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Streamers versus Stationary Receivers

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Abstract

Marine 3D seismic data acquisition technology is progressing rapidly. On the one hand, there has been a very rapid increase in the number of streamers that can be towed by modern seismic vessels, and on the other hand, the variety of stationary-receiver (sea-bed) systems is mushrooming. As a consequence, 3D seismic acquisition surveys may be carried out using quite different techniques, and the question which technique is most appropriate for a given problem needs to be addressed. This paper reviews pros and cons of the various techniques.

One criterion for comparison is the magnitude of the geometry imprint. It is argued that a geometry imprint is always present, but that it might be easier to minimize in sea-bed seismic. The use of streamers always involves the choice of shooting direction. Some geologic features can be imaged better if such a choice does not have to be made. The multi-source, multi-streamer and sometimes multi-boat operations are very efficient, but they also suffer from discontinuities in the crossline offset, leading to irregular illumination of the subsurface.

In stationary-receiver techniques sources and receivers are decoupled, allowing the use of alternative acquisition geometries. Generally speaking, control of the actual receiver positions is better with the stationary-receiver techniques than with streamer acquisition with its (as yet) uncontrollable feathering.

The vertical hydrophone cable technique is a VSP like technique with a series of hydrophones strung along a cable anchored to the sea bottom. At present, the most common stationary-receiver technique is the dual-sensor technique which combines a hydrophone and a vertical geophone in each receiver station in a bottom cable. However, new four-component (3C geophone + hydrophone) techniques are being developed and tested with very encouraging results. Eventually, these techniques will expand the scope of the seismic method with the exploitation of the information carried by shear wave data.

Introduction

Marine 3D seismic data acquisition technology is progressing rapidly. On the one hand, there has been a very rapid increase in the number of streamers that can be towed by modern seismic vessels, and on the other hand, the variety of stationary-receiver (sea-bed) systems is mushrooming. As a consequence, 3D seismic acquisition surveys may be carried out using quite different techniques, and the question which technique is most appropriate for a given problem needs to be addressed. This paper reviews pros and cons of the various techniques.

There is a great deal of similarity between a 2D grid of seismic lines acquired either on land or offshore. In both cases sources and receivers are arranged along coinciding straight lines leading to seismic traces all having the same shot/receiver azimuth within one seismic line. The main difference – as far as geometry is concerned – is that in streamer acquisition an end-on geometry is used whereas in land data acquisition a center-spread geometry is possible.

With the advent of 3D acquisition, marine and land data acquisition geometries started to diverge. In marine acquisition, 3D was most efficiently achieved by repeating the 2D geometry, whereas on land sources and receivers can be decoupled so that other geometries such as orthogonal and zigzag geometries are also feasible, and in fact more cost-effective.

Acquiring parallel lines in 3D marine acquisition means that at the start of the survey a decision has to be made on the best direction of those lines. Assuming a dominant dip and strike direction, various authors have discussed the pros and cons of dip or strike acquisition.[1-3]

Considerable gains in efficiency have been reached in marine acquisition with the introduction of <u>m</u>ulti-<u>s</u>ource <u>m</u>ulti-<u>s</u>treamer (MS/MS) techniques, and even multi-boat operations.[4-7] The record of 10 streamers[6] was broken recently[7] and it now stands at 12. Basically, these configurations have maintained the dominance of the chosen acquisition direction in the shot/receiver azimuths, thus maintaining the question what shooting direction gives the best seismic results. It has been realized that the greater efficiency of MS/MS techniques is achieved at the expense of regular illumination of the subsurface.[8,9] The presence of obstructions such as production platforms, reduces the efficiency of the MS/MS techniques and requires the use of a two-boat operation.[10] Uncontrollable feathering forms another reason for irregular illumination of the subsurface.

Bottom cables have been in use already for quite some time in transition zone waters. Only after the re-discovery that the combined use of pressure and velocity detectors would allow the necessary removal of the receiver ghost – the dual-sensor technique – could the use of bottom cables be extended into deeper waters.[11,12] In particular in areas with many obstructions and in shallow waters, the use of bottom cables (frequently called OBC technique for ocean-bottom cable, though SBC for sea-bed cable might be more appropriate) is now really taking off.[12-17]

A very special bottom-cable technique was developed by Statoil.[18-20] In this SUMIC (subsea seismic) technique 3-component geophones are attached to the cable and planted in the sea bottom by an ROV. A hydrophone is also part of the system, therefore this kind of acquisition is sometimes referred to as 4C (four-component). With SUMIC not only P-waves but also S-waves are recorded, and a gas-chimney which would be uninterpretable on a P-wave section may be resolved in the P-S section. The technique is not suitable for 3D, but investigations are underway to adapt it to 3D.[21]

Other 4C techniques are also emerging, and will be discussed later in this paper.

An interesting stationary-receiver technique is the vertical hydrophone cable (VHC).[22,23] In this technique some 12 to 16 hydrophones are arranged along a vertical cable which is anchored to the sea bottom.

Another stationary-receiver technique is the ocean-bottom seismometer (OBS) in use by academia for some twenty years already, but now also considered for use in 3D seismic data acquisition. An OBS is a self-contained receiving *and* recording unit residing at the ocean-floor (literally this time: OBSs are even used in waters exceeding 3000 m!) for the duration of the survey. Unless a technological breakthrough comes forth, VHC and OBS are only suitable for use in a so-called areal geometry in which the receivers are arranged in a *widely* spaced areal grid, whereas the shots are arranged in a *densely* spaced areal grid (referred to as patch geometry in Ref. 8).

In the following I will expand on the discussion of various marine data acquisition techniques, and compare their relative merits. An important aspect is to what extent the stacked and migrated data is representative of the acoustic impedance of the subsurface. Therefore, the influence the acquisition geometry may have on the final seismic amplitudes is discussed first. Next, streamer acquisition is discussed, the dip/strike question and the effect of using MS/MS techniques. The stationary-receiver techniques are reviewed with an emphasis on the various geometries that are suitable with those techniques.

Geometry imprint

Timeslices and in particular horizon slices of stacked or migrated seismic data often show an amplitude pattern which is typical for the acquisition geometry used in the 3D seismic survey. This amplitude pattern is often referred to as *geometry imprint* or *acquisition imprint*.

For streamer surveys, the geometry imprint manifests itself as a striping effect: slow variation of amplitude in the inline direction (the shooting direction) and rapid variation in the crossline direction. An example of striping is given in Fig. 1. In land geometries the shot and receiver line pattern may be visible in the seismic amplitudes. Shallow data, having lower fold than deeper data, tend to have the strongest geometry imprints. These effects of geometry on amplitude are most undesirable, in particular for lithology and porefill prediction, but also for a reliable structural interpretation. Therefore, it is important to choose an acquisition technique and a geometry with which such effects can be minimized.

The geometry imprint is directly related to the offset distribution as a function of CMP position. Systematic variations in offset sampling or periodicities in the offset distribution may create corresponding variations in amplitude. (I will use the term “offset sampling” for the sampling of offsets *within* a CMP, and the term “offset distribution” for the variation of offset sampling *across* the CMPs.) The effect is also known from 2D seismic data; for instance, the odd/even effect in streamer data acquisition with equal shot and receiver station intervals is linked to the fact that the offset sampling of the even CMPs differs from that of the odd CMPs. Why the offset sampling affects the seismic amplitudes might be discussed on basis of Fig. 2.

Fig. 2 shows an NMO-corrected CMP gather with a very regular offset sampling and virtually constant shot/receiver azimuth. The gather shows many events running across the NMO-corrected primaries, and stacking should be able to suppress most of this noise. Splitting the odd and even traces of this CMP over two separate gathers, followed by stacking would lead to two different stacked traces, as the noise events would have been sampled at different offsets. A similar reasoning applies to the primaries: as amplitude varies with offset (AvO) and the stack is an average of all sampled offsets, the averaged amplitude of the primary also depends on the offset sampling, even if there were no noise.

Often, the noise events do not change rapidly as a function of CMP position. Hence, if there is a periodicity in the offset distribution, then the noise will be sampled at the same offsets periodically, leading to periodicities in the seismic amplitude. Similarly, if there is a systematic change in the way offsets are sampled from CMP to CMP, then the amplitude effect will be systematic. However, in situations where there is no systematic variation in offset sampling, or no periodicity in the offset distribution, the stacked amplitudes are still affected by noise or amplitude variations with offset, even though it may be more difficult to recognize the effect.

The ideal way of reducing the geometry imprint to a minimum is by fine and regular sampling of offsets in each CMP. Unfortunately, in streamer acquisition regularity of sampling is not achievable due to uncontrollable feathering of the streamers, and in stationary-receiver techniques the offset sampling is usually highly irregular.

Streamer acquisition

A main feature in 3D marine data acquisition using streamers is the decision that has to be made on the shooting direction. Another aspect is that MS/MS configurations produce irregular illumination of the subsurface, whereas uncontrollable feathering compounds the illumination problem. In the following these aspects of streamer acquisition are discussed in some detail.

Shooting direction. The choice of shooting direction is sometimes referred to as *dip/strike decision*, but other factors, unrelated to dip or strike, often play a role as well. These other factors could be the presence of a nearby coastline, obstacles in a certain pattern, main current direction and more. If a rectangular survey area is much longer than it is wide, it is more economical to shoot parallel to the long sides of the rectangle than to the short sides. In the latter case it may still be decided to shoot in another direction, if there are good reasons to do so. At any rate, prior to the start of a streamer survey one has to commit to a fixed shooting direction, and many considerations can play a role.

In an area with many obstacles, logistics may dictate the shooting direction. Part of the survey will have to be carried out using an undershoot technique, in which the shooting vessel travels on one side of the obstacle, and the vessel towing the streamer on the other side. The streamer vessel should always remain on the same side (port or starboard) of the shooting vessel.[10] In that way the shot/receiver azimuths all have about the same orientation, which is best for illumination of dipping layers and for DMO.

Often, the undershoot part of the 3D survey and the regular part are designed to create adjacent midpoint coverage. However, this may lead to illumination gaps in the subsurface, because of the difference in shot/receiver azimuths between the two parts. To avoid these gaps, the two parts should have some overlapping midpoint coverage, depending on maximum dip.

Dip/strike decision. To start with, often there is no dip direction that is dominant in the whole survey area. And even if the dipping layers were oriented in some main direction, the fault planes and corresponding diffraction patterns might be mainly oriented in the opposite direction. In such cases the relevance of the dip/strike decision is reduced.

In case there is a dominant dip direction, there are always some reasons to favor dip shooting, and other reasons to favor strike shooting. The reasons may be truly geophysical, but there may also be reasons related to positioning accuracy and sampling deficiencies.

A geophysical reason to shoot along strike is the imaging of a salt flank. Shooting along strike keeps both legs of the raypath outside the salt dome, making imaging fairly easy, whereas when shooting dip one leg of the raypath passes through the salt requiring an accurate estimate of the position of the salt flank for proper imaging. Moreover, much of the energy that should travel through the salt will be reflected before entering the salt, so that less energy is available for reflection against the sedimentary layers. The geometry problem is illustrated in Fig. 3 which shows a horizon amplitude map around a salt dome. There is a clear correlation between reflection amplitude and shooting direction.

Prism waves (raypaths with a double bounce: against reflector and salt flank before returning to the surface) form another complicating factor in dip shooting.[24] In case the position of the salt dome is fairly well known, a concentric circle shoot survey can be carried out.[24-27] With this geometry complicated raypaths are avoided as much as possible.

Another geophysical reason to shoot strike is for AvO analysis. The angle of incidence for a given offset would depend on variations in dip, requiring some correction. When shooting strike this complication can be avoided.

An interesting reason to shoot dip is the existence of a gas chimney along the crest of an elongated anticline. In strike lines along the crest of the anticline the low-velocity anomaly would create a time delay which is difficult to deal with in processing, whereas in dip lines undershooting of the anomaly would take place (Sonny Lim, 1992, personal communication).

Ref. 1 lists a number of practical reasons to shoot dip. First, the economics of streamer acquisition favors a finer midpoint sampling in the inline direction than in the crossline direction. It is better to sample finely in the direction where it matters most, i.e. in the dip direction, and if coarse crossline sampling requires interpolation, this can be carried out best in the strike direction. Another reason – which is no longer of great importance due to the increased positioning accuracy of modern streamers – used to be that positioning accuracy tended to be better in the inline direction than in the crossline direction. For strong dips in the crossline direction positioning errors would lead to mis-stacking.

Ref. 1 also lists reasons to shoot strike: Velocity analysis is easier in strike lines, and steeply dipping coherent noise may be removed easier from sections in which the reflections do not show much dip.

Various authors have investigated the effect of dip versus strike acquisition. The Bullwinkle survey reported in Ref. 28 consisted of shooting a survey in two orthogonal directions. A reason to shoot in two different directions was that during 3D survey design it became clear that no single acquisition direction was optimal. The result confirmed that imaging quality depends on shooting direction, with neither of the two directions being best for all features. Imaging of events was worse when complex raypaths were involved in creating the image, then strike shooting was best. For situations in which such complex raypaths did not play a role, it turned out that steep dips were best imaged with dip shooting. This result might be due to the better sampling in the inline direction, hence better sampling of the fast variations with dip shooting, an argument pro dip shooting also given in Ref. 1. Whether dip shooting would also be better in case of equal binsize in both directions could not be decided from the Bullwinkle experiment.

In a water tank experiment two orthogonal directions were used to find an answer to the dip/strike question for square bins.[3] In this experiment "it was found that the dip survey data produce superior time image results of the target features compared to the strike survey data". Unfortunately, the binsize used in that experiment was very large causing aliasing on input. Aliased input data tends to generate migration noise and incomplete imaging, hence a general conclusion cannot be drawn from that analysis.

Following intuition, I would guess that the imaging capability of well-sampled common-offset gathers with constant shot/receiver azimuth would in general not depend on azimuth. Only in complex geologies with complex raypaths and azimuth-dependent transmission effects one might expect measurable dependencies on orientation. But then it is best to include all azimuths in the acquisition geometry, because there would not be a clear-cut dip direction.

Multi-source multi-streamer acquisition. The first marine 3D surveys were carried out with the conventional 2D geometry of a single boat towing one source (array) and one streamer. To increase efficiency in recording 3D surveys, the industry has seen a gradual increase in the number of midpoint lines (also called bin lines) recorded in one boat pass. The newest vessels can tow eight or even more streamers allowing efficient single-boat operations.

The increase in number of midpoint lines recorded in one boat pass leads to undesirable side effects. In this part of the paper I will first describe various MS/MS configurations followed by a discussion of the undesirable side effects.

Multi-source multi-streamer configurations. Fig. 4 provides a schematic display of some common MS/MS configurations. The sources, represented by black circles in this figure, are always kept as close as possible to the boat to minimize the length of the umbilicals (pressure hoses from vessel to airgun arrays). The number of midpoint lines recorded by these geometries equals the product of number of sources and number of streamers. Very often the distance between midpoint lines is chosen as 25 m. Then the distance between adjacent sources is always 50 m (except in the 4/4 configuration), the distance between streamers is 100 m for configurations with two or four sources, and 150 m for configurations with 3 sources. Ref. 7 describes a configuration with 24 midpoint lines.

Multi-source effect on fold. A disadvantage of using several sources is the reduced fold in the individual midpoint lines. This is caused by the time interval needed between successive shots. In that time interval the vessel moves some distance, so that in practice shot intervals smaller than about 18 m are difficult to achieve. The distance between successive shots in a midpoint line is then *n* times 18 m, *n* being the number of sources.

Multiples with large differential moveout with respect to the primaries may be severely undersampled – even after NMO-correction – due to the low-fold of multi-source configurations.[29-31] Various interpolation techniques have been devised to cure this problem.[30-33] Impressive examples are shown in Refs. 30 and 31. Nevertheless, there is a tendency to prevent the problem by using not more than two sources in modern MS/MS configurations.

Crossline-offset variations. Each midpoint line in a MS/MS configuration is acquired by a unique source/ streamer combination having a constant crossline offset (if there is no feathering). The variation in crossline offset between adjacent midpoint lines leads to variation in shot/receiver azimuths of traces with the same offset across the survey. Interchanging source and receiver position leads to different azimuths, hence crossline offset is to be described by a signed value, e.g., receiver *x* minus shot *x* for sailing in the *y*-direction. For example, the crossline offsets of the 3/3 geometry are: (-100, -150, -200, 50, 0, -50, 200, 150, 100).

Fig. 5 illustrates crossline offset as a function of midpoint line for various MS/MS configurations. Each graph describes the crossline offset for 48 adjacent midpoints, except the graph for the 3/3 configuration which describes 45 adjacent midpoints.

Sailing adjacent boat passes in opposite directions (antiparallel acquisition) instead of in the same direction reduces the difference in crossline offset between the two passes to zero. This may significantly reduce the average variation in crossline offset. Fig. 6 charts the variation in crossline offset (defined as the rms. of the differences in crossline offset between adjacent midpoint lines) for various geometries.

Figs. 5 and 6 also illustrate differences between single-source and multi-source geometries. The crossline offset in single-source geometries varies smoothly within one boat pass, whereas in multi-source geometries it shows in general some rapid jitter. The jitter corresponds to pairs or triplets of sources shooting into the same streamer followed by the same sequence of sources into the next streamer. Note also the large effect antiparallel acquisition has on the variation in crossline offset for the single-source configurations (Fig. 6).

Irregular illumination. The discontinuous behavior of crossline offset leads to irregular illumination of the subsurface. This can be illustrated using the "footprint" of a geometry as in Fig. 7. Here 48 adjacent crossline midpoints are selected. The model consists of a plane reflector with 45° dip and a dip direction of 45° with respect to the crossline direction in a constant velocity medium. The depth of the reflector is 2000 m in (0,0). For each midpoint the (*x*,*y*) coordinates of the reflection points are plotted for inline offsets ranging from 0 to 3000 m. As expected, for the 1/1 geometry the curves behave in a regular way, whereas for the other geometries there is a great deal of irregularity. In the 4/4 geometry (Fig. 7b), there are some areas of the reflector that are never sampled by the large offsets, whereas other areas are sampled more than once. Note that the variations are largest for the large offsets, despite the fact that there the azimuth variations are the smallest. Fig. 7c and d illustrate that with a smaller number of midpoint lines in one boat pass the illumination becomes less irregular, and that antiparallel acquisition also reduces the irregularities**.**

Variation in *feathering* between boat passes leads to additional irregularity. In a single boat-pass the various streamers show usually about the same feathering, which is quite helpful for not getting the streamers tangled up. In the following experiments a uniform distribution of random feathering angles ranging from -1.75° to +1.75° is used. The feathering angle is assumed constant during a boat pass and the same for all streamers.

Fig. 8 shows that feathering may have a dramatic effect for the 1/1 geometry, whereas in this case feathering hardly affects the subsurface illumination by the 2/4 geometry. With the assumption of constant feathering inside a boat pass, effects of differential feathering are only important between adjacent boat passes. This feathering may or may not improve subsurface illumination.

Though Figs. 6 and 7 suggest that antiparallel acquisition is least irregular, especially for single-source configurations, it should be realized that random feathering with zero average has been assumed. If feathering tends to be in a single direction (e.g., caused by prevailing cross-currents), then antiparallel acquisition may increase the differential feathering, and thus the need for infilling.

Effects of irregular illumination. Systematic irregular illumination of the subsurface is a consequence of MS/MS configurations. Figs. 5 and 6 suggest that the effect increases with the width of the geometry and that the largest jumps in crossline offset should create the largest effects. Fig. 9 shows a timeslice through the stacked data of a 4/4 geometry.[34] In this timeslice discontinuities occur at the position of the largest jump in crossline offset (between midpoint lines 8 and 9). The discontinuities are largest where the time contours make an angle of 45° with the sailing direction. In that situation adjacent midpoint lines sample different parts of the reflector (cf. Fig. 7b), leading to sizable differences in stack times. With dip sailing or strike sailing, there are no differences between the traveltimes of lines 8 and 9.

Apart from the time discontinuities as in Fig. 9, the stack will not normally give much cause for concern, as every shot/receiver combination contributes reflection energy to the stack. However, after DMO, the situation may change drastically. As DMO moves data back to their normal-incidence point, the illumination gaps discussed for Fig. 7 will show up as weak seismic amplitudes in the DMO stack. Ref. 9 illustrates this with a synthetic data set. A similar result is shown in Fig. 10. What has not been illuminated cannot be imaged, therefore DMO equalization techniques[35] cannot solve this problem completely, neither will migration correct for the deficiency. Whereas feathering would give rise to a geometry imprint (striping) also with a single source/ single streamer configuration, the irregular illumination with MS/MS configurations will always lead to some geometry imprint, even if there were no feathering.

The irregular illumination of the subsurface affects migration and imaging in two ways: first, the images for areas that have not been illuminated by the long offsets will be incomplete, and second, the cancellation of energy along the flanks of the migration operators will be suboptimal leading to migration noise. Both effects cause loss of resolution.[36]

Remedies. MS/MS configurations are inherently irregular. The larger the discontinuities in the crossline offset, the larger the discontinuities in individual common-offset gathers. The deficiencies of the contributing parts can be reduced by high-fold acquisition. Sometimes the interval between shots can be reduced by sailing into the current, if there is a strong predictable current. Using only one source has the advantage that the crossline-offset variations within a boat pass are smooth. It has the disadvantage that the streamers have to be towed dangerously close together, unless interleaved acquisition is used (100% overlapping boat passes, i.e., a planned 100% infill). Interleaving increases trace density, and reduces illumination irregularity on average.

The illumination irregularities are most severe for steeply dipping reflectors while sailing in the updip or downdip direction (for some configurations there may be a considerable difference between updip and downdip irregularities). Therefore, the irregularities can be minimized by sailing strike to the steepest reflectors.[37]

The most drastic remedy to irregular illumination caused by crossline-offset variations and uncontrollable feathering is to use a stationary-receiver technique.

Operational aspects. There is no doubt that in open waters the MS/MS acquisition technique is highly efficient and cannot be beaten – certainly not in terms of sq. km per day – by stationary-receiver techniques. On the other hand, the seismic vessels for multi-streamer operations must be very powerful, hence are expensive to operate. Towing eight or more streamers is not easy, especially the outer streamers are difficult to control.

A restriction on the production is the amount of time that has to be spent on line turns. In a typical North Sea 3D survey (an interleaved 1/8 configuration) line turns took about 2.5 hours on average. Deployment of the cables took some 9% of total survey time (see also Fig. 11).

Around obstacles MS/MS configurations must leave a large gap in the area of coverage as the streamers have to stay away from the obstacles. This needs to be compensated by a special undershooting survey (a two-boat operation), which is time-consuming and expensive. In the above-mentioned survey, 18% of the survey needed undershooting, at 36% of total cost.

Stationary-receiver techniques

Fig. 12 provides a pictorial overview of the various stationary-receiver acquisition techniques. A common factor in all of these techniques is that the receivers are referenced in one way or another to the sea bottom. Another common feature is that there is a separate source vessel.

An important distinction between the various stationary-receiver techniques is the geometry that is or may be used. This part of the paper starts with a description of the possible geometries, followed by a description of various stationary-receiver techniques.

Geometries for stationary-receiver techniques. The use of stationary receivers allows the decoupling of the source from the receiver as in land data acquisition. In other words, there is more freedom in the choice of geometry, typical land-type geometries may be used, and there is no physical offset limitation.

The main types of geometry available to the designer of a 3D marine survey with stationary receivers are the parallel geometry, the orthogonal geometry and the areal geometry.[8] In the parallel geometry the source lines and the receiver lines run parallel to each other. The MS/MS configurations described in the first part of this paper use the parallel geometry. With bottom cables similar geometries can be arranged.[13]

A main reason to use the parallel geometry with stationary-receiver systems is the familiarity with the geometry in marine circumstances and the possibility to tie in to a similar geometry of an adjacent streamer survey. However, from most other points of view, the parallel geometry seems to be inferior to the orthogonal geometry. It suffers from irregular illumination as described above, and even though feather of the streamer does not play a role, drifting of the source vessel due to side currents may occur and cause gaps in midpoint coverage. The only factor which might be in favor of the parallel geometry is the possibility of creating a regular offset sampling in the midpoints, allowing better multiple suppression by stacking.

In the orthogonal geometry parallel source lines run orthogonal to parallel receiver lines, see Fig. 13a. The shot and receiver interval along those lines determines the resolution of the seismic data, whereas the line spacing determines the shallow coverage. Fold of coverage also depends on the line spacing.

The areal geometry is characterized by an areal grid of widely spaced receiver units and an areal grid of densely spaced sources, see Fig. 13b. The source grid determines the resolution of the seismic data, whereas the receiver grid determines the shallow coverage. Fold of coverage also depends on the receiver grid.

For bottom cables the orthogonal geometry is the preferred geometry, whereas for techniques employing very expensive receiver units, the areal geometry is preferable, as it requires fewer receiver units for a given survey area. The disadvantage of the areal geometry is that it requires a very dense source sampling which is both time-consuming and expensive.

Both the orthogonal geometry and the areal geometry can be considered as a collection of overlapping single-fold 3D data sets. In the orthogonal geometry the subset is called cross-spread and in the areal geometry it is called 3D common-receiver gather. The shape and extent of the subsets is determined by the maximum inline and crossline shot/receiver offsets. For the cross-spreads this is illustrated in Fig. 14.

If properly sampled these subsets are free of discontinuities, i.e., they allow reconstruction of the underlying continuous 3D wavefield, and provide for regular illumination of the subsurface. (This in contrast to the parallel geometry where – in the MS/MS configurations – there is no underlying continuous wavefield for any subset, owing to the discontinuous behavior of crossline offset.) However, the edges of the subsets are discontinuities in the geometry and may lead to discontinuities in illumination. 3D symmetric sampling[8] calls for maximizing the extent of the subsets to minimize the number of discontinuities in the geometry.

The regular illumination of the subsurface ensures optimal prestack migration and imaging. Only the edges of each subset will cause incompletely imaged reflection points and may lead to incomplete cancellation along the flanks of the migration operator. It should be realized that seismic software developed for velocity model analysis is usually implemented on basis of common-offset gathers as provided by the parallel geometry. In the orthogonal and areal geometries such gathers are not available, requiring new approaches to this problem.

The areal geometry can be implemented more efficiently using a hexagonal distribution of sources and receivers. Hexagonal sampling of a function of which the wavenumber spectrum is limited by a circle requires fewer samples than rectangular sampling.[38] It leads to a reduction of 13.4% in the number of required source points in the areal geometry.[39] Similarly, a hexagonal arrangement of the receivers allows a lower density of receivers for the same “largest minimum offset”. Another advantage of this geometry is that the shape of the subsets can be arranged to be hexagonal, allowing a better distribution of the long offsets over azimuth. More efficient signal processing operators can be designed on basis of a hexagonal grid.[40]

A disadvantage of the areal geometry is the sensitivity to obstacles: where there is an obstacle, there will be a hole in the common-receiver gathers. An interesting opportunity offered by carpeting the survey area with shots is that a short streamer might be towed behind the shooting vessel, thus providing a separate short-offset 3D without much additional cost. Due to the distance between the receiver units in the areal geometry, shallow coverage is poor, but with a short-offset 3D, shallow coverage is taken care of, even allowing a larger distance between the receiver units. Carpeting the survey area with shots also allows the simultaneous recording of high-density gravity profiles.[41]

The orthogonal geometry and the areal geometry do not really commit to a particular shooting direction, all shot/receiver azimuths may occur. Hexagonal sampling of the areal geometry provides the least dependence of the 3D survey on direction. The presence of a full range of azimuths also offers the scope for amplitude versus direction (AVD) analysis.[42]

Vertical Hydrophone Cable (VHC). The VHC technique (Fig. 12 top) was developed and patented by Texaco.[43,22,23] A vertical cable along which a string of 12-16 hydrophones is distributed, is anchored to the sea bottom and pulled into a vertical position by a buoyancy sphere. The sphere is kept below the zone of wave action. The signals received by the hydrophones are stored in a storage device located in a recording buoy.

As the patent title[43] suggests, the technique was meant to provide a walkaway VSP without the need of drilling a hole. But it was soon discovered that the technique could also provide an alternative to conventional streamer data acquisition. Because of the expensive nature of the device and the relatively low cost of marine shooting, the use of an areal geometry (Fig. 13b) is the logical choice for this technology. At the same time this choice would allow the acquisition of the full range of azimuths which might be helpful for imaging in complex geologies.

The 12-16 hydrophones provide as many 3D common-receiver gathers, each one recording a slightly different signal. VSP type processing may be applied to separate upgoing and downgoing energy (energy reflected at the sea surface), and may reduce the data set into two representations (up- and downgoing each) of the wavefield at the location of the VHC. This would eliminate the receiver ghost. A high signal-to-noise ratio should be possible with the VHC technique, because a) the hydrophones are located below the zone of wave action, b) there are many elements in the hydrophone array, and c) water-borne noise comes in horizontally, and can be discriminated against easily.

Two full-scale surveys have now been carried out with this technique.[44] One was the 3D Strathspey survey in the North Sea in waters of about 145 m. Processing results are very encouraging.

Due to the limited number of available systems, the Strathspey survey had to be split over 2 x 3 adjacent swaths of 3 x 4 VHCs each. This necessitated considerable overlap of the shot areas between adjacent swaths. For a reasonably sized survey, some 100 to 200 receiver units would be necessary for application of a roll-along technique without repeating shots.

Currently, the VHC technique has also a number of shortcomings. First, with the recording buoys it creates its own obstacles, leading to gaps in the pattern of shots. In a storm, wave action may get hold of the recording buoys and displace the whole system. Unloading tapes and changing batteries has to be carried out while shooting continues, also leading to some missed shots. Another problem is that changing currents will move the cable around, especially the shallowest part, thus violating the assumption of a single receiver position. Improvements in the design should be able to mitigate these problems considerably. However, emerging alternative stationary-receiver techniques might overtake the VHC technique in importance.

A much cheaper version of the VHC technique is the dual-hydrophone Digiseis.[45] In this system only two hydrophones are attached to a vertical cable, allowing immediate radio-transmission of all received data to a recording vessel. It has been used to supplement streamer acquisition in the vicinity of obstacles. In the reported survey[45] an irregular areal geometry was used with a rectangular grid of 350 m x 320 m for the Digiseis units, and a rectangular grid of 40 m x 25 m for the shots. It is not clear to what extent this technique is capable of removing the receiver ghost.

Dual-sensor OBC. In dual-sensor OBC acquisition bottom cables are provided with a pressure and a velocity detector at regular intervals. In 1989 Barr and Sanders presented a field test of the dual-sensor system.[11] In this paper they argue that the water reverberations have opposite polarity, allowing the suppression of reverberations by summation of the signals of the two sensors in one location. This principle is also explained in Ref. 12. Many papers describe techniques for the combination of the hydrophone and geophone signals.[46-48]

Geometry. The OBC can be used most efficiently in an orthogonal geometry. The implementation of this geometry can be done in various ways. The number and length of the receiver lines which are laid out in one “patch” varies, and shotlines may start beyond or within the reach of the receiver lines. Fig. 15 is a patch used by Chevron offshore West-Africa.[13] A similar patch is reported in Ref. 16. A very long and narrow patch is described in Ref. 17. (Here the authors use the word “swath” to describe the patch, whereas elsewhere[13] swath is reserved for acquisition with a parallel geometry. Nomenclature in this field has not been settled yet.) The patches are repeated to generate a full 3D coverage of the survey area.

Until recently the station spacing in bottom cables was virtually always 50 m. This means that frequencies above 15 Hz already run the risk of being aliased. It also means that the potential of the OBC technique to reach higher resolution than streamer acquisition may not materialize.

Whatever patch is used, to maintain a reasonably efficient operation, the recorded cross-spreads will inevitably be asymmetric and different. This may lead to highly variable offset samplings in the CMPs and a noticeable geometry imprint. It is always possible to chop off outside traces in processing in order to create square cross-spreads (or at least rectangular cross-spreads with symmetry around the shot and receiver axes), but in order to make this not too much of a waste, it has to be planned already in geometry design.

Recently a dual-sensor survey was acquired in the North Sea with symmetric sampling in mind. In this geometry the shotlines extended 4500 m beyond the receiver lines allowing the maximum crossline offset to be equal to the maximum inline offset (cf. Fig. 14 and Ref. 8). The shot and receiver interval was nominally 37.5 m. The receiver interval was to be realized by allowing enough slack in a bottom cable with 60 m between stations. However, during deployment, the cable is launched overboard without much control over where it goes beyond that point. In this survey it led to variations in station spacing from 10 to 60 m. The difficulty to control the exact position of a bottom cable is also discussed in Ref. 49. It might compound the problem of carrying out repeat surveys for seismic reservoir monitoring.[49]

Logistics. Operating an OBC survey is a complicated matter: four to six vessels are needed for efficiency: a recording boat, a shooting boat and several cable deployment vessels.[13] A balance has to be struck between the shooting vessel not having to wait for the next patch to be ready, and the next patch being ready while shooting of the previous patch has not been completed. Because laying cables is very time-consuming, cables should be laid out only once at the same spot, necessitating repeat visits of the sources to the same locations. The larger the number of stations available, the smaller the shot repeat factor can be.

At present there is still a water depth limitation of some 150 m to the use of conventional dual-sensor cables. The main problem is the retrieval system, not the strength of the cables. Better retrieval systems should allow extension to greater water depths.

Four-component marine data acquisition. The advent of four-component (hydrophone plus 3C-geophone) marine acquisition techniques could have a great impact on the E&P business. Application of four-component technology may lead to improved (see also Ref. 19):

- lithology and pore fill prediction,
- fracture density and fracture orientation determination,
- seismic reservoir monitoring, including compaction analysis,
- mapping inside and below gas chimneys.

Up till now only 2D 4C experiments have been carried out. In the following some recent developments are reviewed.

SUMIC. Statoil has released results of their experiments with the SUMIC technique.[18,19,21] In this technique a bottom cable is connected to a recording vessel, but unlike conventional OBC, the receiver units are external to the cable, and are planted in the sea bottom using an ROV. The units contain a hydrophone on top, two orthogonal horizontal geophones and a vertical geophone. In their configuration the receiver units were spaced quite closely along the cable, allowing the recording of high-fold 2D lines.

Ref. 18 showed imaging of gas chimneys as the main application of the technique. The PS-wave data produced sections suitable for structural interpretation, whereas the P-wave sections only produced jumble across the gas chimneys.

Ref. 19 also shows a display of common-receiver records acquired with SUMIC (reproduced here as Fig. 16). This record and other records shown in presentations show a remarkable quality of the horizontal components, sometimes even better than the hydrophone data. The quality of these records can be attributed not only to the quiet environment at the sea bottom, but also to the planting of the receiver unit by the ROV, leading to better coupling than possible with gravity-controlled coupling.

If it were possible to apply this acquisition technique in 3D surveys, it would mean a breakthrough in the potential applications of the seismic method. This would require an acquisition geometry with a low density of receiver units to keep it affordable.

Other 4C bottom-cable techniques. A somewhat hybrid technique involving 6 gimbaled geophones from a VSP tool used in OBC mode plus two hydrophones was carried out in 1300 m deep waters offshore Norway.[50] Ref. 51 discusses in detail the coupling conditions of this experiment.

Another technique being rapidly developed is the dragged bottom cable. Rather than retrieving the cable between deployments, this cable is made strong enough that it can be dragged to its next position. Perceived advantages of this technique are a better coupling to the sea floor than possible with conventional OBC deployment, and a constant distance between stations (no slack).

Two major contractors (perhaps more) offer this technique at present. In one implementation each station consists of several hydrophones and geophones located inside and along the cable. Until now only 2D lines have been acquired with this experimental technique. First results look highly encouraging, a common-receiver gather is shown in Fig. 17. However, these results demonstrate only that the inline component is recording a high-quality signal. The behavior of the crossline component – which becomes important in 3D surveys – has not been tested yet.

The other implementation involves separate receiver units which are connected to each other with cable segments which only contain wiring. With these units, there may be less chance that the coupling of inline and crossline component is different, but definitive proof of such a property has not been published yet.

Ocean-bottom seismometers. For some twenty years already, academia has been using OBS units for wide-angle refraction and reflection profiling (WARP). These self-contained units are lowered (by gravity) to the ocean-bottom (see Fig. 12 bottom), left there for two weeks or so while shooting takes place, and then retrieved again. The systems usually consist of a glass sphere, which contains a 2-6 channel recording instrument plus batteries, and sometimes one or three geophones; the (external) hydrophone is standard. Unfortunately, even though gravity may firmly plant the whole system on the bottom, internal geophones cannot record the undisturbed seismic wavefield. In particular, the horizontal geophones suffer severely from rotations of the whole system, induced by the height and size of the set-up.[52,53] For reliable recording of the seismic wavefield, the geophones would have to be external.

Alternatives to the internal geophones would be a gravity-deployed external three-component geophone, or a receiver unit planted by ROV as in the SUMIC technique. For applicability to 3D, the system should be capable of listening during a sufficient length of time, have enough battery power and storage capacity. And the recording fidelity should be state-of-the-art. All these requirements lead to considerable unit cost of such OBSs, necessitating the use of an areal geometry as with VHCs. Moreover, planting of the geophones using an ROV would be time-consuming and expensive. Nevertheless, a 4C 3D OBS survey would be similar in cost as a VHC survey, but easier to handle with the added benefit of shear wave data.

The world's first 4C 3D marine survey. At the time of writing a survey is planned to be carried out in the North Sea (in February!) using an adapted version of the SUMIC technique. Instead of keeping a small distance between the receiver units, these are now spaced at 600 m intervals, but still linked via a wired cable to a recording vessel (see Fig. 18). Sources are fired every 25 m. Hence, this geometry is the same as would be used with a 4C 3D OBS survey. If the test survey turns out to be a success, this would provide another great stimulus for further developments in 4C 3D acquisition.

Future developments and needs. Much experimental work is needed to establish the best ways of achieving good geophone coupling under various sea-bed conditions. If gravity coupling can be sufficient, it would obviate the need for expensive ROV planting of geophones. However, an OBS technique would always require application of the very time-consuming areal geometry.

It will be very interesting to see whether the coupling of any of the 4C bottom-cable systems will be good enough for 3D applications. If so, bottom cables might become more economical while providing the same quality as OBS systems. Note, however, that as long as the total length of available bottom cables is small, a large shot repeat factor is needed, also leading to long acquisition times.

Overview and conclusions

This paper provides a review of currently available marine seismic data acquisition techniques. Table 1 gives a coarse overview and comparison. A major observation is that MS/MS acquisition is superior as far as cost and operation in deep waters are concerned, but that for the highest quality it may be worthwhile to consider one of the stationary-receiver techniques. In a comparison between MS/MS techniques and dual-sensor OBC a similar conclusion is drawn.[54]

The advent of 4C marine recording capabilities opens up a new range of possibilities for the E&P business. SUMIC results have already shown that high-quality shear wave data may be recorded in the marine environment. Further developments and commercialization of those techniques can be expected in the near future.

Processing techniques will also have to be developed to deal with orthogonal and areal acquisition geometries. Processing of full-azimuth shear-wave data provides yet another challenge. Eventually, the achievements on shear data acquisition and processing that can be anticipated for the marine environment, may give a new push to shear-wave recording and processing on land.

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Table 1. Comparison of various marine data acquisition techniques[1)]

	MS/MS[2)]	MS/MS[3)]	VHC	2C OBC	4C OBC	OBS
cost	+	0	- -	0	-	- -
resolution	-	0	+	+	+	+
infilling	-	+	++	++	++	++
undershooting	- -	- -	0	+	+	0
shear	- -	- -	- -	- -	+	++
illumination	-	0	+	+	+	+
dip/strike	-	-	+	+	+	+
max. offset	-	-	+	+	+	+
geom. imprint	-	0	0	0	0	0
repeatability	-	-	0	0	+	0/+
water depth	++	++	+	-	0	+
weather	-	-	0	+	+	+
ambient noise	-	-	0	+	+	+

Symbol	Meaning
++	very favorable/ not applicable
+	favorable
0	OK
-	unfavorable
- -	very unfavorable/ not applicable

1) Caution: quality also depends on sampling, fold, width of MS/MS, etc.
2) for wide geometries
3) interleaved

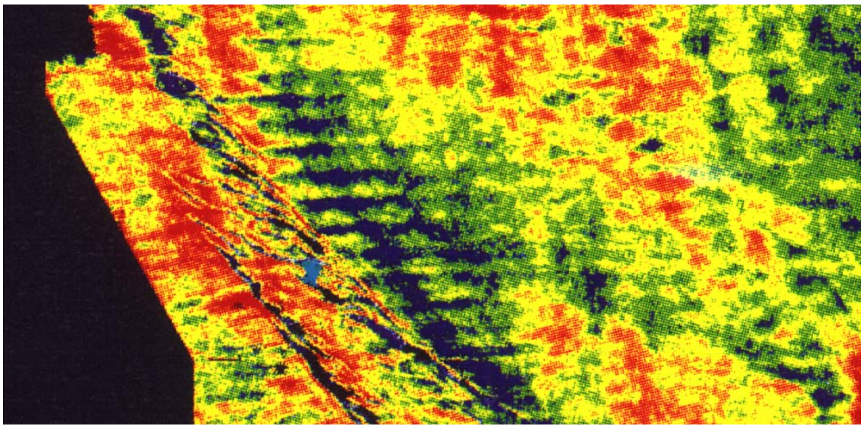

Fig. 1 Amplitude striping in 4/4 geometry. The geometry imprint has a periodicity of 16 in the crossline direction.

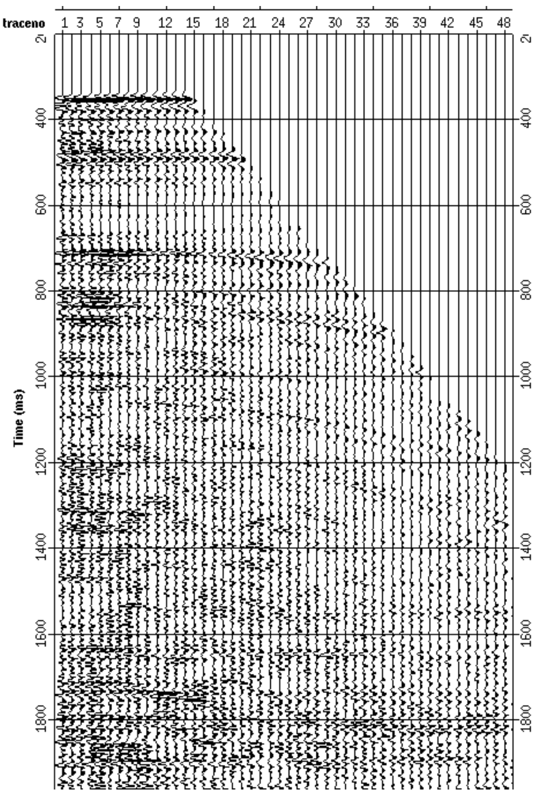

Fig. 2 NMO-corrected CMP gather.

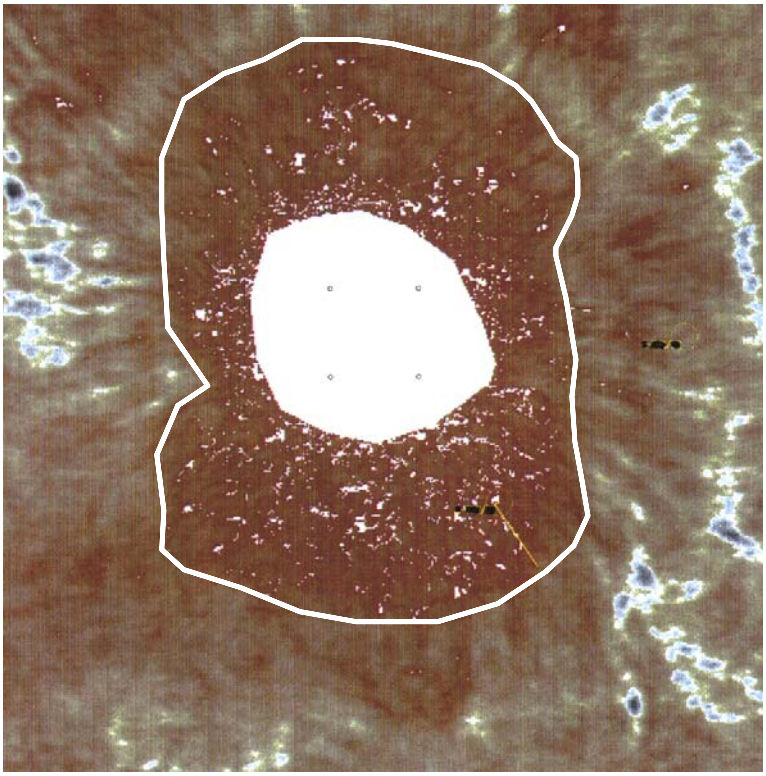

Fig. 3 Horizon amplitude map around salt dome. Dark amplitudes are weak. Left and right of the salt dome strike acquisition provides better illumination of the horizon. White line outlines area of weak amplitudes.

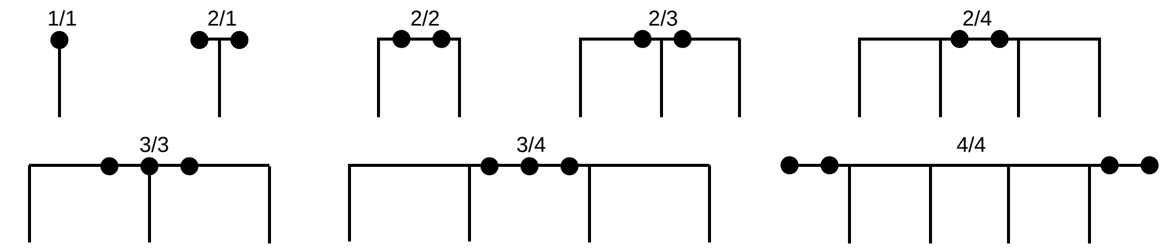

Fig. 4 Schematic description of various acquisition geometries. Black circles represent sources, vertical lines represent streamers. For 25 m between midpoint lines, pairs of shots always are at a distance of 50 m (except the inner two in 4/4). With two or four sources streamers are 100 m apart, with three sources 150 m.

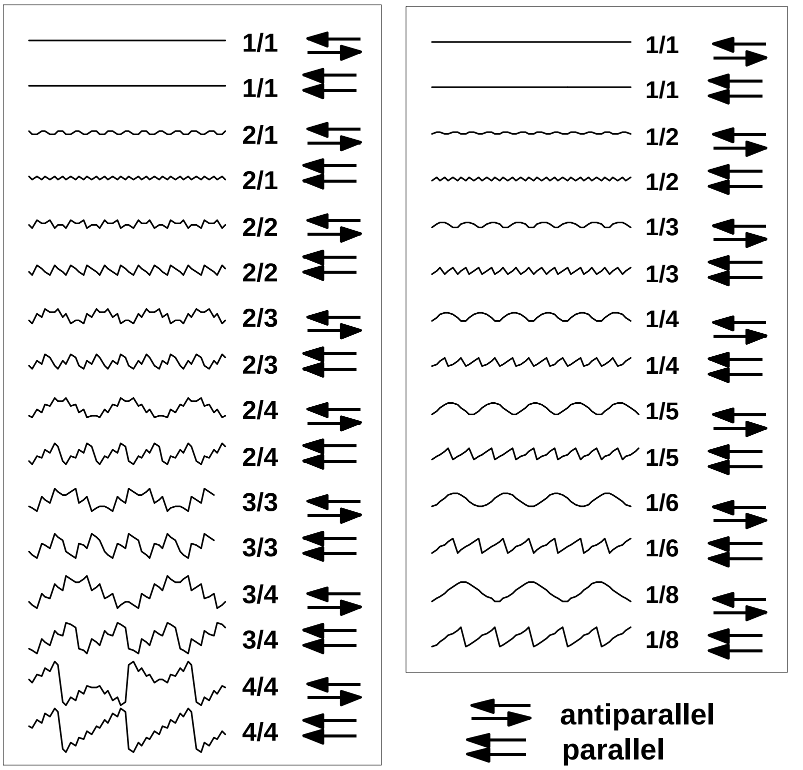

Fig. 5 Crossline offset as a function of midpoint line for various multi source/ multi streamer configurations. On the right only single source configurations are displayed.

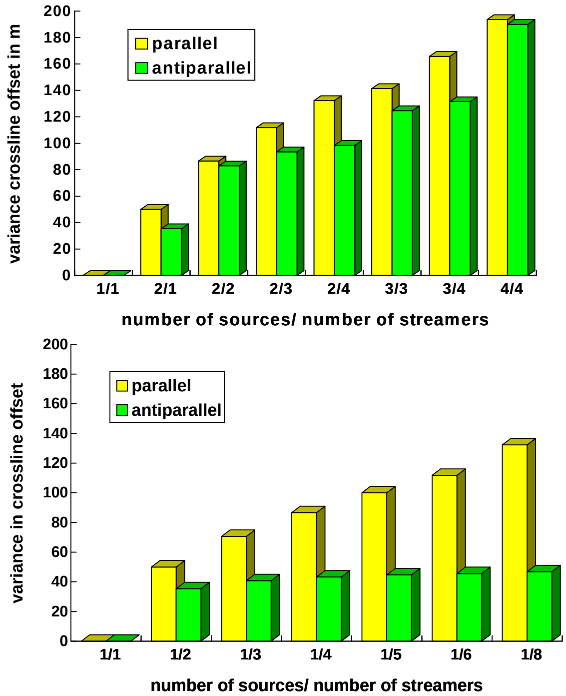

Fig. 6 Variation in crossline offset for various marine 3D configurations. Top: multi source/ multi streamer configurations, bottom: single source/ multi streamer configurations. Note that sailing adjacent boat passes in opposite directions often leads to a significant reduction in the crossline offset variation.

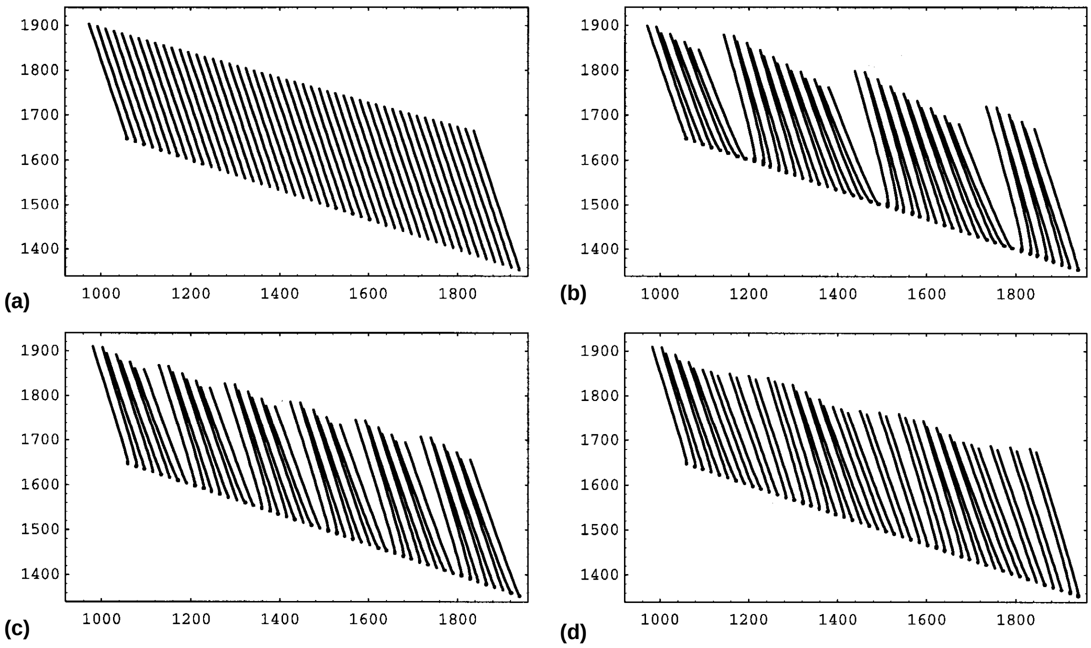

Fig. 7 Footprints of some acquisition geometries. Shown are (x,y)-coordinates of reflection points on a dipping interface with 45° dip and azimuth 45°. Each curve represents the reflection points of one midpoint. The curves are shown for 48 adjacent (in the crossline direction) midpoints. Streamer length is 3000 m. Sailing direction from South to North. Reflector depth is 3000 m in (0,0). (a) single source/single streamer geometry provides regular subsurface sampling, (b) 4/4 geometry, note big gaps in subsurface sampling halfway in each group of 16 midpoints, and oversampling in between, (c) 2/4 geometry showing smaller gaps, and also oversampling in between the gaps, (d) 2/4 geometry, but now acquired in antiparallel mode. In this case antiparallel shooting leads to less irregular subsurface sampling. In b,c,d sampling irregularity increases with offset (longest offsets have moved farthest updip into NE-direction).

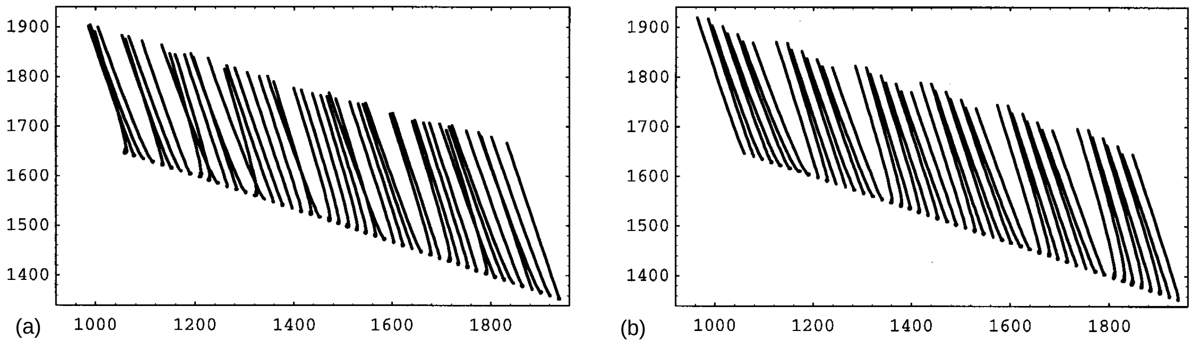

Fig. 8 Effect of random differential feathering on footprint, (a) 1/1 geometry, (f) 2/4 geometry. In this case the curves still correspond to particular source/ streamer combinations, but do no longer correspond to single midpoints as in Fig. 7.

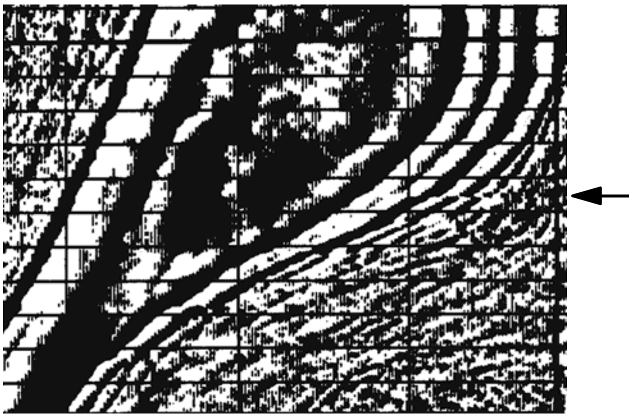

Fig. 9 Timeslice through stacked 3D data set acquired with 4/4 geometry. Note discontinuities every 16th East-West midpoint line (a horizontal gridline is drawn every tenth midpoint line).

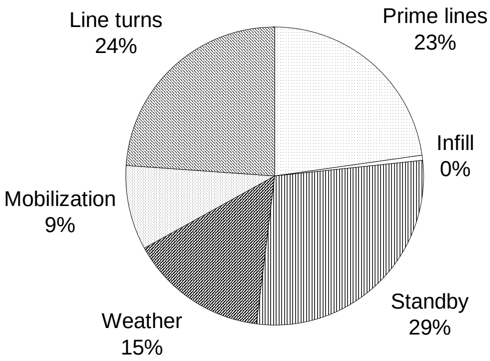

Fig. 11 Relative time spent on various activities during interleaved 1/8 survey in North Sea. Note lack of infill due to interleaving. Downtime due to equipment failure and maintenance not included.

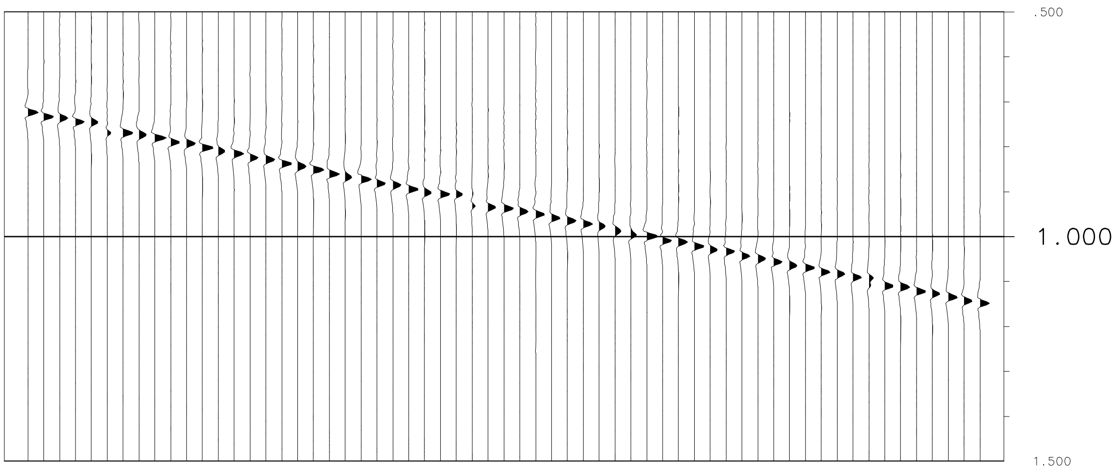

Fig. 10 Crossline acquired with 2/4 geometry and feathering after DMO including equalization. The offset range was 1000 - 1500 m.

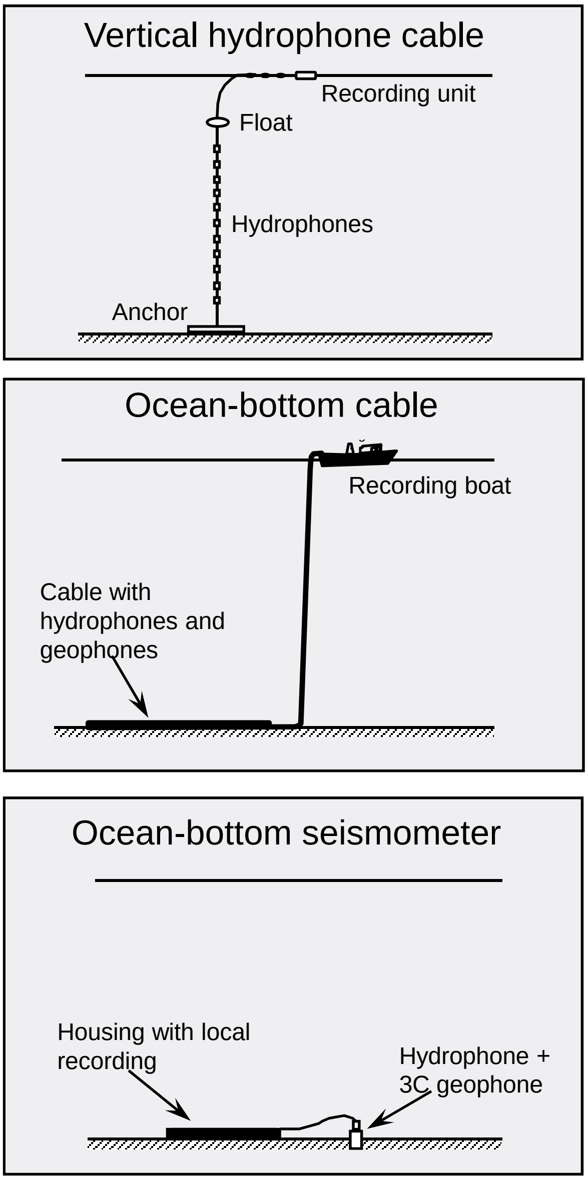

Fig. 12 Various stationary-receiver techniques.

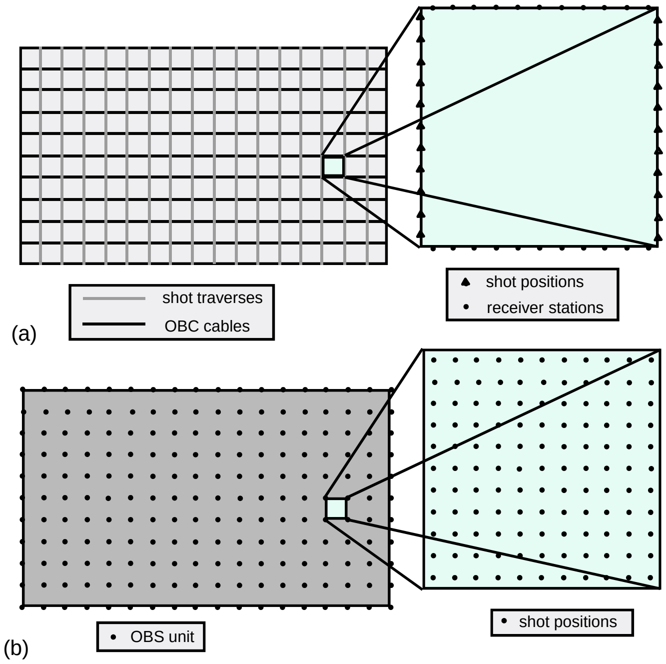

Fig. 13 Land-type geometries suitable for stationary-receiver techniques. (a) orthogonal geometry, (b) areal geometry.

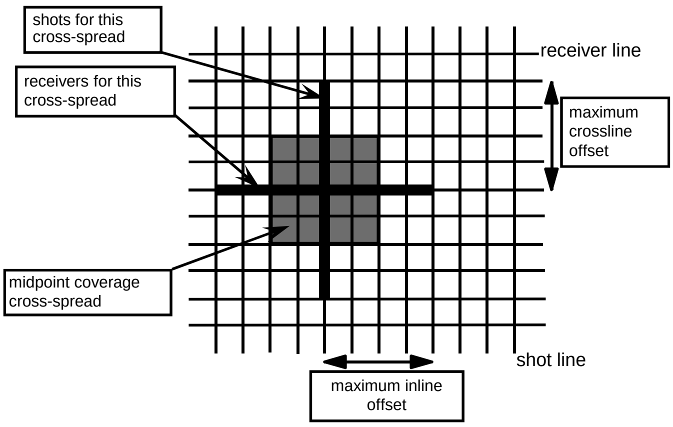

Fig. 14 Cross-spread as subset of orthogonal geometry.

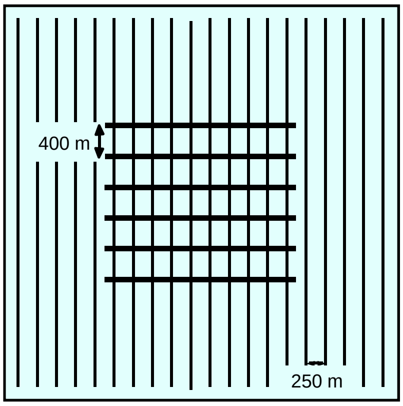

Fig. 15 Typical patch used in OBC acquisition. For the next patch cables will be moved to adjacent positions (no receiver overlap), but sources will have to overlap partially.

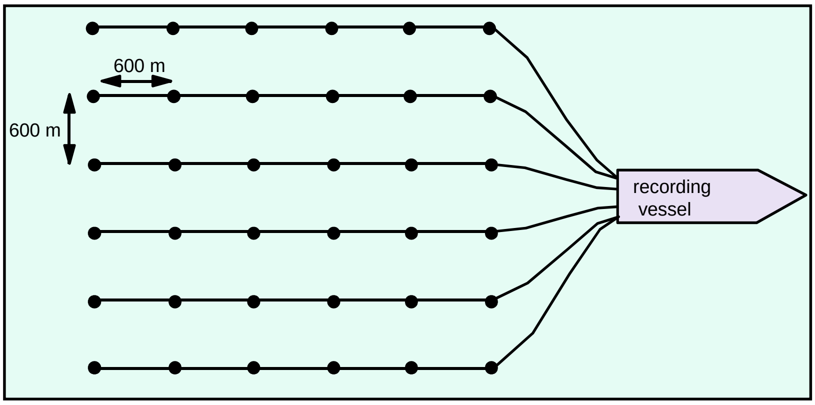

Fig. 18 Planned areal geometry of 4C receiver units to be planted by ROVs.

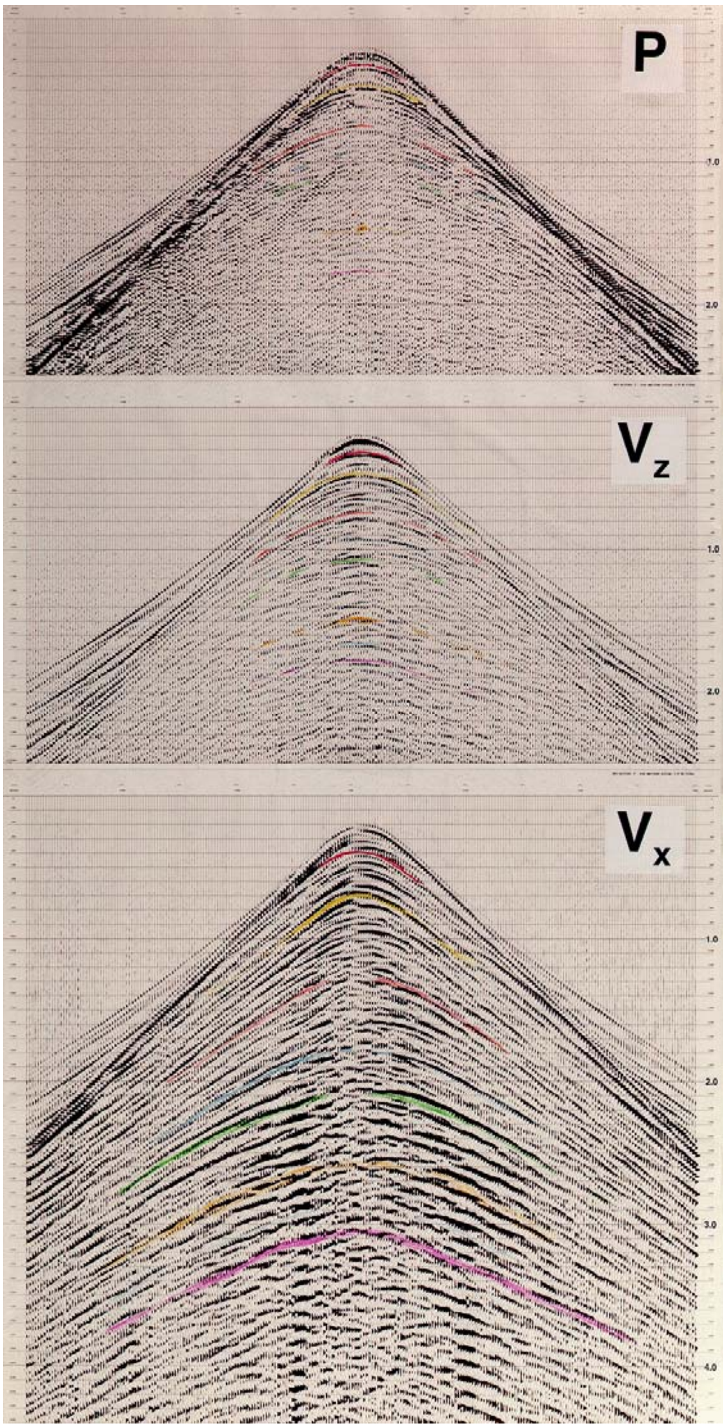

Fig. 16 Common receiver panel acquired with SUMIC technique (courtesy Statoil)

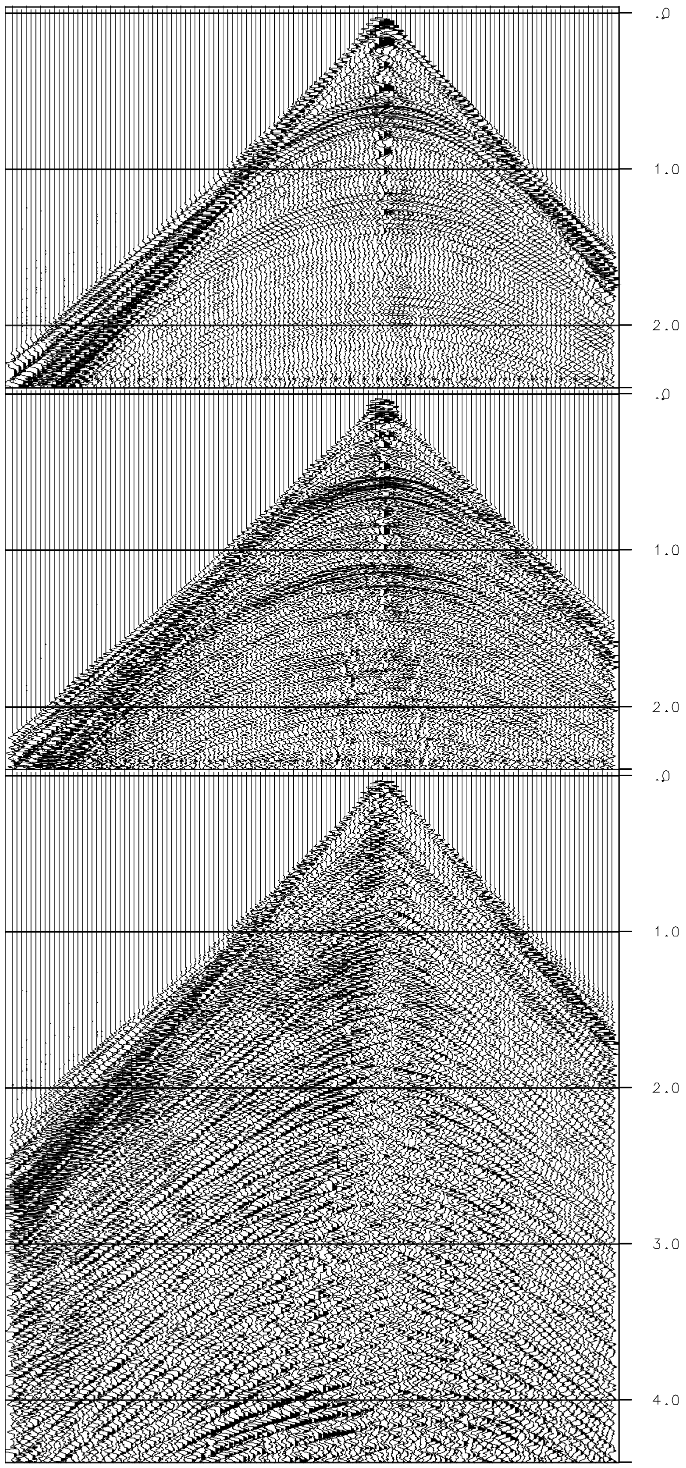

Fig. 17 Common receiver panel acquired with 4C OBC technique.