An ambitious 3D land geometry[1]

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This note has been inspired by some recent papers discussing among other things the number of channels that might have to be recorded in future (single-sensor) seismic data acquisition techniques. Along with the subject of maximum number of required channels, this note also addresses some related aspects of seismic data acquisition.

What station spacing do we really need? Current 3D acquisition geometries tend to have very large station spacings, something in the order of 50 or 60 m. Often shot station spacings are even larger. As a consequence, not even the desired part of the wavefield is sampled without aliasing. On the other hand, there is a lot of talk on the use of single-sensor geometries requiring drastically smaller station spacings (the single-sensor hype). This is driven by two main factors: on the one hand a general feel inspired by Ongkiehong that single-sensor recording is the ultimate in seismic data recording, and every geophysicist would like to have it (the WesternGeco push); on the other hand the fact that digital sensors are inherently single sensors, if you want to use them, you cannot do anything else but use single sensors (the I/O and Sercel push). Given this large discrepancy between the practice of large station spacings and the ideal of very small station spacings, we should perhaps try to answer the question: “What station spacing do we really need?”

The changeover from 50-m station spacings to 25 or 20 m in 2D acquisition provided very much improved data in the late 1970’s and early 1980’s. (In 1980, a seasoned interpreter complained to me that his new data was much more difficult to interpret than the old data, because of the extra detail.) The main reasons for this dramatic improvement are: the desired wavefield is finally sampled without aliasing, there is less loss of high frequencies across the arrays, noise removal is more successful in processing than in the field, and there is less effect of intra-array statics. As sampling requirements of 3D acquisition lines are the same as for 2D lines, it may be expected that reducing the station spacings to 25 or 20 m would give a similarly large (and in most cases sufficient) improvement in data quality. (In marine data acquisition, the benefit of smaller spatial sampling intervals has already been amply demonstrated.) In areas with little ambient noise and little shot-generated noise the smaller station spacings might be implemented with single sensors, especially if these are 3C and allow similar noise reduction (using adaptive filtering) as achievable with arrays of coil geophones. However, in most areas single sensors would have to be spaced at much smaller intervals to be able to cope with shot-generated noise. Moreover, ambient-noise suppression also benefits significantly from the use of a larger number of geophones. This means that the old-fashioned use of strings of coil geophones in 20-m arrays might be the most cost-effective, while being fit-for-purpose, solution.

The nominal geometry. Let us assume a deep target for which something like 5000 m absolute offset would be desirable. However, to be on the safe side, we select a maximum inline offset of 4000 m, and also a maximum crossline offset of 4000 m (this provides a maximum absolute offset of $4000\sqrt{2} \approx 5660$ m). There is no important shallow target, nor the need to use a shallow horizon for statics determination, so the acquisition line spacings may be relatively large, say 400 m (for shot line interval and receiver line interval). This prescription leads to a maximum fold of the survey of (area of cross-spread / area of unit cell) = 4000 x 4000 / (400 x 400) = 100.

For optimal ground-roll suppression we select a combination of linear shot and receiver arrays with length = 20 m. The element interval should be close to the sampling interval required for alias-free sampling of the ground roll; this might be 4 m. However, to ensure sufficient random-noise suppression perhaps 6 rather than 5 geophones per station would be more appropriate (moreover, the industry seems to like multiples of 6). So, the distance between the elements in each array should be 20 / 6 = 3.3 m. The shot array should be similar to the geophone array.

(In the May 2004 feature “Expert Answers” of the CSEG Recorder two experts are asked about their opinion on digital phones. In his answer Tessman extols the virtues of using digital 3C sensors without any arrays. I do not agree with his argument that “linear arrays provide at best some statistical protection against ground coupling variations and deployment tilt errors”. Although field arrays are far from ideal spatial filters, the combination of linear shot arrays and linear geophone arrays should achieve at least 20-dB ground-roll suppression.)

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Having decided on the main parameters of the survey, we can now compute the number of stations and geophones that is required for a one-line roll template (Figure 1a). The template has 20 receiver spreads with length 8000 m, i.e., the total number of active channels is 20 x 8000 / 20 = 8000. This is not even an order of magnitude more than in most current surveys, just a doubling or trebling. The number of geophones in the template would be 6 x 8000 = 48000.

Variations on this base case can go two ways: for an exploration-type 3D survey it might be justified to enlarge the line intervals to perhaps 800 m. In that case total fold reduces to 25, the number of receiver lines in the template to 10, and the number of channels in the nominal template is halved.

The other way is that there is not only a deep target, but that there is a shallow target requiring large fold as well. In that case the acquisition line spacing may have to be reduced to 200 m (in the extreme case). This would lead to 400-fold data at the deep target, to 40 receiver lines in the template and a doubling of the number of channels and geophones from the base case. In this extreme case the total number of active channels in the nominal template is 16000.

Dealing with curved acquisition lines. Often, the acquisition lines have to be shifted (in a smooth way to prevent spatial discontinuities) from their nominal position, and locally this may lead to irregularities in the fold-of-coverage. Most if not all 3D surveys are acquired without any redundancy in the template (if a one-line roll template is used). It would be much more convenient and prudent to always sample a longer spread than the nominal spread. Assuming that a shift of the acquisition line to the right or to the left of more than 3/4 of the line interval is not acceptable nor anticipated, the spread has to be enlarged with 300 m to either side (in my base case), adding 30 channels and 150 geophones to each receiver line, or with 20 lines this would lead to 600 extra active channels and 3600 extra geophones for a total of 8600 channels and 51600 geophones. This approach allows the processing centre to use all redundant data for prestack processing purposes followed by reduction of the data set to the nominal, regular fold-of-coverage.

Of course, for different line intervals, the number of additional channels will be different.

Implementation of the nominal geometry. Depending on the logistics of the survey (type of source, type of terrain), the nominal geometry defined as the one most suited to solve the geophysical problem and succinctly described by the nominal template, may be acquired in many alternative ways.

One quite interesting alternative way is to enlarge the template with a number N of additional receiver lines, and to increase the length of the shot salvo with as many receiver line intervals (Figure 2a). Rather than using a crossline roll of one receiver line, this set-up allows a crossline roll of $N + 1$ receiver lines. All data defined by the nominal template are acquired in this way plus some redundant data which can be thrown out in processing. Note that this set-up is different from the N-line roll often carried out by using a shot salvo of N receiver line intervals, but without increasing the number of receiver lines (Figure 2b). The latter type of rolling produces higher production at the expense of quality and should not be encouraged. The former type of rolling can also be more efficient than the one-line roll, without bringing the data quality in jeopardy. This type of modification would be particularly useful if channel availability is larger than the needs of the nominal template.

A more common alternative is the full-swath roll (Figure 1b). The full-swath roll is characterized by long shot lines extending outside the swath of receiver lines on both sides. If done properly the extent of the shot line outside the swath equals the intended maximum crossline offset, thus ensuring that all cross-spreads acquired with this template can be trimmed to have a positive and negative maximum crossline offset equal to the intended maximum crossline offset. After inline rolling over the width of the survey has been completed, all data for these receiver lines have been acquired and the whole swath of lines can be moved to the adjacent position. This acquisition technique tends to be quite a bit more efficient than the one-line roll of the nominal template. With vibrators, it is more efficient because it involves far less turns of the heavy trucks; with dynamite acquisition many shooting crews can work on the same acquisition line simultaneously. With this technique more data are acquired than specified in the nominal geometry. Initially, these data can be used in prestack processing, to be discarded later to avoid serious acquisition footprints. The shot repeat factor of the full-swath roll depends on the number of receiver lines in the swath NL, on the maximum crossline offset $X_{\max,x}$, and on the receiver line interval RLI: $S_{\text{repeat}} = (2 * X_{\max,x} + (NL - 1) * RLI) / (NL * RLI)$. For the nominal geometry with 20 receiver lines discussed above, and taking now 15 receiver lines instead $S_{\text{repeat}} = 2.267$. For 19 receiver lines, the shot repeat factor would be exactly 2. Note that the additional shots that might be required in case of curved receiver lines are acquired per definition for the inner receiver lines. In case one or both outermost receiver lines are curved inward, some extra shots can be acquired for regular fold. Compensating for curved receiver lines is much more difficult for the nominal template.

The next step. The old-fashioned technique of using strings of coil geophones might still be the most cost-effective way of acquiring high quality data. The quality might be improved even further by using single sensors, such as the single coil geophones in WesternGeco's Q-Land system or Sercel's digital phone DSU1. For optimal ground-roll suppression, the "adequate" sampling interval should preferably be used. This sampling interval is not as small as necessary for sampling of ground roll without aliasing, but it allows noise removal without hurting the signal. If this sampling interval is used, three sensors may be needed for every 20 m, i.e., three times as many channels as in the example used above. Even more improvement in quality might be obtainable using 3C MEMS-type sensors, such as Input/Output's Vectorseis units with three sensors each. This would require 9 times as many channels.

Even though digital cables are much lighter than the now obsolete analogue cables, the weight of cables is considerable and forms an important cost factor in seismic operations. The new technique of collecting the signals from a limited number of channels by a remote acquisition unit (RAU), which transmits the signal to one of many cells in a wireless telephone-type system, may require less total weight. The cables needed in this system are those connecting the geophone strings to the RAU's and fibre-optic cables for transmission of all data from the cells to a central recording unit. This system is offered by Vibtech. It would be interesting to see a weight comparison of this system with conventional telemetry systems for the base case discussed in this note.

Sources. In parallel acquisition geometry, the source interval might be chosen larger than the receiver station interval provided noise removal can be carried out successfully in the common shot gathers. A few papers have demonstrated the benefit of very fine sampling of the hydrophones in a streamer while keeping the shot interval in the order of 25 m. However, this does not apply to orthogonal geometry. In orthogonal geometry shots and receivers play completely complementary roles: what is required for sensors in the inline direction, is also required for shots in the crossline direction. Therefore, the 20-m station interval used for the receivers should also be used for the sources.

Dynamite. There are two schools of thought about dynamite shots. In large parts of the world, deep shot holes in the order of 30 m seem to be the rule. The advantage of deep shot holes is that much less ground roll is generated in general. This reduces the need for small station intervals and also the need for arrays. Therefore, the combination of deep shot holes with single-sensor recording is probably the most feasible land data acquisition technique with MEMS-type sensors. A serious disadvantage of deep holes is the large cost of drilling such holes. Often extra strong (hence heavy) drilling units are required to reach the required depths.

However, there are also many proponents of shallow-hole dynamite arrays. A disadvantage of shallow arrays is that they tend to produce more ground-roll energy than single deep holes, despite the array effect. On the other hand shallow dynamite arrays tend to be less expensive than single deep holes, and lighter equipment can do the job. If an area can produce good quality seismic data with surface sources such as vibroseis, then I do not see the need to use deep shot holes when using shallow dynamite arrays may be just as good or even better.

Vibrators. With a 20-m station spacing, not more than two vibrators can be used for a single shotpoint, because of the physical size of the units (unless an areal array can be used). The base plates of the two vibrators should be kept at a distance of 10 m. The first sweep is followed by two times a move-up of 3.3 m to make up a 6-element shot array that is the same as the 6-element geophone array.

Often it may be necessary to supplement the vibrator points with shallow-hole dynamite arrays in places where the vibrators cannot go, but dynamite crews can.

Weight drops. The old-age technique of weight-dropping has recently been rejuvenated. A new weight-drop system has been developed that is controllable and can exert a considerable force. From Monk et al.: "We have examined a new source unit (the "Explorer 860") and used it to acquire a significant area of 3D seismic. The new source has the capability of generating a very large surface impact, with a very high degree of repeatability, but is also controllable so that the impact effort can be reduced if required. This control can help minimize ground roll generation and improve the resultant seismic data." Each weight-drop unit is much smaller than a vibrator and is also much cheaper. To me this seems to be a very serious candidate for efficient data acquisition using small station intervals at low cost. If the technique proves to be effective also for deep targets, it might even replace vibrators completely. A fleet of tens of these systems might make data acquisition nearly continuous. A small disadvantage of the system is that the energy of the first drop tends to consolidate the soil beneath the base plate such that there is a timing difference between the first and subsequent shots in the same location. In other words, the first shot should not be recorded.

Geometry in areas with much scattered-wave energy. The nominal geometry discussed above is not optimal for areas with much scattered-wave energy. The combination of linear geophone arrays and linear shot arrays does a reasonable job for direct-arrival ground roll, and even for the flanks of the scattered-wave traveltime surfaces, in particular in combination with 3D *fk*-filtering. However, the apices of those traveltime curves are not suppressed. The energy in the apex of a scattered traveltime surface has traveled perpendicular to the shot line from shot to scatterer and perpendicular to the receiver line from scatterer to receiver, hence it has traveled perpendicular to both linear arrays, which have not suppressed this energy. If the problem is serious (like in many areas in the Middle East), areal receiver arrays and/or shot arrays may have to be considered.

Obviously, the areal array has to exploit the time difference of the scattered wave across the width of the array. However, this array effect cannot be supplemented by the effect of 3D *fk*-filtering, because the scattered event is horizontal in the cross-spread domain. Hence, the suppression has to come entirely from the array effect (and from stacking). The wider the array the larger the time difference across the array. The question is then what width of an array is still acceptable given a certain station interval, say 20 m. The reasons for using a small station interval would be defeated by too large a width of the array. Should the intra-array statics not be a real problem, then the width of the array might be at most twice the station interval. (The justification for this limit is that the first notch of a linear-array response is located at $2k_N$. To obtain noise suppression at k_N, a two-trace running mix can be applied. Effectively, this increases the length of the array to twice the station interval.) For serious intra-array statics, a compromise must be found, perhaps by selecting a smaller width of the arrays, while also relying on fold to suppress the unwanted noise.

If everything else fails, a final remedy against side-scattered noise is to use “fat” acquisition lines. Each fat line may consist of three or more closely spaced receiver lines, each one with its own arrays. This will allow the removal of the scattered noise using some kind of beam steering technique. An alternative technique would be the use of an areal shot array combined with single receiver lines, while recording each element of the shot array separately. In this way, the number of required channels is not increased, but acquisition time is.

Assuming that a geophone array can be replaced by three 3C sensors spaced at 6.7 m, and that 3 closely spaced receiver lines are sufficient to suppress the scattered noise, the 400-fold template discussed above (200 m line intervals, 4000 m maximum offsets) would need about 450 000 channels. It is virtually inconceivable that this number of channels can be deployed economically. In other words, arrays of coil geophones are here to stay.

Areal geometry. In some areas single deep shots may be the only (true or perceived) way of acquiring good quality seismic data. Because of the cost of these shots, there is a tendency to use source-point intervals that are larger than the receiver-station intervals. Various shaky arguments (such as “strike direction does not need equally dense sampling as dip direction”) are used to justify the use of these larger intervals in the cross-line direction. In orthogonal geometry, the only way of doing things properly is to choose symmetric sampling, i.e, the same station spacings in the crossline direction as in the inline direction. However, there is also a proper way of using a much lower density of source positions.

The proper way is to use areal geometry instead of orthogonal geometry. In this geometry, sparse source positions are combined with very dense receiver stations. The areal geometry that is equivalent (same trace density, same maximum inline and crossline offsets, same bin size) to the base-case orthogonal geometry discussed above consists of sources in a 400 x 400 m grid and receivers in a 20 x 20 m grid. There would be 400 receiver positions in the *x*-direction as well as in the *y*-direction. The template of the areal geometry would consist of a single shot firing into 400 x 400 = 160 000 receiver positions. Note that the equivalent of the orthogonal geometry with 200-m line spacings would show a 200 x 200 m source grid but no increase in the number of required channels.

The deep shots should be deep enough not to generate ground roll. If the energy of surface scatterers is small, then point receivers (single or bunched geophones) may be used in this configuration. The number of 160 000 channels may be beyond the horizon, but compromising a little bit on maximum offset, say 3000 m inline and crossline, and on receiver station interval, say 30 m instead of 20 m, leads to a maximum of 40 000 channels. That number may be on this side of the horizon.

Conclusions. For all practical purposes the number of channels maximally required for an ambitious acquisition geometry is in the order of 17 000. This supposes the use of conventional arrays of coil geophones. Even more ambitious would be the use of 3C MEMS-type sensors. This might require in the order of 150 000 channels for the same problem. However, the required number of channels can be reduced by selecting a full-swath roll acquisition technique, in which case the number of receiver lines in the swath can be chosen smaller than in the nominal template.

Source station intervals should be the same as receiver station intervals when using orthogonal geometry. A promising non-expensive source is the improved weight-drop system.

The mixing of signals using arrays can be avoided by using single sensors. However, the single-sensor technique is only economically feasible in low-noise situations. These situations may be created in some areas by using deep shot holes. In other areas, the required number of single-sensor units would be cost-prohibitive. It has not been shown yet, and it is unlikely that it can be shown that adaptive filtering of sparse 3C sensors can replace the use of dense arrays of coil geophones in areas with a serious noise problem.

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Suggested reading. On (future) developments in acquisition technology: papers by Heath and by Mougenot in First Break, February 2004. On vision on single-sensor recording: Ongkiehong, First Break, September 1988. On “adequate” sampling interval: Baeten et al, 2000 SEG Convention. On the future of digital geophones: Expert Answers by Tessman and by Cooper in CSEG Recorder, May 2004, and Mougenot and Thorburn in The Leading Edge, March 2004. On adaptive filtering with 3C phones: Tessman et al., 2004 CSEG Convention. On new weight-dropper: Monk et al, 2004 CSEG Convention. On field arrays and 3D acquisition geometries: Vermeer, 2002 (SEG Bookmart). On geophone testing with some fun: Meunier and Menard, 2004 EAGE Conference. On fine receiver and coarse source sampling in streamer acquisition: WesternGeco in First Break, December 2002. On fine spatial sampling in marine data acquisition: Various Expert Answers in CSEG Recorder, June 2004. On beam steering: Özbek, 2000 SEG Convention.

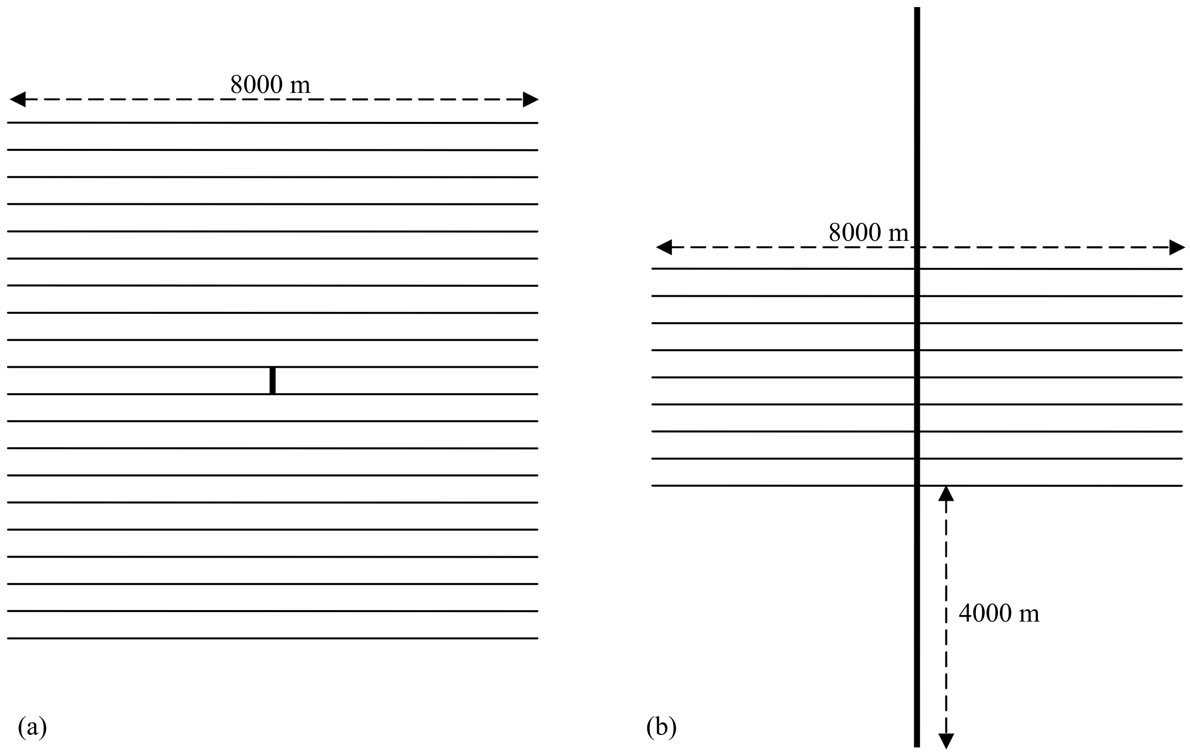

Fig. 1. Symmetric acquisition geometry for deep target. (a) Nominal template consisting of 20 8000-m receiver spreads with 400-m interval. Shot salvo of 400-m length in the centre. (b) Equivalent full-swath roll with 9 receiver spreads and a shot spread with length 8000 + 8*400 = 11 200 m.

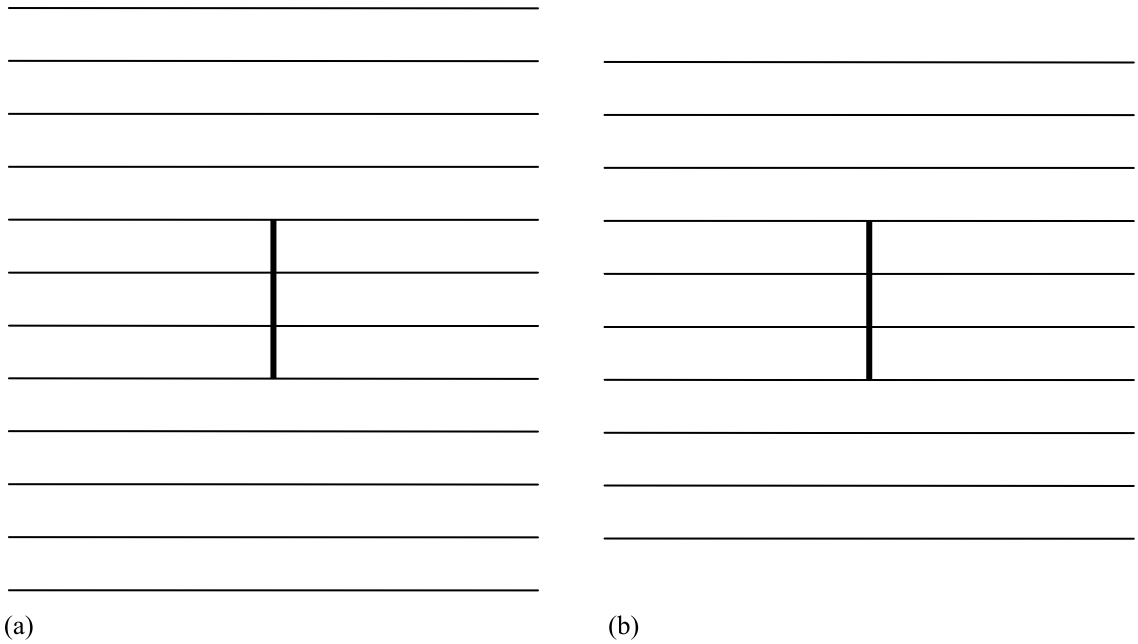

Fig. 2. Multi (3)-line crossline roll implementations. Nominal template consists of 10 receiver spreads. (a) Two additional receiver spreads allow the use of a shot spread consisting of three receiver line intervals. In this case each shot will shoot in at least 5 receiver spreads with positive crossline offsets and into 5 receiver spreads with negative crossline offsets. (b) 3-line roll without any additional receiver spreads. In this case some shots will shoot into only 4 receiver spreads in the positive or negative direction. Of course, the acquired data set can still be regularized by treating it as an 8-line nominal geometry rather than a 10-line geometry.