Discussion and Reply: Introductory remarks for www.3dsymsam.nl

Gijs Vermeer

Strong and Hearn (S&H) (2016) describe survey design for coal exploitation. Not quite a burning subject in this day and age where we want to gradually phase out fossil fuels, beginning with coal. Despite the apparent irrelevancy of the subject, the paper describes 3D survey design for PS seismic data and this is still relevant for hydrocarbon exploration.

The paper takes into account the asymmetry of raypaths that consist of P down and S up. However, it does not take into account how this property translates into different properties of the various sparse acquisition geometries that may be used in 3D seismic land surveys: orthogonal geometry, areal geometry with sparse receivers or areal geometry with sparse shots. My comments are meant to review those properties and to show their significance for 3D seismic survey design for PS acquisition. A kind of tutorial.

In the discussion I refer to quite a number of figures in the S&H paper. For a better understanding I recommend to download a copy of the S&H paper; otherwise my text is difficult to follow. I also refer to Figure 6.7 taken from Vermeer (2012). It is shown below.

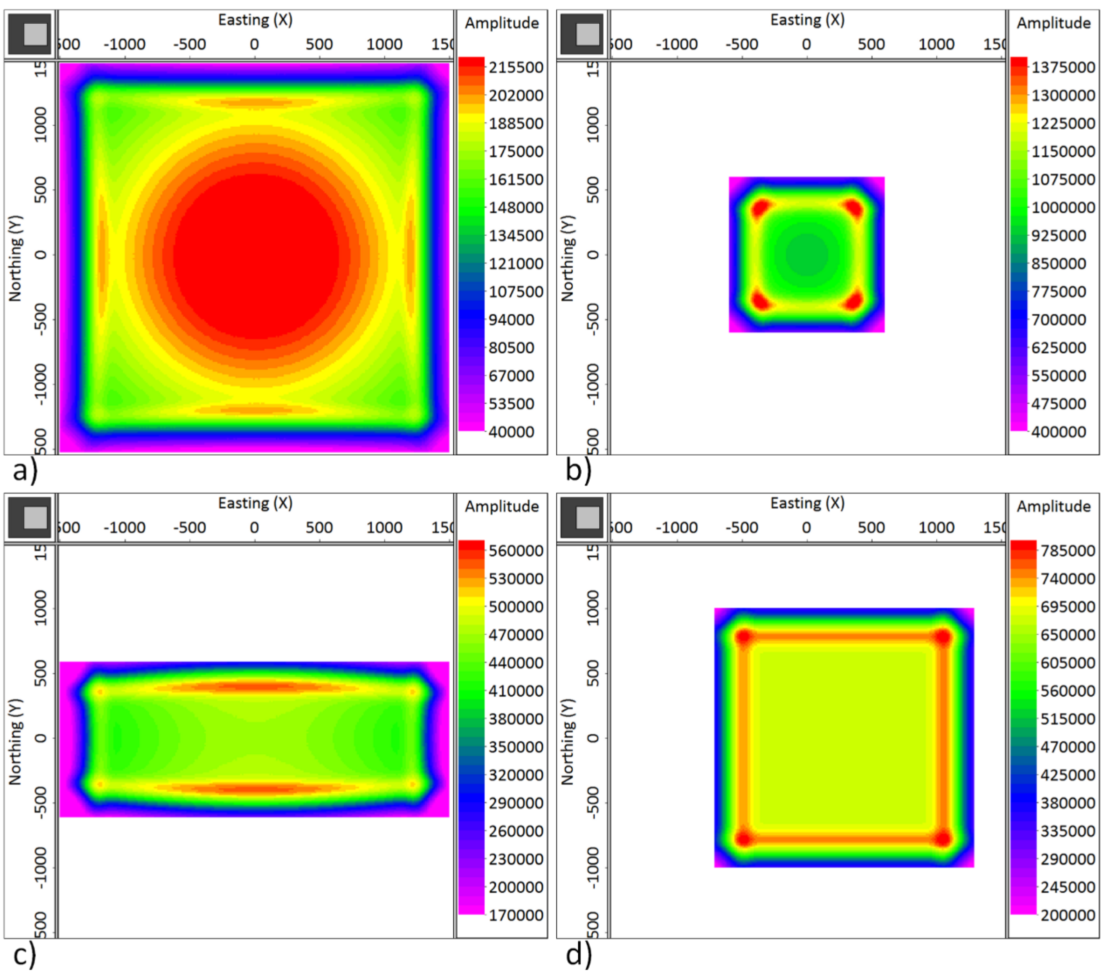

Fig. 6.7. PS-wave imaged horizon slices for various minimal data sets in a constant-velocity medium with $V_P/V_S = 2$ and a horizontal reflector. (a) 3D shot, (b) 3D receiver, (c) cross-spread, (d) COV gather with (h_x, h_y) = (750, 0) m. The midpoint areas of all four data sets are the same. The 3D shot is the basic subset of areal geometry with sparse shots and dense receivers, 3D receiver of areal geometry with sparse receivers and dense shots, and cross-spread is basic subset of orthogonal geometry.

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Discussion and Reply

Comment on: "Survey design for coal-scale 3D-PS seismic reflection" (S. Strong and S. Hearn, Geophysics, 81, no. 6, P57–P70)

Discussion by Gijs Vermeer[1]

Three-dimensional survey design for PS data is more complex than for P-wave data; therefore, I was particularly interested in this paper to see how the authors solved their specific problem. In the following, I make a few suggestions for improvement of the PS design process and I explain how some of the analysis results given in the paper can be better understood.

In the paper's abstract, the objectives of the design are described as "acceptable fold balance between bins and relatively smooth distribution of offset and azimuth within bins." ("Smooth" is a somewhat strange property when describing the distribution of discrete shot-receiver pairs in bins, but the authors apply a smoothing filter during their bin analysis). The authors also aim for "even" (P58l [Pxxl, Pxxr refer to page number Pxx, left column, right column, respectively]) or "regular" (P58r) distributions of offset and azimuth. Certainly, the bin attributes do say something about the quality of the design, but judgment of this quality is not straightforward. Consider "Although offset-azimuth distribution is not as smooth as for the higher density designs, it is acceptable," (P66r); the authors do not clarify why it is judged as acceptable. Of course, all survey design requires some judgmental reasoning at the end, open to change, but the differences between the PS results shown in Figures 8 and 11 are so large that the conclusion "acceptable" for the Figure 11 design would deserve a more clear explanation.

Another problem of focusing the design process on only bin attributes is that there is no attention for the choice of bin size or station interval and corresponding ability to deal with noise. Also, the suitability for prestack migration needs attention for bin size and for sparsity of the geometry. How to go about this?

Usually, in "conventional survey design" (Vermeer, 2012), dense sampling is selected for two of the four spatial sampling intervals for any type of acquisition geometry. These two intervals determine the sampling of the 3D basic subsets of each geometry. The other two sampling intervals determine the sparsity of the geometry. For instance, in orthogonal geometry, the 3D subset is the cross spread and the dense sampling is along the receiver lines and the shot lines, whereas the sparse parameters correspond to the line intervals. In areal geometry (also called nodal or grid geometry), the shots are sampled sparsely and the receivers densely leading to densely sampled 3D shot gathers as shown in Figure 10 of Strong and Hearn (2016) or the receivers are sampled sparsely and the shots are sampled densely leading to densely sampled 3D receiver gathers as shown in Figure 9.

The densely sampled spatial intervals also determine the (natural) bin size of the geometry, whereas the sparsely sampled intervals determine the size of the offset-vector tiles (OVTs) used in migration and other processing steps.

If the 3D subsets are sampled densely enough, then those subsets are eminently suited for noise suppression, especially for coherent noise such as ground roll. This should also apply to coal-seam surveys (although the rapid variation in amplitudes at small traveltimes offers an extra challenge). The authors show that the usable offset range is severely limited by the presence of noise at the short offsets, whereas the largest offsets that can be used are limited as well. Yet, they accept the small usable range as a matter of fact. Instead, I suggest that survey design should tackle this serious problem by selecting the two dense sampling intervals such that noise is recorded without aliasing and can be removed or at least suppressed significantly in processing. The required sampling interval depends on the apparent velocity V_N of the noise (approximately 1040 m/s for the most conspicuous noise event shown in Figure 5a) and on the maximum frequency of the noise. The authors do not discuss how to choose sampling intervals, apart from some words on choosing bin size in relation to the selection of a smoothing filter for bin-attribute analysis: "If we assume … and dominant frequency of 100 Hz, a smoothing radius of 10–15 m appears reasonable. This then provides a guide for choosing bin sizes" (P66l). (The formula to arrive at a radius of 10–15 m is not specified). For a dominant frequency of 100 Hz, the maximum frequency $f_{\max}$ would be approximately 200 Hz, so that alias-free sampling of the noise would require a sampling interval $\Delta x = V_N/(2f_{\max}) = 1040/400 = 2.6$ m, if this maximum frequency would also appear in the noise. The actual maximum frequencies of noise and signal are most likely much smaller than 200 Hz based on the inspection of Figure 5a. However, to determine realistic maximum frequencies and minimum apparent velocities of signal and noise, the survey designer should make and interpret f-k spectra of some representative densely sampled shot records. Next, the required sampling intervals can be determined.

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The smallest sampling intervals in x and y or bin size also influence imaging quality. For imaging, the required bin size $b\,(=\Delta x/2)$ is often determined using the formula $b_{x,y} = V_{\text{int}}/(4f_{\max} \sin\theta)$, where V_{int} is the interval velocity at level of interest (in which the interval velocity, P, S, or some average of these two, depends on the selected geometry/3D subset), $f_{\max}$ is now the maximum frequency of the signal, and θ is the maximum angle used in migration (usually 30° for small dip angles). So, to ensure that the data may be correctly migrated, an adequate choice of the smallest two sampling intervals requires knowledge of the maximum frequency of the signal. The smallest of the two Δx's found for noise suppression and for migration should be selected to satisfy all requirements.

The choice of the two largest sampling intervals is much more arbitrary. Smaller sampling intervals are always better because they increase the fold and reduce the size of the OVTs. The smaller the OVTs, the more each OVT gather looks like a true common-offset-vector gather, and that reduces the acquisition footprint and migration artifacts. The (geophysically) best choice is of course to choose the largest sampling intervals as small as the smallest ones, but that is not normally an affordable choice.

The choice of acquisition geometry is also important for 3D PS-surveys because the asymmetry of the raypaths causes differences in the illumination areas of the various 3D basic subsets. (The illumination area is defined as the area on a reflector covered by the reflection/conversion points of the various shot-receiver pairs in the 3D subset). Those illumination areas can be smaller or larger than the midpoint areas of the subsets. The 3D shot gathers have the largest illumination area because the PS conversion points are located away from the shot closer to the receivers; whereas, the 3D receiver gathers have a much smaller illumination area. In orthogonal geometry, the illumination area of the cross spread is compressed in the crossline direction and expanded in the inline direction, whereas the illumination areas of the 3D shot and 3D receiver have no preference for x or y. Imaging the single-fold illumination areas produces image areas that are larger for 3D shots than for 3D receivers (Vermeer, 2012, Figure 6.7).

The nominal fold-of-coverage of the areal geometries of Figures 9 and 10 is 25 in the 7.5×7.5 m natural bins (fold in x = fold in $y = 300/60 = 5$; 300 m = the maximum inline and crossline offsets). With analysis bins of 15×15 m, there are 100 traces in each such bin. In the top-right figures, we see only 25 colored clusters because the four traces from each 3D subset that end up in the analysis bin have offset-azimuth values that are close enough to merge into one cluster.

The difference in PS illumination between the 3D shot gathers and 3D receiver gathers is responsible for the difference in bin attributes found between Figures 9 and 10. Figure 6 may be used to derive the size of the illumination areas for the 3D shot and the 3D receiver. For $z = 100$ m and $x_o = 300$ m, $C = 0.8275$ for $\gamma = 2$ so that $x_p = 248$ m. In the 3D shot, this is the maximum extent of the conversion point from the shot in the x- and y-directions, thus producing an illumination area of approximately 496×496 m. There is a shot every 60 m in the x- and y-directions, so that in the full-fold area of the geometry, there are at least $8 \times 8 = 64$ overlapping illumination areas. Because the average distance between conversion points in a 3D shot gather is approximately 12.4 m, each one of the 64 overlapping areas provides at least one conversion point in each 15×15 m analysis bin. Indeed, the offset-azimuth plots for $\gamma = 2$ in Figure 10 show at least 64 color clusters, each one corresponding to another 3D shot.

On the other hand, the maximum extent of the 3D receiver is only $300 - 248 = 52$ m in the x- and y-directions giving a total illumination area of approximately 104×104 m. With the receivers in a 60×60 m grid, there are maximum four overlapping illumination areas for the geometry of Figure 9. Indeed, in the offset-azimuth plot of Figure 9, there are four color clusters, one for each illumination area. Some clusters are fairly large because of the large number of conversion points that can be present in a 15×15 m area.

The larger area illuminated by a 3D shot than by a 3D receiver means that the 3D shot geometry provides more subsurface information than the 3D receiver geometry, and an areal geometry with sparse shots is indeed to be preferred over an areal geometry with sparse receivers. Yet, it should be realized that proper imaging of 3D shot gathers requires smaller sampling intervals for the receivers than those required for the shots in the 3D receivers. The reason is that the diffraction traveltime surfaces used in prestack migration of 3D shots are determined by the S-wave velocities, whereas those used in prestack migration of 3D receivers are determined by the P-wave velocities.

In the best areal geometry, the whole survey area has to be covered densely with receivers and sparsely with shots. Areal geometry is usually much more expensive than orthogonal geometry with the same bin size and the same sparsity. Yet, for very shallow targets as in this case, the savings in cost of shots may compensate to a large extent for the extra expense of the receivers while producing the best illumination coverage for PS data.

The base case of Figure 7 has equal sampling of all four spatial coordinates. This would be the ideal choice of parameters, provided that 15 m allows for alias-free sampling of the whole wavefield. If a 15 m sampling interval is not small enough, an even better base case might have been considered. The geometry is called orthogonal geometry by the authors; however, because all sampling intervals are the same, this square sampling of shots and receivers does not only allow for the collection of cross spreads from the data (as in orthogonal geometry), but also 3D shots and 3D receivers can be extracted from data with this very special choice of parameters.

The final choice of sampling intervals illustrated with Figure 13 has only one small sampling interval and three coarse sampling intervals. A choice like this does not allow for a well-sampled 3D basic subset. If 15 m is required for alias-free sampling, then this sampling should not be limited to one direction: 3D acquisition requires proper sampling in x and in y.

In conclusion, suitable parameters for noise removal and imaging cannot be determined by inspection of bin attributes; instead, knowledge of minimum apparent velocities and maximum frequency (of signal as well as of noise) has to be collected first for more confidence in the choice of sampling intervals. Selecting appropriate smallest sampling intervals would allow us to increase the range of usable offsets and would ensure correct migration results. These comments do not by any means describe the full design process but are meant to suggest a line of reasoning that is helpful for an optimal choice of parameters.

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Reply to the discussion

S. Strong and S. Hearn

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We thank Gijs Vermeer for expanding on this topic, and we appreciate the additional insight provided.

In the following, we restate important concepts from the paper and provide additional clarification on specific points.

Our methodology recognizes that practical survey design will invariably involve compromises between geophysical and economic considerations. We believe that plots of fold, offset, and azimuth provide a useful visual indication of the effect of relaxing ideal design parameters. Vermeer correctly observes that such plots are based on discrete shot-receiver pairs. It is true that in raw form, these plots can be complex and misleading.

One way to improve the validity of this type of presentation is to allow for the smoothing effects of limited bandwidth. In our paper, we have followed the spatial filtering approach of Cary and Lawton (2003). This yields distributions that are generally simpler and arguably more meaningful. Of course, it is important to also recognize the dependence of such plots on assumed earth parameters (e.g., P- and S-velocities), particularly in the case of PS modeling. We typically examine a series of plots covering a reasonable range of earth parameters.

We also agree that there is an element of subjectivity in assessing such distributions. However, other factors being equal, we consider that an “even” distribution of fold, azimuth, and offset is more desirable than an “uneven” distribution. The final designs considered for our survey produced distributions (Figures 11, 12, and 13) that were compromises away from the ideal (e.g., Figure 8) but that were considered “acceptable” in terms of the variability in fold, offset, and azimuth.

The specific 3D-PS survey considered here was funded by a research grant, with in-kind contractor support.

The spacings used were accepted as being larger than ideal. Nevertheless, this is quite applicable to coal-industry seismic reflection in which we are often forced to use larger spacings than ideal. Our PS surveys are often done as an extension of a P survey, and parameters may be biased by the demands of the primary exercise.

Unfortunately, receiver spacings are not always designed from first principles, being commonly influenced by client experience and budgets. However, a useful guide for bin sizes, and hence receiver intervals, is provided by the expected resolution limits.

For the 3D survey described in the paper, we have used the equations provided by Chen and Schuster (1999) to deduce a nominal resolution of order 10–15 m at the target depth. We have used this as a guide for designing the receiver interval.

We agree with Vermeer that when compromises need to be made, finer inline spacing is generally more important than crossline. This is especially true in the shallow coal environment and, as pointed out, tends to allow for better coherent-noise removal and improved spatial imaging. Our production P and PS surveys generally do use spacings that are finer in the inline direction and sparser in the crossline direction. For the particular survey discussed in the paper, one of the primary goals was to investigate the influence of azimuthal variation on the seismic data. The reduced crossline spacings used were aimed at improving azimuthal distributions in the raw data.

Despite the design constraints, this survey provided a data set that enabled the overall project goals to be achieved.

Again, we thank Vermeer for his insightful contribution to this topic.

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