Shooting direction: A 3-D marine survey design issue

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In the mid-1970s, 3-D marine survey design was primarily constrained by the ability to locate the position of the boat and streamer. Line spacings were, therefore, typically greater than 100 m. (Even if the navigation technology had been more accurate, it is likely that denser grids would not have been acquired because of the cost. This new method, 3-D, carried a price tag that was often considered uncomfortably high for a technology that was as yet unproven.) To minimize crossline aliasing effects, it was most prudent to record data in the dip direction.

By 1980, the accuracy of boat-and-cable positioning had improved to the point where line spacing on the order of 50 m could be supported. The viability and benefits of 3-D had been established (thereby loosening purse strings), so line spacings in the 50–75 m range became typical. Unfortunately, the denser spacing meant that platforms and buoys could no longer be ignored. Rather than veering around these obstructions (as had previously been done), lines had to be terminated, leaving sizable gaps in midpoint coverage. Although it was still desirable to orient 3-D surveys in the dip direction, the orientation was sometimes altered in order to minimize the size of these gaps.

As the 3-D method became more of an exploitation tool, it became imperative that the obstruction-induced gaps be filled with CMP coverage. This required multivessel operations. In 1982, a procedure for platform undershooting was started whereby a source boat sailed on one side of the platform and a recording boat sailed on the other. The resulting CMP lines were coincident with the platform itself. (This acquisition technique is still commonly employed in congested areas of the Gulf of Mexico.) The high cost associated with these two-boat operations motivated geophysicists to design their 3-D surveys in a manner that would minimize the extent of the two-boat zones. Although it was still geophysically desirable to orient the surveys in the dip direction, it often became true that obstruction maps were more influential than geology in the design of a program.

Continual improvements in positioning science permitted the line spacing in 3-D surveys to shrink further. In the mid-80s, spacings as small as 25 m were sometimes being used. The ability to sample data this finely in the crossline direction permitted the advent of strike-oriented surveys. There were many operational reasons why some surveys could be better recorded in the strike direction—closeness of the survey to shore, the presence of shipping lanes, etc. In addition, Ken Larner and Patrick Ng showed that there were geophysical reasons that this could be advantageous (see *3-D marine seismic survey direction: strike or dip?, SEG Expanded Abstracts,* 1984).

By the late '80s, advances in processing further influenced the issue of shooting direction. Three-dimensional dip moveout correction (DMO) removed the azimuthally dependent dip effects in data, thereby stabilizing NMO velocity fields. Improved trace interpolation routines permitted the de-aliasing of data prior to crossline migration. These advances almost led to a euphoria that geology could be ignored in survey design, and that the operational issues of data acquisition were all that needed to be considered.

Factors influencing the choice of shooting direction. The above statement is, of course, somewhat facetious. When selecting the orientation of a 3-D marine survey, three basic concerns should be kept in mind. The geologic objective and the geophysical design required to attain that objective constitute the first concern; operational issues (in acquisition and processing), the second; and cost, the third.

These issues are inseparable. For instance, the best geophysical plan for illuminating a geologic objective might be difficult to implement in the field and/or in processing. This would naturally affect the cost. Field issues include the presence of shipping lanes, currents, wave action, kelp beds, and platforms. Many of these issues and their effects on shooting direction are not new, and will not be covered here. Processing issues include sampling requirements. For optimal results, the sampling must be adequate in time, space, offset, and azimuth. Some of these issues—and how they are related to shooting direction—are new. The routines that are typically most sensitive to direction are DMO and migration.

DMO and boat heading in undershoot surveys. If we assume, for simplicity's sake, that we have a constant velocity medium, then the DMO operator takes on a 2-D shape. The orientation of the elliptical operator is along the azimuth connecting the source and receiver. To see what relevance this has to shooting direction, consider the scenario depicted in Figure 1.

Here we see the map view of several CMP tracks for a hypothetical 3-D survey. A platform sits left of center in the diagram. The solid lines portray CMP tracks recorded by the conventional single-boat method. The dashed lines denote tracks acquired via the two-boat method. (The source boat can be envisioned as sailing across the top of the map, and the receiver boat as sailing across the bottom.) We will investigate the importance of azimuthal sampling and shooting direction by considering the reflections from a plane that dips to the right. Since the source-receiver azimuths are of keen interest here, arrows showing some sample source-receiver directions have been superimposed on the map.

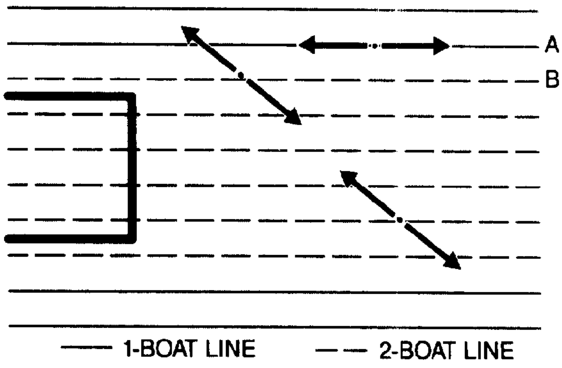
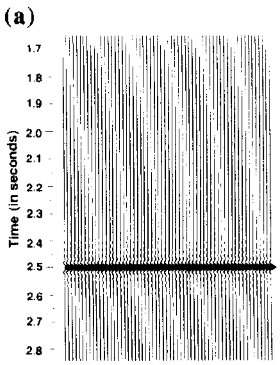


Figure 1. Map view of several CMP tracks for a hypothetical 3-D survey. A platform sits left of the center in the diagram. Solid lines portray CMP tracks recorded by one boat and dashed lines denote tracks acquired by the two-boat method. (The source boat can be envisioned as sailing across the top of the map, and the receiver boat as sailing across the bottom.) Arrows show example source-receiver directions.



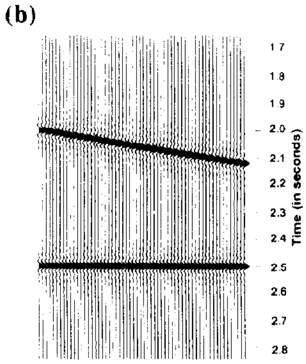


Figure 2a. Modeled reflection of a CMP from line A. NMO and 2-D DMO corrections have been applied. The planar reflector dips down to the right when viewed from the vantage point of Figure 1.

Figure 2b. The same reflection after NMO and 3-D DMO corrections have been applied. The abrupt change in azimuthal sampling inherent at the edge of the two-boat zone causes an artifact to be generated in the 3-D DMO correction process.

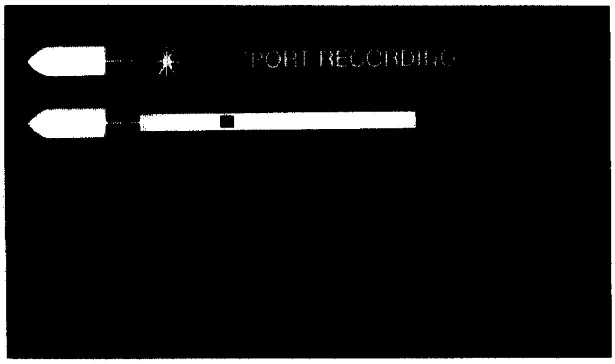


Figure 3. (upper) Two-boat orientation for the black CMP tracks drawn in Figure 4. A sample receiver group is noted. (lower) Two-boat orientation for the gray CMP tracks drawn in Figure 4. Again a sample receiver group is noted.

As a way of introducing the direction-related issues of this section as well as the 2-D versus 3-D issues of this section and the next, let's see what happens at line A (a single-boat line). If there were no feathering in the acquisition of A, then all of the source-receiver azimuths would be inline. This means that DMO correction could be properly executed there by using a 2-D DMO algorithm. This is demonstrated in Figure 2a. The reflection from our hypothetical event has had NMO correction and 2-D DMO correction applied. (The zero offset time of this event is 2.5 s.) As expected, it is flat—ready to be stacked. In contrast, now consider what this reflection would look like if 3-D DMO correction had been performed. The moveout-corrected data are shown in Figure 2b. As in the case of Figure 2a, the true event appears at 2.5 s. Above this event, though, is a well-defined artifact that sweeps across the gather. This is energy that DMO migrated from the two-boat zone into the plane of line A. The interference among DMO operators that was needed to destroy the artifacts did not take place here because only half of the DMO aperture was present. This artifact can go unnoticed since it exhibits residual moveout (meaning it gets suppressed in stack). But if analysis of the prestack DMO-corrected gathers is required (as in an AVO study), then such an artifact can be misleading and dangerous.

Actually, the problem at line A could be solved by restricting the azimuths that are allowed to contribute to A. This was done naturally by the 2-D DMO operation. But to solve this edge problem at line B, we need to have data DMO migrating down along the same azimuth from above line A. That is, the two-boat zone should be extended for the sole purpose of providing full-aperture DMO correction at line B.

Now consider what happens nearer the middle of the two-boat zone. Let's assume that all but one of the boat lines were recorded by vessels that were sailing from the right to the left, as shown in the upper portion of Figure 3. This means that the azimuth between the source and the sample receiver noted in that figure will be in the direction denoted by the black arrows in Figure 4. (For simplicity, we have assumed that the crossline separation of the boats is the same for each line recorded.) Three-dimensional DMO correction of the data from these lines will work rather well. All of the DMO operators from these lines will be oriented in the same direction. Constructive interference among these operators will form the image of the signal, and destructive interference will suppress the unneeded portions of the operators.

But let's see what happens with the one line that is shot in the opposite direction. The orientation of the boats for this case is shown in the lower portion of Figure 3. We see that this situation arises if each vessel simply reverses its direction from before. Now the source-receiver direction for our sample recording group is contrary to that for all the other two-boat lines. This is shown by the gray arrow in Figure 4. Thus the DMO operator will be oriented differently from the operators on all other lines. For most geologic situations, this will result in improper constructive and destructive interference of the DMO impulse responses. That is,

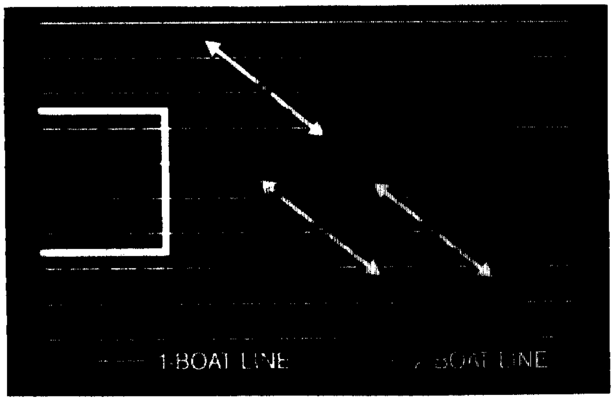


Figure 4. Map view of the CMP tracks for the hypothetical 3-D survey. Arrows show source-receiver azimuths for the receiver groups noted in Figure 3.

3-D DMO correction will cause energy to be sprayed from the line shot in the opposite direction into the planes of the other lines. Artifacts will be generated throughout much of the two-boat zone.

What does this mean? Do all two-boat lines have to be recorded in the same direction? Happily, the answer is *no!* To see this, consider the vessel orientation depicted in Figure 5. The configuration of the boats shown in the upper portion of this figure is the same as that shown in the upper portion of Figure 3. That is, the vessels are sailing from right to left and the recording boat is on the port side of the source boat. We will label this "port recording." The configuration of the boats shown in the lower portion of Figure 5 shows the vessels sailing in the same direction as the vessels in the lower portion of Figure 3, but this time the relative position of the boats has been flipped. That is, the recording vessel is on the port side of the source boats in the lower portion of Figure 5 while it is on the starboard side of the source boat in the lower portion of Figure 3. We see now that the source-receiver azimuths for the two recording examples in Figure 5 are the same, regardless of sailing direction. This is demonstrated by the black and gray arrows in Figure 6. Now all of the DMO operators will be oriented in the same direction. This will result in fewer (if any) artifacts than in the case described in Figure 4. Thus if the relative orientation of the recording vessels is kept consistent (that is, if we maintain "port recording" all of the time, or we maintain "starboard recording" all of the time), then the issues of shooting direction and azimuthal sampling are decoupled. This permits the choice of shooting direction to be made on the basis of other factors such as array effects.

DMO and boat heading in wide line surveys. In the previous discussion, 2-D DMO correction was more appropriate than 3-D DMO for imaging line A. Actually, this is an unfair statement. The 3-D DMO result was subpar because of the inconsistent azimuthal sampling of the data. If the input to the 3-D DMO correction process had been limited only to those azimuths that were well sampled (namely, the inline azimuths of A), then the 3-D DMO result for line A would have been acceptable, too. In fact, it would have been identical to the 2-D result. This demonstrates a point that has been well understood for some time: When single-boat acquisition exhibits no feathering, 2-D DMO correction and 3-D DMO correction are the same. But when feathering exists and/or multivessel recording is used, 2-D DMO correction is inadequate. By definition, both NMO and DMO comprise the moveout process. Therefore, if 2-D DMO is used when 3-D DMO is needed, the resultant amount of moveout applied will be incorrect. Thus the degree to which 2-D DMO correction is not appropriate can be measured in terms of stack response. The necessary calculations are quite simple. They require use of the 2-D and 3-D NMO equations. The results from some sample computations for a single, dipping, planar reflector are shown in Figure 7. The true dip of the reflector was assumed to be 60°. The velocity, fold, and reference frequency were 7500 ft/s, 60, and 20 Hz. The graph shows the stack response degradation incurred by using 2-D DMO correction instead of 3-D DMO correction. The response curves are plotted as a function of the relative azimuth between the boat heading and the true dip direction. The annotated feather values are in relation to the boat heading. We can see from the graph that if feathering in the area were such that it stayed less than 5°, then 2-D DMO correction would probably be acceptable as long as the shooting direction for the survey was within 20° of the true dip or true strike direction, since this would result in less than 3 dB degradation in the response of the stack (at the reference frequency).

Why is this important? Most processing shops offer 3-D DMO today, so why worry about the compromises made with 2-D DMO? The answer lies in the fact that, even if azimuthal sampling is sufficiently consistent, there is no guarantee that spatial sampling is adequate. DMO correction is a migration process and is, therefore, sensitive to spatial sampling. If the source-receiver azimuths in a survey are such that the DMO migration will take place oblique to the inline binning direction, then the crossline spacing becomes

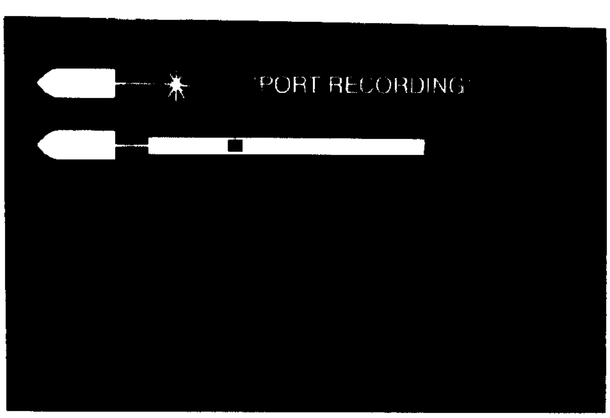


Figure 5. (upper) Two-boat orientation for the black CMP tracks drawn in Figure 6. A sample receiver group is noted. (lower) Two-boat orientation for the gray CMP tracks drawn in Figure 6. A sample receiver group is also noted.

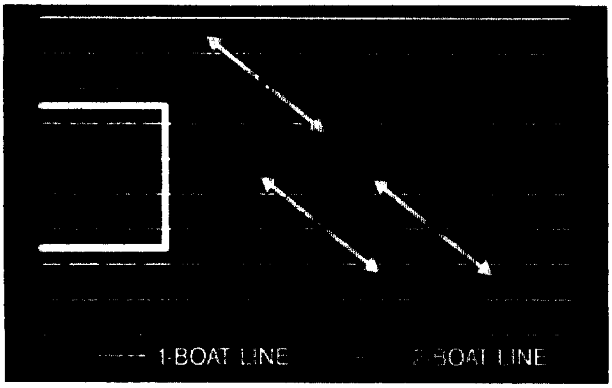


Figure 6. Map view of CMP tracks for the hypothetical 3-D survey. Arrows show source-receiver azimuths for the receiver groups noted in Figure 5.

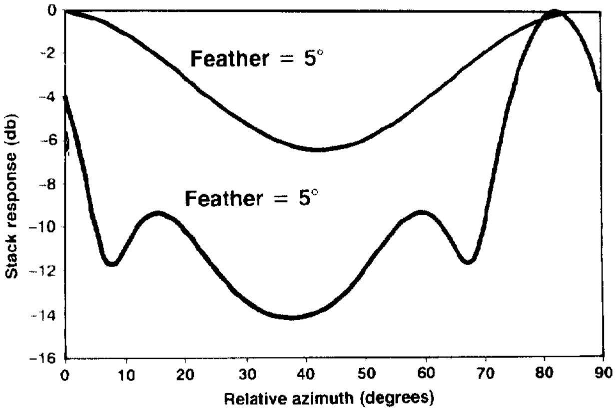


Figure 7. Degradation in the stack of a dipping reflection incurred (at the reference frequency) when using 2-D DMO correction instead of 3-D DMO correction. Single-boat recording is assumed. The curves are plotted as a function of the relative azimuth between the boat heading and the true dip direction. The annotated feather values are relative to boat heading (see text for the model parameters).

an issue. Much attention has been given to this problem over the last several years (see Suggestions for further reading). Attempts are made now to dealias the DMO process, but situations can still arise (especially when reprocessing older 3-D data sets) where the crossline sampling is simply too coarse to support proper 3-D DMO correction. In such instances, the geophysicist can perform an analysis similar to that in Figure 7 to see if the deleterious effects of performing only 2-D DMO correction (which relies only on the inline CDP spacing) are small enough.

This issue of aligning a 3-D survey in the dip or strike direction not only has implications in DMO, but also in 3-D migration.

Three-dimensional migration and shooting direction. It has been known for some time that when velocity is constant, the 3-D migration process can be legitimately partitioned into an inline and crossline succession of migrations. If we ignore spatial sampling issues, it would not matter in which direction the survey was oriented and it would not matter which of the inline or crossline migration sequences was done first. The result would always be the same, and it would always be correct.

In the real world, of course, rock velocities do change. An implication of this is that single-pass, 3-D migration is more appropriate. Indeed, the single-pass implementation is frequently used today, but there still are some occasions when geophysicists select the two-pass approach. Reasons for doing this range from cost and the availability of bigger computers (single-pass methods require more memory) to the preference of where to perform crossline interpolation. (Some geophysicists like to interpolate to a finer crossline spacing after the inline migration has been done. The reasons for this are two-fold. First, inline migration increases the signal-to-noise ratio, thereby providing the interpolation routine better quality data with which to work. And second, delaying the interpolation until after inline migration means there there are fewer data to migrate, thereby reducing cost.)

The compromises made by migrating in the two-pass mode can be analyzed fairly easily when the predominant velocity gradient is in the vertical direction. A technique was outlined by John Dickinson in *Evaluation of two-pass, three-dimensional migration* (GEOPHYSICS, 1988). Figure 8 shows an earth model where the velocity varies solely with depth. In general, two-pass 3-D migration will misposition the dipping plane. A way to describe the error is to compute the vertical misplacement defined in Figure 9. Using Dickinson's equations, this temporal error was computed for the model. The results appear in Figure 10. The temporal error caused by using two-pass 3-D migration, rather than the single-pass approach, is plotted as a function of the azimuth between the inline direction and the true dip direction. We see that when the inline direction is coincident with dip or strike, two-pass and single-pass 3-D migrations yield identical results. This means that if a significant vertical velocity gradient exists in a survey and if (for whatever reason) the two-pass migration approach is intended to be used, then it would be prudent to perform those passes of migration in the dip and strike directions. Unless rebinning of the data into these directions is planned, the easiest way to prepare the data for this is to align the shooting direction in either the dip or strike manner

Dip versus strike. As we saw above, shooting dip or strike (rather than oblique) can simplify several imaging issues. But which is better? At SEG's 60th Annual International Meeting, 1990, Jim O'Connell et al. reported (*Bullwinkle: A unique 3-D ex-*

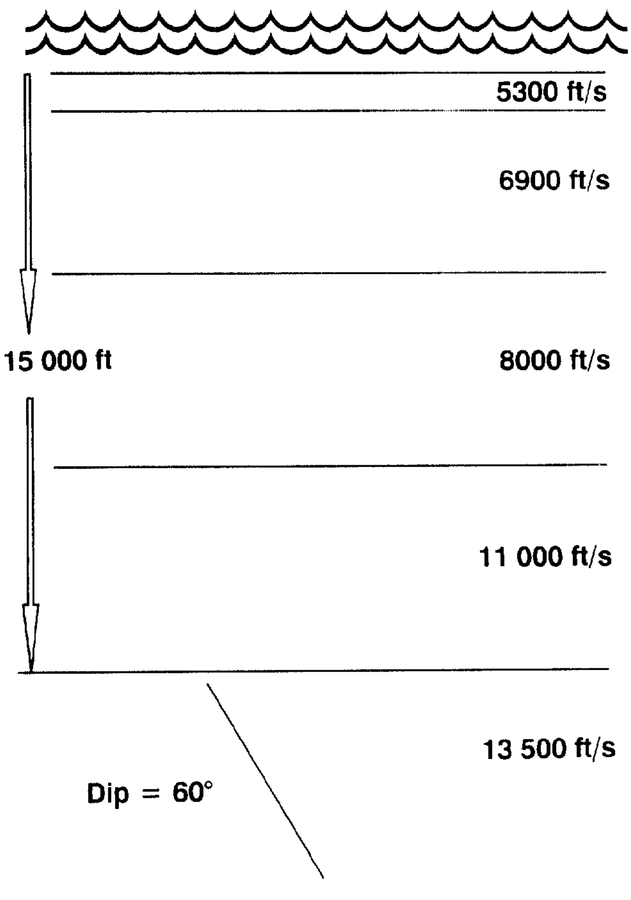


Figure 8. The earth model used in Figure 10 for evaluating the error associated with two-pass 3-D migration.

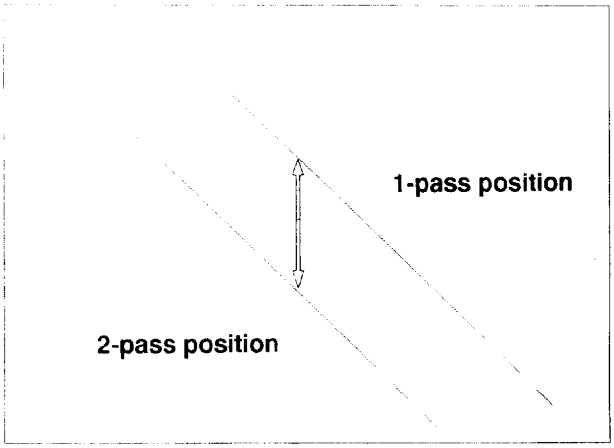


Figure 9. The definition of temporal error associated with the mispositioning of events in two-pass, 3-D migration. (This is the same definition as specified by Dickinson.)

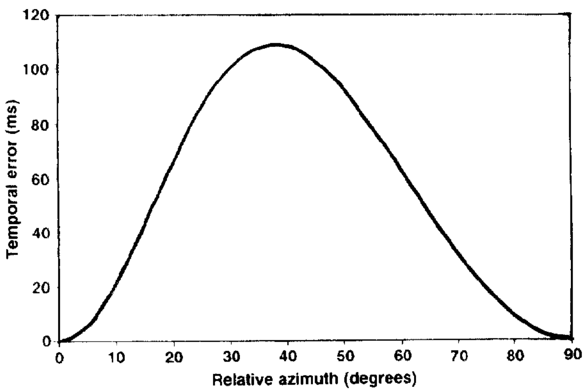


Figure 10. The temporal error induced by migrating the dipping event of Figure 8 with a two-pass algorithm. The error is plotted as a function of the azimuth between the inline direction and the true dip direction.

periment) the findings from two different, orthogonal 3-D surveys collected over the same field. Although there was good agreement between the surveys, they noted that the parts of each survey that were shot strike to the structure yielded the superior image. Indeed, strike shooting should produce raypaths which generate events that are more consistently hyperbolic within CMP gathers than in the case of dip shooting. This was partially the motivation for acquiring the program reported by J. Durrani et al. (*New directions for marine 3-D surveys,* SEG's 57th Annual International Meeting, 1987) in which data were obtained strike to a salt dome by shooting in a circular fashion.

However, it remains popular today to record 3-D surveys in the dip direction. In fact Cristine Morshedi et al. recorded a 3-D survey over a salt dome in a radial manner (*A radial 3-D seismic technique for imaging around a salt dome—design, acquisition, and processing,* SEG's 60th Annual International Meeting, 1990). Actually, the proponents of both the circle-shoot method and the radial-shoot method admit that the chief motivation for using these techniques is often not geophysical, but operational. Each of these methods appears to provide cost savings compared to the more conventional rectilinear technique.

Final remarks. The continual improvement in marine 3-D data acquisition and processing technology has caused an ongoing evolution in the science of survey design. A key parameter here is shooting direction. We have noted that geologic objectives, operations, and cost all play a role in the process of selecting the optimal shooting direction. Every survey is unique, so the relative weights of these factors needs to be analyzed on a project-by-project basis. We have tried to show that this analysis does not have to be subjective. Simple modeling tools are available to review the proposed acquisition and processing parameters. These allow the geophysicist to predict the degree to which he will be able to image his objective, and at what cost.

Suggestions for further reading. Some articles, in addition to those cited in the text, which the authors feel will be of benefit to anyone interested in this subject include: *Amplitude and anti-aliasing treatment in (x-t) domain DMO* by C. Beasley and E. Mobley (*SEG Expanded Abstracts,* 1988); *De-aliasing of the dip moveout correction process* by M.S. Egan et al. (*SEG Expanded Abstracts,* 1987); *Dip Moveout Processing* by D. Hale (SEG Course Notes, 1988); *A simple exact method of 3-D migration-theory* by H. Jakubowicz and S. Levin (*Geophysical Prospecting,* 1983); and *Wave-equation trace interpolation* by J. Ronen (GEOPHYSICS, 1987). LE

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