Responses to wide-azimuth acquisition special section

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The Special Section in the August 2002 issue of TLE was of great interest to me - subjects that are near to my heart, sufficiently near to be called "relentless" in the Introduction by Cambois et al. I have written some comments to four papers in that section. The comments to two papers (Cambois et al., and Cordsen and Galbraith) are lumped together to avoid overlap. I hope these ideas and replies by the authors will generate further discussion about this important subject.

Comments on "Wide-azimuth acquisition: True 3D at last!" by Cambois et al., and "Narrow- versus wide-azimuth land 3D seismic surveys" by Cordsen and Galbraith. The first thing one has to decide upon when designing a 3D seismic survey is the type of geometry to be used. This is an important choice, because the properties of different geometries are different. There are three main geometries available to choose from: parallel geometry, orthogonal geometry and areal geometry. From a geophysical point of view, orthogonal geometry and areal geometry should preferably be as wide as long, i.e., have aspect ratio equal to one, for the simple reason that the properties of these geometries are essentially the same in the x- (inline) and in the y- (crossline) direction. (For orthogonal geometry, C-wave acquisition constitutes an exception. Due to the asymmetric nature of the raypaths, the maximum crossline offset should preferably be larger than the maximum inline offset.) Often, practical, non-geophysical reasons force the designer to select an actual geometry with aspect ratio different than 1.

On the other hand, again from a geophysical point of view, parallel geometry should be selected as narrow as possible. Wide parallel acquisition geometries used in streamer acquisition tend to produce illumination gaps when shooting downdip. The wider the configuration the larger the gaps. Apart from reducing the width of the configuration, the problem can be mitigated by antiparallel acquisition (shooting adjacent boat passes in opposite directions). These and other ideas I have published in a variety of papers in the course of time, all ideas together can be found in the recent book "3-D seismic survey design" published by the SEG.

Cordsen and Galbraith quote from one of those earlier papers: "some areas of a dipping reflector are never sampled by the large offsets, whereas other areas are sampled more than once. These variations are largest for the large offsets. …". Unfortunately, the quote is pretty much out of context, because my statement was made in a discussion of wide parallel geometries. The statement does not refer to narrow orthogonal geometries as being discussed by Cordsen and Galbraith. Although a narrow orthogonal geometry may have similar width as a wide parallel geometry, their properties would still be different, and a statement made for one does not necessarily apply to the other. In this particular case it does not apply to narrow orthogonal geometries.

In the introduction to the Special Section on wide-azimuth acquisition, Cambois et al. suggest that all wide is better regardless of acquisition geometry, when they note that there appears to be processing advantages to wide-patch geometries, as demonstrated by improved multiple elimination in Hadidi et al.'s paper. In actual fact, the Hadidi paper shows (compare Figure 10 with Figure 17) that the wider the towed-streamer geometry, the more difficult it is to apply the surface related multiple elimination technique (SRME). This is for good reasons, because SRME requires the presence of a source and a receiver at each surface reflection point (point A in Figure 1 of Hadidi et al.). The wider the geometry the sparser sources and receivers and the heavier the assumptions to be made in the multiple prediction scheme.

Comments on "Wide-azimuth marine acquisition by the helix method" by D.V. Sukup. At the 2002 EAGE Conference, Paffenholz et al. introduced an all azimuth marine streamer recording technique as devised by the SMAART JV group of companies. Their method is based on having one or more separate source vessels looping around while the streamer vessel covers the whole surface area with receiver positions. Apparently, this is not the only example of lateral thinking carried out by this group. Another method born from their discussions is presented by Sukup in The Leading Edge of August 2002. Sukup's method uses four source boats of which two tow a complete streamer configuration. With both techniques 3D common shot gathers are produced. The techniques are examples of using streamers to acquire areal geometry data (sparse sources with dense receivers).

In the ideal areal geometry, the 3D shots occupy a regular square grid or, better still, a regular hexagonal grid. However, in the proposed configuration the inline distance between the 3D shots is 200 m, whereas the crossline distance alternates between 50 m and 950 m. This configuration would lead to more irregular coverage of the shallow subsurface than obtainable with a regular grid. Yet, with some modifications of the proposed technique it should be possible to get considerably better coverage. The idea is to tow the sources not right behind the vessel but at 250 m on either side of the vessel. In this way a regular interval of 500 m can be created between the 3D shots. Up till now air gun arrays have always been kept as close as possible to the vessel, for good reasons. Especially in combination with widely towed streamers it would be difficult to achieve wide tow of the sources as well. Yet, in view of all technological advances that we have seen over the past few years, it might be possible to find a solution to this challenge. Once this configuration will be achievable, the difficult question (posed in Sukup's paper) whether to acquire complete 3D shots at 1000 m crossline intervals or half 3D shots at 500 m crossline intervals does not have to be answered, because we will get the best of both worlds.

The receiver interval in the crossline direction of the proposed technique is 100 m. This pretty coarse crossline sampling may lead to undesirable migration artifacts in the crossline direction. However, towed streamer configurations with 50 m between streamers have been reported in recent years. Therefore, another improvement would be to tow 20 streamers at 50 m rather than 10 at 100 m, while at the same time keeping the two sources at a distance of 500 m from each other.

Should the combination of wide-tow streamers with wide-tow sources not be feasible in the short term, another variation upon Sukup's theme would be to have two streamer vessels with one source and 10 streamers each at 50 m between streamers and three source vessels in between, each vessel with two sources spaced at 500 m. This configuration would also produce 3D shots with 500 m between shots in the crossline direction and with 200 m in the inline direction. Because of the narrower streamer tow, it would need twice as many passes through the survey area, but with the advantage of 50 m crossline sampling of the receivers.

These discussions illustrate that modifying streamer acquisition to achieve adequately sampled areal geometry is perhaps not as cost-effective as Sukup suggests for his basic configuration ("the cost of this helix method compares very favorably to that of the conventional survey"). The alternative technique of using a node system to acquire areal geometry might be quite competitive and provide horizontal-component data as a bonus.

Finally, a remark about using overlap data in the fold count. In P-wave acquisition, interchanging shot and receiver position would lead to the recording of reciprocity traces. Such traces are essentially identical and it is therefore discouraged to record reciprocity traces. That is why in 2D land data acquisition source positions should always be halfway receiver station positions. Only in cases of severe ambient noise might shooting of reciprocity traces or repeating shots into the same configuration lead to improved data quality.

In the marine situation, ambient noise is usually hardly a problem, and therefore, the overlap of shot 7 of swath 1 and shot 1 of swath 4 (Sukup, Figure 5) is not likely to produce any new information. This means that crossline fold in the helix method effectively alternates between 3 and 4. The recommended way of achieving constant crossline fold would be to discard absolute crossline offsets larger than 3000 m. This would produce a regular crossline fold of 3 and a midpoint width of each 3D shot of 3000 m. This discarding of redundant traces would also be necessary and work as well in the alternative wide-tow source methods proposed above.

Comments on "Processing the Hod 3D multicomponent OBS survey, comparing parallel and orthogonal acquisition geometries" by Kommedal et al. It is not occurring all too often that oil companies or contractors acquire 3D seismic data across the same area using two or more different acquisition geometries. And if it happens, it does not always occur that the results are shared with the geophysical community at large. Therefore, BP Norway is to be commended for sharing the results of the interesting Hod 3D survey with us in which parallel and orthogonal acquisition geometries are compared.

The acquisition of both parallel and orthogonal geometry gave the authors "an opportunity to compare the seismic images produced from these shooting geometries to see if there is factual support for the rumors that parallel shooting results in better converted PS-wave images than orthogonal shooting". And indeed, the authors show that the results for orthogonal geometry are inferior to that of parallel geometry. However, they suggest that this is not due to geometry differences but to the use of conventional DMO, stack, and migration, rather than proper prestack depth migration.

The rumors alluded to in the previous paragraph may be related to some geophysicists having read the abstract of my paper "Converted waves: properties and 3D survey design" presented at the 1999 SEG Conference, which states "parallel geometry tends to be better geometry for PS acquisition than orthogonal or any other crossed-array geometry". That paper argues that there are good theoretical reasons to predict that parallel geometry is better for PS than orthogonal and it is great to see this confirmed now by results using real data. I would like to take this opportunity to illustrate some theoretical insights on C-wave acquisition using the Hod geometries as examples. Yet, I would like to start with some comments on the P-wave results and make some suggestions for improvement.

Parallel geometry, P-waves. Figure 4 of Kommedal et al. shows amplitude striping in two horizon amplitude maps for the P-wave data. Such stripings can be caused by irregular fold, irregular offset distributions and/or irregular illumination. It is the task of the survey designer to minimize each of these contributions to striping, whereas the seismic processor has to reduce any remaining effects to acceptable levels. Figure 1describes a cross-section in the crossline direction through the template of the parallel geometry. (The authors provided a puzzle to the reader wanting to reconstruct this template. 50 m between shots along each shot line track and a shot line length of 10500 m requires 210 shots per shot track. With a total of 8841 shots per template this leads to 42.1 shot tracks, which does not fit. However, with 210 and 211 shots on alternating shot tracks a round number of 42 shot tracks results. With 75 m between shot tracks, there are 6 such tracks between each pair of receiver cables, hence 18 tracks between the outer cables and 2 x 12 tracks = 2 x 2 cable intervals outside the cables, leading to Figure 1.) The width of this template is 7 x 450 m = 3150 m. Hence the coverage per cable equals 3150/2 = 1575 m. The crossline roll of the template equals 4 x 450 m = 1800 m. Hence the average crossline fold is 4 x 1575 / 1800 = 3.5. This irregular crossline fold is one of the causes of striping. It might have been reduced by using a template width of 8 x 450 m = 3600 m. In that case the coverage by each cable would have been equal to the template's crossline roll of 1800 m.

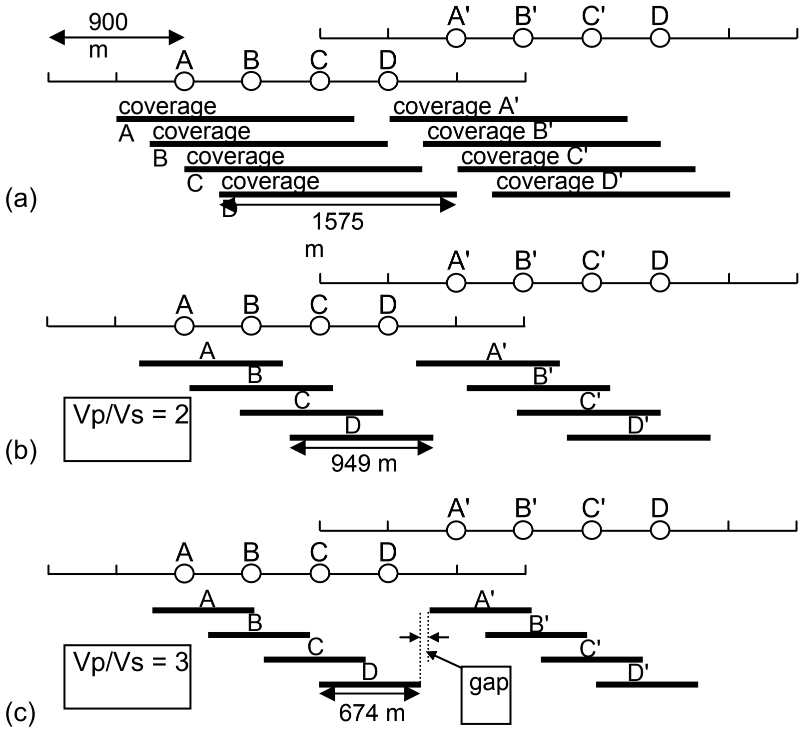

Fig. 1. Coverage and illumination of P- and C-waves for swath used in Hod 3D survey. Shown is cross-section through swath in crossline direction. The 4 cables are designated with A, B, C, and D. The range of shotlines is indicated by a thin horizontal line with 450 m tick marks. Two swaths are shown. The shotlines extend 900 m on either side of the group of cables. (a) Crossline fold-of-coverage. Note that crossline fold jumps between 3 and 4. Crossline fold would be continuous by extending the swath 225 m in both directions. Coverage equates to P-wave illumination for horizontal reflector. (b) C-wave illumination of horizontal reflector at 2000 m depth for Vp/Vs = 2. (c) as (b) for Vp/Vs = 3. Now there is a small illumination gap between consecutive swaths.

A regular crossline fold of 4 cannot be obtained after the fact. However, fold can be regularized by removing all traces with a crossline offset larger than 900 m. In that case each cable records a symmetric coverage of 900 m and the average crossline fold is 4 x 900 / 1800 = 2. This should reduce the striping in the data without affecting the S/N ratio too much: the data quality is excellent.

Orthogonal geometry, P-waves. The parameters given in Table 1 of Kommedal et al. are even more of a puzzle when trying to reconstruct the template or patch of the orthogonal geometry than it was for the parallel geometry. With a line length of 7350 m, there should be 7350 / 25 = 294 shots per shot line. This leads to 6682 / 294 = 22.73 shot lines. I guess that the outer shot lines have been shortened, but to what extent is impossible to reconstruct. Anyway, the most important parameters for this geometry are clear. A template with 22 shot lines is drawn in Figure 2.

The inline fold in this geometry builds up gradually from 0 along the edges to 10 in the center of the configuration. The crossline fold is irregular because the run in / out of 3000 m is not a multiple of 450 m, the receiver line interval. 2700 m or 3150 m would have been adequate as run in / out. In processing the traces with crossline offset larger than 2700 m should be removed for regular fold. This applies to the crossline offsets of all four cables. If the offsets larger than 2700 m are not removed from the data set, the asymmetry of the cross-spreads would lead to additional spatial discontinuities in the crossline direction.

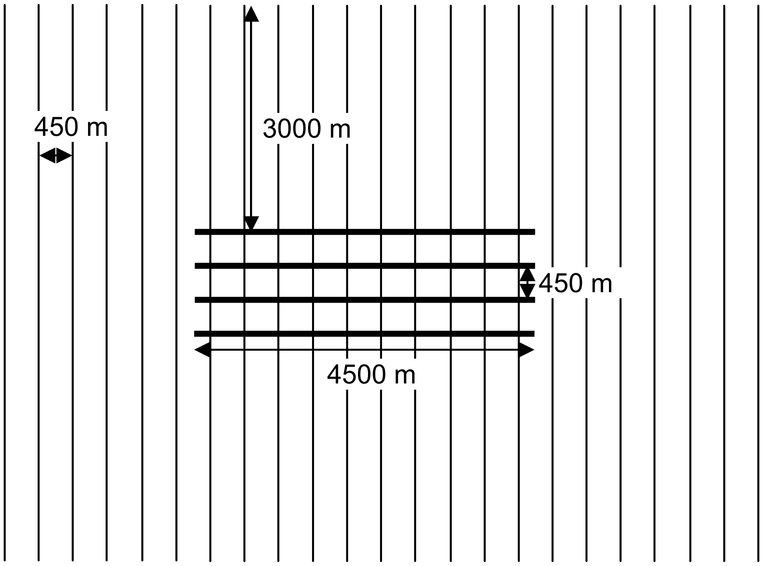

Fig. 2. Approximate template used for acquisition of orthogonal geometry.

After removal of all redundant traces, the crossline fold of this geometry would reduce to 2700 / 450 = 6, with total fold being 60 in the center and tapering off to the edges. Taking these steps in processing would probably reduce the acquisition footprint and any remaining footprint will be due to variations in offset distribution and in illumination.

Regularizing fold in P-wave acquisition automatically leads to more regular illumination and imaging, because illumination fold and image fold tend to be close to fold-of-coverage. In horizontal geology illumination fold and image fold are even equal to fold-of-coverage. This does not apply to C-wave acquisition, because illumination fold is always different than fold-of-coverage. Regularizing the images can only be achieved by expensive prestack depth migration techniques. Yet, the irregularities are larger in data acquired with orthogonal geometry than in parallel geometry, as I will now discuss.

Parallel geometry, C-waves. The conversion point from P-wave to S-wave tends to lie much closer to the receiver than to the source. With the receiver cables in the middle of the swath, the illumination range of a horizontal reflector is less wide than the midpoint coverage as illustrated in Figures 1b and 1c. Note that at the illustrated depth of 2000 m, a small gap in illumination develops between adjacent swaths for Vp/Vs = 3. For larger Vp/Vs ratios and/or smaller depths these illumination gaps become larger, leading to incomplete images and striping. At other places crossline illumination is inevitably irregular. On the other hand, there are no spatial discontinuities in the inline direction. In this direction illumination is regular. An interesting consequence of this illumination behavior is that conventional prestack migration algorithms will produce migration smiles in the crossline direction, whereas the migration results in the inline direction will not show any serious migration smiles.

Orthogonal geometry, C-waves. Illumination with C-waves generated in orthogonal geometry is quite different than discussed above for parallel geometry. Now the total data set consists of a large number of partially overlapping cross-spreads with each cross-spread having its own limited-size illumination area on each reflector. The illumination areas on a horizontal reflector at z = 2000 m for one cross-spread are shown in Figure 3, one for Vp/Vs = 2 and one for Vp/Vs = 3. These illumination areas differ considerably from the midpoint area, unlike the situation for P-wave illumination. The data inside each illumination area are well-behaved and are suitable for prestack migration. However, the edges of each illumination area are as many causes of edge effects, i.e., migration smiles. As a consequence, conventional prestack migration algorithms will produce migration smiles not only in the crossline direction, but also in the inline direction. These migration smiles will severely affect the S/N of the imaged data, both in inline direction and in crossline direction.

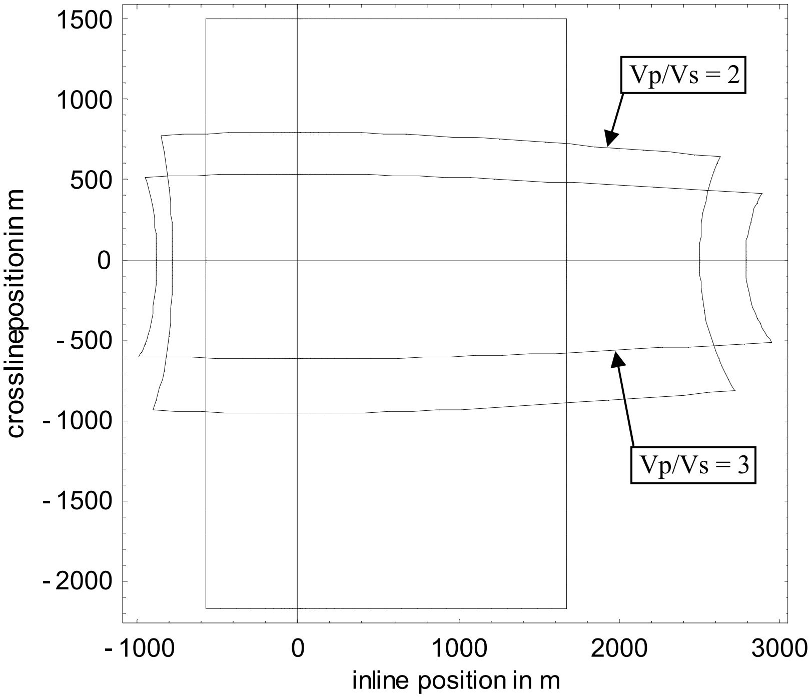

Fig. 3. Illumination of horizontal reflector by C-waves of single cross-spread from Hod survey. The cross-spread corresponds to the ninth shotline from the left and to the top receiver line of the template in Figure 2. The rectangular area represents the midpoint area of the cross-spread. The edges of this midpoint area are defined by shots at (0, 3000) and at (0, -4350) and by receivers at (-1150, 0), and at (3350, 0). These same shots and receivers determine the edges of the illumination area on a horizontal reflector at z = 2000 m, depicted for Vp/Vs = 2 and Vp/Vs = 3.

Comparison parallel versus orthogonal, C-waves. The differences in illumination properties between the two geometries is the main reason to expect better image quality for parallel geometry than for orthogonal geometry. On top of that, there are also differences in resolution that will further increase the difference. See for a discussion Chapter 6 in Vermeer (2002). Yet, it should be possible to mitigate the problems with orthogonal geometry by tapering the edges of all cross-spreads, i.e., by making the edges softer. This should be done for each cross-spread individually, and it must be time-variant as well. Therefore, the spatial taper should be made part of the mute operation. Tapering of the crossline edges in parallel geometry might also be attempted, but in this geometry the number of points available for tapering is limited (only 42 in the Hod survey), and tapering across illumination gaps as in Figure 1c will further reduce effective illumination.

Vector fidelity. Another reason for quality differences between orthogonal and parallel geometry may be the lack of vector fidelity between the horizontal geophones inside a bottom cable. The vector infidelity is clearly demonstrated in the comparison between azimuth sectors of the orthogonal geometry in Figure 8b and c in Kommedal et al. The section created predominantly by the crossline geophones (Figure 8c) is considerably worse than the section created by the inline geophones. In orthogonal geometry, vector fidelity is essential for good quality results, whereas in parallel geometry the crossline geophone plays a much more modest role than the inline geophone, hence reliance on vector fidelity is less. The issue of vector fidelity has been solved to a large extent by the introduction of self-contained node systems in which a 3-component geophone plus hydrophone is planted separately in the sea bed by a subsea robot. The expense of this system necessitates the use of areal geometry (sparse distribution of nodes and dense distribution of shots). This geometry also suffers from inherent spatial discontinuities (the edges of the illumination areas of the 3D receiver gathers), but here as well these might be softened by tapering.

Conclusions. This reaction to Kommedal et al. suggests that there is theoretical support for the "rumors that parallel shooting results in better converted PS-wave images than orthogonal shooting". Prestack migration is not going to remedy this problem, which is essentially a geometry problem. The asymmetry between inline and crossline direction in orthogonal geometry makes this geometry less attractive for 4-component sea-bottom acquisition. Better alternatives are parallel geometry (in case azimuth-dependent effects are not of interest) or areal geometry (for analysis of azimuth-dependent effects). This paper presents some suggestions to improve the results of the processing of the P-wave as well as of the C-wave data. It would be interesting to learn about the results of such processing.

Suggested reading. On migration of P-wave data: "From acquisition footprints to true amplitude" by Gesbert (Geophysics, 2002, 830). Geometry comparison for C-waves: "Converted waves: properties and 3D survey design" by Vermeer (SEG 1999 Expanded Abstracts). An expanded version of this abstract has appeared as Chapter 6 in "3-D seismic survey design" by Vermeer (SEG, 2002). This book also discusses properties of parallel, orthogonal, and areal geometries for P-wave acquisition.

Last minute note: At the SEG Conference in Salt Lake City I noticed that Input/Output found a very ingenious solution to the vector fidelity problem of bottom cables. In their new design there is a much reduced coupling between sensor unit and cable.

Response from Kommedal et al. First of all I would like to thank Gijs Vermeer for his comments and for contributing to the discussion on wide azimuth acquisition, which is an important discussion.

And then I have to apologize for not being more explicit in our description of the survey geometry; we didn’t intend to present the readers with a puzzle. So to make this clear:

> For the In-line (parallel) shooting, there were 22 passes of the dual source shooting vessel for each deployment of the four cables, in other words 44 shot lines (or tracks) were recorded for each layout.
>
> For the Cross-line (orthogonal) shooting, 25 shot lines were recorded for each layout (so add one shot line on each side in Vermeer’s figure 2, which shows 23 shot lines).

The number of shots listed in table 1 of our paper is the number of shots processed after editing out noisy data for the first layout.

Our reference to “rumours that parallel shooting results in better converted PS-wave images than orthogonal shooting”, actually alluded to conversations we have had with geophysicists in other companies where they have made this claim, but for various reasons they have not been able or willing to publish material supporting it. Our experience from the Valhall, Lomond and Alba fields also seem to support the claim.

We did not allude to Vermeer’s 1999 SEG paper on the subject, - a published paper can hardly be called a rumor, but we are grateful for being reminded of this paper, and for the additional references Vermeer gives in his comment. I must admit I have not read his book yet, but I am sure that it will be equally relevant as the other references he mentions.

As for the suggestion of removing all traces with offset greater than 2700 m for the orthogonal P wave data, this is already accomplished since the outer mute at this offset is about 3.5 s, well below target.

For PS converted wave data we observe that application of conventional time processing works better with single azimuth data than with multi azimuth data. As we explain in our paper, even for 2D data with only two azimuths, one set of stacking velocities did not work equally well for both azimuths. This problem is exacerbated when more azimuths are introduced. In our opinion, proper pre stack depth migration will have a better chance of correctly position the seismic events for all azimuths, provided that we are able to find a good velocity model both for P- and S-waves and account for anisotropy, and thus reduce mid-positioning and mis-stacking. This is true both for PP and PS events. In our paper, we show that the P waves are more forgiving, and that conventional time processing seems to work fairly well for the P wave data in the case of the Hod 3D OBS survey.

But this is not to say that pre stack depth migration can somehow compensate for lack of fold. We need to get both aspects right: both to have sufficient and uniform fold, and to apply appropriate processing methods.

With regards to vector fidelity, clearly it is a great advantage if the equipment record data correctly for all azimuths. Even if node systems promise to do this there may be a number of practical considerations (cost being one of them) which will dictate that we use cables, and then the issue of proper calibration of the receiver components will still be important.

Having said this, we do agree with the key point Vermeer makes: no matter what processing routes one chooses, careful analysis of fold is essential in planning acquisition and processing of multi-azimuth data to get an optimum seismic image.

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Final remark by Gijs Vermeer: The last sentence of Kommedal's reply would better describe my intentions if "careful analysis of illumination fold", would replace "careful analysis of fold".