel to parallel receiver lines) allows the construction of gathers that are not too different from COA gathers, and the same velocity analysis procedure can still be applied.

In contrast, data acquired with orthogonal geometry in land or OBC surveys do not allow the construction of common-offset gathers. Instead, the data of an orthogonal geometry 3D survey can be described as a collection of cross-spreads. Each cross-spread has illuminated its own little part of the subsurface that can be imaged by migration. However, the resulting CIGs do not bear a direct relationship with offset, making it considerably more difficult to diagnose and correct for velocity errors. Moreover, the cross-spreads have only limited extent.

The main purpose of this paper is to discuss a strategy for choosing single-fold data gathers, which are best suited as input for optimal CIGs. These input gathers are called "pseudo-minimal data sets".

A starting point in the discussion is the "minimal data set", a concept introduced by Padhi and discussed in Padhi and Holley (1997). The minimal data set is a single-fold data set, suitable for DMO and migration. In order to make the single-fold data set suitable for migration, it should be a continuous 3D subset of the 5D prestack wavefield; moreover it should have a wide areal coverage. (If the coverage of the continuous subset is not wide, such as the coverage of a single streamer with constant and small feathering, then it may be suitable for DMO but not for migration.) Examples of minimal data sets are given in Table 1.

Table 1 Examples of minimal data sets

Minimal data set	Shot coordinates	Receiver coordinates	Acquisition geometry

3D shot	(X, Y)	(x_r, y_r)	Areal geometry
3D receiver	(x_s, y_s)	(X, Y)	Areal geometry
Cross-spread	(X, y_s)	(x_r, Y)	Orthogonal geometry
COA-gather	(x_s, y_s)	$(x_s + X, y_s + Y)$	Parallel geometry

X and *Y* are fixed, lower case coordinates vary.

The seismic data acquired with the most commonly used acquisition geometries can be viewed as a collection of minimal data sets, which are unique for each geometry. These common geometries are also listed in Table 1. 3D symmetric sampling is based on proper sampling of the minimal data sets of a geometry (Vermeer, 1994).

The COA-gather is the only minimal data set, which extends across the entire survey area. All other minimal data sets have limited extent in practice due to offset limitation. Prestack migration of COA-gathers produces an image of the subsurface of the entire survey area, but prestack migration of the other minimal data sets can only produce an image of a limited part of the subsurface. Therefore, to improve the chances of obtaining interpretable CIGs for any point in the survey area, it would be desirable to create single-fold subsets across the entire survey area which are as suitable as possible for imaging. These subsets I call *pseudo*-minimal data sets, because they do not fully satisfy the conditions of the minimal-data set definition as given above. Hopefully, pseudo-minimal data sets are reasonable approximations to true minimal data sets, in the sense that once migrated, the migration result does not suffer from large artefacts.

In the following I first discuss prestack migration using single minimal data sets, and then the construction of pseudo-minimal datasets and their use in prestack migration. For those situations where the pseudo-minimal data sets are not approximations of common-offset gathers, the vector-weighted diffraction stack (Tygel et al., 1993) is proposed as a means to estimate the offset of the image trace. This offset can be used in conventional migration-velocity analysis. The proposals are yet to be tested with synthetic and real data.

Prestack migration with minimal data sets

Per definition, all minimal data sets are suited for migration and capable of producing a single-fold image of the illuminated part of the subsurface. The migration result, i.e., vertical and horizontal resolution, is dependent on the source wavelet, the velocity model, and on the acquisition geometry, but, if these data sets have been properly sampled, then the result is independent of sampling (Vermeer, 1997b).

$$\left(\sqrt{z^2+s^2}+\sqrt{z^2+r^2}\right)/V = d/V, \qquad (1)$$

The dependence of the migration result on the acquisition geometry is illustrated with Figures 1 and 2, which allow comparison of illumination and imaging by a COA-gather and by a cross-spread. Figures 1d and 2d represent the shape of the reflection traveltime surface after conversion to depth *z* according to the migration condition

where *s* (*r*) is the distance from shot (receiver) position to surface position of output point (*x*, *y*, *z*), *d* is the length of the raypath from shot to receiver via the reflector, and *V* is the velocity of the medium. The left side of the equation represents the diffraction traveltime surface for the output point (*x*, *y*, *z*) as shown in Figures 1c and 2c; the right side of the equation represents the reflection traveltime surface across the minimal data set as shown in Figures 1b and 2b.

The migration result in the output point (*x*, *y*, *z*) is just the (weighted) horizontal summation of all data described by the depth surfaces of Figures 1d and 2d. The apex of this surface corresponds to the depth of the reflector *z* in the output point. It is the point of stationary phase in the migration integral. The heavy curve in Figures 1d and 2d is a depth contour 60 m above the apex. If the length of the seismic wavelet is 60 ms (= 60 m for *V* = 2000 m/s), then all reflections inside the heavy curves contribute to the migration result at depth *z*. In analogy to the discussion in Brühl et al. (1996), the area inside the heavy curve may be called "zone of influence". It is often erroneously referred to as the Fresnel zone. All energy outside of the zone of influence contributes only to the flanks of the migration operator. This energy should cancel in the migration summation, which it does to a large extent, provided that the data are properly sampled.

Even if amplitude corrections for the geometry are applied (Schleicher et al., 1993, Vermeer, 1995), the results of migrating the two minimal data sets will be different for the same output point, mainly because of differences in stretch effects. Yet, both minimal data sets can produce a correct image for most illuminated reflector points (apart from edge effects). This reasoning leads us to define - for each minimal data set - a midpoint area (the area covered by the midpoints), an illumination area (the area on the reflector illuminated by all shot-receiver pairs), and an image area (the area on the reflector for which correct imaging is possible). Should a number of minimal data sets have overlapping midpoint areas, then we may define

"fold-of-coverage": number of overlapping midpoint areas,

"illumination fold": number of overlapping illumination areas, and

"image fold": number of overlapping image areas.

In general, illumination fold will not be very different from fold-of-coverage, though it may be locally higher or lower. Image fold is the same as illumination fold, if we neglect edge effects. Fold-of-coverage and image fold provide a statistical means of suppressing noise. If the data are properly sampled, fold is not necessary to improve the migration result itself, because single-fold data are sufficient for imaging.

An important consequence of this reasoning is that in migration velocity analysis on basis of CIGs, the number of traces in each CIG should be equal to the fold-of-coverage M, because fold-of-coverage is approximately equal to image fold. This means that the total data set should be subdivided into M single-fold input gathers. Assuming that each input trace contributes to one image gather only, a smaller number of input gathers would produce overlapping images, and a larger number of input gathers would produce incomplete images. ("image gather" or "single-fold image gather" is defined as the collection of all image traces - many output points - produced by an input gather, whereas CIG is the collection of all image traces produced by all input gathers in a common output point.)

Ideally then, we would like to be able to extract M minimal data sets extending across the entire survey area from the acquired data. However, in practice, this is not possible. In the following I outline a strategy for selecting data gathers, called pseudo-minimal data sets, which are reasonable approximations of minimal data sets, and extend across the entire survey area.

Prestack migration with pseudo-minimal data sets

Parallel geometry

Marine 3D acquisition is most frequently carried out using multi-source multi-streamer configurations. Also OBC data are often acquired with a configuration in which the shotlines are parallel to the receiver lines. In these parallel geometries the crossline offset (= distance between source track and streamer track) is different for the various midpoint lines, which are acquired in one vessel pass. This leads to variations in the shot-receiver azimuths across the shooting configuration; in other words, common-offset gathers do not have constant azimuth.

The discontinuities in the crossline offset lead to irregular illumination as illustrated in Figure 3 for a two sources and four streamers configuration. Because the reflection points move updip with increasing offset, these points move towards the sources when shooting downdip (Figure 3a) and towards the receivers when shooting updip (Figure 3b). The net result is irregular illumination in particular for the long offsets. Between vessel passes large gaps in illumination may exist when shooting downdip and overlaps when shooting updip. Feathering may compound the problem, whereas antiparallel acquisition (sailing adjacent vessel passes in opposite directions) and sailing strike to the steepest dips reduce the impact of the discontinuities in crossline offset (Vermeer, 1997a, Brink et al., 1997). Figure 4 illustrates the behaviour of the migrated depth surface of a dipping event for equal inline offsets. Figure 4a shows the migrated depth surface for ideal input, Figures 4b and 4c show the effect of the discontinuities in the geometry on the migrated depth surface. The differences between Figures 4b and 4c lead to amplitude and phase variations of the migrated event.

Figure 4 has been computed assuming a dense sampling of the inline-offset coordinate. In practice, the number of different inline offsets is equal to the number of channels per streamer, whereas the fold-of-coverage is usually at most 1/4 of the number of channels for a dual-source configuration. This means that individual offsets are undersampled, and that a number of different inline offsets have to be taken together to form one single-fold pseudo-minimal data set. The obvious procedure for grouping the offsets is to split the data over as many offset ranges as the fold count, while making sure that each range contains the same number of traces. In case of feathering, not only the reflection points will have areas with low and high density sampling, but also the midpoints. Rather than flexi-binning, it should be considered to regularise the midpoints of each pseudo-minimal data set by interpolation prior to prestack migration. The average offset of each pseudo-minimal data set can be taken as the offset to be used in velocity-error analysis.

Padhi and Holley (1997) describe a methodology for measuring the deviation of traces in a pseudo-minimal data set from the ideal minimal data set. This methodology might also be used for collecting the traces for each pseudo-minimal data set.

Orthogonal geometry

Orthogonal geometry (parallel shotlines orthogonal to parallel receiver lines) poses a much larger problem to migration-velocity analysis than parallel geometry. In the first place, common-offset gathers cannot be assembled from that geometry, and in the second place, the minimal data sets of this geometry, the cross-spreads, have limited extent.

Figure 5 illustrates that it is impossible to generate single-fold common-offset gathers from orthogonal geometry. Not all offsets are present everywhere, moreover they have a wide variety of azimuths. The simplest way to generate single-fold coverage across the entire survey, i.e., a pseudo-minimal data set, is to make a tiling of cross-spreads (minimal data sets) with adjacent midpoint areas. In a regular geometry, it is possible to construct as many single-fold tilings as the fold count. However, even though the midpoint coverage of each tiling can be complete and regular in this way, the illumination of the subsurface will not be regular, because of the discontinuities in shot-receiver azimuths across the edges of the cross-spreads. This irregular illumination is illustrated in Figure 6. Figure 7a illustrates the discontinuities in the traveltime surface of the same dipping event across four adjacent cross-spreads, and Figure 7b shows that the migrated-depth surfaces for one output point are discontinuous across the edges as well.

A characteristic of tiling with cross-spreads is that reflection times behave smoothly in the inside areas of each cross-spread, but may show large discontinuities from cross-spread to cross-spread. An alternative to tiling with cross-spreads is tiling with offset-azimuth tiles. To this end each cross-spread is split over as many offset-azimuth tiles as the fold. Each offset-azimuth tile has the size of a unit cell (= rectangle defined by two adjacent shotlines and two adjacent receiver lines. The offset-azimuth distribution of the geometry has unit-cell periodicity). The number of times the unit cell fits on the cross-spread in the crossline direction equals the crossline fold, in the inline direction it equals the inline fold. In this way a tiling across the 3D survey consists of adjacent offset-azimuth tiles of the same kind, for instance, all top-right corners of all cross-spreads form one such tiling. The advantage of this pseudo-minimal data set is that there are no big jumps in shot-receiver azimuth in this data set as in the cross-spread tiling, in particular if the fold is large. A disadvantage is that there are many more edges across which the migration-depth surfaces will show discontinuities.

Figure 8 illustrates imaging with offset-azimuth tiling. Figure 8a shows the traveltime surface, and Figure 8b the migration-depth contours for one output point. From this we may get the feeling that offset-azimuth tiling is more robust than cross-spread tiling. An additional advantage of offset-azimuth tiling may be that it is easier to handle the shallow data (just drop the tiles that do not contribute to a certain level).

Which choice of pseudo-minimal data set is most suitable for single-fold imaging remains to be evaluated with synthetic and real data. It should be realised that the end product being the sum of all single-fold images does not depend on the chosen tiling.

Irregular geometries

Often, acquisition geometry, even if nominally regular, is very irregular in practice. In other cases it may be regular, but coarsely sampled. Then it is impossible to collect properly sampled minimal data sets from the geometry, and the construction of pseudo-minimal data sets may be quite impractical. As a consequence, the conditions for good single-fold images are not met. Firstly, the zone of influence around each point of stationary phase is not well sampled, so that amplitude and phase of the image are not correct. Secondly the flanks of the migrated-depth surface are not well sampled either, leading to incomplete cancellation, i.e., migration noise, further reducing the possibility of picking reliable images. This reasoning underlines the importance of proper sampling techniques in acquisition.

However, even if it is impossible to generate reliable single-fold images, it may still be possible to obtain reasonable images from the total data set. Statistical averaging of noise and amplitude variations has to compensate for the irregular sampling. Velocity model updating of such data has to resort to geological knowledge and velocity scanning as discussed in e.g., Schmid and Bouska (1997).

Vector-weighted diffraction stack

Migration-velocity updating techniques that make use of upward or downward curvature as a function of offset, cannot be directly applied to the single-fold images produced with the pseudo-minimal data sets of orthogonal geometry. Perhaps, if the unit cell is small, an average offset may be allocated to each offset-azimuth tile, and computations might be carried out using this value as a yardstick. However, even with small acquisition line intervals of 200 m, the range in offset will be 400 m in both inline and crossline direction. Therefore, even with these small tiles it may be necessary to find a better estimate of the offset of the imaging trace. If cross-spread tiling is used, an estimate of that offset is essential. How to find a good estimate for the offset of the image trace (the point of stationary phase at the apex of the migration-depth surface of an event as shown in Figure 7b and 8b) is the subject of this section.

Tygel et al. (1993) discussed the use of the vector-weighted diffraction stack for the estimation of the attributes of the image trace, following an idea of Bleistein (1987). The idea is based on the observation that the amplitude of a migrated event is determined by the interference of all traces in the zone of influence (indicated by a heavy line in Figures 1d, 2d, 4abc, 7b and 8b) around the point of stationary phase. The amplitudes of the traces outside this area should cancel. This would also apply if all input traces were multiplied by the value of an attribute which varies slowly across the data set, for instance the *x*-coordinate of the midpoint of each trace. Migrating the data twice, once without changes to the amplitudes, and once after multiplication with the *x*-coordinate, allows making an estimate of the *x*-coordinate in the point of stationary phase by dividing the weighted amplitude by the unweighted one. Repeating the exercise with the *y*-coordinate provides sufficient information to determine which trace formed the imaging trace. If the trace is known, its offset is known, and that offset can be used in velocity updating. Note that this technique does not necessarily increase compute time by a factor of three, because the weighting can be implemented in existing migration operations such that the bulk of the computational effort does not have to be repeated.

Liu (1997) uses the same method of repeated migration with different weights to find properties of the trace in the point of stationary phase. These properties are needed for his velocity model updating technique based on perturbation of parameters. In Liu (1997) it is applied to common-offset gathers of the 2D Marmousi model with reasonable success. As far as known to me, application of vector-weighted diffraction stack to synthetic or real 3D data has not yet been published. Yet, testing this technique seems a worthwhile endeavour, if only because it allows the use of existing offset-based velocity update techniques to data acquired with orthogonal geometry. Of course, the amplitude division can only be applied to the extrema of the strongest events, elsewhere the interference is not optimal, and noise would degrade the result. Furthermore, it may be necessary to carry out some spatial averaging to further improve the reliability of the offset estimate.

Conclusions

For 3D acquisition geometries as acquired in practice, a strategy for the selection of pseudo-minimal data sets has been outlined. These pseudo-minimal data sets are single-fold data sets, which extend across the entire survey area. The pseudo-minimal data sets provide the input data for the creation of optimal single-fold image gathers. The output traces of all migrated pseudo-minimal data sets can be collected into CIGs. In parallel geometry the offsets of the image traces in each CIG are known and can be used immediately for velocity analysis, but in orthogonal geometry the offset of the image trace is unknown and may be determined using the vector-weighted diffraction stack technique (method of stationary phase). If other attributes than offset are required for velocity updating, then the method of stationary phase may be helpful for parallel geometry as well as orthogonal geometry. More research is needed to determine the best way of selecting the data for each pseudo-minimal data set from orthogonal geometry: cross-spreads or unit-cell tiling. The feasibility of using the vector-weighted diffraction stack for determining the attributes of the image trace needs to be tested as well.

Acknowledgement

I'd like to thank Stéphane Gesbert for many useful suggestions for improvement of this paper.

REFERENCES

Bleistein, N., 1987, On the imaging of reflectors in the earth: Geophysics, **52**, 931-942.

Brink, M., Roberts, G., and Ronen, S., 1997, Wide-tow marine-seismic surveys: parallel or opposite sail lines: OTC8317, paper presented at 1997 Offshore Technology Conference.

Brühl, M., Vermeer, G.J.O., and Kiehn, M., 1996, Fresnel zones for broadband data: Geophysics, **61**, 600-604.

Deregowski, S.M., 1990, Common-offset migrations and velocity analysis: First Break, **8**, 225-234.

Liu, Z., and Bleistein, N., 1995, Migration velocity analysis: Theory and an iterative algorithm: Geophysics, **60**, 142-153.

Liu, Z., 1997, An analytical approach to migration velocity analysis: Geophysics, **62**, 1238-1249.

Padhi, T., and Holley, T.K., 1997, Wide azimuths – why not?: The Leading Edge, **16**, 175-177.

Schleicher, J., Tygel, M., and Hubral, P., 1993, 3-D true-amplitude finite-offset migration: Geophysics, **58**, 1112-1126.

Schmid, R., and Bouska, J., 1997, 3D prestack depth migration and velocity analysis for sparse land data: 67th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, paper ST13.3

Tygel, M., Schleicher, J., Hubral, P. and Hanitzsch, C., 1993, Multiple weights in diffraction stack migration: Geophysics, **58**, 1820-1830.

Vermeer, G.J.O., 1994, 3D symmetric sampling: 64th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 906-909.

Vermeer, G.J.O., 1995, On: "3-D true-amplitude finite-offset migration" by J. Schleicher, M. Tygel, and P. Hubral (Geophysics, **58**, 1112-1126, August 1993) with reply by the authors: Geophysics, **60**, 921-923.

Vermeer, G.J.O., 1997a, Streamers versus stationary receivers: OTC8314, paper presented at 1997 Offshore Technology Conference, 331-346.

Vermeer, G.J.O., 1997b, Factors affecting spatial resolution: 67th Ann. Internat. Mtg., Soc. Expl. Geophys.