Wide-azimuth towed streamer data acquisition and simultaneous sources

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At SEG's 2006 Annual Meeting, a flurry of papers associated with wide-azimuth towed-streamer acquisition (WATS) dealt with modeling and design, with implementation and acquisition, and with processing and imaging. Earlier, in a special workshop at the 2006 EAGE Conference, much of that material had been presented in a more informal way.

The first WATS marine data acquisition was carried out in 2005. The technique uses 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. The technique has a number of implementations and the newest extension is to consider simultaneous sources to improve the efficiency of the acquisition.

Many modeling tests to analyze the virtues of various parameter choices in WATS acquisition have been carried out but an 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 based more on intuition than on analysis, I believe. With this paper I try to fill this gap.

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. If viewed as an areal geometry, the inline source sampling is often quite dense, whereas the crossline source sampling is often quite coarse. Other aspects of the WATS geometry, such as bin size, edge effects and feathering, are discussed in the context of what would be an ideal areal geometry. These analyses lead to the conclusion that simultaneous sources will reduce acquisition cost and time of areal WATS configurations if more than about eight sources are used.

Geometries that would benefit from simultaneous sources are those that require dense sampling of sources along the source lines such as zigzag WATS. This paper rounds off with a discussion of pros and cons of zig-zag WATS configurations.

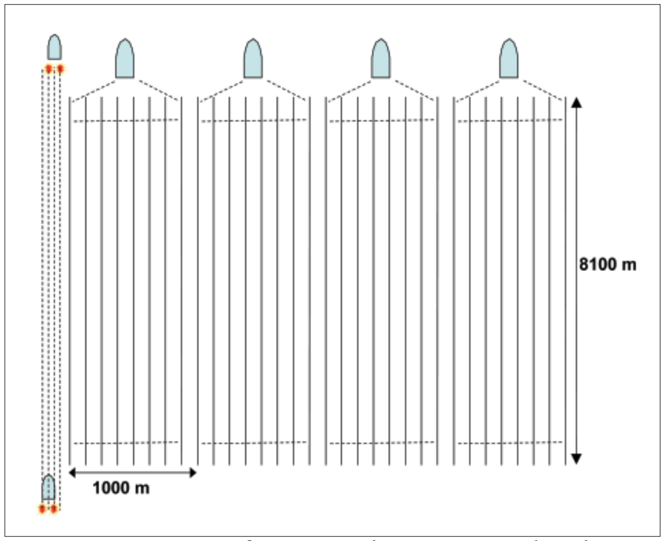

Figure 1. BP WATS configuration with two source vessels with two sources each and a single streamer vessel. The source vessels traverse the same source tracks four times while the streamer vessel moves up over 1000 m each time. Next the whole configuration moves up over 250 m in the crossline direction.

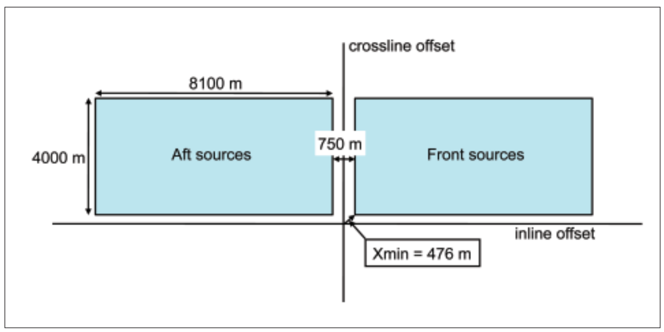

Figure 2. Offset and azimuth distribution of BP WATS configuration. Only positive crossline offsets larger than about 296 m are acquired. There is a 750-m gap in the middle of the range of inline offsets. Minimum absolute offset equals 476 m.

Characteristics of wide-azimuth towed-streamer acquisition

I use the geometry in Figure 1 (designed by BP and acquired by Veritas) to illustrate the characteristics of WATS acquisition and refer to this as the BP WATS geometry.

This geometry features two source vessels, each towing two sources. In this way, acquisition can be efficient but also quite complicated. 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 of 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 tracks is 31.25 m, a fourth of the streamer interval. This leads to a distance of 15.625 m between the midpoint lines of this parallel geometry (crossline bin size = 15.625 m). For safety, there is a minimum of 200 m 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 being the long recording time needed for a large target depth in very deep water. As a consequence, the source interval along each track becomes 150 m, leading to an inline fold of 27 (8100/2*150). The crossline fold is 8 (4000/2*250), which means that the total fold of this geometry is 216. The station interval along the streamers is 12.5 m, so that the bin size is 6.25 x 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 shows why the geometry is not optimal.

First, 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 center of the inline offset range. This gap leads to inadequate imaging by the central azimuths. The gap can be 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 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 bin size 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) for this shortcoming in crossline sampling.

It is also interesting to analyze this geometry and other WATS geometries using a subdivision into offset-vector tile (OVT) gathers as introduced earlier for orthogonal geometries. In an orthogonal geometry, the midpoint area of a cross-spread (the basic subset of orthogonal geometry) is subdivided into $Mi \times Mc$ equal rectangles (Mi and Mc 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 four consecutive sources (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 the 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 dimensions of the tiles are 150 x 250 m which corresponds to inline and crossline periodicity of the geometry. In orthogonal geometries, the periodicities correspond to source-line interval and receiver-line interval; compared to commonly used line intervals in orthogonal geometries of around 300 m, the dimensions of the OVTs in this BP WATS geometry are relatively small, which is quite good.

On the other hand, the bin size, 6.25 x 31.25 m, is extremely unbalanced. The number of bins in each single-fold tile is 192 (150/6.25*250/31.25 = 24 * 8). In contrast to an 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 eight bins in the crossline direction correspond to two sources shooting into four different streamers. These irregularities must lead to some additional migration artifacts when compared to an 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.

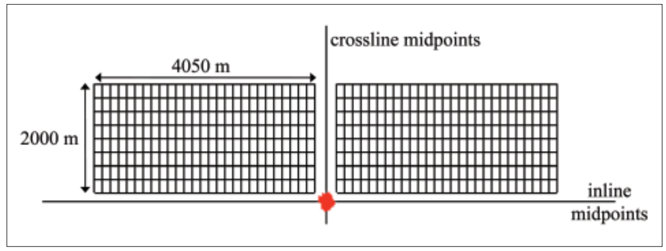

Figure 3. *Quad-source midpoint area with OVTs in BP WATS configuration. Width of tiles in inline direction is 4050/27 = 150 m; in the crossline direction, the width is 2000/8 = 250 m.*

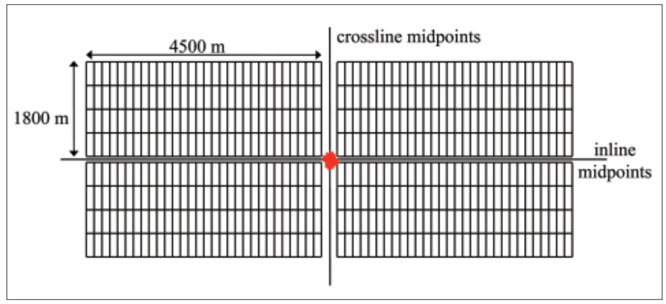

Figure 4. *Quad-source midpoint area with OVTs in Shell WATS configuration. Width of tiles in inline direction is 4500/30 = 150 m; in the crossline direction, the width is 1800/4 = 450 m.*

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 in the Shell WATS configuration was 450 m. Figure 4 shows the OVTs in the Shell WATS configuration. This geometry includes the acquisition of reciprocal OVTs.

Parallel or areal geometry?

In the previous section, I called WATS a 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 a parallel geometry, the midpoint line, is not as well sampled 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

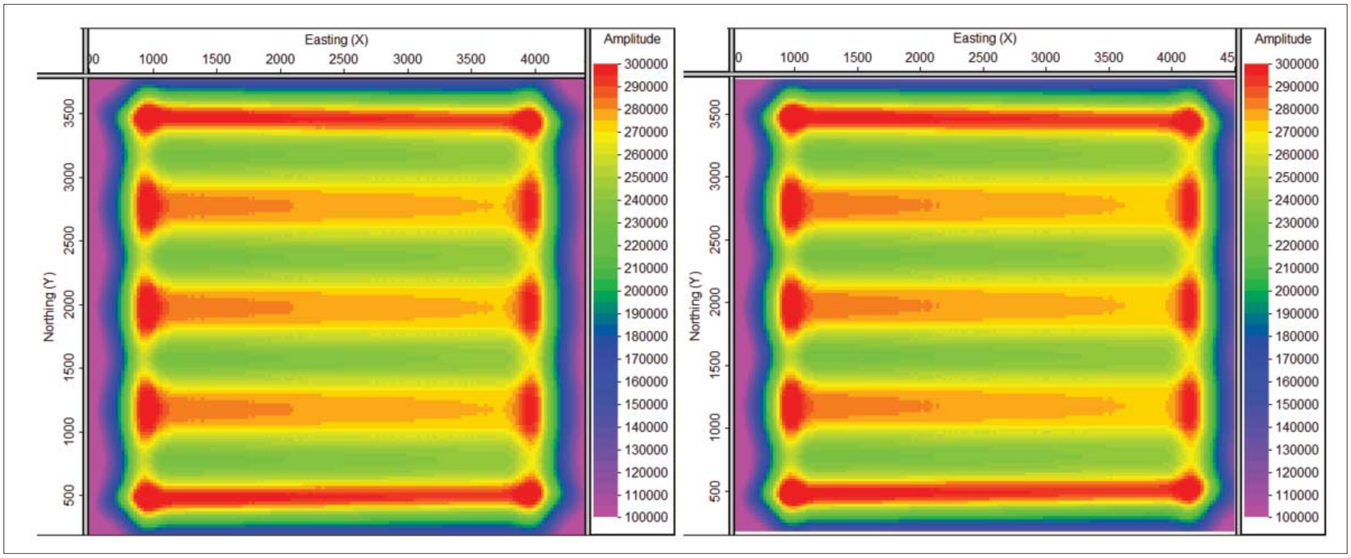

Figure 5. *Horizon slices of migrated single-fold gathers for dipping event acquired with two different narrow-azimuth configurations. Left = 2 sources/8 streamers, right = 1 source/16 streamers. In both cases, nine antiparallel boat passes were acquired. The amplitudes in these two displays are virtually the same.*

than the more common 37.5 m (in the Gulf of Mexico) or 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 an argument in favor of using simultaneous sources.

There are also good reasons to call WATS geometries areal geometries. In an areal geometry, sparse receivers are combined with dense shots as in marine surveys using nodes. The receivers in node geometries are sparse because of the expense of constructing and deploying the nodes. In those geometries, 3D receiver gathers are acquired. Another version of an areal geometry is the use of sparse shots and dense receivers that would collect 3D shot gathers. An attractive aspect of an areal geometry is that 3D shot gathers or 3D receiver gathers are suitable for shot-profile migration.

Two of the four shots in Figure 3 shoot into the first quadrant; the other two shoot into the second quadrant. In Figure 4, two of the shots shoot into the first and the fourth quadrant; the other two shoot into the second and the third quadrants. So, in both cases, there are just two sources corresponding to a "continuously" sampled midpoint area. If these two sources are sufficiently close, their behavior is similar to one source shooting into twice as many streamers. A horizon amplitude comparison of one versus two sources is shown in Figure 5 for a 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 data behave as if they were acquired with a single shot. Similar reasoning applies to Figure 4. In both narrow-azimuth and WATS geometries, using two sources produces two midpoint lines for each streamer; this allows twice the streamer separation as with single source for the same crossline bin size. It is not ideal, but it is perhaps the least serious of all compromises in WATS acquisition.

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.

An 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 x 300-m grid might be adequate in many situations, whereas the receivers may be acquired in a 25 × 25-m grid. If the maximum useful offset is 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 bin size 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

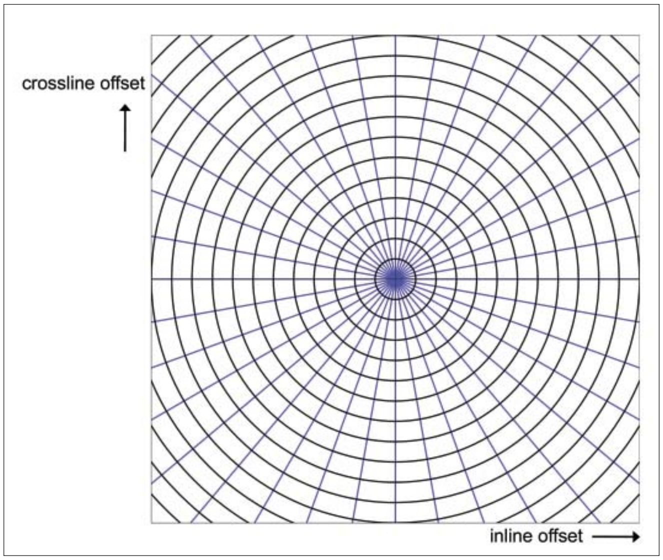

Figure 6. *Rose diagram for equivalent areal and orthogonal geometries with maximum inline offset = maximum crossline offset = 6000 m. Each circle represents constant absolute offset; the interval between the radii of the circles is 500 m. The segment interval between the radial lines is 10° In a regular 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.*

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.

This example illustrates that an areal geometry tends to be more time-consuming and expensive to acquire than orthogonal geometry: In areal geometry there is a serious imbalance 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 an areal geometry with quite unbalanced parameters as already mentioned when discussing the BP WATS configuration. In the following I discuss bin size, 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 improving 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 sufficiently 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.

Bin size. The bin size of the BP WATS configuration is 6.25 x 31.25 m, a factor of 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 bin size produces migration artifacts 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. Most WATS configurations used to date have 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 four. 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 ensure azimuth coverage in all four quadrants. Interestingly, CGGVeritas acquired in 2007–2008 the Walker Ridge survey using four source vessels (see *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 and, hence, reduce migration artifacts 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

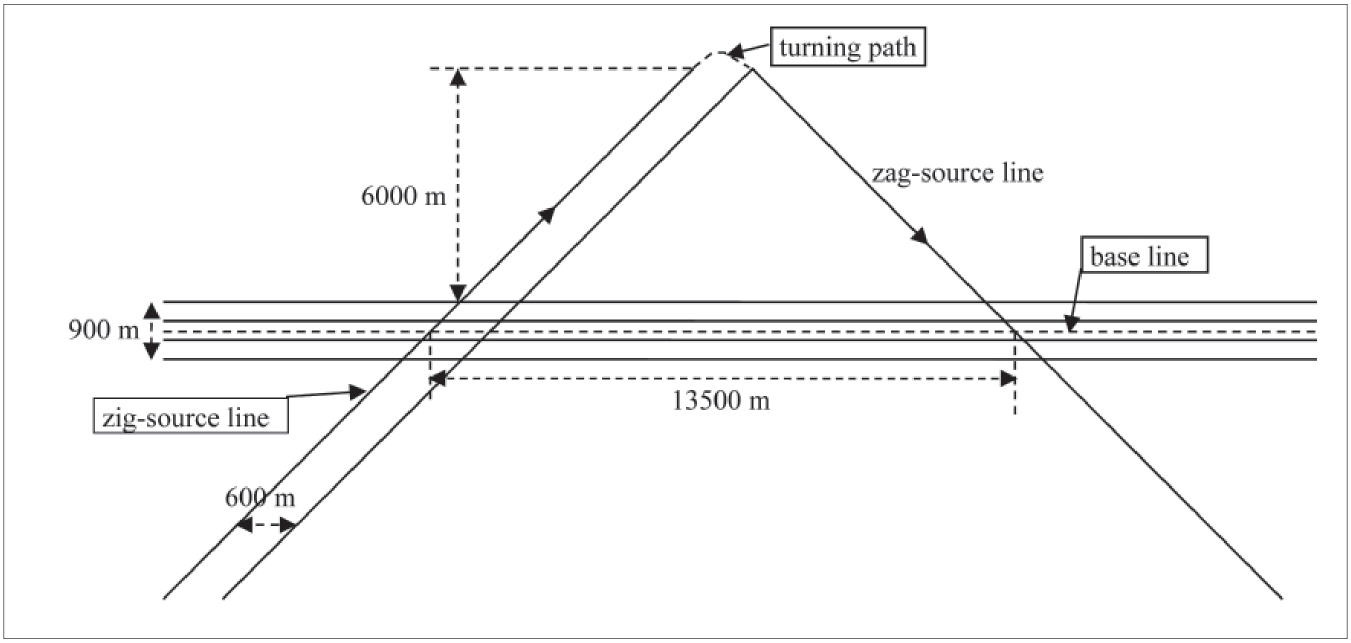

Figure 7. *Wide-azimuth zig-zag geometry; 4 streamers @ 300 m. Maximum crossline offset 6000 m. Streamers to be towed deep enough to allow crossing with source vessel and sources (figure is not to scale). The source vessel is given 600 m in the inline direction to turn over 90° at the end of each shot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

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 also acquire 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 and 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 eight sources is a better utilization 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 on 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 bin size 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 prize 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 neighboring 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 interpolation across holes should be attempted.

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

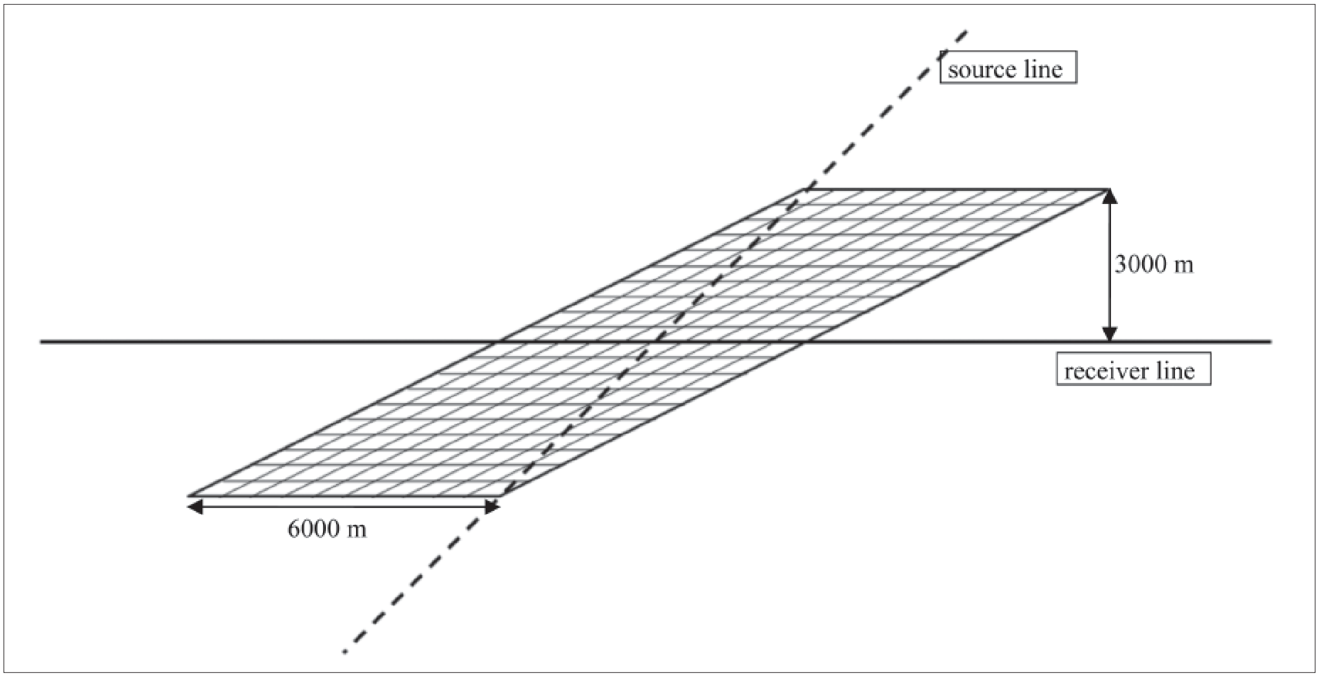

*Figure 8. Zig-spread with offset-vector tiles for geometry with active spread length 12,000 m, maximum inline and crossline offset 6000 m, receiver-line interval 300 m, and source-line interval 600 m. There are 10 * 20 OVTs in this zig-spread, corresponding to a fold of the zig-spreads only of 200. Adding zag-spreads would bring fold to 400.*

usually high fold of areal WATS helps to suppress artifacts, but it is no replacement for good illumination.

Simultaneous sources helpful for areal WATS?

Various authors of recent papers suggest that simultaneous sources would offer an opportunity for better WATS acquisition. For instance, Beasley 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 not a 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 for the areal geometry that is being acquired.

For the case of eight sources, 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 artifacts 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 if dense sampling of sources is required as in line geometries, such as orthogonal and zig-zag geometry, but not in an 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.

An application of simultaneous sources

A wide-azimuth geometry that can benefit from simultaneous sources is a crossed-array geometry, in particular the zig-zag geometry. A separate source vessel sails zig-zag lines across the seismic streamers while maintaining a center-spread position. Figure 7 illustrates this idea for a zig-zag geometry that is equivalent to the 300 x 300-m orthogonal geometry and 300 x 300 m areal geometry discussed earlier in this paper. The parameters of the zig-zag geometry are equivalent to the 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 zig-zag 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 the zag-spreads are the same as the absolute offsets in the cross-spreads of the orthogonal geometry. Also, the number of traces in a cross-spread is equal to the number of traces in a zig-spread or in a zag-spread. To generate an equivalent zig-zag geometry from a given orthogonal geometry, all odd-numbered source lines are rotated clockwise by 45° and all even numbered source lines are rotated anticlockwise by 45°. In this way the total fold of the two geometries is the same as well. Figure 6 also represents the range of inline and crossline offsets for the zig-zag WATS geometry being considered.

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. The horizontal side of the parallelogram-shaped OVT is 600 m long whereas the crossline dimension is 300 m (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 the 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. The maximum crossline offset should also be a multiple of the receiver-line interval. This means that for this example geometry the zig- and zag-spreads as acquired in 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 six streamers with 300-m separation instead of 4, then efficiency would increase by 50%.

Zig-zag geometry in combination with a single seismic streamer was used in the Dutch Waddenzee as far back as 1988. The source vessel sailed a zig-zag 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 four-fold data with amazingly good results.

It is interesting to compare zig-zag 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 zig-zag geometry, the repeat factor (= number of boat passes along the same track) depends on the length of the zig- and zag-lines and on the receiver-line interval. The example zigzag geometry would require a repeat factor of 45 for every 1200 m crossline progress. This sounds like a pretty large receiver repeat factor; however, in zig-zag WATS, it does make sense to use simultaneous sources (as proposed by several authors in the July 2008 issue of *TLE*). 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 zig-zag geometry with all sources shooting center-spread. 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, I assume 37.5 m for inline and crossline components of the source interval in the zig-zag WATS geometry (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 four 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 which is five in our example geometry. With source tracks every 300 m, this means that, to cover 1200 m in the crossline direction, 20 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 zig-zag geometry, corresponding to 300 x 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 is 400. However, with the commonly used 120-m streamer interval in the areal WATS, the crossline bin size is 30 m, whereas the crossline bin size in the zig-zag WATS is 18.75 m. The inline bin size is the same in both geometries and is dependent on the station interval in the streamers. This means that the trace density in zig-zag WATS is a factor of 1.6 larger than in areal WATS. The larger number of traces in the zig-zag WATS increases the attractiveness of this geometry considerably.

For the example geometry, the zig-zag WATS with one source vessel requires 45 boat passes, whereas the five-vessel areal WATS needs only 20 boat passes for every 1200 m. However, simultaneous shooting can be applied in the zig-zag WATS, needing 23 or 16 boat passes for two or three simultaneous sources, respectively. This analysis shows that the zig-zag geometry is about as efficient as conventional WATS for two simultaneous sources and even more efficient, if it would be possible to extract clean data from three simultaneous sources.

The obvious objection against using zig-zag geometry is that it requires the source vessel to sail across the seismic streamers. Can that be done? Probably not with conventional streamers with sources at 7-8 m and streamers at some 11 m. This is too close; so 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, or even better, with the dual-sensor streamer. 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 1-2 source points may have to be dropped across each streamer to avoid damage to the sensors.

Discussion

Zig-zag WATS has some disadvantages as compared to areal WATS.

- Zig-zag geometry needs special attention in true-amplitude processing, because imaging data inside the oblique angle between source line and receiver line behaves differently than imaging 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 artifacts.
- Crossing the streamers with a source vessel may disturb the streamers.
- The streamers should be extra long because of center-spread acquisition.
- It requires at least two simultaneous sources to match acquisition time using areal WATS.
- The best geometry requires an over/under technique or else dual-sensor streamer.

Zig-zag WATS also has some advantages as compared to areal WATS.

- Imaging is more successful with zig-zag WATS.
- Crossline bin size can be 18.75 m, whereas a common crossline bin size (in a quadrant) in areal WATS may be 30 m.
- There are no gaps in short offsets (unless shallow-tow streamers are used and, 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 2–3 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.
- Less towing strength is required.
- Much less investment required, especially important for expensive dual-sensor streamers.
- Expansion to six streamers with effective width 1800 m may be feasible.

From this discussion of pros and cons, it is clear that the zig-zag 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 depends 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. Sources close to each other do not have to occur in zig-zag WATS, because the sources split the width of the swath evenly between them.

It may be argued that areal WATS may be acquired with data in only two azimuth quadrants, whereas the zigzag geometry would require center-spread acquisition. This is not correct: If two quadrants would be good enough for areal WATS, they would be even better for zig-zag WATS, but nobody would consider acquiring zig-zag data with positive crossline offsets only.

The geometry comparison carried out in the previous section pertains to ideal geometry parameters (except the crossline bin size 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 zig-zag WATS. Further savings in the acquisition of zig-zag 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.

Circular WATS using a conventional seismic vessel that traverses circular paths is another alternative to areal WATS. 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 in the literature (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 centers 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 a parallel geometry can also be described as an areal geometry (areal WATS). Major shortcomings in this geometry are the crossline bin size, 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 eight without hurting final data quality, whereas acquisition with eight sources is more efficient than the currently common number of four sources.

A viable alternative to areal WATS is zig-zag WATS in which the source line makes an angle of 45° with the receiver tracks. Its main advantages are: no missing short offsets, robust behavior in case of feathering, and a smaller crossline bin size. 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 zig-zag 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 are required -- one on each side of the swath.

Suggested reading. Papers on WATS acquisition or processing at the 2006 SEG Annual Meeting: "Implementing a wide azimuth towed streamer field trial: the what, why and mostly how of WATS in Southern Green Canyon" by Threadgold et al. (detailed description of BP WATS geometry); "Using 3D finite-difference modeling to design wide azimuth surveys for improved subsalt imaging" by Regone (WATS modeling); "Wide-azimuth streamer acquisition for Gulf of Mexico subsalt imaging" by Corcoran et al.; "Marine survey design for rich-azimuth seismic using surface streamers" by Howard and Moldoveanu; "Wide azimuth streamer imaging of Mad Dog: Have we solved the subsalt imaging problem?" by Michell et al.; "Improving resolution of top salt complexities for subsalt imaging" by Shoshitaisvili et al. (Use of offset-vector tiles in WATS for tomographic migration velocity analysis); also "Wide azimuth tomography—is it necessary?" by LaDart et al.

For a description of the Shell WATS configuration: "From narrow-azimuth to wide- and rich-azimuth acquisition in the Gulf of Mexico" by Moldoveanu and Egan (*First Break*, 2006).

More on WATS modeling: "Using 3D finite-difference modeling to design wide-azimuth surveys for improved subsalt imaging" by Regone (Geophysics, 2007).

Description of offset-vector tiles in orthogonal geometry; definitions of areal, parallel, zigzag, and orthogonal geometries; illumination problems of parallel geometry: "3D seismic survey design" by Vermeer (SEG 2002, *Expanded Abstracts*).

Benefit of using reciprocal offset-vector tiles: "From acquisition footprints to true amplitude" by Gesbert (Geophysics, 2002) and "Reciprocal offset-vector tiles in various acquisition geometries" by Vermeer (SEG 2007 *Expanded Abstracts*). "Combining techniques in integrated 3D land, shallow water and deep channel seismic acquisition" by Bukovics and Nooteboom (*First Break*, 1990) is first description of zig-zag geometry with towed streamers. "A new look at simultaneous sources" by Beasley et al. (SEG 1998 *Expanded Abstracts*) demonstrates suitability of using simultaneous sources in narrow-azimuth acquisition. Three papers on simultaneous sources: "A new look at simultaneous sources" by Beasley; "Acquisition using simultaneous sources" by Hampson et al.; and "Changing the mindset in seismic data acquisition" by Berkhout (*TLE*, 2008). Moreover, there were eight papers on simultaneous source acquisition and processing at Special Session 5 at the 2008 SEG Annual Meeting.

Over/under acquisition: "Over/under towed-streamer acquisition: A method to extend seismic bandwidth to both higher and lower frequencies" by Moldoveanu et al. (*TLE*, 2007).

Description of dual-sensor streamer: "Increased resolution and penetration from a towed dual-sensor streamer" by Carlson et al. (*First Break*, 2007) or "First look at seismic data from a towed dual-sensor streamer" by Pharez et al. (*TLE*, 2008). Circular WATS: "Full-azimuth imaging using circular geometry acquisition" by Moldoveanu et al. (*TLE*, 2008).
TLE

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