Toward subsurface illumination-based seismic survey sesign

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ABSTRACT

The usual approach to the acquisition of 2-D and 3-D seismic surveys is to use a recording template designed from the maximum target dips and depths. This template is used though out the survey area irrespective of changes in the dips, depths or propagation velocities of the targets. I propose to base the survey design on an initial structural and velocity model of the subsurface. The initial structural and velocity model is used to trace rays to the surface at uniform illumination angles from all reflecting points of interest. The emergence ray points are recorded as tentative source and receiver positions and a constrained inversion is used to optimize them given logistic and economic restrictions. I apply this strategy to a very simple 2-D synthetic model and show taht in order to image steep dips larger offsets are required than would be anticipated from the traditional approach. This in turn implies the need for different source and receiver positions.

INTRODUCTION

The usual strategy for the design of 2-D and 3-D seismic surveys starts from the estimation of "critical" values for subsurface parameters such as maximum geological dip, maximum target depth, minimum target rms velocity and minimum target thickness. From these values (and an estimation of the minimum required fold), we choose acquisition parameters such as receiver group and source interval, maximum offset and number of active channels per shot. In 3-D we also compute the number of active receiver lines, the number of shots per salvo, the width of the active patch and the geometry of the acquisition template (Stone, 1994). More often than not these parameters are held constant across the whole survey irrespective of changes in the geometry of the subsurface we wish to image or of its associated velocity field.

Common usage in 3-D seismic acquisition focuses on regularity of source and receiver positions on the surface of the earth according to one of a few "standard" geometries. These geometries are designed to provide as regular offset and azimuth coverage in each CMP bin as possible while at the same time allowing for relatively easy logistics. Although there are important differences between the different "standard" geometries in terms of their offset and azimuth distributions (Galbraith, 1995) and other less obvious characteristics such as the sym-

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metric sampling of the wavefield (Vermeer, 2001), these regular geometries all share these characteristics:

- Quality control is essentially qualitative and relies on regularity of offsets and azimuth in adjacent CMP surface bins. The actual subsurface bin population at the target location (which is clearly a function of the reflector dip and the dips and velocities of the overburden) is completely ignored or considered only as an afterthought of the design.
- As a result of the regularity in the position of sources and receivers, the data often shows strong footprints which are deleterious of the quality of the processed data.
- Worst of all, these geometries make no attempt whatsoever to guarantee or even promise any sort of uniformity in subsurface illumination. This may be critical when trying to image under salt flanks and in overthrust areas with large fault displacements (which are common in foothill data). No amount of clever processing can compensate for problems generated by poor illumination during acquisition.

The choice of the parameters for these “standard” geometries can be posed as an optimization problem once the basic template is chosen (Liner et al, 1999) and even the logistics and economics of the acquisition can be incorporated into the computation, at least to some extent (Morrice et al, 2001). The basic premise, however, is that the underlying acquisition template is regular and chosen before hand, so that the optimization is restricted to look for the best combination of the parameters consistent with the chosen template.

The quality of the overall design is evaluated based on such surface attributes as uniformity of fold of coverage and regularity of offset sampling (and azimuth sampling in 3-D). This is equivalent to an implied assumption of a layered, constant velocity subsurface model. Illumination is only considered as a forward problem (if considered at all). Illumination maps may be constructed at the target reflectors for each of a few competing geometry templates and the best one selected by a qualitative comparison of those maps (**?**). Although this is an important step in the right direction, there is no guarantee that the chosen geometry will in fact produce optimum illumination.

A better strategy would be to base the design on an initial structural and velocity model of the subsurface, even if only a crude one. Obviously at the time of acquisition we don’t have a detailed subsurface model, otherwise we may not even have to acquire the data. Oftentimes, however, we know the rough features we wish to image. Is it a salt dome, an overthrust faulted anticline or a deep channel turbidite system?. This information may come from previous seismic data, from well logs, from a conceptual geological model, from surface geology and usually from a combination of the all of them. This wealth of information is ignored in the usual acquisition design but it does not need to be. It is possible and indeed desirable to use the existing knowledge of the subsurface structure and velocity model to improve the acquisition of new data. I show with a very simple synthetic 2-D example that we can reduce the number of shots without compromising the quality of the image by selectively ignoring shots whose contribution to the image is less than, say, half the number of traces of a regular shot.

The two key points are: we are not required to use the same parameters or indeed the same geometry all across the survey and regularity of *surface* parameters is not necessarily the mark of an optimum design. A better indicative is regularity of *subsurface* attributes such as target illumination.

THEORY OVERVIEW

2-D Land Seismic Acquisition Design

The traditional approach to the design of land 2-D seismic surveys follows these steps:

1. Measure or estimate from existing seismic data, from well logs or from geology data the maximum dip of interest in the survey area. This is not necessarily the maximum dip of the reservoir unit itself but may be the dip of a sealing fault or an important unconformity or any other such relevant geological feature. With this value, estimate the maximum receiver group interval (Δx) in order to avoid spatial aliasing in the data given the maximum frequency (f_{max}) expected or required in the data (in turn a function of the minimum target thickness)

   $$\Delta x \leq \frac{V_{\text{min}}}{2 * f_{\text{max}} \sin \alpha_{\text{max}}} \tag{1}$$

   In this equation α_{max} is the maximum target dip.

2. Set the maximum offset equal to the maximum target depth (again, not necessarily the maximum depth of the reservoir itself).

3. Compute the number of active channels per shot (nc) from the maximum offset and the receiver group interval

   $$nc = \frac{offmax - offmin}{\Delta x} + 1 \tag{2}$$

   For symmetric split-spread cable (equal number of receivers on both sides of the shot) the number of channels is multiplied by 2.

4. From the expected signal/noise ratio in the data (estimated from previous vintages of seismic data in the survey area or nearby), estimate the minimum required fold of coverage (usually something like 30, 60 or 120).

5. From the fold, the number of channels and the receiver group interval, compute the source interval (Δs)

   $$\Delta s = \frac{2 * Fold * \Delta x}{nc} \tag{3}$$

6. The migration aperture (M_{a}) is computed from the depth z and dip α of the steepest dipping reflector at the end of the survey. In 2-D it is usually estimated as

   $$M_{\text{a}} \approx z * tan(\alpha) \tag{4}$$

Because the velocity increases with depth this estimation tends to be a little pessimistic and sometimes a fraction of it is actually used.

These are the relevant parameters for 2-D acquisition. Another important consideration is the type of source (for example charge size and hole depth for acquisition with an explosive source) which is usually determined with field tests just before the start of the acquisition.

PROPOSED METHODOLOGY

In 2-D acquisition the geometry of the layout is almost always chosen to be either split-spread (land) or end-on with the shot pulling the cable (marine), so there isn't much flexibility in that respect. Illumination requirements essentially control the maximum offset of interest, which will change along the line profile as the target depths, dips and velocities change. The fold requirements may also change along the line profile but this situation is less common. The other parameter that may change is the receiver group interval but we have a strong limitation in the choice of this parameter because the seismic cables usually have take outs only at predetermined distances.

The strategy for a more flexible acquisition is the following:

1. Construct a subsurface model of the survey area as accurately as possible in terms of the geometries of the target reflections and interval velocities.
2. Do non-zero-offset exploding reflector modeling using this model. This means to consider "all" points along each of the target reflections as a Huygen's source and to track rays up to the surface at given uniform reflection aperture-angle increments. This would guarantee perfect illumination if in fact the given rays can be generated during the acquisition. For each pair of rays (with the same aperture angle on opposite sides of the normal to the reflector) record their emergence positions at the surface.
3. Clearly, the optimum source and receiver positions for each target will be different from those of the other targets. Reconciling these optimum illumination source and receiver positions can be posed as a non-linear inversion procedure. Inputs will be the source and receiver positions required to illuminate each target and output will be the source and receiver positions that minimize the sum of the deviations from the requirements for each target. For this process to be useful, several constraints must be imposed. For land acquisition the most important ones will be:
    (a) The receivers must be equally spaced at a distance consistent with the cable takeouts of the expected recording equipment.
    (b) The number of shots should be kept to a minimum.
    (c) in 2-D, source and receivers should be kept along the profile line.

More subtle, and perhaps more difficult constraints to honor, will be related to spatial sampling considerations for prestack migration. Since the emphasis of the acquisition design will be placed on maintaining regularity of subsurface illumination, surface parameters such as offset and fold will not be uniform. Adequate sampling of offsets and azimuths, however, is a stringent requirement that must be honored by the inversion procedure. It is also important to note that the optimum geometry may not provide uniform illumination, but will likely provide better illumination than the usual approach.

4. Finally, the optimum source and receiver positions will be output in a suitable format such as Shell's SPS geometry format. These geometry files can be readily input to the acquisition instrument.

A SIMPLE 2-D MODEL EXAMPLE

Description of the model

As a first test of the above ideas, I created a simple model shown in Figure 1. The model has constant velocity background of 3000 m/s.

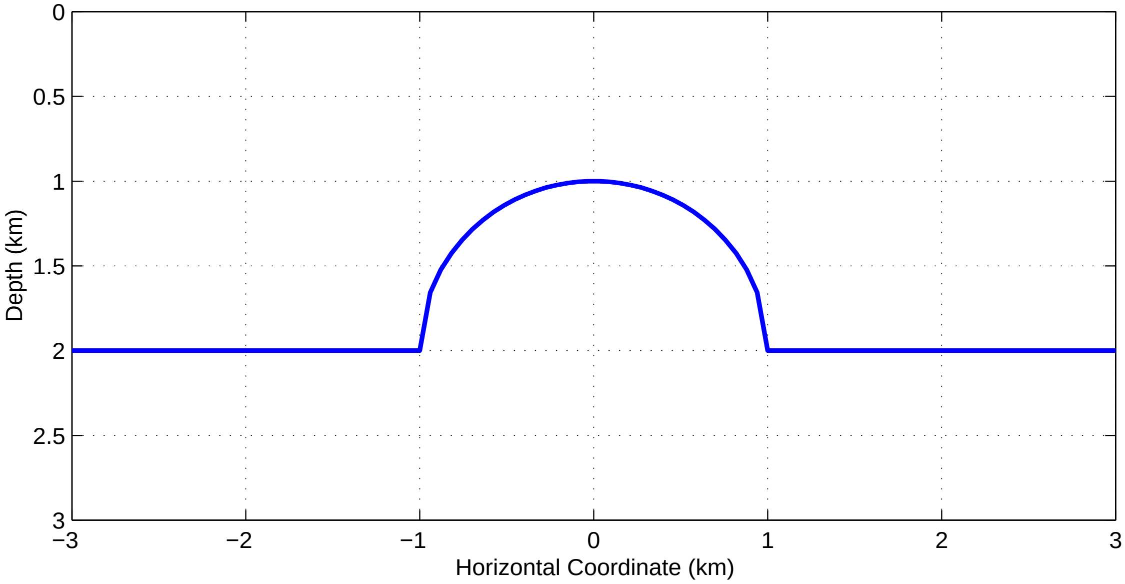

Figure 1: Simple model used to illustrate the proposed methodology. The background velocity is constant (3000 m/s) model1 [NR]

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Modeling with traditional parameters

In this case $v_{\text{min}} = 3000$ m/s, $\alpha_{\text{max}} = 90$ and $f_{\text{max}} = 50$ Hz. Applying Equation 1 we get $\Delta x = 30$ m. The maximum depth of the target is 2000 m, so assuming an off-end cable (receivers to one side of the shot only) this will give about 67 receivers. This number rounds up nicely to 72, which means an actual maximum offset of 2160 m (assuming that the first receiver is at an offset of 30 m). The shot interval is chosen as $\Delta_s = \Delta_x = 30$ m so that the fold of coverage (number of receivers per CMP) is 36. The trace length was chosen to be 4 s. With these parameters I simulated acquisition using an analytical ray-tracing program. Obviously, we cannot expect to image the dips of the semicircular reflector up to 90 degrees because according to Equation 4 that would imply infinite aperture. The best we can do is image the maximum dip for which the reflection time is less than or equal to the trace length. In this case, given the simple geometry of the reflector, a quick computation shows that for the zero offset trace this corresponds to shot positions $\approx \pm 6700$ m. The corresponding maximum dip is ≈ 73 degrees.

The acquisition proceeds from left to right in Figure 1. When the shot is to the left of the semicircle the longer offsets have shorter arrival times (from the semicircle) which means that we can actually achieve full fold at that point by extending the acquisition to the left by half cable-length (1080 m). The first shot is therefore at -7780 m. When the shot is to the right of the semicircle, on the other hand, longer offsets have longer arrival times and so we cannot expect to have full fold at 6700 m. Any shot past that point will only contribute reflections longer than the trace length. In summary, with the standard approach (using the off-end cable described above) in order to image the maximum dip we need shots between -7780 and 6700 m. At 30 m shot interval this implies 483 shots.

Figure 2 shows some of the modeled shot records. At both sides of the semicircle we see two reflections coming from the flat and the semicircular reflector, whereas above the semicircle only the reflection from the semicircular reflector is seen. Figure 3 shows some CMP gathers. Since the design is completely regular, the CMP's are also regular. This is further illustrated in Figure 4 which shows the fold diagram. Note that we have full fold at -6700 m but not at 6700 m.

Figure 5 shows the stacked section. The noise at the intersection between the flat and the dipping reflections reflects the inherent difficult in picking a stacking velocity appropriate to both (no DMO was applied). Finally, Figure 6 shows the post-stack migrated section using a Stolt algorithm. As expected, dips in the semicircular reflector higher than 73 degrees were not recovered.

Modeling with the proposed design

For the first step I used an analytic ray tracer to compute the surface emergence positions of rays originating at equally-spaced reflection points along the reflector. These reflection points were taken every 18 m, corresponding to the CDP interval in the traditional design. For the flat reflector the number of pairs of rays originating at each point was kept equal to the fold in the standard design. The rays correspond to a uniform increase in reflection aperture angle and therefore will not correspond to uniform offsets in a CMP gather. In the semicircle the number of rays was increased as a function of the reflector dip, so that where the dips are larger more rays were generated. The maximum offset was not constrained except for the obvious requirement that any reflection time were less than the chosen trace length.

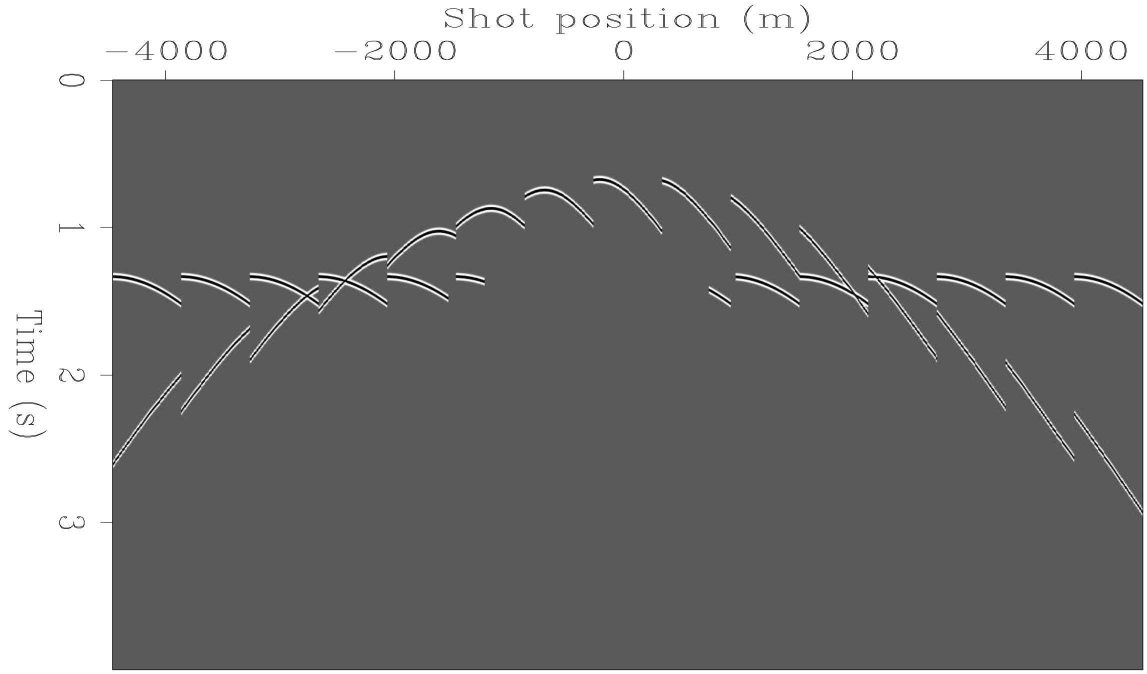

Figure 2: Synthetic shot records modeled with the standard geometry. modcirc1_shots [ER,M]

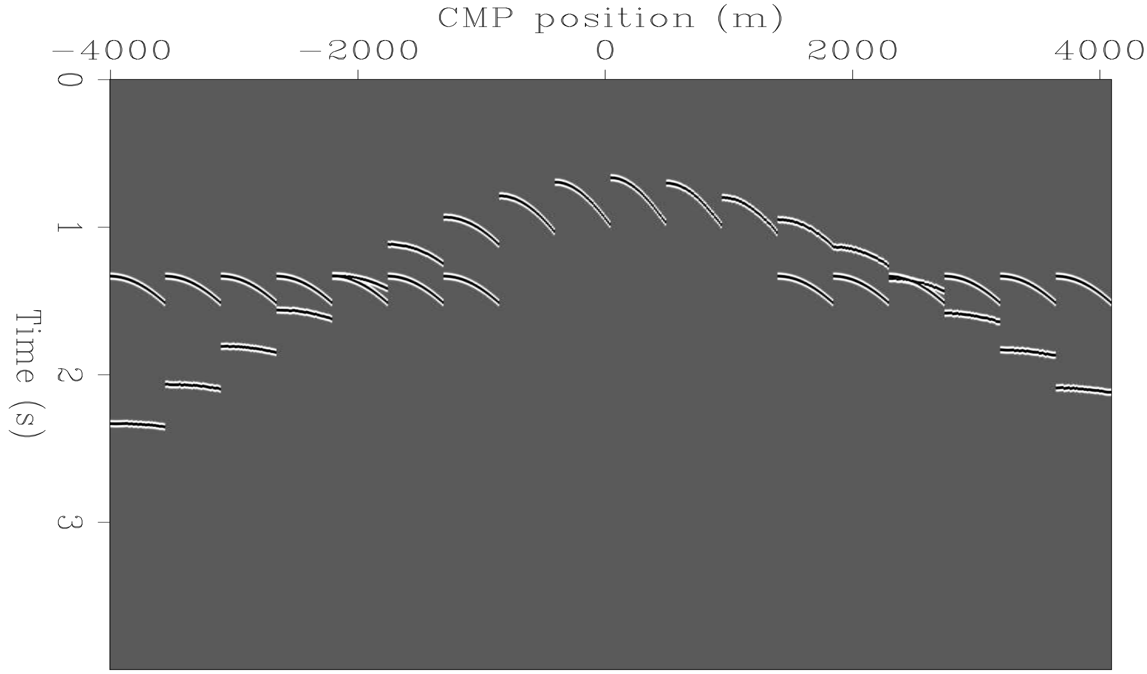

Figure 3: CDPs modeled with the standard geometry modcirc1_cdps [ER]

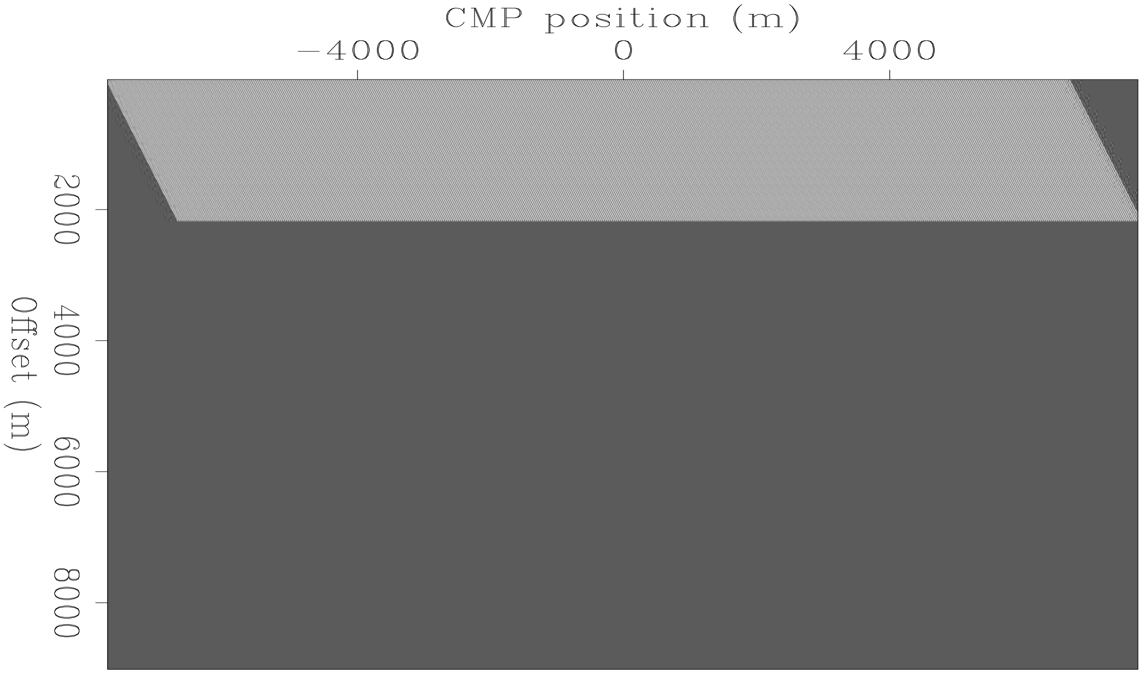

Figure 4: Fold diagram for the standard geometry modcirc1_fold [ER]

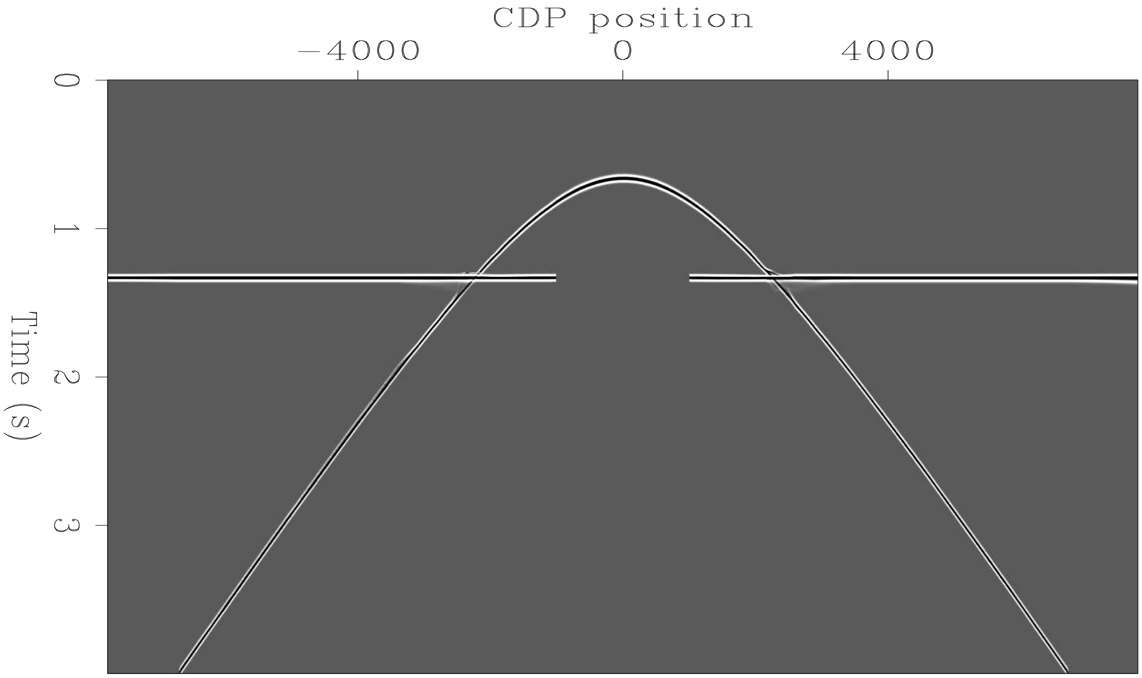

Figure 5: Stacked section of modeled data generated with the standard design modcirc1_stack [ER]

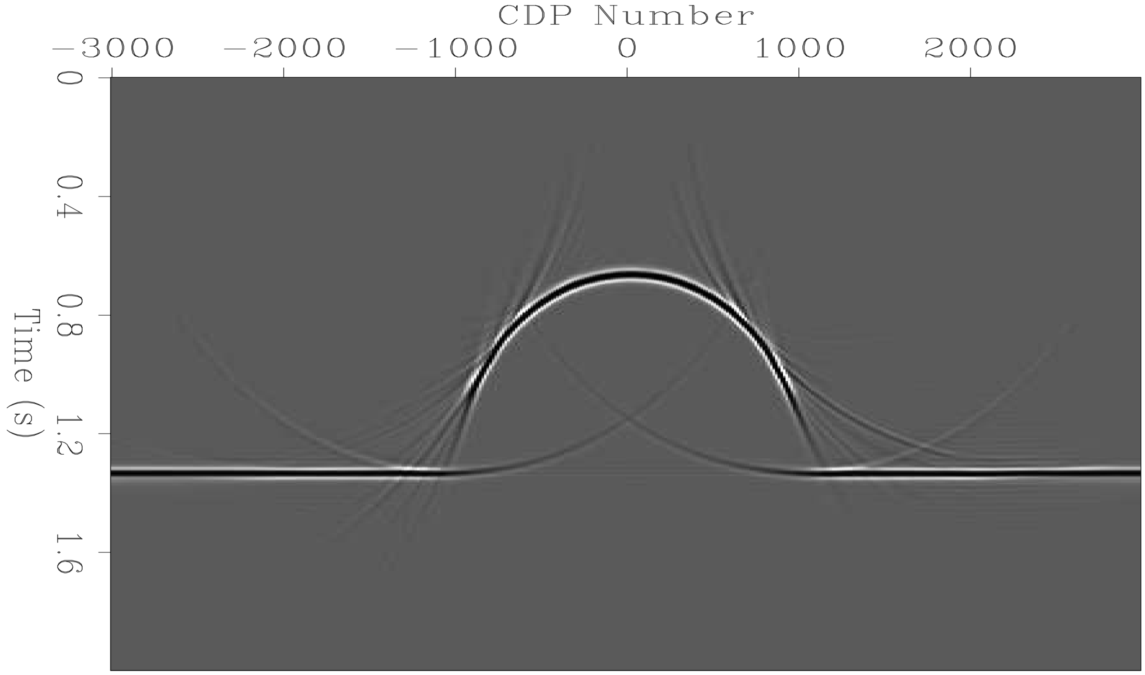

Figure 6: Migrated section of modeled data generated with the standard design modcirc1_mig_all [ER]

The next step is to use non-linear inversion to find the optimum source and receiver positions from the different targets. In this case, however, since there is only one target, the inversion reduces to a simple binning to honor the constraint that the receivers should be at equal distance along the line profile. I chose for the receiver interval the same value obtained in the standard design so that the results can be easily compared. The shots were also binned at the same receiver interval to further regularize the design (and guarantee equal distance between CDPs and between the stacked traces). Only shots that contribute at least half the number of traces of the standard geometry shot (that is 36) were considered. A total of 402 shots met this criterium (which is rather arbitrary). The number of traces per shot, and hence the maximum offset, was allowed to change from shot to shot. In this example this is the only degree of freedom that I used to adapt the acquisition effort to variations in the subsurface dip. In a real case, where the reservoir location is known or suspected, we could locally vary the receiver group interval or more likely the shot interval. In 3-D there are extra degrees of freedom associated with the azimuth and the choice of geometry template.

The next step is to simulate the acquisition of the data using the computed shot and receiver positions. Again, this was done with an analytic ray tracer. Figure 7 shows some of the shots. Note that they have different number of traces. Also, they look irregular because the plotting program places the traces together at the same distance irrespective of their offset. Figure 8 shows some CMPs along the line profile. As with the shots, the number of traces changes from CMP to CMP. Also note that there are “holes” in the CMP’s illustrating the difference between uniform offsets and uniform illumination. Figure 9 shows the fold diagram. In this case there are differences in the fold coverage from CMP to CMP. As long as the minimum

CMP fold is maintained, this shouldn't be a problem. More importantly, note the large offsets at both sides of the semicircle and the smaller offsets above the semicircle (compare with Figure 4). Figure 10 shows the stacked section. Comparison with Figure 5 does not reveal any striking difference because the stack smoothes out the effect of the irregular offsets. The important difference between the two figures is the lateral extent of the semicircular reflection. Figure 11 shows the migrated section and Figure 12 shows a comparison with the migrated section obtained with the standard acquisition. Not surprisingly, the two images are almost the same, since they were computed with the same aperture. Recall that the proposed design required about 180 fewer shots.

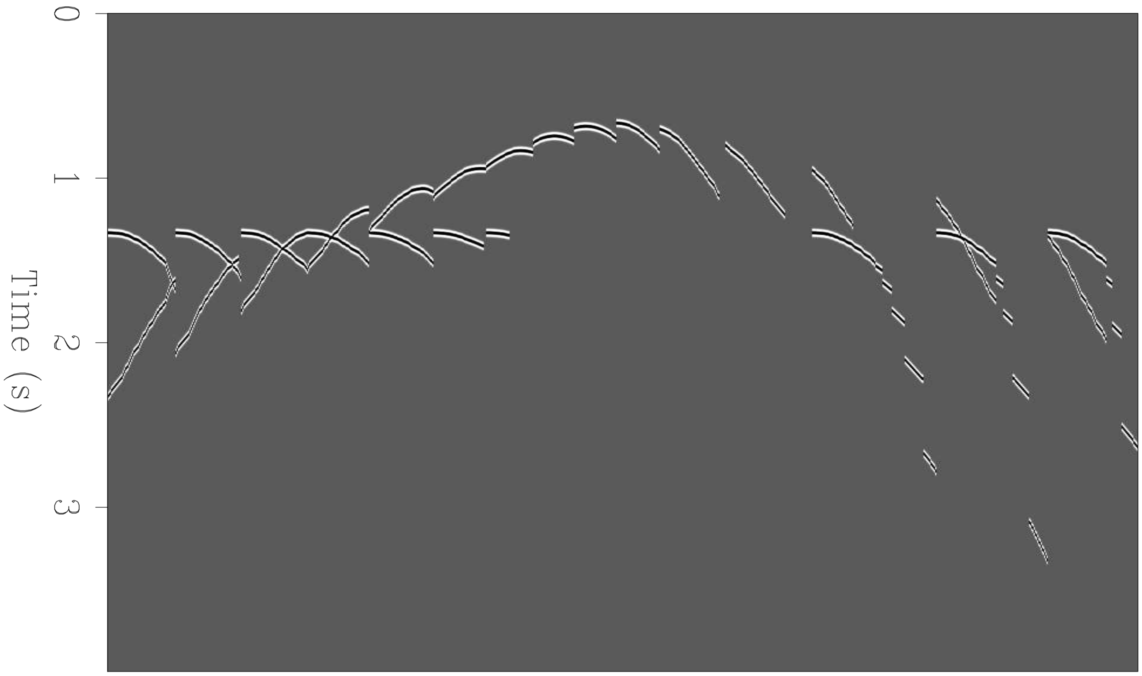

Figure 7: Synthetic shot records modeled with the proposed acquisition design. modcirc3_shots [ER]

This example is rather artificial in that the savings in the number of shots comes simply from a realization that not all shots contribute the same number of traces to the subsurface image. In the real case a more important consideration would be *to what part of the image* every shot contributes. Those shots that contribute to the reservoir location (or any other critical part of the image) will be kept even if they contribute only a small number of traces. This flexibility is important when faced with obstacles which force us to displace shots or receivers. The effort that we put into it may depend on the relative contribution of those shots and receivers to the critical parts of the image as opposed to the standard approach in which all shots and receivers are considered equally important.

In order to see the importance of the fewer shots in the quality of the image, I modeled the data again with the standard approach but using only 402 shots (the same that I used in the proposed approach). The first shot will now be at -5350 m which translates to a maximum dip angle of 69 degrees with one fold and 60 degrees with full fold. Figure 13 shows a comparison

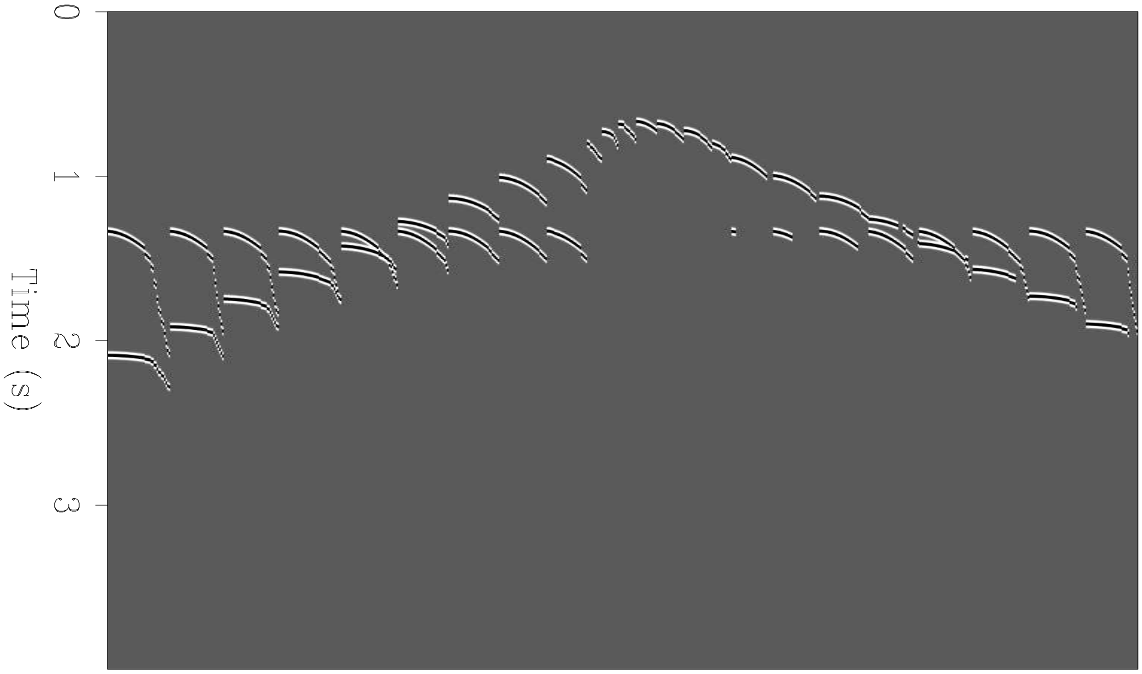

Figure 8: Selected CDPs modeled with the proposed methodology. modcirc3_cdps [ER]

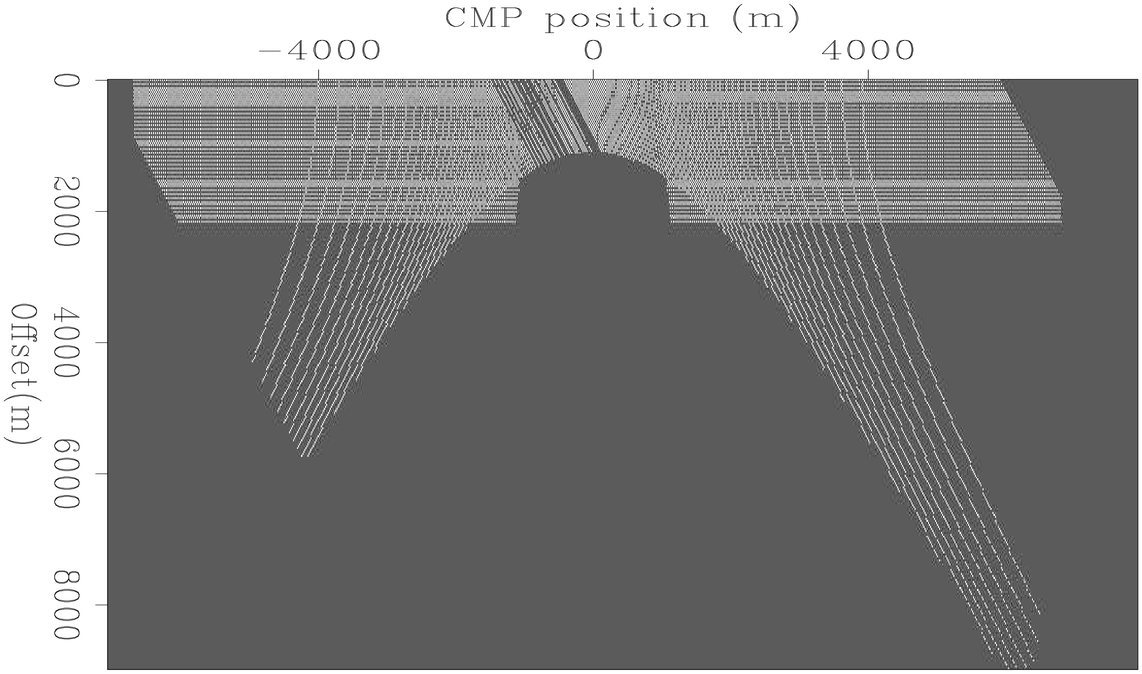

Figure 9: Fold diagram for the proposed methodology modcirc3_fold [ER]

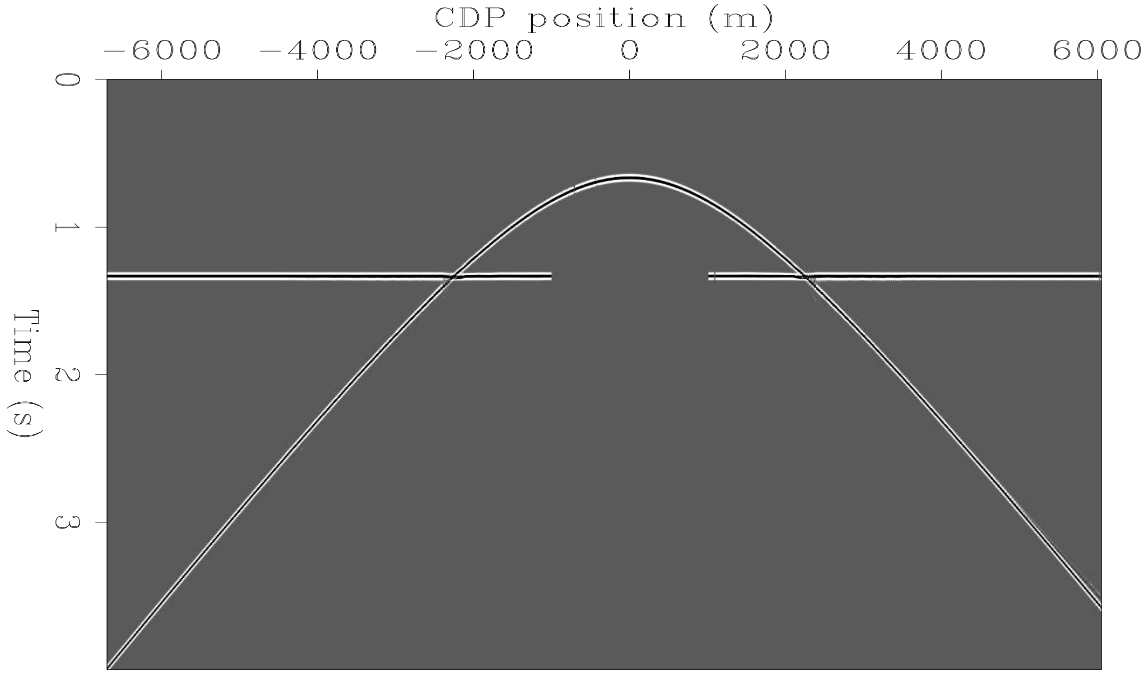

Figure 10: Stacked section of modeled data generated with the proposed design modcirc3_stack [ER]

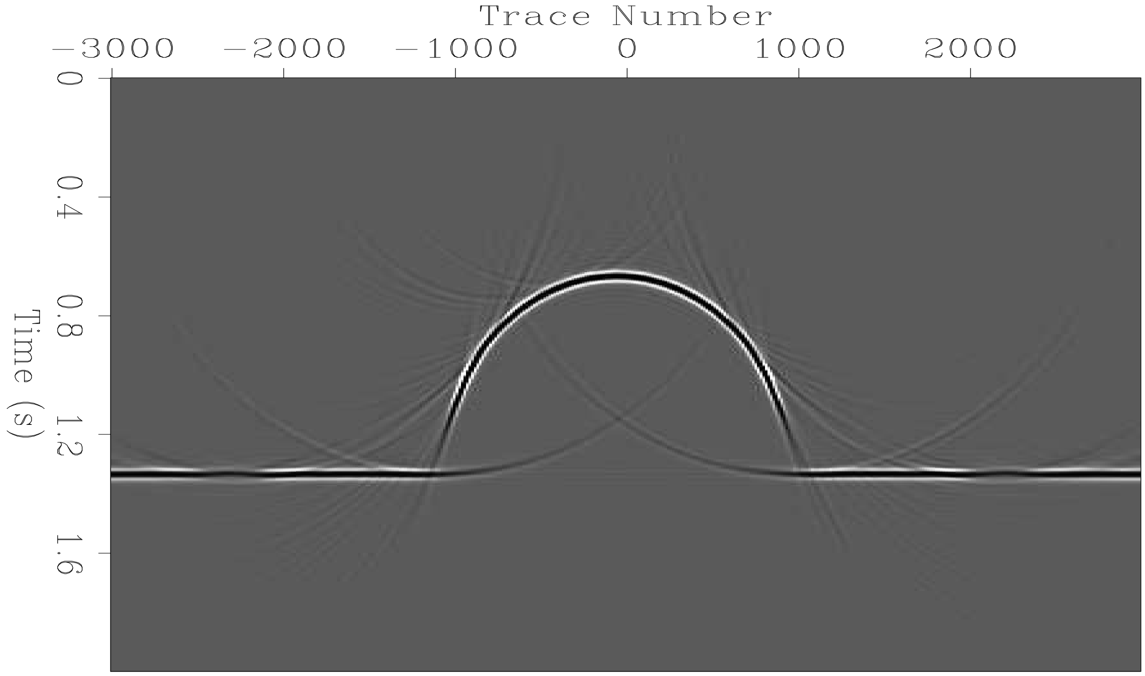

Figure 11: Migrated section of modeled data generated with the proposed design modcirc3_mig [ER]

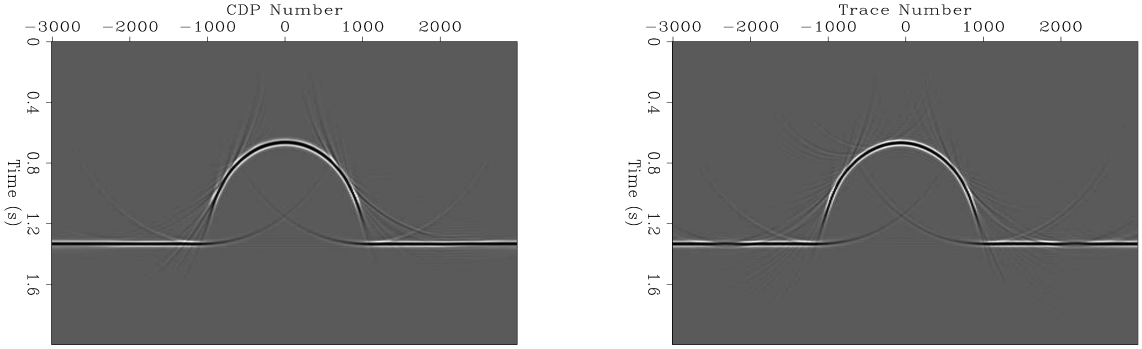

Figure 12: Close up comparison of migrated sections generated with the traditional (left) and proposed (right) design modcirc13_comp [ER,M]

with the proposed approach. The difference in the high dips of the images on the left-hand-side of the semicircle is clearly visible.

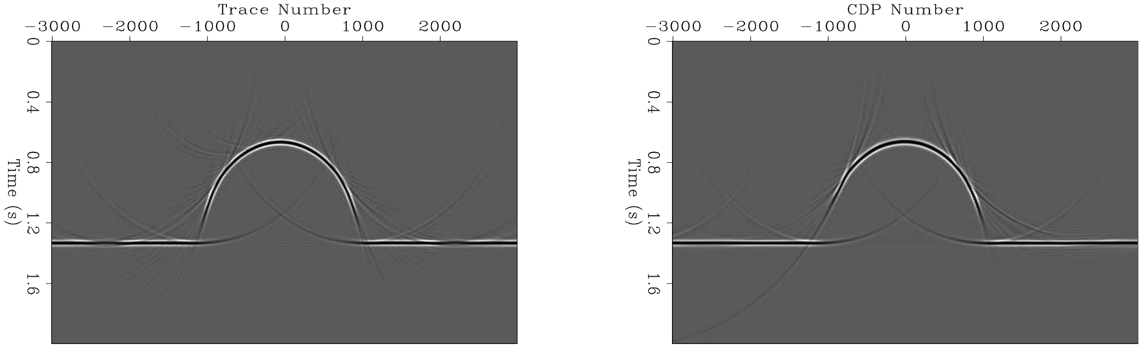

Figure 13: Close up comparison of migrated sections generated with the proposed design (left) and the standard design with the same number of shots. modcirc13_comp2 [ER,M]

An obvious improvement to the above methodology consists in acquiring, for every shot, not only those receiver positions obtained form the inversion, but also those in between. After all, if the intermediate geophones are available, why not use them? Figure 14 shows the fold diagram in this case. The number of shots is the same as in the previous case, and the increase in fold is due entirely to the intermediate receivers.

DISCUSSION

It should be obvious that the real difference between the standard and the proposed methodology will only surface when the data is imaged before stack. Then the larger offsets corresponding to the larger dips and the better illumination will really come into play. Here I chose to image the data post-stack only for simplicity. Also, it should be apparent that the expected differences between the standard and the proposed approach will be an order of magnitude larger for 3-D data, because in 3-D (especially in land) we usually have to compromise the

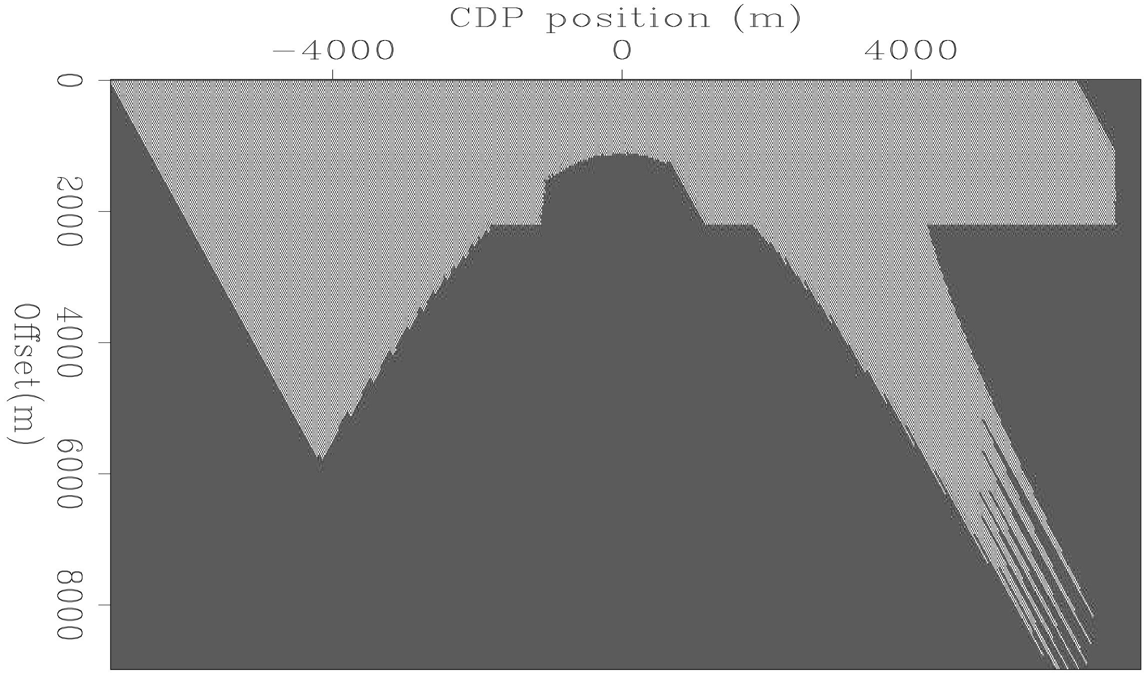

Figure 14: Fold chart of modeled data generated with the proposed design using intermediate traces modcirc4_fold [ER]

parameters in the standard approach and because of the extra degree of freedom afforded by the choice of azimuth.

I will now addressed some questions that are important and whose answers may not be immediately obvious or may be a matter of conjecture.

1. Why not simply use all the available receivers for each shot and forget about optimum designs?.

   In 2-D, with todays recording equipment having thousands of available channels, it may be reasonable to consider a “brute force” approach in which receivers for the whole line are deployed on the ground at the beginning of the acquisition and offsets 2, 3 or 5 times larger than the maximum target depth are used for every shot. This is clearly overkill and relies on the assumption that during processing the useful offsets will be “sorted out”. The problem is that at processing it may be too difficult or time consuming to determine which traces to actually keep for each shot or CMP. As a result, we may end up with lots of essentially useless traces getting in the way of efficient processing.

   In 3-D the brute approach will not work at all for any reasonably large survey because of the sheer volume of equipment it would require. Even if the recording equipment itself can handle all the channels, there are still the problems of the cables, the recording boxes, the communication channels, the antennas, the batteries, and so on.

2. What are the implications for the logistics of operation of the proposed methodology?

The logistics of operation do not need to be strongly affected since the receivers will be deployed as usual and the recording equipment will electronically connect and disconnect the required receiver stations for each shot based on the information of the geometry (SPS) files. Thus, the fact that the template may change from shot to shot (or from salvo to salvo in 3-D) is not a negative logistics issue.

3. Why acquire the intermediate traces?. If we already computed the optimum positions for sources and receivers so as to have "perfect" illumination what valuable information can there be in the intermediate traces?. Why go to all the trouble of finding optimum receiver positions if we are going to use the intermediate receivers as well?.

   The intermediate traces, although possibly contributing redundant illumination, will be useful for random noise suppression, for velocity computations and for offset sampling necessary for prestack migration. Besides they will not require any significant extra acquisition effort.

4. What are the implications of the non-uniform offset distribution for prestack migration of the data?. Can we guarantee that there will not be spatial aliasing in the offset dimension?

   This is an open question for which I don't have a definitive answer yet. The idea is to include the sampling requirements for prestack migration as constraints to the inversion process, so that additional receiver or shot positions be considered to satisfy that constraint. The details of how to do that, especially in 3-D, is an interesting research issue.

5. What would be the situation for 3-D acquisition?

   For 3-D the situation is more challenging but also much more interesting and useful. We have now not only the degree of freedom afforded by the choice of offsets but by the choice of azimuths as well. Besides, the basic geometry template can also be considered a design parameter that (unlike common practice) can change spatially. The inversion process will be extremely difficult and strongly non-unique.

A more philosophical question, but one that has an important meaning is: What kind of data would we regard as ideal from the point of view of imaging? That is, assuming that we have no logistic or economic restriction whatsoever (except that the data can only be acquired at the surface), what would be the ideal data?

For the standard approach, some characteristics of this ideal data immediately come to mind: data in a very fine regular grid with a very large aperture. This is fine, and would provide us with a good image. I believe, however, that the ideal data would be data with very fine, regular subsurface illumination, with aperture being a function of the illumination requirements.

That subsurface illumination is an important attribute of a good design is not new. In fact most commercial software for seismic survey design offer an option to trace rays into the subsurface for a given design to produce illumination maps of the targets of interest. The maps obtained with different designs are compared and this information taken into account when deciding what the best design is or changes may be introduced to the designs and the process iterated. This is an example of the *forward* problem. What I propose is to base the survey design on the *inverse* problem: start with an initial model and choose the layout of sources and receivers to obtain optimum illumination.

SUMMARY AND CONCLUSIONS

Using all the available subsurface information to design the acquisition parameters of new seismic surveys in a given area seems like the sensible thing to do. Common practice, however, uses only maximum and minimum values of targets velocities, dips and depths. Starting from a subsurface model may seem to bias the acquisition, but we have to keep in mind that by not using any model we are in fact imposing a model of flat layers and constant velocity.

The real impact and usefulness of this methodology arises in 3-D land seismic acquisition where the cost of the surveys oftentimes requires the design to be a compromise of the different subsurface parameters in different parts of the survey. The design is then kept constant for the whole area. By adapting the acquisition effort locally to the imaging demands of the subsurface we could in principle acquire better data at the same cost or perhaps even cheaper.

It is all too common in 3-D land data that significant obstacles force us to deviate from the original design. The common practice is to displace shots and receivers to alternative positions chosen to maintain, as much as possible, the uniformity of fold and the regularity of offsets and azimuth distribution. All sources and receivers are considered equally important to the subsurface image, which is probably not a good idea in general. The presence of large obstacles can be incorporated into the design procedure and alternative source and receiver locations chosen to optimize the regularity of the illumination as opposed to the regularity of fold, offset or azimuth distributions as is standard practice. It may very well happen that some shots in the excluded area turn out not to contribute significantly to the critical parts of the image and so can be simply ignored if they are difficult to replace. On the other hand, it may turn out that those shots are critical and then there are concrete reasons to make a stronger effort to acquire them.

In conclusion, we should be able to use all the available information when designing the acquisition of a new survey and make decisions with as much information as possible. Shifting the emphasis from surface parameters (fold, offsets and azimuths) to subsurface parameters (illumination) is a step in the right direction.

THE WAY AHEAD

Clearly, the methodology described in this paper is only weakly supported by the simple 2-D example presented here. The challenge lies in the implementation of the non-linear inversion process capable of computing the optimum source and receiver positions given all the geophysical, logistical and financial constraints for 3-D data.

The sensitivity of the acquisition geometry to the accuracy of the initial structural and velocity model is also clearly an important issue to be analyzed in detail. Extensive research will have to be done before clear guidelines can be established in that respect.

REFERENCES

Cain, G., Cambois, G., Gehin, M., Hall, R. 1998. Reducing risk in seismic acquisition and interopretation of complex targets using a Gocad-based 3D modeling tool. Expanded Abstracts. pp 2072-2075. Society of Exploration Geophysicists.

Galbraith, M., 1995, Land 3-D survey design by computer. Australian Society of Exploration Gephysicists **25**, 71-78.

Liner, C., Underwood, W., Gobeli, R., 1999. 3-D seismic survvey design as an optimization problem. The Leading Edge of Eploration. September 1999, pp. 1054-1060. Society of Exploration Geophysicists.

Morrice, D., Kenyoun, A., Beckett, C., 2001. Optimzing operations in 3-D land seismic surveys. Geophyisics **66**, 1818-1826.

Stone, D. G., 1994, Designing Seismic Surveys in two and three diensions: Society of Exploration Geophysicists.

Vermeer, G. J., 2001, Fundamentals of 3-D seismic survey design. PhD thesis, Delft University of Technology.