# Wide-azimuth towed streamer data acquisition and simultaneous sources

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## Introduction

At the 2006 SEG Conference suddenly a flurry of papers associated with wide-azimuth towed streamer acquisition (WATS) was presented. The papers dealt with modelling and design (Regone), with implementation and acquisition (Threadgold et al., Corcoran et al., Howard and Moldoveanu), and with processing and imaging (Michell et al., LaDart et al., Shoshitaisvili et al.). Earlier, in a special workshop at the 2006 EAGE Conference many of those papers had been presented already in a less official way.

The first WATS marine data acquisition was carried out in 2005. The technique makes use of one or more streamer vessels plus two or more source vessels cruising along parallel courses. This extension from narrow-azimuth acquisition and multi-azimuth acquisition to wide azimuth has gained a lot of interest in the industry. The technique has been tried with many different implementations and the newest extension is to consider simultaneous sources to improve the efficiency of the acquisition.

Although especially Regone (2006, 2007) carried out many modelling tests to analyze the virtues of various parameter choices in WATS acquisition, analysis of the acquisition geometry using common design principles has not often been discussed. For instance, the idea to use simultaneous sources for WATS acquisition is more based on intuition than on analysis, I believe. With this paper I try to fill this in.

This paper starts with the description of some characteristics of a typical WATS configuration. Next I argue that this configuration can be viewed not only as parallel geometry but also as areal geometry, because a major objective of WATS is to acquire 3D shot gathers. If viewed as areal geometry, the inline source sampling is often quite dense, whereas the crossline source sampling is often quite coarse. Other aspects, such as binsize, edge effects and feathering, are discussed as well in the light of what would be an ideal areal geometry. These analyses lead to the conclusion that simultaneous sources will only help to reduce acquisition cost and time of areal WATS configurations if more than about 8 sources are used.

Geometries that would benefit from simultaneous sources are those that require dense sampling of sources along the source lines. Narrow-azimuth geometry and zigzag WATS are discussed as examples of such geometries. This paper is rounded off with a discussion of pros and cons of zigzag WATS configurations.

## Characteristics of wide-azimuth towed streamer acquisition

Threadgold et al. (2006) discuss the first implementation of a WATS survey carried out in the Gulf of Mexico. The configuration is described in Figure 1. I use this WATS geometry (designed by BP and acquired by Veritas) to illustrate the characteristics of WATS acquisition.

This geometry features two source vessels, each vessel towing two sources. In this way, acquisition can be efficient, but it is also quite complicated as described clearly in Threadgold et al. (2006). Each source track is traversed four times with the streamer vessel moved up 1000 m each time. Effectively, this means that each source is recorded by 32 streamers with streamer separation 125 m. The whole configuration of Figure 1 was repeated every 250 m in the crossline direction, i.e., the crossline roll was 250 m.

The four sources in this geometry each follow their own source track. The distance between the tracks is 31.25 m, which is ¼ of the streamer interval. This leads to a 15.625 m distance between the midpoint lines of this parallel geometry (the crossline binsize = 15.625 m). For safety reasons there is a 200-m minimum distance between the right paravane of the first source vessel and the left paravane of the streamer vessel. As a consequence, the geometry has a pretty large minimum inline and crossline offset.

The inline source interval is 37.5 m. The reason for this large interval is the long recording time to allow for a large target depth under very deep water. As a consequence, the source interval along each track becomes 150 m, leading

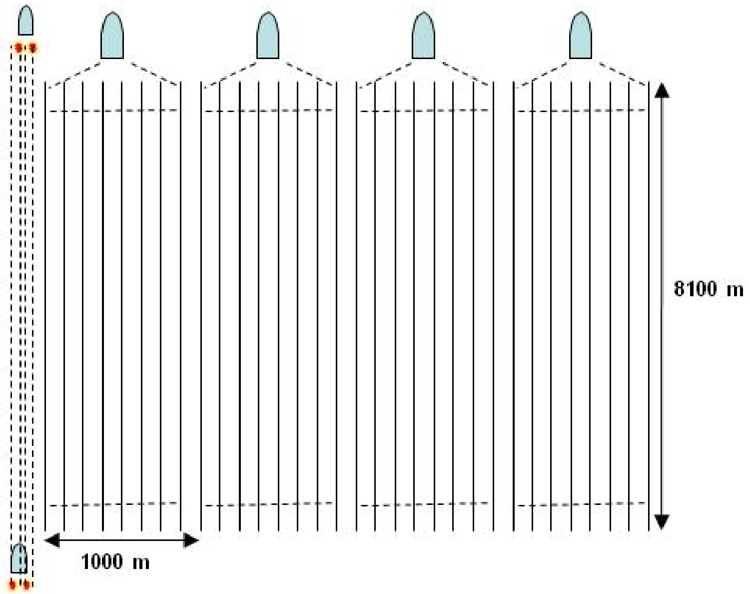


Figure 1. BP WATS configuration with two source vessels with two sources each and a single streamer vessel. The source vessels traverse the same source tracks four times while the streamer vessel moves up over 1000 m each time. Next the whole configuration moves up over 250 m in the crossline direction.

to an inline fold of 8100 / (2*150) = 27. The crossline fold is 4000 / (2*250) = 8, which means that the total fold of this geometry is 216. The station interval along the streamers is 12.5 m, so that the binsize equals 6.25 × 15.625 m.

The BP WATS geometry illustrates the difficulty of generating wide-azimuth geometry with towed streamers. In many respects this geometry leaves something to be desired. Figure 2 can be used to describe why the geometry is not optimal. It describes the range of inline and crossline offsets acquired with this geometry.

In the first place, the minimum shot-receiver distance is 476 m; this is quite large and may cause some accuracy problems in velocity determination and depth conversion. Furthermore, there is a gap of 750 m in the centre of the inline offset range. This gap leads to inadequate imaging by the central azimuths. The gap might have been avoided by sailing the second source vessel 750 m closer to the first source vessel. In that way continuous azimuth coverage would have been obtained at the cost of a 750-m reduction in the absolute value of the longest negative inline offsets. Yet, a good reason not to sail alongside of the streamer swath is to avoid getting too close to the streamers in case of feathering.

The objective of wide-azimuth acquisition is to cover a complete range of azimuths for all offsets. However, in this case the aspect ratio of the geometry is even less than 0.5. This may mean one of two things: either the inline offsets are longer than required, or the geometry is not wide enough in the crossline direction. Finally, even though Figure 2 may suggest otherwise, the two separate inline offset ranges are sampled with a crossline binsize of 31.25 m rather than 15.625 m. The data acquired by the two source vessels are strictly speaking two separate but interleaved surveys. Therefore, crossline imaging is prone to migration-operator aliasing. On the other hand, the large fold of the acquired data will partially compensate (with careful processing) this shortcoming in crossline sampling.

It is also interesting to analyze this geometry and other WATS geometries using a subdivision in offset-vector tile (OVT) gathers as introduced earlier for orthogonal geometry.(Vermeer, 2002). Shoshitaishvili et al. (2006) use such a subdivision to facilitate tomographic migration velocity analysis for the BP data. In orthogonal geometry the

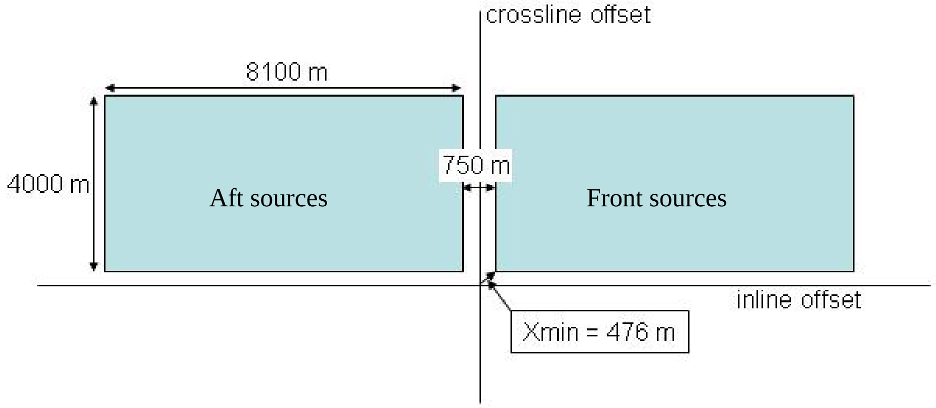


Figure 2. Offset and azimuth distribution of BP WATS configuration. Only positive crossline offsets larger than about 296 m are acquired. There is a 750-m gap in the middle of the range of inline offsets. Minimum absolute offset equals 476 m.

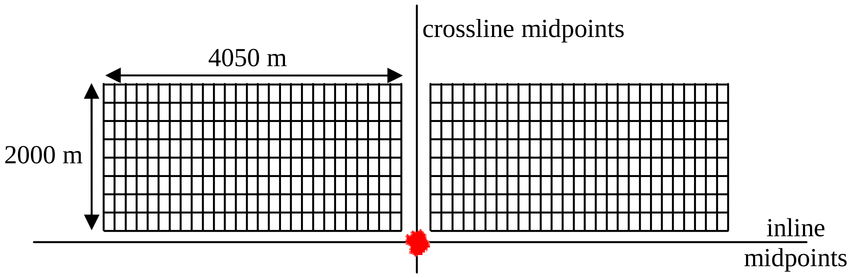


Figure 3. Quad-source midpoint area with OVTs in BP WATS configuration. Width of tiles in inline direction is 4050/27 = 150 m; in the crossline direction the width is 2000/8 = 250 m.

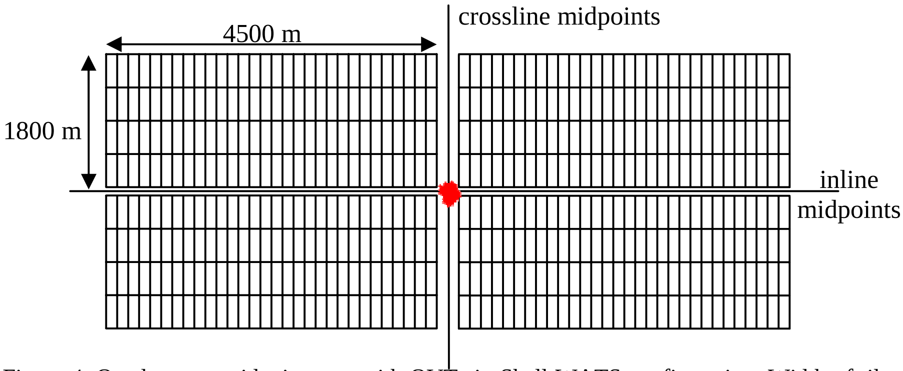


Figure 4. Quad-source midpoint area with OVTs in Shell WATS configuration. Width of tiles in inline direction is 4500/30 = 150 m; in the crossline direction the width is 1800/4 = 450 m.

midpoint area of a cross-spread (= basic subset of orthogonal geometry) is subdivided into $M_i \times M_c$ equal rectangles ($M_i$, $M_c$ are inline and crossline fold, respectively). In this wide-azimuth parallel geometry there is no such well-sampled basic subset, and the partitioning has to be carried out in a different way. Because OVTs are normally described in terms of midpoints, Figure 2 must be translated first to the midpoint domain for a group of 4 consecutive sources as shown in Figure 3. Dividing the inline midpoint range by the inline fold (27 in this case) and the crossline midpoint range by the crossline fold (8 in this case) provides OVT partitioning. It should be realized that this has to be done for the front-end sources and tail-end sources separately, as they form interleaved surveys. This resulting subdivision in OVTs is also shown in Figure 3.

The tiles have dimension 150 × 250 m. Actually, this 150 m is the inline source interval in each midpoint line, i.e., it is the inline periodicity of the geometry, whereas the crossline dimension corresponds to the crossline roll of 250 m, i.e., the crossline periodicity of the geometry. These values correspond to source line interval and receiver line interval in orthogonal geometry; compared to commonly used line intervals in orthogonal geometry of around 300 m, the dimensions of the OVTs in this BP geometry are relatively small, which is quite good.

On the other hand, the binsize of the OVTs is 6.25 × 31.25 m, which is extremely unbalanced. The number of bins in each tile is 150/6.25 * 250/31.25 = 24 * 8. Because each OVT is single fold, the number of traces in each OVT is 24 * 8 = 192. In contrast to orthogonal geometry where each OVT is a spatially continuous data set, the OVTs in this geometry are moderately spatially discontinuous. This is caused by the fact that in this implementation of parallel geometry each midpoint line corresponds to a unique source/streamer pair. The 8 bins in the crossline direction correspond to two sources shooting into four different streamers. These irregularities must lead to some additional migration artefacts as compared to what happens in orthogonal geometry. Another shortcoming of this geometry is that reciprocal offset-vector tiles do not exist, because only positive crossline offsets are acquired. In orthogonal geometry, pairs of reciprocal offset-vector tiles take care of each other’s illumination irregularities (Vermeer, 2007).

Even with all its shortcomings, the BP WATS geometry discussed here is quite a dense geometry with relatively small OVTs. By now many other WATS geometries have been described in the literature, virtually always with a larger crossline roll than the 250 m used in BP WATS. For instance, the crossline roll used in the Shell WATS configuration as described by Moldoveanu and Egan (2006) was 450 m. Figure 4 shows the OVTs in the Shell WATS configuration (after Vermeer, 2007). This geometry includes the acquisition of reciprocal OVTs. In actual fact, the WATS configuration used by Shell had a crossline roll of as much as 900 m, with front and aft shots following separate source lines, 450 m apart (Corcoran et al., 2007).

## Parallel or areal geometry?

In the previous section, I have called the WATS geometry parallel geometry. The geometry fully satisfies the definition of parallel geometry because the source lines are parallel to the receiver lines. However, the basic subset of parallel geometry, the midpoint line, is not sampled as well as it normally is in narrow-azimuth streamer surveys. In WATS geometries the source interval for each midpoint line is in the order of 150 m rather than the more common 37.5 m (in the Gulf of Mexico) and 18.75 m (in the North Sea). The coarse source interval in the inline direction reduces the inline fold, but this is compensated by a larger crossline fold (8 in case of BP WATS) as compared to the crossline fold of 1 that is common in narrow-azimuth acquisition. The coarse inline source interval might be used as an argument in favour of using simultaneous sources.

There are also good arguments to call WATS geometries areal geometries. In areal geometry sparse receivers are combined with dense shots (Vermeer, 2002) as in marine surveys using nodes. The receivers in node geometries are sparse because of the expense to construct and/or to deploy the nodes. In those geometries 3D receiver gathers are acquired. Another version of areal geometry is the use of sparse shots and dense receivers. This geometry would collect 3D shot gathers. An attractive aspect of areal geometry is that 3D shot gathers and also 3D receiver gathers are most suitable for shot-profile migration.

Two of the four shots in Figure 3 shoot into the first quadrant, whereas the other two are shooting into the second quadrant. In Figure 4 two of the shots shoot into the first and the fourth quadrant, whereas the other two are shooting into the second and the third quadrant. So, in all cases there are just two sources corresponding to a "continuously" sampled midpoint area. If these two sources are sufficiently close, their behaviour is not very different from just one source shooting into twice as many streamers. A horizon amplitude comparison of one versus two sources is shown in Figure 5 for narrow-azimuth geometry. It shows that the horizon amplitudes of single-fold subsets obtained with a 2/8 geometry are nearly the same as obtained with 1/16 geometry. In other words, although two different source locations are used for each quadrant in Figure 3, the acquired data behave much as if they were acquired with a single shot. Similar reasoning applies to Figure 4. In narrow-azimuth geometry as well as in WATS, using two sources produces two midpoint lines for each streamer; this allows twice as large a streamer interval as with single source for the same crossline binsize. It is not ideal, but it is perhaps the least serious of all compromises in WATS acquisition.

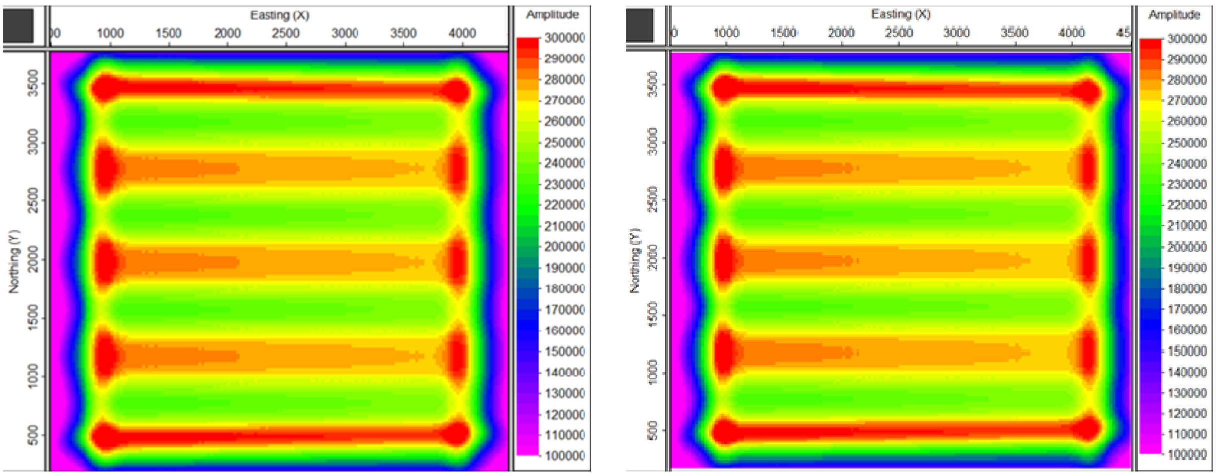


Figure 5. Horizon slices of migrated single-fold gathers for dipping event acquired with two different narrow-azimuth antiparallel configurations. Left: 2 sources / 8 streamers, right: one source / 16 streamers. The amplitudes in these two displays are virtually the same. The acquisition footprint is caused by the width of one boat pass (400 m in midpoints).

It should be noted, though, that each shot location in these WATS configurations is visited several times, because there are not enough receivers available to generate complete shot records in one go. This repeating of shots is one of the important cost factors in WATS acquisition.

Nevertheless, it may be stated that the aim of WATS configurations such as in Figure 1 is to acquire 3D shot gathers. This means that the WATS configuration can also be viewed as areal geometry. To distinguish this type of WATS geometry from other types, I will call it areal WATS. It is interesting to compare the parameters of some areal WATS configurations with those used in other areal geometries or in equivalent orthogonal geometries.

Areal geometry may be acquired in a rectangular grid, but also in a hexagonal grid. A hexagonal grid saves some 13.4% on sampling. For comparison with orthogonal geometry (which cannot be acquired in a hexagonal grid) it is more convenient to look at an areal geometry with a square grid of receivers and a square grid of sources. If sources are the sparse units, then for instance a 300 × 300 m grid might be adequate in many situations, whereas the receivers may be acquired in a 25 × 25 m grid. If maximum useful offset would be 6000 m, then each shot may be recorded by 12,000 * 12,000 / (25 * 25) = 230,400 receivers. The reader who is perhaps more familiar with orthogonal geometry than with areal geometry may compare this areal geometry with the equivalent orthogonal geometry. The equivalent orthogonal geometry would feature shot and receiver line intervals of 300 m, maximum inline and maximum crossline offsets of 6000 m, and shot and receiver station intervals of 25 m. Two geometries are called equivalent if the distribution of absolute offsets would be the same (this implies the same binsize as well). In this orthogonal geometry there would be 230,400 traces in each cross-spread. That is just as many as in the 3D shot gather of the equivalent areal geometry, but now these traces are acquired by as many sources as receivers, 12000/25 = 480. The offset/azimuth distributions of these two example geometries are identical and are described by Figure 6, whereas the fold-of-coverage of both geometries is equal to 6000/300 * 6000/300 = 400. The offset-vector tiles in these two equivalent geometries have dimension 300 × 300 m. These two geometries also feature reciprocal OVT gathers, which are composed of OVTs in opposite quadrants in the offset/azimuth domain. Such gathers are quite useful to have because they partially compensate the coarse sampling of these sparse geometries (Gesbert, 2002; Vermeer, 2007).

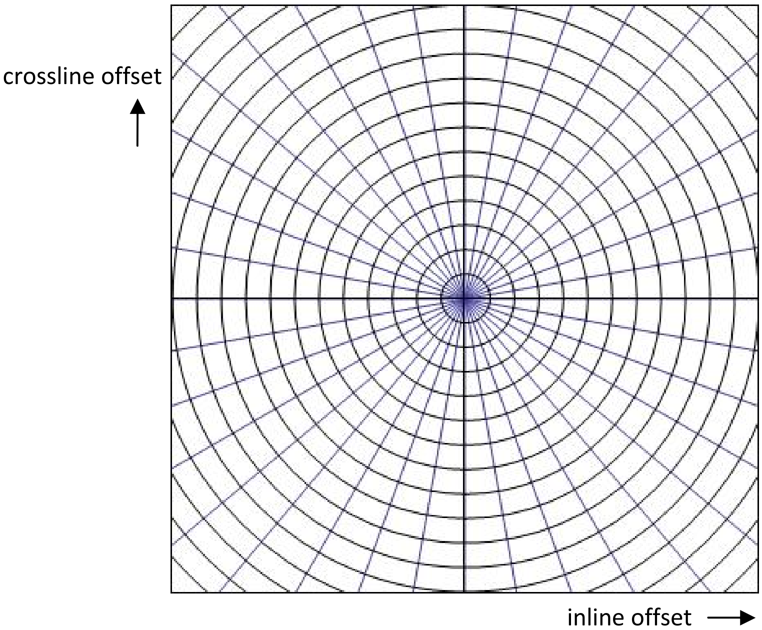


Figure 6. Rose diagram for equivalent areal and orthogonal geometries with maximum inline offset = maximum crossline offset = 6000 m. Each circle represents constant absolute offset; the interval between the radii of the circles is 500 m. The segment interval between the radial lines is 10°. In a regular geometry the distribution of traces inside the square is constant. Often, the number of traces in each little segment of the rose diagram is color-coded; however, this number is directly proportional to the area of each segment so that color-coding is not really necessary.

This example illustrates that areal geometry tends to be more time-consuming and expensive to acquire than orthogonal geometry: in areal geometry there is a serious unbalance between number of shots and number of receivers per unit area. Therefore, it is not surprising that various compromises in the parameter choice of WATS configurations lead to areal geometry with quite unbalanced parameters as already mentioned when discussing the BP WATS configuration. In the following I discuss binsize, number of sources, crossline roll, number of boat passes required for each source track, maximum offset, edge effects, and feathering aspects. This discussion also includes some suggestions for improvement of the acquisition parameters. The underlying principle in all discussions is that in 3D symmetric sampling one aims to achieve single-fold subsets of the data that already produce good quality images (barring illumination problems). In areal geometry the 3D shots are single-fold gathers that should be sampled good enough to produce high quality images. However, these 3D shots also have edges, and the edge effects are reduced by ensuring regular geometry. (In the full-fold region of regular geometry there are as many OVT gathers as the total fold *M* of the geometry. Each bin contains *M* traces, with each trace belonging to one of the *M* OVT gathers.) Moreover, reciprocal OVT gathers are required to further reduce the edge effects. The requirement of good-quality single-fold gathers ensures maximum benefit from prestack imaging.

### *Binsize*

The binsize of the BP WATS configuration is 6.25 × 31.25 m, a factor 5 difference between inline and crossline. Of course, it should be granted that the inline direction is oversampled, which does not hurt normally. However, 31.25 m is very large and can only be justified by claiming that one is not interested in frequencies above 20 Hz. The large crossline binsize produces migration artefacts in the crossline direction; this processing generated noise can be avoided by better sampling. Sampling requirements are dependent on the low water velocity, especially in deep water. The obvious remedy is to decrease streamer intervals.

### *Number of sources*

In a balanced acquisition geometry the OVTs are square or nearly square. In most WATS configurations used to date, there are only four sources leading to a periodicity in the inline direction of 150 m. This is small as compared to the periodicity in the crossline direction, which was 450 m in the Shell WATS configuration discussed earlier and 600 m in some other WATS configurations. Without changing the interval between consecutive shots (37.5 m in all Gulf of Mexico WATS configurations), the acquisition can become more balanced by using eight sources rather than 4. This would increase the inline dimension of the OVTs from 150 m to 300 m. This increase in number of sources, e.g., eight sources on four vessels, could be used to ensure azimuth coverage in all four azimuth quadrants. Interestingly, CGGVeritas acquired in 2007/2008 the Walker Ridge survey using four source vessels (see http://www.cggveritas.com/default.aspx?cid=1738&lang=1; the fact that four source boats were used is not clear from that web address; it can be found in the CGGVeritas brochure Wide Azimuth - Worldwide); however, only four sources were used, leading to 150 m between the shot points in each midpoint line.

### *Crossline roll*

The distance between the source tracks that are traversed several times is 250 m in the BP WATS configuration. This is quite acceptable, but in other WATS configurations much larger crossline roll has been used, up to 600 m. The reason is that the crossline roll is one of the two major cost factors determining the number of boat passes across the survey area. (The other factor is the number of times each source track has to be traversed.) For a better balance between inline and crossline source interval, the crossline roll has to be reduced to about 300 m. This would reduce the range of crossline offsets across each OVT; hence reduce migration artefacts along the outsides of the OVT gathers that can be constructed from OVTs along the outside of the midpoint areas as depicted in Figures 3 and 4.

### *Number of boat passes required for each source track*

The other major cost factor is the number of boat passes per source track. This number depends on the required total range of crossline offsets, on the width of the swath, and on the number of sources (or source pairs, for two shots per shooting boat) in the crossline direction. In the BP WATS configuration these figures were 4000 m for range of crossline offsets, 1000 m for width of swath and 1 for number of sources measured in the crossline direction. Geophysically, it is not attractive to reduce the range of crossline offsets; on the contrary, it would be desirable to acquire also crossline offsets in the other two quadrants as in the Shell WATS configuration. Geophysically attractive is to increase the width of the swath or to increase the number of sources as mentioned above. Doubling the number of sources in the crossline direction would halve the required number of boat passes, whereas it does not hurt that the inline source interval would double to 300 m at the same time. The limited number of streamers listening to each shot is the real problem in areal WATS acquisition. It is such a problem, because in areal geometry with 3D shots, a horrendous number of receivers has to listen to each shot. Shooting with 8 sources is a better utilisation of the limited number of receivers.

In narrow-azimuth acquisition the quality of the final data deteriorates with increasing width of the streamer swath, especially if no antiparallel acquisition is used. However, in areal WATS acquisition, the more streamers are listening the better.

### *Maximum offset*

Most WATS configurations use very long offsets in the order of 8000 m. Long offsets may be useful for undershooting purposes, but other than that the best illumination is usually obtained with short offsets. For best illumination of complex geology it is more important to have offsets for all azimuths and to have sufficiently large aperture between recorded midpoints and the depth points to be imaged. Therefore, it may be more important to balance crossline and inline offsets than to maintain the very long inline offsets. Shorter streamers would allow towing more streamers, which would help crossline binsize and would reduce acquisition times.

### *Edge effects*

Normally, the 3D receiver gathers acquired with node geometry are continuous throughout the whole midpoint area of the 3D receiver, and the only edges in areal geometry are the edges of the 3D receivers. However, in areal geometry generated in WATS configurations, there are many more edges with the corresponding edge effects in imaging, because the short offsets, both inline and crossline, are not acquired (Figures 3 and 4). These edge effects can be mitigated by ensuring regular geometry and by using reciprocal OVTs. Unfortunately, regular geometry also comes at a price as discussed next.

### *Feathering aspects*

Feathering is one of the major problems in marine streamer acquisition. It is perhaps even more serious in areal WATS acquisition than in narrow-azimuth acquisition. Feathering in opposite directions between neighbouring boat passes for the same source track generates elongated holes in the coverage of the 3D shots. Such holes produce migration smiles perpendicular to the long axis of the holes and phantom horizons parallel to the holes. Therefore it should be attempted to apply interpolation across holes.

In case of serious cross currents, interpolation across holes in coverage may not be all that successful. The number and size of the holes may be reduced by using partially overlapping boat passes rather than adjacent boat passes as in Figure 1. Partially overlapping boat passes are also used in 4D acquisition to improve the chances of finding matching pairs of traces. Of course, to propose such a procedure for WATS acquisition is very unpopular, because there is already a shortage of receivers in this type of acquisition. Overlapping streamers would increase that problem. Yet, it is important to realize these shortcomings of WATS configurations. Of course, the usually high fold of areal WATS helps to suppress artefacts, but it is no replacement for good illumination.

## Simultaneous sources helpful for areal WATS?

Various authors of recent papers suggest that simultaneous sources[1] would offer an opportunity for better WATS acquisition (Beasley, 2008; Hampson et al., 2008; Berkhout, 2008). For instance, Beasley (2008) states: "There is immediate application in today's market for wide-azimuth surveys in which multivessel operations are already employed." Yet, as discussed here, the number of sources is no problem in current WATS acquisition. The number of sources could be easily doubled from four to eight without needing simultaneous shooting and still providing adequate source sampling in the areal geometry that is being tried to acquire.

In case eight sources would be used and some of those sources would shoot simultaneously, the total fold of the geometry would be increased in the inline direction. This would help to reduce artefacts caused by irregular geometry and coarse crossline sampling, but at the same time it might introduce residual noise because it is most likely that simultaneous sources cannot be separated perfectly.

Simultaneous sources would be particularly helpful in case dense sampling of sources is required as in line geometries, such as orthogonal and zigzag geometry, but not in areal geometry that is based on using sparse sources and dense receivers. The real problem in areal WATS is the number of receivers that can listen simultaneously to the sources. As suggested above, more streamers are needed to increase the efficiency of each individual shot. Furthermore, *considerable savings and/or improvements in data quality can be achieved when accepting that the source interval in the inline direction can be easily doubled to 300 m.*

[1] Simultaneous shots: not necessarily firing at the same time, but certainly with overlap in recording times.

# Applications of simultaneous sources

## *Narrow-azimuth geometry*

A major problem in narrow-azimuth streamer acquisition is that the streamer swaths cannot be made very wide because of edge effects that increase with dip, offset and width of the configuration (Vermeer, 2002, 2007). It has been proposed to use antiparallel acquisition to remove the spatial discontinuities that exist between two adjacent boat passes (Vermeer, 1997). However, a much better solution is to simulate centre-spread acquisition by using front and aft sources (Vermeer, 2007). Of course, this requires a separate source vessel, but it would enable much better quality narrow-azimuth data.

Obviously, this type of acquisition is very suitable for simultaneous sources as demonstrated in Beasley et al., (1998), and Beasley (2008). This would allow an increase in fold of the narrow-azimuth geometry and at the same time a relatively large number of streamers may be employed. Because of this, it would also be possible to use some overlap of adjacent boat passes, thus allowing correction for feathering effects by regularization.

*There may well be a class of acquisition problems that can be solved with simultaneous shooting of narrow-azimuth configurations. Some problems that are currently tackled with multi-azimuth acquisition or even wide-azimuth acquisition might be solved in this way.*

## *Wide-azimuth geometry*

Rather than aiming for areal geometry, it may be attempted to aim for a crossed-array geometry, in particular the zigzag geometry. A separate source vessel sails zigzag lines across the seismic streamers while maintaining a centre-spread position. Figure 7 illustrates this idea for a zigzag geometry that is equivalent to the 300 × 300 m orthogonal geometry and 300 × 300 m areal geometry discussed earlier in this paper. The parameters of zigzag geometry are equivalent to orthogonal geometry if the lengths of the active receiver spreads are the same, the maximum crossline offsets are the same, and if the crossline component of the source interval of the zigzag geometry is equal to the source interval of the orthogonal geometry (25 m in the example discussed earlier). In that case the absolute offsets in the zig-spreads and in the zag-spreads of the zigzag geometry are the same as the absolute offsets in the cross-spread of the orthogonal geometry and the number of traces in a cross-spread is equal to the number of traces in a zig- or in a zag-spread. To generate an equivalent zigzag geometry from a given orthogonal geometry, all odd-numbered source lines should be rotated clockwise over 45° and all even numbered source lines should be rotated anti-clockwise over 45°. In this way the total fold of the two geometries is the same as well. Figure 6 also represents

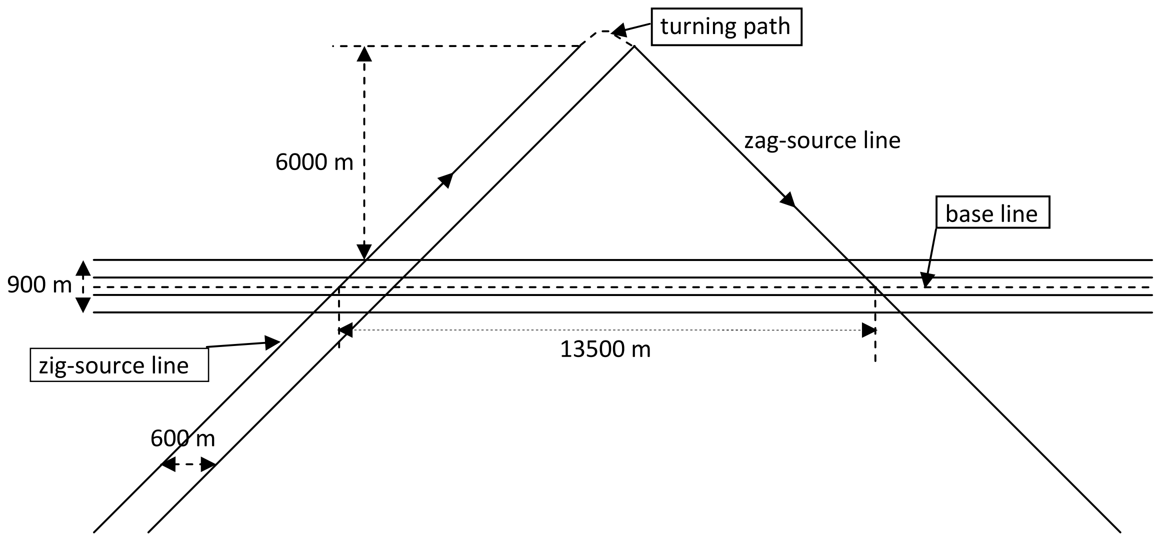


Figure 7. Wide-azimuth zigzag geometry. 4 streamers @ 300 m. Maximum crossline offset 6000 m. Streamers to be towed deep enough to allow crossing with source vessel and sources (Figure is not to scale). The source vessel is given 600 m in the inline direction to turn over 90° at the end of each shot line.

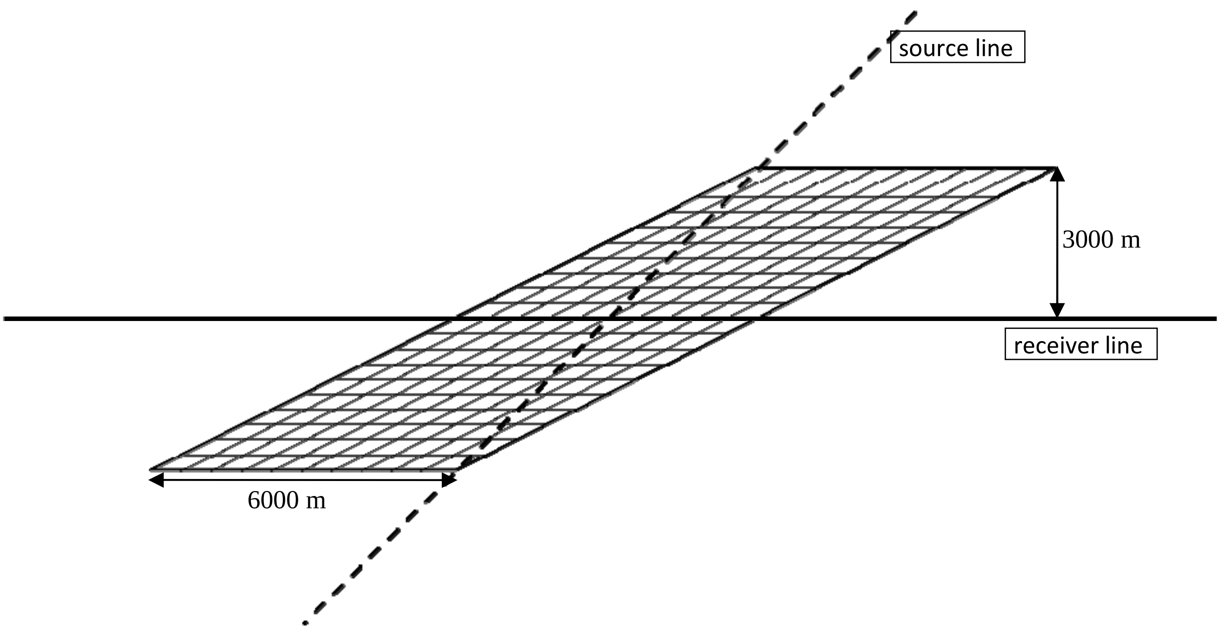


Figure 8. Zig-spread with offset-vector tiles for geometry with active spread length 12000 m, maximum inline and crossline offset 6000 m, receiver line interval 300 m, and source line interval 600 m. There are 10 * 20 OVTs in this zig-spread, corresponding to a fold of the zig-spreads only of 200. Adding zag-spreads would bring fold to 400.

the range of inline and crossline offsets for the zigzag WATS geometry being considered.

Thus, in zigzag geometry there are two families of source lines; the zig-lines cross the receiver lines at an angle of 45°, whereas the zag-lines cross at an angle of 135°. The corresponding parallelogram-shaped zig- and zag-spreads are skewed in opposite directions (Vermeer, 2002). There are also two families of OVTs, one for the zig-spreads and one for the zag-spreads. The horizontal side of the parallelogram-shaped OVT has length 600 m (in the zigzag geometry that is equivalent to the 300 × 300 m orthogonal and areal geometries discussed earlier; it is 600 m in this case because the horizontal distance between zig shot lines is 600 m), whereas the crossline dimension equals 300 m (see Figure 8). This means that the periodicity of this geometry is 600 m in the inline direction and 300 m in the crossline direction.

The geometry illustrated in Figure 7 would be called a full-swath roll in land data acquisition. The source vessel needs to cruise at a velocity that equals the streamer vessel velocity times square root of 2. A design principle for full-swath roll is that the crossline length of the source line outside the outer receiver line equals the desired maximum crossline offset (which by itself should be an integer multiple of the receiver line interval), being 6000 m in the example geometry. This means that the zig- and zag-spreads acquired in the geometry of Figure 7 are all somewhat larger than the nominal zig-spread shown in Figure 8. The acquired excess traces should be discarded at some point in the processing sequence before imaging. Full-swath roll becomes more efficient when the number of receiver lines can be chosen larger. If it would be possible to tow 6 streamers with 300-m separation instead of 4, then efficiency would increase by 50 %.

An interesting application of zigzag geometry in combination with a *single* seismic streamer is described in Bukovics and Nooteboom (1990). The source vessel sailed a zigzag course alongside the streamer vessel, thus acquiring only positive inline and positive crossline offsets. The crossline distance between the two vessels varied between 100 and 1000 m. The streamer vessel traversed each receiver line twice, with a 900-m inline shift between the two source boat passes. Together with a crossline roll of 225 m this provided 4-fold data with amazingly good results. (Bukovics and Nooteboom, 1990, described the geometry as a 16-fold geometry; however, they used a large binsize of 25 × 25 m to count fold, rather than counting the number of overlapping zig and zag spreads.)

It is interesting to compare zigzag WATS with areal WATS. For both configurations I assume a 1200-m effective width of the swath (effective width = number of streamers * streamer interval), and full-azimuth acquisition. For the zigzag geometry, the horizontal distance travelled for one source line equals the vertical length of the shot line, which is 2 * maximum crossline offset + ($N_c$ – 1) * *RLI*, or, (2 $M_c$ + $N_c$ – 1) * *RLI*, where $N_c$ is number of streamers, *RLI* is streamer interval, and $M_c$ is crossline fold. A turning distance (see Figure 7) of some 300 m (i.e., ≈ *RLI*) has to be added to this. Every *SLI* m there should be a source line (*SLI* is source line interval); hence, the number of times $R_{zz}$ the system has to traverse the same streamer track is given by

$$R_{zz} = (2M_c + N_c)RLI / SLI \qquad (1a)$$

Note that in the example of Figure 7 the turning distance equals 2 * *RLI*, rather than *RLI*; this is caused by the requirement that the zag-shot line in the figure has to cross the base line at an odd multiple of the source line interval of 300 m from where the zig-shot line (traversed by the same source vessel) crossed the base line. Therefore, in this example the formula for $R_{zz}$ is (assuming *RLI* = *SLI*)

$$R_{zz} = 2M_c + N_c + 1 \qquad (1b)$$

For the example geometry, this would lead to a repeat factor of 45. Every 1200 m 45 boat passes are needed for this geometry. 45 sounds like a pretty large receiver repeat factor, which it is actually. However, in zigzag WATS it does make sense to use simultaneous sources as proposed by Beasley, Hampson et al., and Berkhout in The Leading Edge of July 2008. For simultaneous shooting the source lines are split into as many pieces as there are source vessels; each source vessel traverses its own part of the zigzag geometry with all vessels continuously shooting centre-spread. Each source vessel needs its own turning path, so that for $N_s$ simultaneous sources equation (1a) (again assuming *RLI* = *SLI*) changes into

$$R_{zz} \approx (2M_c + N_c + N_s - 1)/N_s \qquad (1c)$$

The "≈" indicates that the computed value of $R_{zz}$ may need small modification to arrive at an integer number or to achieve a practical implementation of the geometry. In case two simultaneous sources are used the repeat factor reduces to 23 and for three sources the factor reduces to 16 repeats for every 1200 m crossline progress.

Rather than 25-m source interval as in the example geometry discussed earlier, I assume 37.5 m for inline and crossline component of the source interval in the zigzag WATS geometry; this to conform to the standard source interval used in the Gulf of Mexico.

Now I turn to areal WATS. As discussed earlier, the most efficient WATS configuration corresponding to a full-azimuth geometry is to use 4 source vessels with two sources each. This would lead to an inline grid interval of 300 m in case there is a shot every 37.5 m. The number of times each source track has to be traversed equals maximum crossline offset / width of swath or $M_c$ * *SLI* / 1200 (or 6000/1200 = 5 in our example geometry). To compare this with the 1200 m covered in the crossline direction by the zigzag geometry, this expression has to be multiplied by the number of times the crossline roll *SLI* fits on the width of the swath, i.e., 1200 / *SLI*. This means that to cover 1200 m in the crossline direction, $M_c$ boat passes with the five vessels have to be completed.

In the comparison thus far, I have selected line intervals equal to 300 m for the zigzag geometry, corresponding to 300 × 300 m grid intervals of the sources in the areal WATS. In both geometries maximum inline offset = maximum crossline offset = 6000 m. This means that the fold-of-coverage in both geometries equals 400. However, with the commonly used 120-m streamer interval in the areal WATS, the crossline binsize equals 30 m, whereas the crossline binsize in the zigzag WATS equals 18.75 m. The inline binsize would be the same in both geometries and is just dependent on the station interval used in the streamers. This means that the trace density in zigzag WATS is a factor 1.6 times as large as in areal WATS. The larger number of traces in the zigzag WATS increases the attractiveness of this geometry considerably.

For maximum crossline offset of 6000 m and *SLI* = *RLI* = 300 m, the zigzag geometry requires 45 boat passes, whereas the five vessel WATS needs only $M_c$ = 20 for every 1200 m. However, simultaneous shooting can be applied in the zigzag geometry, needing 23 or 16 boat passes for two or three simultaneous sources, respectively. This analysis shows that the zigzag geometry is about as efficient as conventional WATS for two simultaneous sources and even more efficient, if it would be possible to separate three simultaneous sources.

The obvious objection against using zigzag geometry is that it requires the source vessel to sail across the seismic streamers. Can that be done? I guess it can, although I am not the technical person who can answer that question. If you look at conventional supply vessels that are used as source vessels as well, the draft of these vessels is in the order of 3 to 4 m. Hence, it is more likely that the umbilicals are the deepest part of the source system. Sources at 7 m with umbilicals at some 8 m and with streamers at 11 m might be doable, but such a configuration would not likely draw cheers from the engineers or from the HSE people. Therefore, with conventional streamers it is better to stay away from the streamer swath. In that case, there should be a source vessel on either side of the swath thus producing a gap in the crossline offsets. The two sources should fire simultaneously for better sampling along the source lines.

A much nicer option is to use this technique in combination with over/under acquisition (Moldoveanu et al., 2007), or even better still, with the dual-sensor streamer (Carlson et al., 2007 or Pharez et al. 2008). These techniques use much deeper streamers, so that a depth can be chosen where the streamers are no longer affected by the turbulence caused by the source vessel.

Another problem with source vessels crossing the streamers is the impact of the direct wave for sources right above a streamer. The sensors should be strong enough to cope with the impact, or else one or two source points may have to be dropped across each streamer to avoid damage to the sensors.

## Discussion

The zigzag WATS has some disadvantages as compared to areal WATS.

- Zigzag geometry needs special attention in true-amplitude processing, because imaging of data inside the oblique angle between source line and receiver line behaves different than imaging of data inside the obtuse angle between source line and receiver line,
- OVT gathers have twice the inline dimension than in equivalent orthogonal or areal geometry; this is partially compensated by overlapping OVT gathers of the zig and zag varieties,
- Steep flanks in part of the asymmetric diffraction traveltime surfaces require extra caution in processing to prevent migration artefacts,
- Crossing the streamers with a source vessel may disturb the streamers,
- It requires at least two simultaneous sources to match acquisition time using areal WATS,
- The streamers should be extra long because of centre-spread acquisition,
- Best geometry requires over/under technique or else dual-sensor streamer.

The zigzag WATS also has some advantages as compared to areal WATS.

- Imaging more successful with zigzag WATS,
  - Crossline binsize can be 18.75 m, whereas a common crossline binsize (in a quadrant) in areal WATS may be 30 m,
  - There are no gaps in short offsets (unless shallow-tow streamers are used; in that case small crossline offsets are not acquired); hence, no migration smiles caused by those gaps as in areal WATS,
  - Each OVT is a fully continuous subset of the fully continuous basic subsets of this geometry,
  - Feathering has a minor effect on the continuity of the basic subset (zig- or zag spread) in case of two or more sources, whereas it seriously affects the continuity of the 3D shot acquired with areal WATS,
- In case of serious feathering the source lines can be adapted while shooting to ensure optimal coverage,
- Only two or three source vessels are required with single sources each,
- Single sources can be more powerful than dual sources on the same source vessel,
- Only four streamers are needed to cover an effective width of 1200 m,
  - Requires less towing strength,
  - Much less investment required, especially important for expensive dual-sensor streamers,
  - Expansion to 6 streamers with effective width 1800 m may be feasible.

From this discussion of pros and cons it is clear that the zigzag geometry is already more attractive in case only two sources are used. This set-up would reduce the number of required source vessels by a factor of 2 and it would provide much better quality data. Of course, this conclusion is dependent on the assumption that the data acquired by simultaneous sources can be faithfully separated. The best approach for this separation is still open to debate and to further testing. Beasley (2008) used sources fired simultaneously, whereas Hampson et al. (2008) show results for sequential firing with some jitter between firing times. Berkhout (2008) is (as yet) more visionary than practical, but suggests that nearby sources should be fired with large delay differences to avoid high correlation between their data. Sources at close distance do not have to occur in zigzag WATS, because the distance between two sources can be maintained equal to the maximum crossline offset; in case of three sources that distance would be two-thirds of the maximum crossline offset.

It may be argued that areal WATS may be acquired with data in only two azimuth quadrants, whereas the zigzag geometry would require centre-spread acquisition. This is not correct: if two quadrants would be good enough for areal WATS, they would be even better for zigzag WATS, but hardly ever zigzag data are acquired with positive crossline offsets only.

The geometry comparison carried out in the previous section pertains to ideal geometry parameters (except the crossline binsize of areal WATS). If the crossline fold is reduced by decreasing the maximum crossline offset, acquisition cost can be reduced accordingly for areal as well as for zigzag WATS. Further savings in the acquisition of zigzag WATS can be made by increasing the (average) source line interval to perhaps 400 m. In areal WATS this could be matched by increasing the crossline roll to 400 m.

Moldoveanu et al. (2008) describe circular WATS as another alternative to areal WATS. They propose to use a conventional seismic vessel that traverses circular paths. This interesting solution relies entirely on fold-of-coverage for imaging, because there are no well-sampled single-fold subsets to be perceived in circular WATS. In fact, all four spatial coordinates are sampled in more or less the same way on average, which means that all spatial coordinates are sampled in a coarse way. Moreover, unless the "roll" of this geometry is chosen very small, the azimuth distribution across the survey area may be quite irregular. This would be the case for a roll in inline and crossline direction of 1200 m as proposed (periodicity of geometry equals 1200 m in inline and in crossline direction). An improvement in the proposed geometry can be made by selecting a hexagonal grid for the centres of the circles instead of a square grid.

Without any doubt, the best (in a geophysical sense) alternative to WATS acquisition is acquisition with nodes. In node acquisition areal geometry is used that can be fully regular with appropriate sampling intervals.

## Conclusions

WATS configurations acquired with parallel geometry (parallel source tracks that are parallel to the streamer tracks) can also be described as areal geometry (areal WATS). This description illustrates the many problems and shortcuts associated with these configurations in general. Major shortcomings are the crossline binsize, the lack of short offsets and the negative effect of feathering on the sampling of the 3D shot gathers. Furthermore, crossline roll and acquisition in all azimuth quadrants are parameters that often suffer from the push to reduce acquisition cost.

The data of areal WATS do not really benefit from simultaneous shooting, because this geometry only requires a sparse grid of sources. In fact, the number of consecutive shots can be increased to 8 without hurting final data quality, whereas acquisition with 8 sources is more efficient than the currently common number of four sources.

A viable alternative to areal WATS is zigzag WATS in which the source line makes an angle of 45° with the receiver tracks. Its main advantages are: no missing short offsets, robust behaviour in case of feathering, and a smaller crossline binsize. These advantages should produce better imaging results. A serious restriction is that crossing the streamers with a source vessel is only feasible with deep-towed streamers, such as used in the over/under technique or in dual-sensor streamers. Because zigzag geometry requires dense sampling of sources along the shot lines, this technique would benefit from the use of simultaneous sources; in case two simultaneous sources are used, the acquisition time is similar to that of an equivalent areal WATS configuration. With conventional streamers the use of simultaneous sources is a must, as two source vessels would be needed - one on each side of the swath - that must turn 90° when they are as close to the streamer swath as tolerance allows.

In my view, circular WATS does not offer a satisfactory alternative, unless a grid of circles is used with a very small grid interval. On the other hand, areal geometry acquired with nodes remains the best option for high-quality regular geometry with long offsets for all azimuths.

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