Reciprocal offset-vector tiles in various acquisition geometries

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Summary

With the recent developments in marine streamer acquisition, all three main types of acquisition geometry – orthogonal, areal, and parallel – can now be used to acquire wide-azimuth seismic data. On top of this, marine streamer acquisition may also be used to acquire multi-azimuth data. In this paper these geometry types are compared with each other on basis of offset-vector tile (OVT) gathers. Contrary to popular belief that reciprocal azimuths do not contribute to better illumination, reciprocal OVTs are highly desirable to compensate for coarse sampling. These reciprocal OVTs are not always integrated in the design criteria of wide-azimuth streamer acquisition. Instead, the parameters of this acquisition technique tend to suffer from serious compromises.

Introduction

Over the last two decades, 3D marine streamer acquisition has seen an enormous progress in efficiency based on the use of multisource multistreamer configurations. The data acquired with these configurations remained essentially narrow azimuth. It was even shown that increasing the width of the configurations would lead to more and more illumination irregularities (Vermeer, 1994). Yet, these narrow-azimuth configurations served the industry quite well, and high-quality results have been achieved with multisource multistreamer configurations.

However, it gradually transpired that narrow-azimuth acquisition is not optimal for complex geology, notably not for illumination and imaging around and below salt. O'Connell et al. (1993) demonstrated with a dual-azimuth experiment that shooting parallel to the salt produced better images than shooting across the salt. Houllevigue et al. (1999) acquired four different azimuths around a salt structure; their results showed that shooting in a single direction misses about 15% of the information provided by the other three directions. Many other multi-azimuth experiments have been discussed in the literature, culminating recently with Keggin et al. (2006) reporting on multi-azimuth streamer acquisition using as many as six different azimuths.

In 2005 BP conducted a so-called wide-azimuth towed streamer (WATS) field trial (Threadgold et al., 2006). Shell followed suit in 2006 with another WATS configuration (Corcoran et al., 2006; Moldoveanu and Egan, 2006). In contrast to multi-azimuth, the sailing direction remains the same throughout the WATS survey but the range of crossline offsets between sources and receivers is increased drastically. Wide-azimuth acquisition is quite common for orthogonal and areal geometry; now that wide-azimuth is also becoming feasible for parallel geometry it is interesting to compare the various types of geometry.

The analysis starts with a review of some relevant properties of orthogonal geometry, notably the existence of cross-spreads and offset-vector tile (OVT) gathers as characteristic features of this geometry. Based on the use of OVT gathers, it is shown that inherent spatial discontinuities caused by the limited extent of cross-spreads can be mitigated provided the geometry is regular. This methodology is then extended to areal geometry and subsequently to parallel geometry. This paper concludes with a discussion of factors influencing the quality of WATS acquisition and proposes some ways of improving this quality.

OVT gathers in orthogonal geometry

The data of regular orthogonal geometry can be considered as a collection of cross-spreads, all having the same maximum inline offset and the same maximum crossline offset. The cross-spread is a continuous 3D subset of the 5D prestack wavefield. This means that the spatial attributes (inline offset, crossline offset, absolute offset, and azimuth) in a cross-spread vary smoothly from trace to trace. Only the edges of each cross-spread form spatial discontinuities in the total data set. Because each cross-spread is a single-fold data set, the number of cross-spreads contributing to any bin is equal to the fold-of-coverage M.

Figure 1a illustrates that the midpoint area of each cross-spread can be subdivided into offset-vector tiles (OVTs; Vermeer, 2002, 2005) each with the size of a unit cell (the area between two adjacent receiver lines and two adjacent source lines). In regular orthogonal geometry the number of these OVTs is equal to the fold-of-coverage. This means that there are M different single-fold OVT gathers in the full-fold area of the geometry. In other words, each trace in any bin in the full-fold area belongs to one of the M OVT gathers. The tiles of the OVT gathers are again spatially continuous, but there are spatial discontinuities between tiles. These spatial discontinuities are much smaller than those along the edges of the cross-spreads; therefore, it may be said that the inherent spatial discontinuities of orthogonal geometry are spread thinly across the OVT gathers. The smaller the size of the unit cell, i.e., the line intervals, the smaller the spatial discontinuities in the OVT gathers.

The OVT gathers consist of a small range of inline and crossline offsets. Therefore, these gathers are most similar to

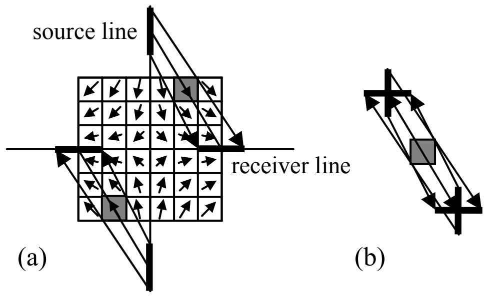

Figure 1: Cross-spread in 36-fold orthogonal geometry. (a) Each offset-vector tile has its own characteristic small range of inline and crossline offsets. The two grey OVTs represent a pair of reciprocal OVTs. Their corresponding receivers and sources are indicated by heavy lines. (b) In full-fold area of geometry two-fold data sets can be constructed from reciprocal OVTs as indicated in the figure. Note complementary nature of these OVTs. The sources of one cross-spread form a cross with the receivers of another cross-spread and vice versa.

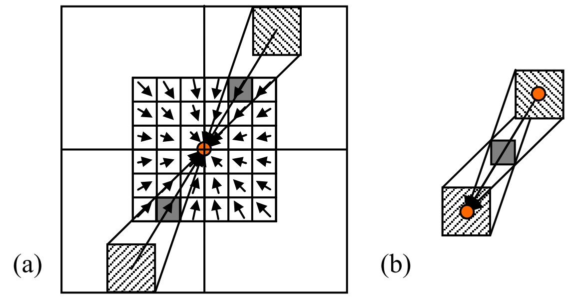

Figure 2: 3D receiver in 36-fold areal geometry. (a) The large square indicates the area of all sources that are being recorded in the receiver in the center of the figure. Each offset-vector tile has its own characteristic small range of inline and crossline offsets. The two grey OVTs represent a pair of reciprocal OVTs. They share the same receiver whereas the sources are located in the cross-hatched squares. (b) In full-fold area of geometry two-fold data sets can be constructed from reciprocal OVTs as indicated in the figure. Note complementary nature of these OVTs. The sources of one receiver are centered around the other receiver and vice versa.

common-offset vector (COV) gathers in which all traces have the same inline offset and the same crossline offset. COV gathers are ideal data sets for prestack migration as they extend across the whole survey area and do not show any internal spatial discontinuities. (Champions of shot-profile wave-equation migration may disagree on COV gathers being ideal, but that is a different story.) The small spatial discontinuities in the OVT gathers can be reduced further by combining each gather with its reciprocal OVT gather formed by traces with the same small range of inline and crossline offsets but with opposite sign (see Figure 1b). Using two-fold data sets consisting of the combination of an OVT gather with its reciprocal OVT gather produces imaged sections with minimal artifacts (Vermeer, 2002; Gesbert, 2002). These "reciprocal" OVT gathers are not truly reciprocal to each other, they are really quite complementary. Only reciprocal COV gathers would consist of duplicate traces. Together reciprocal OVT gathers compensate for the coarse sampling of two of the four spatial coordinates (corresponding to the line intervals).

In irregular geometry not all cross-spreads are the same, which means that some of the OVT gathers will not be complete, even if the full-fold area of the geometry shows constant fold. Then the gaps in the OVT gathers represent spatial discontinuities in the total data set. Multi-line roll and poorly designed full-swath roll geometry are examples of irregular geometry leading to spatial discontinuities and corresponding acquisition footprints. Serious acquisition footprint caused by poorly designed full-swath roll is discussed in Drummond et al. (2001).

OVT gathers in areal geometry

In areal geometry a sparse grid of receivers is listening to a dense grid of sources. It is typically a geometry used in sea-bed acquisition with nodes. The data of areal geometry can be considered as a collection of 3D receiver gathers. This gather is also a continuous 3D subset of the 5D prestack wavefield. Only the edges of each 3D receiver form spatial discontinuities in the total data set. Because each 3D receiver gather is a single-fold data set, the number of 3D receivers contributing to any bin is equal to the fold-of-coverage M.

Figure 2a illustrates that the midpoint area of each 3D receiver can be subdivided into offset-vector tiles (OVTs; Vermeer, 2002, 2005) each with the size of a unit cell (the area between four nodes arranged in a square). In regular(ized) areal geometry the number of these OVTs is equal to the fold-of-coverage. It may be clear that much the same remarks can be made about OVT gathers in areal geometry as about OVT gathers in orthogonal geometry.

Also in areal geometry reciprocal OVT gathers exist (Figure 2b). Each OVT gather produces irregular illumination of the subsurface, depending on the dip and on the size of the unit cell, but the reciprocal OVT gather would be complementary, so that together a pair of OVT gathers creates relatively regular 2-fold illumination.

OVT gathers in multi-azimuth marine streamer acquisition

Figure 3a illustrates the splitting of a 60-fold marine streamer configuration into 60 OVTs, each of which can provide complete single-fold coverage in the full-fold area of the geometry. The configuration consists of two sources and ten streamers with 100-m interval between the streamers. The interval between pops is 25 m, leading to a shotpoint interval of 50 m for each midpoint line. This parallel geometry is just about as continuous as can be in the inline direction but strongly discontinuous in the crossline direction. Because the

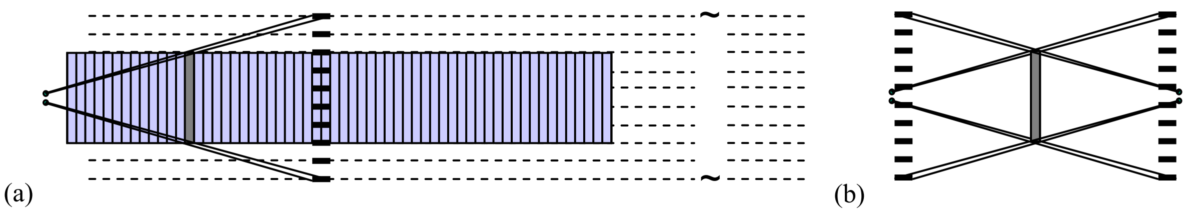

Figure 3: OVTs in typical 60-fold two sources, ten 6000-m streamers configuration. Size of OVTs is 50 × 500 m. (a) Dashed lines indicate streamers; light-grey area is midpoint area of configuration. The dark-grey area is a single OVT; with the heavy lines indicating the corresponding streamer segments. Note that the offset-vector tiles are not fully continuous as in Figures 1 and 2. (b) Reciprocal OVTs. Note again complementary nature of the reciprocal OVTs.

crossline fold of this geometry is equal to 1, all OVTs are arranged in the inline direction. Their width is equal to the shotpoint interval and their height equals the crossline midpoint range which is 10 * 100 / 2 = 500 m. These OVTs have an aspect ratio of 10, which is pretty much out-of-balance, especially as compared to the aspect ratio of the unit cells in orthogonal and areal geometry.

The wider a conventional streamer configuration the more it suffers from spatial discontinuities in the crossline direction. The effect can be mitigated by antiparallel acquisition in which adjacent boat passes are acquired in opposite directions (Vermeer, 1997). In that case reciprocal OVTs (Figure 3b) are not on top of each other as in the orthogonal and areal geometry but they alternate in the crossline direction, in this way reducing the spatial discontinuities in the crossline direction. However, it would be much better to traverse each shot line in two directions, thus simulating center-spread acquisition and providing a crossline fold of two with reciprocal OVTs that average out each other's illumination irregularities.

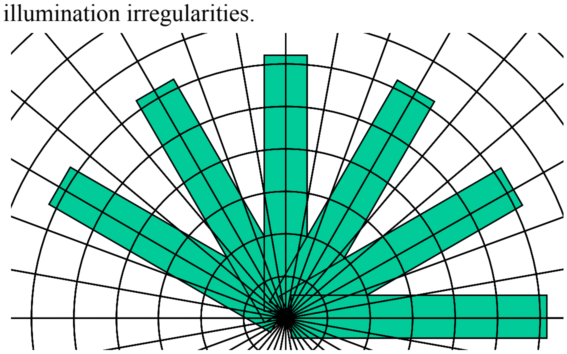

Figure 4: Six-azimuth configuration used in the Nile Delta (Keggin et al., 2006).

The configuration described above and in Figure 3 is the basis configuration used by BP in their six-azimuth streamer acquisition carried out in the Nile delta (Keggin et al., 2006; Page et al., 2007; Keggin et al., 2007). Whether or not anti-parallel acquisition has been used in each of those 6 acquisitions is not mentioned in those papers; therefore, it is likely that the racetrack system has been used to acquire these data (many parallel boat passes in one direction and next to these many parallel boat passes in the other direction). This means that the configuration is basically described by Figure 4. The papers on this very special data set show considerable improvements obtained with the multi-azimuth acquisition over the single azimuth. Whether 6 azimuths were really necessary for this area has not really been demonstrated. The poor crossline illumination (Keggin et al., 2007) from a single-azimuth configuration might also be repairable by simulating center-spread acquisition rather than by shooting 6 poor illuminations on top of each other. It may well be (perhaps depending on the complexity of the geology) that three-azimuths center-spread acquisition would provide better results than six-azimuths end-of-spread acquisition.

OVT gathers in wide-azimuth towed streamer acquisition

Most WATS configurations tested so far consist of a single streamer vessel and two source vessels, each towing two sources. Both source vessels traverse the same source line N times, whereas the streamer vessel moves up in the crossline direction between passes, thus simulating a streamer vessel towing N times the number of streamers.

In these WATS configurations, it is attempted to acquire 3D source gathers. However, the gathers are not truly 3D source gathers, because each gather is constructed from sources following at least two different source tracks. This provides a smaller crossline bin size than one source track would do.

Figures 5 and 6 show the midpoint coverage and OVTs of one "pseudo shot" in the BP (Threadgold et al., 2006) and Shell (Moldoveanu and Egan, 2006) WATS configurations, respectively. Both configurations lack small inline and small crossline offsets, thus creating spatial discontinuities not only for the long offsets (as in the cross-spreads and 3D receivers discussed above) but also for the short offsets. The midpoint areas can be subdivided into OVTs as before. (Shoshitaishvili et al., 2006, and LaDart et al., 2006, applied narrow-azimuth tomography software to all OVT gathers of the BP WATS data.) The width of the offset-vector tiles is determined by the source interval for one midpoint line which is 4 * 37.5 = 150 m in both cases. The crossline dimension of the OVTs is determined by the crossline roll in the geometry which is 250 m for BP and 450 m for Shell. The Shell configuration acquires reciprocal OVTs which compensate each other's illumination irregularities, whereas the BP configuration does not have reciprocal OVTs but uses a much smaller crossline roll.

The number of streamers contributing to each OVT is equal to crossline roll * 2 / streamer interval, which is 10 in the narrow-azimuth geometry of Figure 3, 4 for the BP WATS configuration, and 6 for the Shell WATS configuration.

A troubling feature of both WATS configurations is the large imbalance between inline binsize and crossline binsize. In the BP configuration the bins are 6.25 × 31.25 m, whereas in the Shell configuration the bins are 6.25 × 37.5 m.

Discussion

The introduction of towed streamers into wide-azimuth acquisition has broadened the scope of the seismic acquisition techniques. However, the first attempts still suffer from serious compromises. Compared to wide-azimuth land acquisition, the aspect ratios of all configurations are quite small. The crossline binsizes larger than 30 m limit the accuracy of the salt body definition and, as a consequence, limit subsalt resolution. There is also a large imbalance between inline and crossline fold.

Compared to the OVTs in orthogonal and areal geometry, the OVTs of the WATS configurations have a rather small inline dimension, whereas the crossline dimension of the OVTs in the Shell configuration (and even more so in the exploration WATS currently being acquired by PGS; Long, 2006) is relatively large. Efficiency gains could be made by using 8 sources rather than four, thus doubling the inline dimension of the OVTs to 300 m. However, managing four source vessels rather than just two might be a bridge too far at present.

Ideally, reciprocal OVTs should be acquired as in the Shell WATS. However, an intermediate compromise can be found by acquiring alternate pseudo 3D shots in opposite directions. This would create antiparallel strips of OVTs, thus mitigating the spatial discontinuities at the large crossline offsets.

There is a wide-spread conviction that infill shooting can be reduced considerably by multi-azimuth and wide-azimuth configurations. This idea relies on the higher fold of the data to mitigate spatial irregularities. However, the nominal geometry is the ideal geometry, and missing coverage in any subset of the data must lead to loss of quality. Therefore, it would be much better (actually in all streamer acquisition, be it wide or narrow) to tow at least two extra streamers in each configuration thus allowing for regularization in the presence of feathering and reducing the required infill shooting.

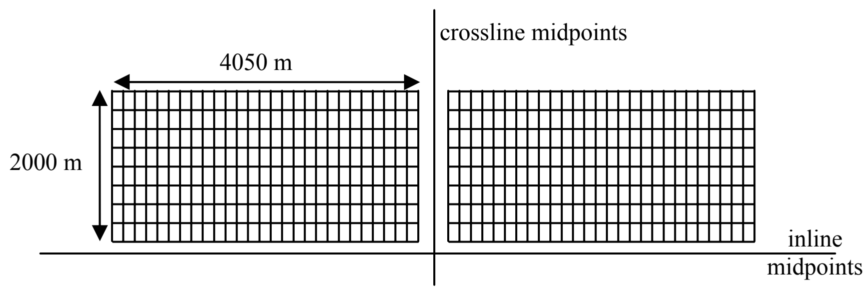

Figure 5: OVTs in BP's WATS configuration. Size of each OVT is 150 × 250 m. Bin size is 6.25 × 31.25 m. No reciprocal OVTs exist in this geometry.

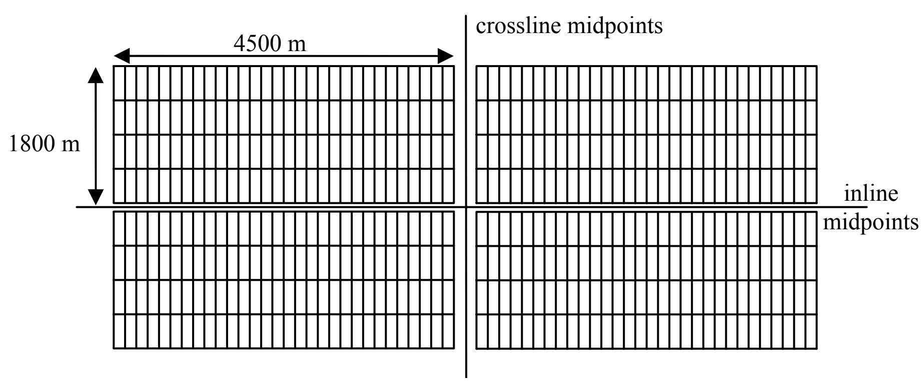

Figure 6: OVTs in Shell's WATS configuration. Size of each OVT is 150 × 450 m. Bin size is 6.25 × 37.5 m. Reciprocal OVTs provide complementary illumination.

Conclusions

Offset-vector tiles are not only useful to analyze typical land-type geometries, but also for a better understanding of the merits of various parameter choices in narrow and wide parallel geometry. Reciprocal offset-vector tiles compensate each other's illumination irregularities and are desirable products of any acquisition geometry. Multi-azimuth acquisition would benefit from simulating center-spread acquisition, thus acquiring reciprocal OVTs. Wide-azimuth towed streamer configurations suffer from compromises. However, efficiency gains are possible by using more sources in each WATS configuration. Without any extra effort, using antiparallel configurations can reduce spatial discontinuities in WATS configurations not having reciprocal OVTs.

References

Corcoran, C., C. Perkins, D. Lee, P. Cattermole, R. Cook, and N. Moldoveanu, 2006, Wide-azimuth streamer acquisition for Gulf of Mexico subsalt imaging: 76th Annual International Meeting, SEG, Expanded Abstracts, 2910-2914.

Drummond, J., J. Ryan, and R. Kasmi, 2001, Adapting to noisy 3-D data: Enhancing Algerian giant field development through strategic planning of 3-D seismic in Berkine Basin: The Leading Edge, **20**, 718-729.

Gesbert, S., 2002, From acquisition footprints to true amplitude: Geophysics, **67**, 830-839.

Houllevigue, H., H. Delesalle, and E. de Bazelaire, 1999, Enhanced composite 3D cube derived from multi-azimuth 3D marine acquisitions: 61st Meeting, EAGE, Extended Abstracts, Paper 1-08.

Keggin, J., et al., 2006, Multi-azimuth towed streamer 3D seismic in the Nile delta, Egypt: 76th Annual International Meeting, SEG, Expanded Abstracts, 2891-2895.

Keggin, J., M. Benson, W. Rietveld, T. Manning, P. Cook, and C. Page, 2007, Multi-azimuth 3D provides robust improvements in Nile Delta seismic imaging: First Break, **25**, no.3, 47-53.

LaDart, S., J. Lee, E. Shoshitaishvili, J. Etgen, and S. Michell, 2006, Wide azimuth tomography – is it necessary?: 76th Annual International Meeting, SEG, Expanded Abstracts, 3398-3402.

Long, A., 2006, How multi-azimuth and wide-azimuth seismic compare: First Break, **24**, no.12, 55-61.

Moldoveanu, N., and M. Egan, 2006, From narrow-azimuth to wide- and rich-azimuth acquisition in the Gulf of Mexico: First Break, **24**, no.12, 69-76.

O'Connell, J.K., M. Kohli, and S. Amos, 1993, Bullwinkle: A unique 3-D experiment: Geophysics, **58** , 167-176.

Page, C., R. van Borselen, E. Fromyr, J. Keggin, T. Manning, and W. Rietveld, 2007, Experience with towed streamer multi-azimuth processing and acquisition: First Break, **25**, no.3, 41-44.

Shoshitaishvili, E., S. Michell, J. Etgen, D. Chergotis, and E. Olson, 2006, Improving resolution of top salt complexities for subsalt imaging: 76th Annual International Meeting, SEG, Expanded Abstracts, 3061-3065.

Threadgold, I.M., K. Zembeck-England, P.G. Aas, P.M. Fontana, D. Hite, and W.E. Boone, 2006, Implementing a wide azimuth towed streamer field trial: the what, why, and mostly how of WATS in Southern Green Canyon: 76th Annual International Meeting, SEG, Expanded Abstracts, 2901-2904.

Vermeer, G.J.O., 1994, 3-D symmetric sampling: 64th Annual International Meeting, SEG, Expanded Abstracts, 906-909.

Vermeer, G.J.O., 1997, Streamers versus stationary receivers: Proceedings of the 29th Annual Offshore Technology Conference, OTC, 331-346.

Vermeer, G.J.O., 2002, 3-D seismic survey design: SEG.

Vermeer, G.J.O., 2005, Processing orthogonal geometry – what is missing?: 75th Annual International Meeting, SEG, Expanded Abstracts, 2201-2204.