3D symmetric sampling of sparse acquisition geometries

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Summary

All seismic data acquisition geometries that are being used today sample at least one but usually two of the spatial coordinates in a sparse way, whereas the other coordinates are sampled densely to some extent. Usually, the dense coordinates are not sampled dense enough for optimal quality, whereas reducing the sampling interval of the sparse coordinates invariably leads to better quality data. This paper reviews these opportunities for improvement. However, not only these parameters can be improved. Resolution can also be improved by using higher maximum frequencies and higher fold. In narrow-azimuth marine streamer acquisition significant improvements are possible using center-spread acquisition with an extra source towed behind the streamers. Nevertheless, in both narrow and wide towed-streamer acquisition feathering tends to spoil good intentions unless extra measures are taken to counteract this effect. Developments in node technology may make this technique a viable alternative to streamer acquisition. Most measures to improve data quality cost money, but gain in quality should outweigh the extra cost.

Introduction

The theme of this Special Session is: "Seismic Acquisition: Are we spending too much money?" In this paper I try to answer that question in the light of past technological changes and further technological change to be expected. One aim of seismic data acquisition and processing is to provide the interpreter with crisp and clear images of the subsurface. Another aim is to be able to extract reliable information on rock properties and pore fill from the available seismic data. This paper is meant to show that these requirements can be met better by a variety of measures that all cost more money. A more detailed version of this paper has been submitted for publication in the December 2010 issue of Geophysics.

Review of 3D symmetric sampling

The most common 3D acquisition geometries are parallel geometry, orthogonal geometry and areal geometry (Vermeer, 2002). Parallel and orthogonal geometry are line geometries in which sources and receivers are sampled densely along the respective acquisition lines, whereas the line intervals correspond to the sparsely sampled coordinates. There are two types of areal geometry; in type 1 the sources are densely sampled and the receivers are coarsely sampled in x and y; in type 2 it is the other way around.

Each geometry is (partially) characterized by its basic subset. In the line geometries the basic subset consists of the combination of all data corresponding to one shot line and one receiver line; i.e., in parallel geometry the basic subset is a midpoint line, whereas in orthogonal geometry the basic subset is the cross-spread. In areal geometry type 1 the basic subset is the 3D receiver gather, whereas in areal geometry type 2 it is the 3D shot gather.

A common feature of these basic subsets is that two of the spatial coordinates are fixed, whereas the other two are densely sampled. Therefore, a common factor in defining 3D symmetric sampling for the three types of geometries is the requirement of proper sampling of the basic subsets of the geometries. In array-based acquisition geometries proper sampling of the desired signal rather than the total wavefield is also considered acceptable in 3D symmetric sampling. Proper sampling of the basic subsets implies proper sampling of two of the four spatial coordinates. The other two coordinates will be sampled sparsely, in general.

For each one of the three main acquisition geometries the sampling requirements of the basic subsets have to be supplemented with additional requirements for complete 3D symmetric sampling. In parallel geometry the additional requirement is to achieve square bins; this boils down to a distance between the midpoint lines (= crossline binsize) that is equal to one half of the shot and receiver station intervals. In marine streamer acquisition, 3D symmetric sampling is never achieved, because the shot interval is always larger than the receiver station interval.

Orthogonal geometry can be characterized by three pairs of parameters: shot and receiver station intervals, shot and receiver line intervals, and maximum inline and crossline offsets. These pairs determine binsize, unit cell and midpoint area of cross-spread, each pair having its own aspect ratio. 3D symmetric sampling of orthogonal geometry requires that all three aspect ratios of the geometry are equal to 1, because in that way inline and crossline direction are treated in entirely the same way. 3D symmetric sampling also requires the geometry to be regular; that means that all cross-spreads of the geometry have same-size midpoint areas with center-spread acquisition for shots and for receivers. An impressive example of this kind of acquisition (enabled by large channel capacity) is described in Girard et al., (2007). They used 25-m station intervals, 200-m line intervals and 3000-m maximum offsets.

Areal geometry may be sampled in a similar way as orthogonal geometry. For instance for type 1 areal geometry, the shot station interval can be small in x and y, the receiver grid interval would be large in both x and y, and the maximum offsets may be the same in x and y. This would again lead to three aspect ratios (station interval, grid interval and midpoint range of 3D receiver). A geometry equivalent to the example orthogonal geometry of the previous paragraph would consist of 25-m shot sampling intervals in x and y, 200-m grid intervals in x and y and 3000-m maximum offsets in x and y. However, a better alternative is to use hexagonal sampling of areal geometry.

Main benefits of 3D symmetric sampling are noise removal in basic subsets, prestack imaging of single-fold gathers (OVT gathers, see below), and better rock property analysis.

Ways to improve data quality

Higher maximum frequency. The maximum frequency that can be acquired in a given survey area is usually taken for granted. It may often be in the order of 70 Hz. Baeten and van der Heijden (2008) did not take maximum frequency for granted. They carried out an elaborate experiment in the Oman desert and achieved maximum frequencies of 150 Hz for layers as deep as 2000 m. This remarkable achievement required considerable effort; the vibroseis sweep consisted of two parts, one for the lower frequencies up to 80 Hz and a number of repeated non-linear sweeps for frequencies from 80 to 150 Hz. They also found that single-sensor recording with very accurate positioning was essential to preserve the high frequencies. The kind of effort they spent is not easily adopted in production-oriented data acquisition; nevertheless, this experiment proved that higher frequencies are achievable, and it is likely that further developments in technology will allow the acquisition of higher maximum frequencies, also in a production environment. If maximum frequency could only be raised to 110 Hz, this would already provide enormous benefits.

Smaller station spacing. Ideally, the station intervals should be equal to the basic sampling interval Δx, defined as $\Delta x = V_{min} / (2f_{max})$, where V_{min} is minimum apparent velocity of any coherent events in the wavefield and f_{max} is maximum frequency. A somewhat less strict requirement is to use the adequate sampling interval defined in Baeten et al. (2000). Even less strict is to use the basic *signal* sampling interval that depends on the minimum apparent velocity of the desired signal rather than that of the total wavefield. In this case it may be necessary to compensate coarse sampling of the noise by the use of field arrays.

Often, larger intervals than the basic signal sampling interval are used; quite common is to select an event-oriented sampling interval that samples reflection events without aliasing in the zero-offset section. In that case part of the signal wavefield is still aliased, in particular the diffractions and shallow events with smaller apparent velocities and higher frequencies. For maximum frequencies in the order of 70 Hz, it is usually sufficient to use sampling intervals in the order of 20 or 25 m; yet in current practice, it is quite common to use station intervals of 50 m, 220 feet (67 m) or more. Of course, higher maximum frequencies call for even smaller station intervals.

In case the desired wavefield is properly sampled, it is not necessary to prevent migration-operator aliasing (Biondi, 2001) by high-cut filtering; instead, the data can be and should be interpolated to half the basic signal sampling interval, thus preserving precious high frequencies.

Interesting examples of the benefit of small station intervals are shown in Lansley (2004) for land data and in Calvert et al., (2003), for marine data. In the latter case not only the choice of station interval proves to be important, but also the crossline binsize, which is determined by the streamer interval and the number of shots in multisource multistreamer acquisition.

Smaller line intervals. The line intervals in orthogonal geometry determine its sparsity. The line intervals also determine the size of the offset-vector tiles (OVTs) that may be used to construct OVT gathers or pseudo-COV gathers (common offset-vector gathers). In the ideal COV gather all shot receiver pairs have the same offset vector (same absolute offset and same shot/receiver azimuth). The smaller the OVTs the closer the pseudo-COV gathers look like true COV gathers. For small OVTs single-fold prestack imaging of the pseudo-COV gathers leads to minimal migration artifacts, whereas for larger OVTs (larger line intervals) reciprocal OVT gathers may be used to mitigate the effect of the spatial discontinuities between the tiles in a pseudo-COV gather (Vermeer, 2007). Similar reasoning applies to areal geometry, but then for the grid interval of the sparsely sampled unit.

Figure 1a and b illustrate the effect of using reciprocal OVT gathers of areal geometry to suppress migration noise of single-fold OVT gathers with 400 × 400 m tiles, whereas Figure 1c shows the significant improvement in data quality with smaller grid interval of 200 × 200 m.

Increase fold. Reducing line intervals also leads to an increase in fold assuming the same maximum inline and maximum crossline offsets. An increase in fold should lead to an increase in S/N, also for the higher frequencies, thus also improving the resolution of the data. This was illustrated vividly by Anderson et al., (2006), who used a 3D survey with 200-m line intervals to simulate surveys with larger line intervals of 800 and 400 m. The maximum useful frequency was approximately 40, 50, 57, and 72 Hz for surveys with 24, 48, 144 and 300+-fold. Other authors also report considerable data quality improvements with increased fold.

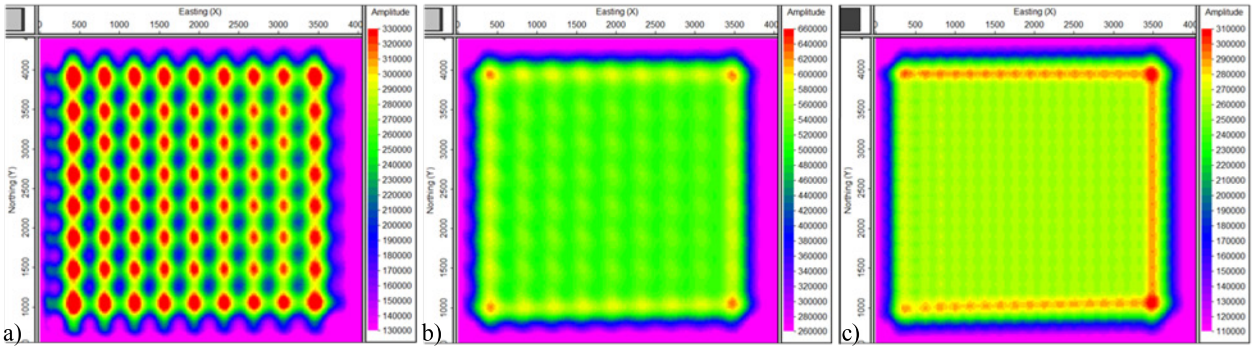

Fig. 1. Imaging of a reflector with 15° dip by OVT gathers in areal geometry. a) Horizon slice for 400 × 400 m OVTs from upper right corner of 3D shot, b) 400 × 400 m reciprocal OVTs from upper right and lower left combined, c) 200 × 200 m OVTs from upper right corner of 3D shot.

Center-spread acquisition with marine streamers. OVTs (allowing to construct single-fold OVT gathers) in conventional narrow-azimuth marine streamer acquisition are determined by the shot intervals in the inline and the crossline direction. These OVTs may have dimensions in the order of 40 × 400 m, where the crossline roll of 400 m equals half the width of the streamer swath. The wider the streamer swath the larger is the sparsity of the geometry leading to more migration artifacts. The seriousness of the migration artifacts may be mitigated by antiparallel acquisition (Vermeer, 1997), but even more so by center-spread acquisition (Beasley and Chambers, 1999). The effects are illustrated in Figure 2, which shows the dramatic improvement that can be obtained using reciprocal OVTs for a configuration with two sources and 8 streamers.

The implementation of center-spread acquisition can be achieved easiest by using a source-only vessel steaming directly behind the streamers of a conventional marine streamer swath. The main problem with this solution is the effect of feathering. To ensure optimal regularity the streamer swath should be wider than twice the crossline roll, with a margin depending on the expected feathering.

Use nodes instead of wide-azimuth towed streamer acquisition. Wide-azimuth towed streamer acquisition (WATS) as implemented over the past years suffers from many shortcuts in parameter choices (Vermeer, 2009). In particular binsizes as well as OVTs tend to be highly unbalanced with very small aspect ratios. Also the geometries tend to have maximum crossline offsets that are much smaller than the maximum inline offsets. Using what is basically parallel geometry, the aim of WATS configuration design is to approximate as well as possible areal geometry with well-sampled 3D shot gathers. These 3D shot gathers must be acquired in several adjacent passes of the streamer vessel for repeated passes of the source vessels. This leads to yet another problem, which is gaps and overlaps that will exist in the 3D shot gathers due to feathering. To really reap the benefit of a wide-azimuth geometry with regular 3D shot gathers distributed in a balanced way, considerable extra efforts are required with towed streamers. It is not impossible to do it right, but it is extremely difficult, time-consuming and expensive.

The real solution lies in regular areal geometry that can be acquired with ocean-bottom sensors (nodes). Further developments in node technology should make all attempts

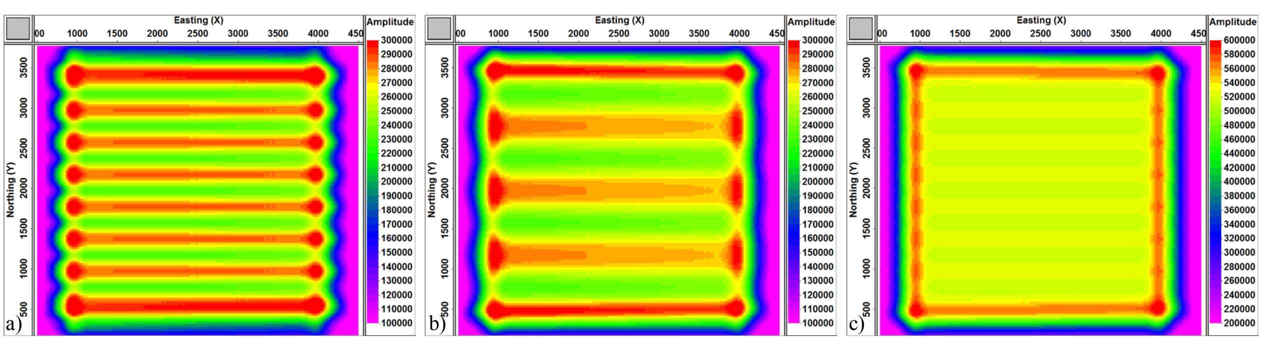

Fig. 2. Horizon amplitude slices of migrated pseudo-COV gathers in 2/8 configuration. The input gathers have a regular midpoint grid of 25 × 25 m and have inline offsets 2350 and 2400 m. Reflector dip is 15°. a) shooting downdip, parallel acquisition; b) antiparallel shooting; c) center-spread acquisition, with use of reciprocal pseudo-COV gathers.

to improve WATS acquisition obsolete.

What about dense sampling of three of the four spatial coordinates (hybrid geometry)? A new type of acquisition geometry has been implemented over the past decade both in marine and in land data acquisition. In this new geometry there are three densely sampled spatial coordinates rather than two as in conventional 3D acquisition. I call this geometry hybrid geometry because it combines elements of parallel, orthogonal and areal geometry.

The first hybrid geometry was a 4C OBC survey acquired over the Statfjord field (Rognø et al., 1999). Other hybrid OBC surveys are reported for the Caspian Sea Azeri and Gunashli fields in Bouska and Johnston, (2005), and for the North Sea Hild field in Vaxelaire et al., (2007). Hybrid geometry is also acquired in the Life of Field Seismic across Valhall in the North Sea (Kommedal et al., 2004; Nolte et al., 2004). Hybrid geometry has even been acquired on land in Oman (Bouska, 2010; Sambell et al., 2010). Table 1 lists the receiver and source sampling intervals used in these acquisitions. In all surveys the only sparsely sampled coordinate is the crossline receiver interval. However, all of these geometries acquire rather poorly sampled 3D receiver gathers as the source sampling is at least 50 × 50 m.

Table 1 Receiver and source sampling intervals (m) used in various hybrid geometries (and one areal geometry)

	Δr_x	Δr_y	Δs_x	Δs_y
Statfjord	25	300	50	50
Valhall	50	300	50	50
Azeri/Gunashli	25	360	75	75
Hild	25	400	50	50
Oman_BP	50	450/550	50	100
Oman_PDO	25	200	50	50
Oman_3DSS	200	200	25	25

With 50-m sampling, the maximum unaliased frequency in water-borne noise with apparent velocity 1500 m/s will be 15 Hz; hence, this noise will be heavily aliased leading to a lot of trouble in trying to remove it (Boelle et al., 2008). Noise suppression in these hybrid geometry data is mostly the result of high fold levels rather than enabled by adequate sampling.

For noise suppression as well as for resolution, a source sampling of 25 × 25 m would be much better, but would require four times as many shots. Alternatively, instead of using the sources in a 50 × 50 m grid, they might also be used in a 100 × 25 m grid with the same number of shots, but now arranged for orthogonal geometry only (100-m source-line intervals) with properly sampled cross-spreads. The corresponding data sets would have the same trace density, but prestack noise removal would not be as successful with the coarsely sampled hybrid geometry as with the well-sampled orthogonal geometry.

This reasoning applies with extra force to land data such as acquired in Oman, because there is more noise and the noise has lower velocities. An interesting alternative to a properly sampled orthogonal geometry is a properly sampled areal geometry, listed as Oman_3DSS in Table 1. In this geometry the 3D receivers are still rather coarsely sampled at 25 × 25 m shot intervals, but this can be compensated by using 25 × 25 m areal receiver arrays at the 200 × 200 m receiver locations. The limited number of receiver stations allows laying out a vast area with receiver arrays, so that the "distance-separated simultaneous sweeping" technique (Bouska, 2010) can be used with a large degree of simultaneousness.

Discussion

Very powerful interpolation techniques are available these days to improve the sampling of the seismic data. In my view these techniques can be used with great effect to regularize irregular data. Regularization is an essential step toward optimal final results. It is nearly always necessary, because there are hardly any surveys in which the acquisition geometry can be acquired according to the nominal design. On the other hand, regularity is essential to minimize artifacts caused by variations in fold, and spatial discontinuities such as caused by gaps in the acquired data. Interpolation techniques always have limitations as well; therefore, I would not recommend to design a 3D survey on basis of gains to be expected from interpolation.

I have reviewed various ways of improving data quality. The discussed list of possibilities is definitely not exhaustive; in particular longer offsets also may lead to better ways of rock property analysis.

Conclusions

Technology developments continue to offer opportunities for better data quality. Virtually all seismic surveys use sparse acquisition geometries. Reducing the sparsity by reducing line intervals will often lead to better data quality, but also increasing sampling density of the densely sampled coordinates will often be beneficial. There is still a wealth of improvement to be realized by using higher maximum frequencies. In marine data acquisition improvements can be obtained using center-spread acquisition, whereas high-quality wide-azimuth acquisition with streamers is nearly impossible. In marine data acquisition nodes may be the systems of the future. The answer to the question of this Special Session "Seismic Acquisition: Are we spending too much money?" must be an unequivocal "NO".