Seismic Acquisition 3:
3-D Data Acquisition

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3-D symmetric sampling

Gijs J.O. Vermeer, *Shell Research, The Netherlands*

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Summary

In the course of time many different geometries have been devised for the acquisition of 3D seismic data. Many of these geometries can be classified as either patch or line geometries. Patch geometries have either the shots or the receivers in a dense areal arrangement, whereas line geometries deploy shots and receivers along separate acquisition lines.

Criteria for symmetric sampling have been established for 2D acquisition based on the properties of the seismic wavefield in the common-shot gather, combined with the reciprocity principle.

The same insights are now applied to propose 3D symmetric sampling criteria for the patch and line geometries. For the patch geometries this leads to a square grid of prestack data for each patch. For the line geometries the 2D criteria for symmetric sampling – equal shot and receiver intervals, and equal shot and receiver patterns – directly apply, but have to be extended with additional criteria dependent on the type of line geometry: parallel, orthogonal or zigzag.

Application of these criteria leads to a subdivision of the various geometries into single-fold 3D subsets which are eminently suited for prestack processing, including true-amplitude prestack depth migration.

Introduction

Though a large number of publications concern various ways of acquiring 3D surveys, a consistent theory about 3D sampling has not yet been published. This paper offers a first attempt at doing so. The starting point is formed by the symmetric sampling theory developed for 2D as published in Vermeer (1990, 1991).

In 2D, the problem is one of sampling a three-dimensional wavefield with two spatial coordinates (shot x and receiver x) and the temporal coordinate. Symmetric sampling of the two spatial coordinates is a direct consequence of the principle of reciprocity. In 3D, we are faced with the sampling of a five-dimensional wavefield, with shot (x,y) and receiver (x,y) as the spatial coordinates. It is out of the question to completely sample this 5D wavefield. Even sampling a large number of closely spaced 2D lines (with coincident shot and receiver lines) would only record receivers with the same azimuth for each shot. In this paper I propose the 3D symmetric sampling technique as the best alternative to full sampling of the prestack wavefield. This technique ensures correct sampling of *3D subsets* of the 5D prestack wavefield.

This paper sets out with a classification of various ways of acquiring seismic data: random geometries, patch geometries, line geometries, and miscellaneous geometries. Then the sampling of the patch and line geometries is discussed, followed by a discussion of the importance of symmetric sampling and the relation to prestack processing.

Classes of 3D geometries

Depending on the arrangement of shots and receivers, 3D geometries can be classified as random geometries, patch geometries, line geometries, and miscellaneous geometries.

Random geometries are characterised by the absence of regularity in the shot and receiver positions. An example is described in Bertelli et al. (1991), who applied a random geometry in an area surrounding the city of Milan. Such a geometry is very difficult to process. The absence of spatial continuity necessitates high multiplicity to obtain satisfactory results.

Patch geometries are characterised by a dense areal arrangement of receiver stations and sparse sampling of shots, or the other way around. An ideal geometry is the true 3D shot: a single shot surrounded by an areal arrangement of receiver stations. Numerous papers have been published about migration of the 3D shot. Single-fold data is sufficient for imaging this kind of data. The single shot only illuminates a small part of the subsurface, so that several shots are needed to cover the survey area.

A very interesting application of this geometry is described in Stubblefield (1990) and Krail (1991, 1993). They describe the vertical hydrophone cable recording an areal arrangement of shots. In this case receiver depth is yet another spatial coordinate being sampled. Their technique offers great scope for innovative prestack processing techniques. Crews et al. (1989, 1991) describe a patch geometry for 3D land seismic acquisition. However, their technique is too “patchy” to allow for single-fold imaging, as each patch only covers a relatively small area.

Line geometries are characterised by dense sampling of shots and receivers along acquisition lines, which are not necessarily closely spaced. There are three main types of line geometry: parallel geometries, orthogonal geometries and zigzag geometries.

In the *parallel* geometry, shot and receiver lines are parallel. This geometry is basically an extension of the 2D geometry where shot and receiver lines coincide. It is mainly used for marine data acquisition, using multi-source and multi-streamer configurations, e.g., the quad/quad geometry (Naylor, 1990), but it has also been used on land, e.g., Dickinson et al. (1990).

In the *orthogonal* geometry shot and receiver lines are orthogonal. This is a typical land geometry allowing 3D coverage with a minimum of effort required in the field. There are numerous variations on this theme with the *brick-wall* geometry (Galbraith, 1993) and the *cross-spread* geometry (Dickinson et al., 1990) as the two main patterns applied. In the brick-wall geometry staggered shotlines are used, and in the cross-spread geometry the shotlines are sampled more or less regularly. An important consideration for the orthogonal geometry is whether to use a *narrow* or a *wide* layout.

The *zigzag* geometry is another land geometry, but with the shots being fired along zigzag lines between the receiver lines. This is a very efficient geometry for data acquisition in deserts.

Apart from the three main types of line geometry, the *seis*-loop method (Ritchie, 1991) may be mentioned as one of the early attempts at cost-effective 3D land acquisition.

Many 3D surveys have been carried out that cannot be categorised in any of the discussed geometries, and are therefore left stranded in the category *miscellaneous*. An interesting example is the (concentric) *circle shoot* geometry (Durrani et al., 1987).

3D symmetric sampling of patch geometries

In the patch geometries, the 3D subset of the 5D prestack wavefield that can be properly sampled, is formed by the 3D common shot or the 3D common-receiver dataset (see Figure 1 a). Proper sampling of these patches allows any non-recorded point inside the patch to be reconstructed from the recorded points. In principle this requires sampling using the *basic sampling interval* in the two spatial domains (basic sampling interval: single-receiver interval required for alias-free sampling of the total wavefield of a single shot, see Vermeer, 1990). Patterns can be used as anti-alias filters and resampling operators to allow sampling at the basic *signal* sampling interval (basic signal sampling interval: interval required for alias-free sampling of the desired wavetype, normally P-waves).

The patch geometry, as proposed in Crews et al. (1989) is quite a labour-intensive technique even if no patterns are used: half the survey area needs filling with receiver stations. The requirement of alias-free sampling makes it even more laborious, as this calls for an areal fill with geophones spaced at the basic sampling interval in both *x* and *y*. For a (sub)horizontal geology the use of an areal shot pattern in the 3D shot seems to be a good alternative to plastering the area with areal geophone patterns.

For deep water acquisition the basic sampling interval is equal to the basic signal sampling interval, there patterns are not needed to suppress unwanted coherent energy. Therefore the technique proposed in Stubblefield (1990) for recording of 3D receiver records is not prohibitively expensive.

Extending 2D symmetric sampling criteria to 3D leads to the 3D symmetric sampling criteria for patch geometries:

- equal receiver station intervals in both *x* and *y;*
- areal and adjacent patterns;
- as many receivers in *x* as in *y;* and
- receiver patch to be centred around shot.

(Interchange "shot" and "receiver" for common-receiver patches.) Texaco's vertical cable geometry is shot according to these criteria (Krail, 1993), except the second criterion, which does not need to be applied if sampling is at the basic sampling interval.

3D symmetric sampling of line geometries

In the line geometries, the 3D subset of the 5D prestack wavefield that can be properly sampled is formed by all traces that have a shotline and a receiver line in common. For the parallel geometry this subset is the midpoint line, halfway between the receiver line and the shotline (shot track in marine surveys). For the orthogonal geometry the subset is called the cross-spread. In case the zigzag pattern between receiver lines allows the construction of two families of shotlines, the basic subsets of the zigzag geometry are the zig and the zag spreads. The various subsets of the line geometries are illustrated in Figure 1 b-d.

Proper sampling of the 3D subsets of the line geometries requires sampling using the basic sampling interval for shots and receivers along their respective acquisition lines. Again, patterns can be used as anti-alias filters and resampling operators to allow sampling at the basic signal sampling interval. The two 2D symmetric sampling criteria (Vermeer, 1991)

- equal shot and receiver intervals,
- equal shot and receiver patterns,

have to be extended with additional criteria for symmetric sampling of 3D surveys. These criteria are different for each one of the line geometries. Symmetric sampling in the orthogonal geometry also requires:

- an equal number of receivers in the common shot as shots in the common receiver.

In the zigzag geometry where centre-spread shooting means moving the range of active receiver channels for each shot, the additional criterion reads (somewhat awkwardly):

- an equal number of receivers in the common shot as shots in the common inline-offset gather.

In the parallel geometry there are already as many receivers in the common shot as shots in the common receiver as a consequence of the 2D symmetric sampling criteria. For this geometry proper handling in the 3D world requires:

- a spacing between midpoint lines equal to half the station interval,
- the same distance between all shot and receiver lines.

These criteria not only provide symmetric sampling of the midpoint lines, but also proper sampling of 3D common-offset common-azimuth gathers.

In marine data acquisition the parallel geometry is more or less the rule. Unfortunately 3D symmetric sampling is far from the rule. The first marine 3D surveys were often shot as a series of 2D lines which obeyed the 2D symmetric sampling criteria, but which used line spacings that were too large, requiring later reshoots. Modern multi-source/multi-streamer surveys have varying crossline offsets leading to irregular subsurface sampling, even if surface sampling is regular. This is illustrated in Figure 2, which shows the "footprint" (subsurface locations of the reflection points) of the quad/quad geometry for a plane dipping layer in a constant-velocity medium. If the range of crossline offsets is smaller, the irregularity is less severe and it may still be possible to construct reasonably sampled common-offset gathers. Nevertheless, true symmetry is difficult to achieve with the parallel geometry. Owing to the directional acquisition technique inline and crossline character of the final data will be different unless zero-offset data can be faithfully reconstructed.

The 3D symmetric sampling criteria applied to the orthogonal geometry lead to the acquisition of square cross-spreads. The first 3D surveys using square cross-spreads were acquired by Exxon in the late sixties (Walton, 1971, 1972). They offered a cost-effective alternative to the geophysicists' dream of areal recording of the single shot (Walton, 1971). Properties of the cross-spread and interpretation techniques on timeslices through cross-spreads are discussed in Dunkin and Levin (1971). At that time the single-fold cross-spreads were still a big burden to the interpreter, but with the advent of digital processing the data from partially overlapping cross-spreads could be stacked and migrated for easier interpretation (Durschner, 1984). The introduction of recording instruments with tens of thousands of active channels brings 3D symmetric sampling "providing well-distributed azimuth and offset sampled data" (Ritchie, 1991) within reach.

Why 3D symmetric sampling?

3D symmetric sampling provides single-fold low-alias 3D subsets that are eminently suited for prestack processing, of which dual-domain f-k filtering is but one example. These subsets are also suitable for prestack imaging. Schleicher et al. (1993) describe how true-amplitude prestack depth migration may be applied to the 3D single-fold subsets generated by various geometries.

Conclusions

This paper may provide the starting point for 3D seismic data acquisition based on well-defined sampling principles. In particular the cross-spread technique on land, and the repeated acquisition of (vertical cable) receiver gathers at sea provide the best bets for future high-quality 3D surveys. Efficient deployment of numerous vertical cables to cover a large survey area is one of the challenges to be met. Proper prestack processing techniques that fully exploit the spatial continuity offered by symmetric sampling, have yet to be developed.

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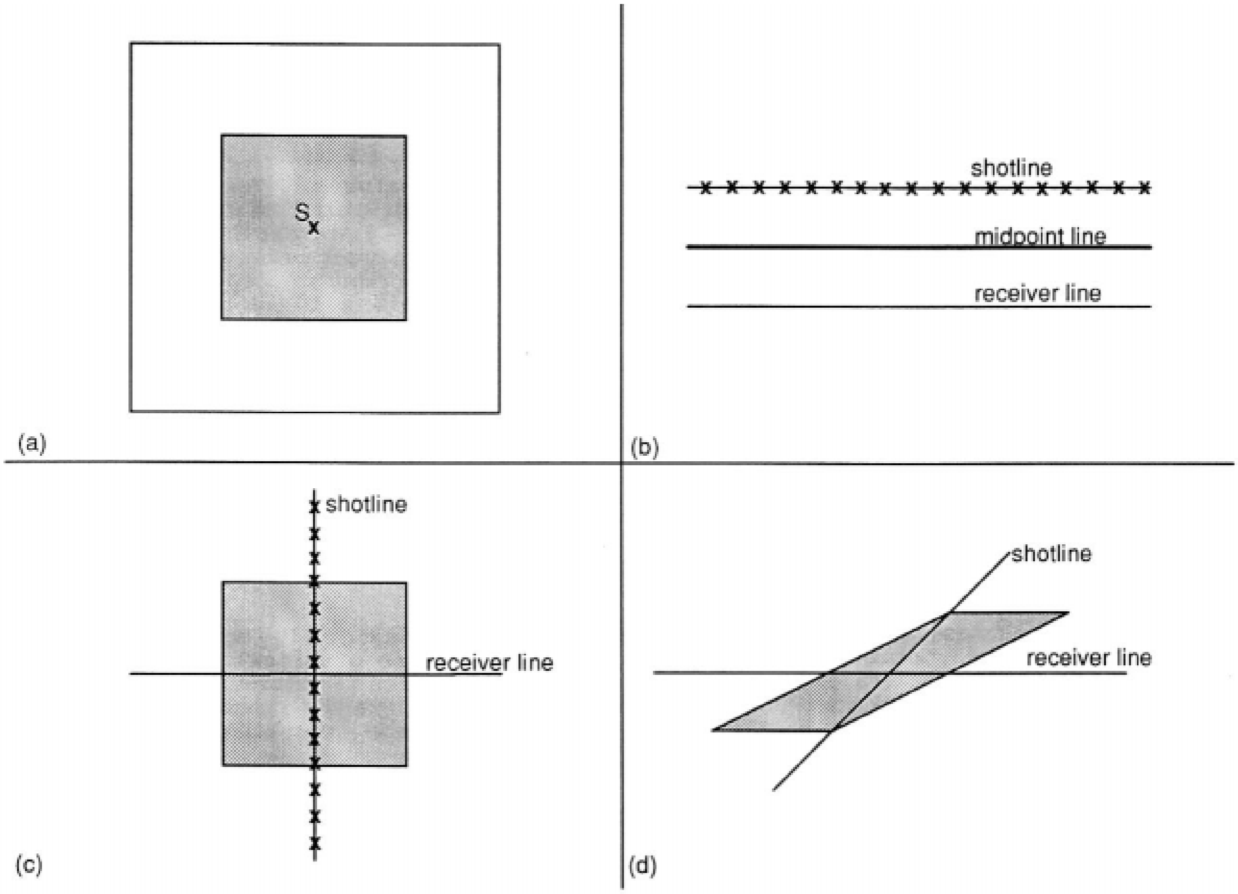

Figure 1 3D single-fold subsets of various geometries. (a) midpoint area created by patch of geophones (large square) recording single shot , (b) midpoint line between shotline and receiver line in parallel geometry, (c) cross-spread in orthogonal geometry, and (d) zig spread in zigzag geometry.

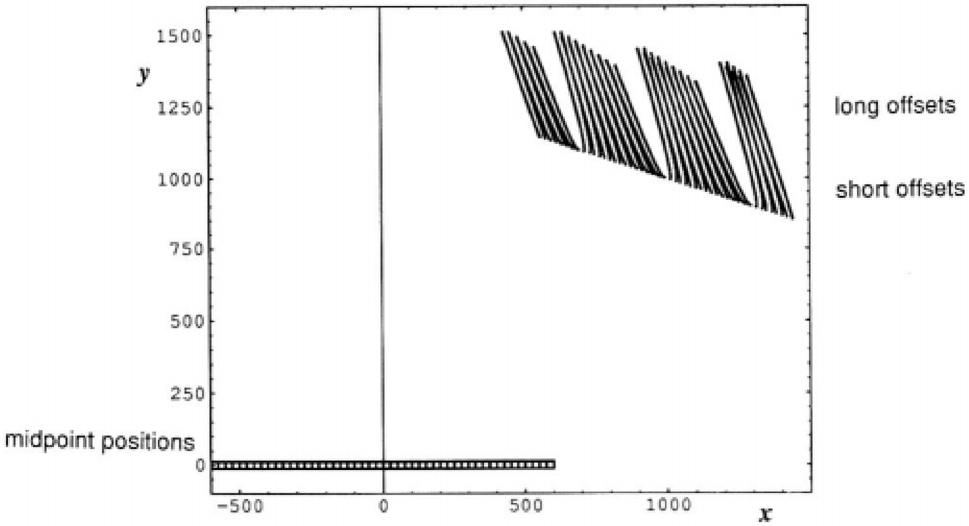

Figure 2 Footprint of quad/quad geometry for 45° dip reflector that makes an angle of 45° with the shooting direction. The reflection points are shown for 48 neighbouring midpoints (three passes of 16 binlines each). The reflection points of the short offsets are quite regularly spaced, but the long offsets do not properly illuminate the subsurface.