A world of reality—Designing land 3D programs for signal, noise, and prestack migration—Part 2

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This article is the continuation of a two-part tutorial. The first part (October, 2004) reviewed methods of estimating signal and understanding noise in a given project area, discussed the concepts of trace density and statistical diversity, and addressed concepts in prestack migration. This part begins with a brief discussion of the merits of various model types, which will lead to a discussion of robustness during implementation. The tutorial concludes by suggesting a data simulation method to evaluate the characteristics of a survey design.

3D model types. Much discussion about survey design has focused around the potential advantages of different survey geometries or model types (orthogonals, staggered orthogonals, bricks, diagonals, etc.). When compared using fixed source and receiver densities, Cooper and Herrera (2002) found very little difference amongst many of these variations. By focusing on limited statistics (for example nearest contributing offset in each bin), differences can be presented that favor some designs over others. However, when other statistics are presented (for example, the gap from nearest to second nearest offsets) the preferences often reverse.

I have attempted to study the various common models using more generalized statistics as well as data simulations. The model types were divided into two classes: *orthogonal* designs (rigid orthogonal, offset orthogonal and staggered orthogonal) and *diagonal* designs (double brick, triple brick, skewed diagonals, rotated diagonals). I concluded that there were some clear benefits within each category. The staggered orthogonal design showed less bin-to-bin erratic behavior (refer to the offset homogeneity histograms at the top of Figure 14 and the azimuth homogeneity histograms at the top of Figure 15). Similarly, the 26.56° skewed diagonal design exhibited somewhat better statistics than related brick patterns, but the differences between the best of the orthogonal class (the staggered orthogonal) and the best of the diagonal class (the 26.56° skewed) were very subtle.

This research suggests that there is very little difference between well-designed diagonal and well-designed orthogonal surveys. For similar source and receiver densities, a diagonal survey will require more linear kilometers of access trails and, for this reason, this design is not recommended in areas where a high percentage of access trails must be newly cut. However, if there is a natural diagonal trend to existing trails, then by all means embrace that model. In other words, use the operational efficiency of each design to determine when it is appropriate.

Robustness under perturbation. In addition to studies of these models under ideal conditions, I have also conducted studies on the ability of each model type to retain its desirable characteristics when typical amounts of geometry perturbation are imposed. During implementation of 3D survey designs in the field, geometry perturbations result for many reasons, such as:

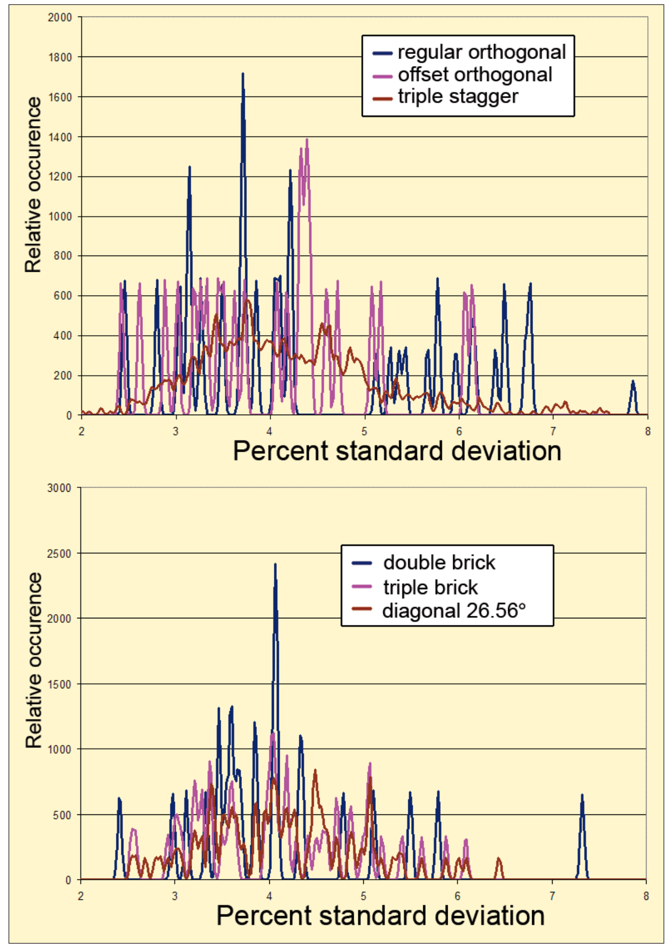

Figure 14. *Offset homogeneity summary. (top) Orthogonal classes: The staggered orthogonal geometry provides less bin-to-bin erratic behavior compared to other orthogonal classes. (bottom) Diagonal classes: The diagonal geometry appears to be less erratic than the bricks. The staggered orthogonal design may be slightly smoother than the diagonal design and offers slightly better offset distribution. However, the differences are subtle.*

- requirements to use existing access trails where feasible
- skids and offsets of source points due to wells, buildings and pipelines
- lakes and rivers
- steep cliffs or other topographic constraints
- parks and restricted areas
- permit lockouts
- many other operational considerations and obstacles

My studies have indicated that statistical distributions of well-designed orthogonal models tend to be more robust when subjected to typical perturbations than those of diago-

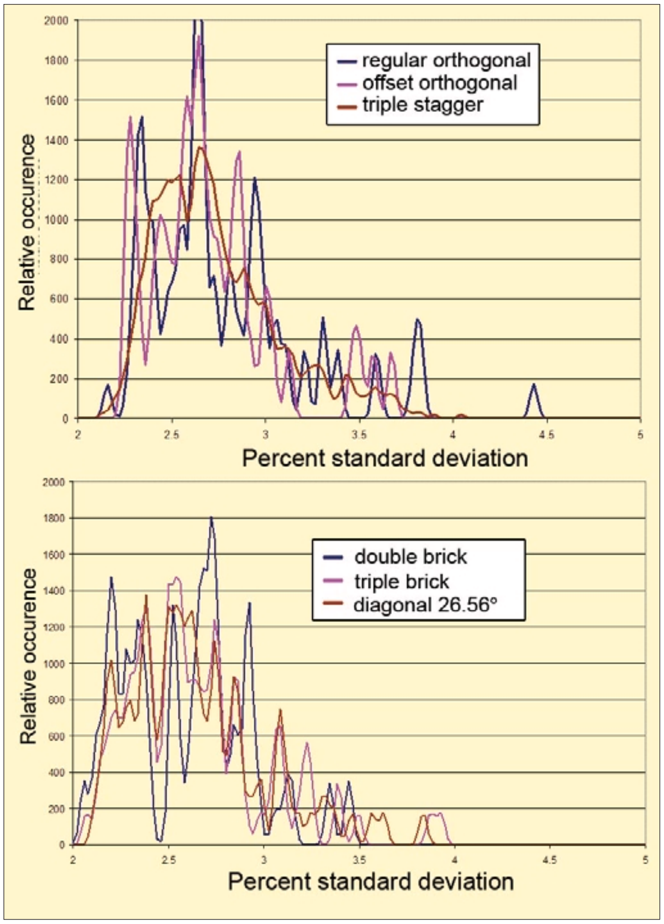

Figure 15. *Azimuth homogeneity summary. (top) Orthogonal classes: The staggered orthogonal design provides less bin-to-bin erratic behavior compared to other orthogonal classes. (bottom) Diagonal classes: All diagonal classes exhibit some erratic bin-to-bin behavior. The staggered orthogonal geometry is slightly smoother than the diagonal geometry. Once again, the differences are subtle.*

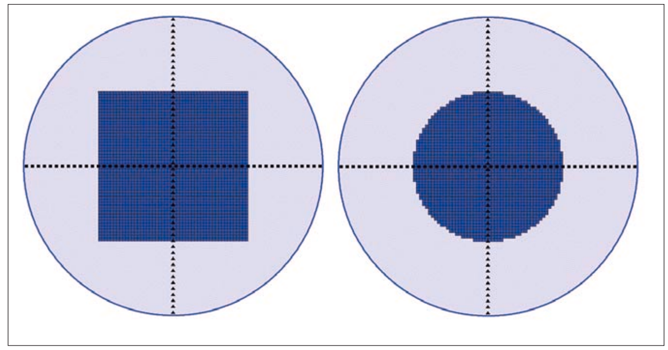

Figure 16. *Crossed-line 3D model. A line of shots, recorded by an intersecting line of receivers will create a subsurface area of one-fold coverage. Near offsets cluster near the intersection. Longer offsets will form progressively larger rings centered on the intersection. The figure on the left shows the result of finite length lines with no offset limits. The figure on the right depicts the coverage expected for a limited range of offsets. In the subsurface, the radius of this circle will be one half of the maximum useable offset.*

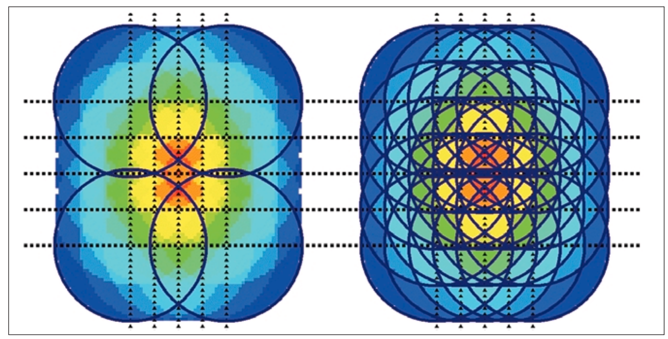

Figure 17. *Many intersections provide overlapping fold. Each intersection produces a one-fold circle of coverage. Many adjacent intersections produce overlapping coverage. Bins near centers of circles are near offsets; bins near edges of circles are far offsets.*

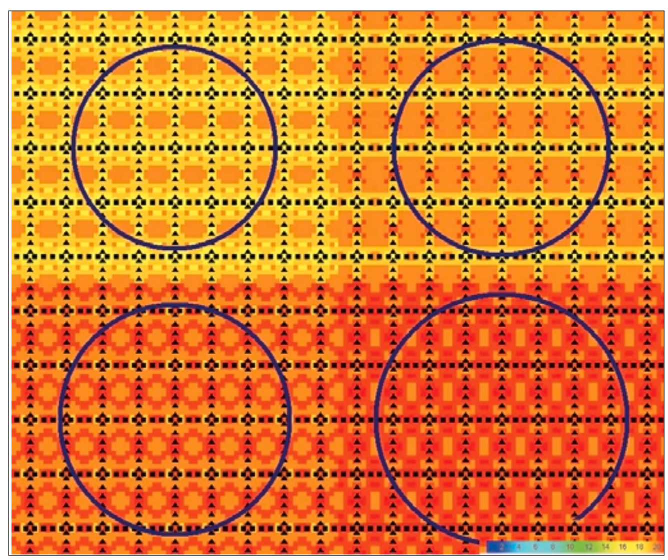

Figure 18. *Fold variations due to changes in mute. In this diagram, the grid and recording patch are constant throughout the survey. However, the maximum offset limit (mute) is varied. Top left = 1440 m; top right = 1470 m; bottom left = 1500 m; and bottom right = 1530 m.*

nal surveys. One explanation for this observation involves the application of Gjis Vermeer's crossed-line model to evaluate fold, offset and azimuth statistics. Figure 16 introduces this concept. Using these simple building blocks, one can construct a 3D survey consisting of many intersections by using a grid of lines (such as in Figure 17). The amount of fold accumulated will depend on the radius of the circle (related to maximum useable offset) and the density of intersections (grid density). This analysis leads to the same equations for fold presented in Part 1 of this tutorial.

Geophysicists embroiled in discussions regarding the merits of orthogonal versus diagonal surveys often use geometric imprinting as evidence of the superiority of one model versus another. Geometric imprinting refers to the appearance of strong and weak amplitudes in final processed volumes due to variations in fold, offset or azimuth distributions. Once again, I have found only marginal differences in such observations when comparing well-designed orthogonal surveys to well-designed diagonal surveys of comparable source and receiver density. Model type is not the major factor in patterns of high and low fold.

Of much greater influence on statistical distributions is the offset limit imposed on data. For shallow targets, where the recording patch totally embraces all useable offsets, the useable offset is determined by the data processor's choice of a mute pattern. This is ultimately determined by such factors as target depth, stacking velocity functions (in the case of an automated stretch mute), and modes of noise at far offsets (trapped near-surface waves). All these factors are likely to vary across a given project. Therefore, the effect of a variable mute across a survey program should be anticipated. Figure 18 illustrates the typical changes that may be expected in fold patterns due to four different mutes. Notice that these changes in footprint patterns are much greater than the differences one would expect between model types.

This analysis of sensitivity of fold to variable mute can be similarly extended to offset and azimuth statistics. The study, as presented here, includes only the offset orthogonal model. It illustrates the concept of constructing a 3D survey design by overlapping circular "building blocks" on a regular interval. However, many causes of geometry perturbation listed earlier will result in compression and/or sparsening of grid intersections. Consider Figure 19, which illustrates the fundamental building block for an orthogonal design versus that for a diagonal design. When a grid is perturbed, some intersections move closer together and others are pulled further apart, much like distorting a fishing net. For intersections that are pulled apart, the overlap of the building blocks decreases. The orthogonal models (with circular building blocks) will maintain some robustness for perturbation in any azimuth. The diagonal surveys (with elliptical building blocks) will maintain more overlap than orthogonal designs for perturbation along the major axis of the ellipse, but will be more vulnerable to perturbation along the minor axis. Furthermore, for any given offset limit, the area of a circle will be greater than the area of an ellipse. This becomes more pronounced with increasing skew of the source lines (greater aspect ratio to the ellipse). Therefore, orthogonal models should maintain the integrity of their statistics better than diagonal models when both are equally perturbed. Results of my initial experiments with actual surveys support this conclusion.

Before leaving the discussion of model types, I should briefly comment on so-called megabin surveys. These are basically wide aperture swath surveys. When conventional survey designs result in very small line spacing, the megabin style of shooting is often more cost effective since access trails can serve as both source and receiver lines. The disadvantage of megabin surveys is that they generally do not provide statistical diversity in midpoint scatter. They tend to have highly redundant midpoints, and these tend to be finely sampled in one direction and sparsely sampled in the orthogonal direction.

I have had very good success with megabin surveys in the Michigan Basin and southeast Alberta. The target zones in both of these areas are fairly shallow. Unfortunately, I have seen this technology applied in deeper basins by moving the swath lines far apart. This creates serious undersampling of the wavefield in the crossline direction. Results are claimed to look good, but that may be due to spatial aliasing of crossline complexities, which tends to make reflections look strong and coherent. Time may prove that these interpretations failed to properly image the true geology. I feel the megabin design is an important tool to use where it is applicable. However, spatial sampling requirements should not be distorted in order to justify the use of the tool.

Multiple targets at different depths. How do we approach surveys where multiple target depths vary greatly? I recommend selecting a grid spacing that will deliver sufficient trace density for the shallowest targets. Then, the size of the recording patch should be adjusted to account for the minimum required offsets for the deeper target. Considerations for minimum required offsets may include:

- sufficient NMO for velocity analysis (that is, differential moveout of at least 1.5 times the dominant period of the data)
- sufficient differential moveout for multiple discrimination
- sufficient incident angles for AVO

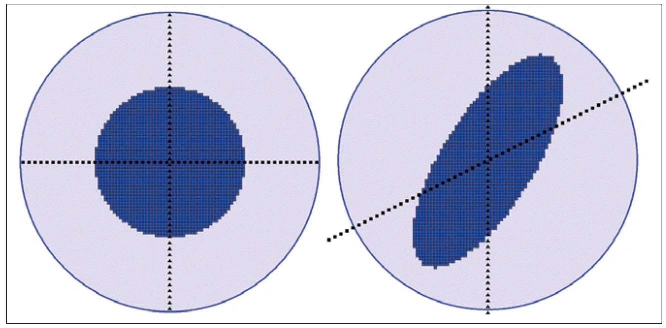

Figure 19. *Survey "building blocks." Statistics for orthogonal surveys are obtained by overlapping circles of coverage (left). For diagonal surveys, the basic building block becomes an ellipse. The diagram on the right is prepared for a 26.57° diagonal design. Diagonal designs with higher angles yield ellipses with much higher aspect ratios.*

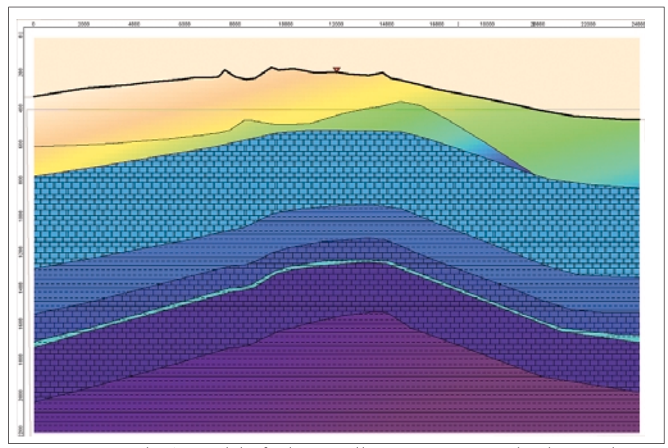

Figure 20. *Geologic model of a large rollover structure. The deepest layer represents a prospective reservoir. The depth at the crest of the structure is about 1600 m, while on the flanks this zone deepens to more than 2000 m. Along strike (perpendicular to this section) there is little expected change.*

- clear observation of refraction breaks to determine low-velocity layer models

Large surveys where target depth changes. Another frequent situation is where a single target is of prime interest, but its depth varies considerably across the prospect. Although this problem is related to the previous one, a modified solution known as the flared grid is recommended. Consider the geologic model in Figure 20. A grid could be designed to achieve a given trace density over the crest of this structure where useable offsets extend to about 1800 m. However, a large survey with such parameters may prove expensive. The outer flanks of the model deliver useable data to offsets beyond 2400 m. The same fold could be achieved with a much sparser (and therefore cheaper) grid as the survey extends away from the structural crest. But then a sparse survey over a large area would do a poor job of imaging the shallow crest. Furthermore, the patch required to capture offsets to 1800 m over the crest of the structure could be narrower, but as we extend down the flanks of the structure, the patch should be enlarged.

The survey design model sketched in Figure 21 could be tailored to meet all these objectives. Note that box area remains small over the crest of the structure and increases with target depth. Note also that a patch with a fixed number of receiver lines will represent a wider patch as the target deepens. A one-sided version of the flared grid can be used in areas where dip increases uniformly in one direction only. I have successfully conducted a considerable number of these surveys. With modern survey methods they are not difficult to implement

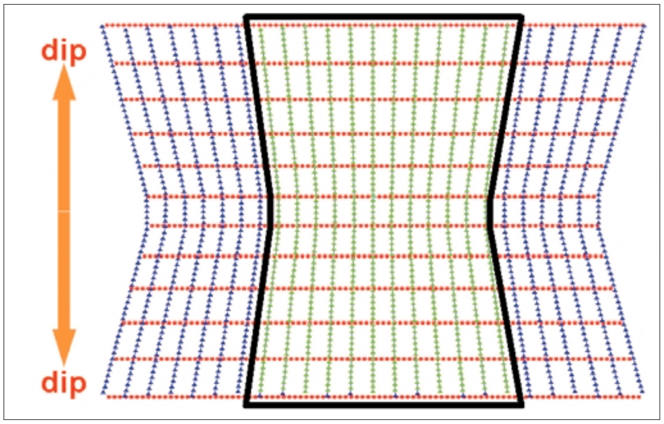

Figure 21. Flared grid model. Receiver lines run across the strike of the structure (in the dip direction). The line spacing is smaller over the crest of the structure and flares outward in directions of increasing target depth. Source lines run along strike and line spacing varies, increasing uniformly with generally increasing target depth.

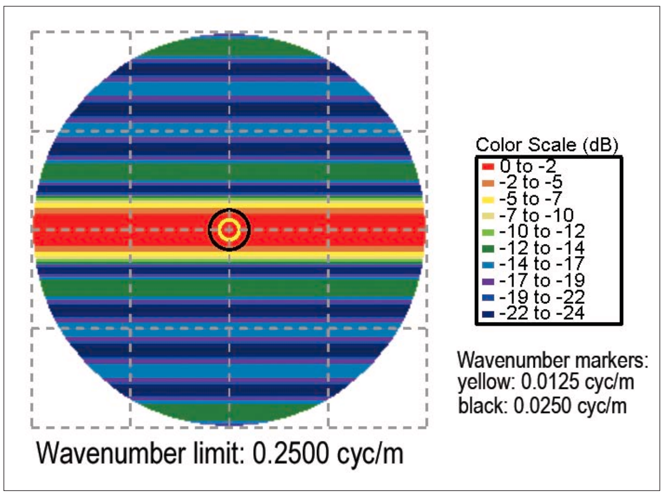

Figure 22. 3D array response for a point source and an array of six receivers laid out uniformly over a 20-m effective length in a north-south direction. Any straight line drawn from the center of the plot to the perimeter will represent the array effect for sound traveling from the source to the receiver array along that azimuth. The wavenumber scale along that radius will be 0 cycles/m (equivalent to infinite wavelength) at the origin and will increase to 0.25 cycles/m (4-m wavelength) at the perimeter of the colored circle. The yellow circle indicates 0.0125 cycles/m (wavelength of 80 m). The black circle indicates 0.025 cycles/m (wavelength of 40 m).

in the field.

The key to successful implementation of flared grids is to ensure that the grid density varies slowly over the project area. The intent is not to change grid density with every mapped high and low on the prospect. Rather, the flare of the grid should only honor very low-order surfaces. Note that a regular bin grid is overlaid on these surveys at the time of stacking. Stacked or prestack-migrated traces will therefore be output to a regular spacing in both dip and strike directions.

Randomization. For environmental survey methods such as LIS (low impact seismic) and surveys in cultured areas, it becomes increasingly important to allow survey models to deviate significantly from any organized grid. I plan to publish a formal presentation of survey randomization in the future. Here, I simply remark that if trace density is appropriate for the target and that statistical diversity is maintained, some degree of randomization should not be feared.

Controlled randomization (that I refer to as pseudo-random) generally maintains one source per planned surface source bin and one receiver per planned surface receiver bin. This type of randomization is quite successful at eliminating geometric imprints and enhancing statistical diversity.

Arrays in 3D programs. In theory, the orthogonal components of source and receiver arrays should have similar filtering characteristics in order to avoid azimuth-dependent filtering effects. In practice, however, single-point sources are often used in combination with distributions of receiver arrays. One possible result is the filter shown in Figure 22.

One philosophy is to shrink the receiver array to a small radius in order to match the filtering (or rather nonfiltering) effect of a point source. However, I prefer to keep the receiver array with an effective length of about one third of the receiver interval. This ensures that the array length is small compared to signal wavelengths of interest. If analog groups of receivers are clustered too close together, the benefit of any array effect is lost, as well as attenuation of random noise due to superposition and the statistical averaging of variable ground coupling. Notice that the potential benefit in signal-to-noise ratio due to superposition of N elements is the square root of N (or in decibels: $20 \text{ Log}_{10} \sqrt{N}$). For just six receivers per group, this results in a potential 7.8 dB gain in signal-to-noise ratio, provided the receivers are distributed far enough apart to be considered in different local noise environments.

In addition, an organized distribution of these elements along a line will create an array effect. Newman and Mahoney (1973) demonstrated that errors in spacing and coupling of array elements reduce the effectiveness of an array. In practical operations, errors in implementation should be in the range of 20%. This would limit the attenuation of short wavelength noise to about 24 dB. The combination of superposition to attenuate random noise and arrays to further attenuate short wavelength noise creates an opportunity to gain some 30 dB in signal to noise ratio.

Consider the example in Figure 22. Experience shows that very few areas yield signal wavelengths shorter than 60-80 m. The vast majority of desired signal wavelengths exceed 120 m. Therefore, the desired signals probably lie inside the small yellow circle at the center of this plot. Red indicates less than 2 dB of attenuation at these wavelengths. And yet short-wavelength noise may be suppressed by up to 24 dB. Only traces with azimuths within about ±10° of the direction orthogonal to the receiver array will not experience some of this attenuation of noise. As long as we are quite certain the signal is safely protected, then to forego this opportunity to attenuate noise seems a bit foolhardy. Keep in mind that to attenuate this noise up to 24 dB is equivalent to a signal-to-noise improvement of about 16. To obtain this improvement by stacking would require a CDP fold of more than 250!

The potential downside to the use of arrays is when topography or very near-surface velocity variations result in different static shifts for each receiver within the group. If the statics are on the order of 2 ms, this will cause a signal loss of about 1 dB at 100 Hz and about 3 dB at 200 Hz. This is not a significant concern. However, if the statics exceed 6 ms, then losses increase to about 5 dB at 100 Hz and more than 12 dB at 150 Hz. Field operations are generally programmed to limit topographic changes across an array. My studies indicate that non-topography-related statics are usually less than about 3 ms.

Data simulation. For sensitive situations where judging the character of noise and determining required trace density is difficult, data simulation has proved a valuable tool. Cooper and Cooper (2001) presented one application of data simulation. Conventional 3D modeling determines which offsets

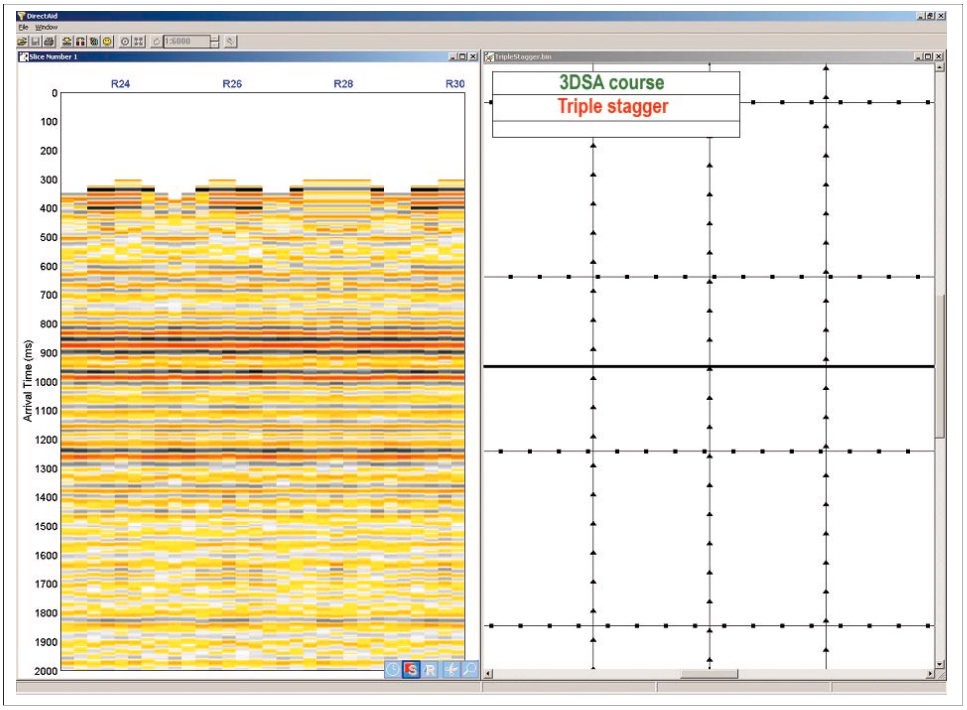

Figure 23. Crossline data simulation. A simulated stacked section for a line running east-west through an orthogonal survey. The line is half way between two source lines. The "noise" evident on the simulated stack is "geometric noise." Each trace is the average of a different collection of offsets.

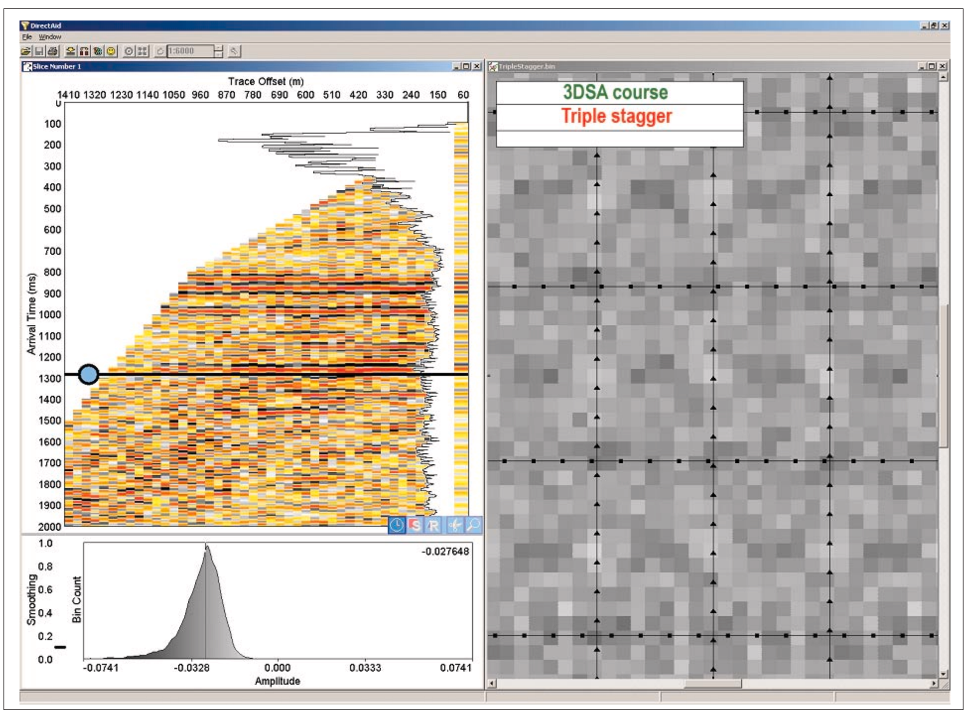

Figure 24. Data simulation time slice. This is a good orthogonal design that shows a fairly stable estimate of reflectivity in all bins.

belong in each bin of a survey. A reference common-offset stack is then selected to represent the data quality in an area. Preferably the common offset stack will be of low fold (so that individual trace noise has not been suppressed by superposition) and will be finely spaced (perhaps from 2D data with a small receiver interval). Specific traces are borrowed from this reference common-offset gather that closely match the required offsets to populate a bin. The traces are then stacked to produce a simulated trace for that bin. The process is repeated for all bins. In this manner, a simulated data volume is prepared that contains no structure or geology (since all traces were borrowed from the same common offset gather). The only differences that will be observed from trace-to-trace can be attributed to the offset heterogeneity of the model. Figure 23 is an example of a simulated crossline.

Another useful display is the simulated time slice (Figure 24). Viewing the simulated data volume at one horizon, gives an estimate of the reflectivity for that horizon. In the simulation, the geology does not change from bin-to-bin, so the reflectivity (amplitude) should be consistent from bin-to-bin. Since each bin uses a different mixture of offsets to average the amplitudes at a given zone, the offset heterogeneity will result in some variation in reflectivity estimates. Since every bin gives a slightly different answer, then the estimate of reflectivity must be formed from some statistics. A good design will result in a nearly Gaussian distribution with a small standard deviation. A poor design will result in a scattered distribution and large standard deviation. In Figure 24, the amplitude for one reflection time is shown for each bin on the right of the display. A horizontal black line on the muted common-offset gather (on the left) indicates the time. The lower left is a density distribution showing that all bins are in reasonably close agreement as to the reflectivity for the considered time. The black curve running up the inside offsets is an indication of the standard deviation of amplitude estimates for each time sample. Note that at shallow times, the standard deviation moves far to the left (large values) indicating that the survey is unreliable for those shallow zones.

Since each simulation is based on a single reference, it is best to test several simulations using good, fair, and poor samples of existing data. Data simulations conducted on final survey data can help calibrate the nature of geometrical imprinting. Simply compare time slices or horizon slices of the final processed data to the time-slice data simulation for the same target. Use common-offset gathers from the processed 3D volume that are near the anomaly of interest.

So far, I have used data simulations to evaluate only offset distributions. However, by using 3D common offsets as a reference, including azimuth effects should be possible as well.

Summary. This summary covers Part 1 and Part 2 of the tutorial. In my survey design approach, little emphasis is placed on bin size. I strongly encourage the use of prestack migration and midpoint scatter to achieve an output trace spacing that is optimal for the local data quality and bandwidth. Rather than fold, I focus on *trace density* (generally normalized to traces/km^2). This allows visualization of the imaging effort as a "point cloud." The geologic nature of the target(s) to be imaged and the character of the noise in the area determine the required density of the point cloud.

Statistical diversity is essential to optimize the information provided by recorded traces. Maximum diversity in source and receiver locations, source-receiver offsets, source-receiver azimuths and midpoint locations is desired. Model rigidity is not necessary, nor is it consistent with the concept of statistical diversity. Geometry perturbations to planned grids are permissible, provided the perturbations continue to enhance diversity and do not result in redundancies of information. In most field operations, planned grids will be perturbed. Guidelines should be made available to surveyors to ensure that survey quality is enhanced by perturbation wherever possible. Chosen survey designs should anticipate perturbation and their desirable qualities must be *robust under perturbation*.

A geophysicist's job is to produce and interpret images of the remote subsurface that are both clear and accurate. Our goal is to assist exploration and exploitation by adding to the understanding of known and potential reservoirs. In a competitive world, we must acquire data at a low cost and in a time frame that does not significantly delay development time from play concept to on-stream production. Therefore, survey designs must *optimize project economics*. The key is to seek the best value. The cheapest cost of acquisition does not provide the best value if it results in images that lead to dry holes. Conversely, survey designs that consistently cost much more than what is necessary should be avoided. If the cost of seismic surveys consistently exceeds their true economic value, then the future trend will be towards less use of the seismic method.

One way to minimize costs is to *optimize field operations*. Seek an understanding of the tools and techniques that are used to produce the survey grid and acquire the data. During the design process, there are several opportunities to accommodate more efficient operations without significantly sacrificing image quality. Balance source and receiver movement by selection of a box aspect ratio within the defined limits. Temper selection of patch width with a knowledge of the movement of recording equipment. Allow the use of efficient survey and line preparation methods by embracing certain forms of perturbations and providing meaningful working tolerances. Where possible, tailor the survey design and choice of model type to *minimize environmental impact*. Encourage designs that allow the use of low-impact techniques. Support development of methods that allow reduced environmental footprint. Once again, embrace and encourage geometry perturbations that avoid locally sensitive areas.

Think of reservoir characteristics as acoustic anomalies that introduce small bumps and wrinkles on a propagating wavefront. These form a part of the wavefield that may appear at the surface as a survey is recorded. These distortions of the wavefield are like pieces of fruit that we are trying to capture. We can often buy fruit in the grocery store that is packaged in plastic mesh nets. Look at the types of nets that are used to contain grapefruit (large mesh). Look at the nets that contain cherries (tighter mesh). Notice that the mesh of each net can be significantly distorted and yet the net still retains the fruit. 3D design requires that we first understand the nature of the fruit we are trying to capture (what is the character of the reflected wavefield?). Then we must select a net with the correct density for that fruit (trace density and statistical diversity). Then we must ensure that net will still retain the fruit when it is stretched, warped, and distorted (robust under perturbation). We must select the right material for the netting and a good manufacturing process (operations, tools and techniques in acquisition). We must take care that the cost of the net does not exceed the cost of the fruit (economics). And we must make the net biodegradable (our footprint must leave no long-term marks on the environment).

Let's stay focused on our objectives. Work on the variables that make a significant impact on image quality, program efficiency and cost. Let's make sure that 3D seismic remains a desired part of exploration and exploitation projects in a changing and competitive world!

Suggested reading. "Acquisition and processing of point receiver measurements in land seismic" by Baeten (SEG 2000 *Expanded Abstracts*). "A Review of Some 3D and 2D Models Using Data Simulation" by Cooper and Herrera (presented at 2002 CSEG National Convention). "3D model evaluation by data dimulation" by Cooper and Cooper (presented at 2001 CSEG National Convention). "Megabin 3D versus conventional 3D methods with examples from the Michigan Basin" by Cooper and Egden (presented at 1999 OPI Annual Meeting). "Impacting low-impact seismic" by Heath (*Hart's E&P*, 2003). "Patterns-with a pinch of salt" by Newman and Mahoney (*Geophysical Prospecting*, 1973). "3D symmetric sampling in theory and practice" by Vermeer (*TLE*, 1998). TLE

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