Introduction

The first edition of this book was a slightly modified version of my dissertation (defended in February 2001). This second edition has been extended considerably. Many technological developments of the past 10 years have been included. Feedback from students attending my course on 3D survey design has helped clarify various not-so-clear discussions in the book. Another major difference is the inclusion of many new figures copied from the literature. Most of the existing figures have been redrawn to comply with the high standards used for figures in GEOPHYSICS, and all references are now compiled in a single list. Although the main text for this edition was ready by the end of 2010, some developments in the field of seismic data acquisition that occurred in 2011 and 2012 have still been included.[1]

Three-dimensional seismic surveys have become a major tool in the exploration and exploitation of hydrocarbons. In 1999, Exxon received the SEG Distinguished Achievement Award for inventing the 3D seismic method in the 1960s and acquiring many singlefold cross-spreads before 1970 (Walton, 1972). The first multifold 3D seismic survey was acquired on land in 1971 (Hardman, 1999), soon followed by more 3D surveys on land (van der Kallen and Pion, 2010) and marine (Watson, 2009), although it took until the early 1990s before they gained general acceptance throughout the industry. Until then, the subsurface was mapped using 2D seismic surveys.

Theories on the best way to sample 2D seismic lines were not published until the late 1980s, notably by Anstey (1986), Ongkiehong and Askin (1988), and Vermeer (1990). These theories were all based on the insight that offset forms a third dimension, for which sampling rules must be given.

The design of the first 3D surveys was severely limited by what technology could offer. Gradually, the number of channels that could be used increased, providing more options on the choice of acquisition parameters, which naturally led to discussions on what choice constitutes a good 3D acquisition geometry. The general philosophy was to expand lessons learned from 2D acquisition to 3D survey design. This approach led to much emphasis on the properties of the common-midpoint (CMP) gather (or bin) because good sampling of offsets in a CMP gather was the main criterion in 2D design. Then 3D design programs were developed, which mainly concentrated on analysis of bin attributes and, in particular, on offset sampling (regularity, effective fold, azimuth distribution, etc.).

This conventional approach to 3D survey design does not acknowledge the differing properties of the many geometries that can be used in 3D seismic surveys. In particular, the sampling requirements for optimal prestack imaging were not taken into account properly. My book addresses these problems and provides a new methodology for the design of 3D seismic surveys.

The approach used in this book is the same as in my *Seismic Wavefield Sampling*, a book on 2D seismic survey design published in 1990. Before the sampling problem can be addressed, it is essential to develop a good understanding of the continuous wavefield to be sampled. In 2D acquisition, only a 3D wavefield has to be studied, consisting of temporal coordinate t and two spatial coordinates: shot coordinate x_s and receiver coordinate x_r. In 3D acquisition, the prestack wavefield is five-dimensional, with two extra spatial coordinates: shot coordinate y_s and receiver coordinate y_r.

In practice, not all four spatial coordinates of the prestack wavefield can be sampled properly (proper sampling is defined as a technique that allows the faithful reconstruction of the underlying continuous wavefield). Instead, it is possible to define 3D subsets of the 5D prestack wavefield that can be sampled properly. In fact, the 2D seismic line is but one example of such 3D subsets.

The 2D seismic line is a multifold data set with midpoints on a single line only. However, in 3D acquisition, many possible 3D subsets are singlefold, whose midpoints extend across a certain area. These subsets are called minimal data sets (MDSs), a term coined by Trilochan Padhi in 1989 in an internal Shell report. An MDS represents a volume of data (sometimes called a 3D cube) that has illuminated part of the subsurface. If there were no noise, a single MDS would be sufficient to create an image of the illuminated subsurface volume.

Most acquisition geometries used in practice generate data that can be considered as a collection of sampled

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[1] A concise version of many changes in this second edition can be found in Vermeer (2010).

MDSs. Therefore, the properties of the MDSs need to be studied for a better understanding of acquisition geometries as a whole. This allows an optimal choice of acquisition geometry (if there is a choice; often, the geometry type is dictated by economic or environmental constraints) and of the geometry parameters.

The continuous wavefield to be sampled can be reduced to the wavefield of the characteristic MDS of the chosen geometry. Proper sampling of that wavefield means that at least two of the four spatial coordinates of the 5D prestack wavefield will be sampled properly. It is also recommended to maximize the useful extent of each minimal data set. Together, these two recommendations ensure minimal spatial discontinuities in the total data set. Spatial continuity is maximized, and the migrated minimal data sets contain a minimum of artifacts. Sampling of the other two spatial coordinates will be coarse in general. The coarsely sampled coordinates determine the sparsity of the geometry. Reducing the sparsity of the chosen geometry further reduces migration artifacts. Cost considerations determine in general how far sparsity of the geometry may be reduced.

The ideas and results discussed in this book should help one to achieve a better understanding of the structure of 3D acquisition geometries. With this understanding, geophysical requirements can be satisfied with an optimal choice of acquisition geometry and its parameters. Processing techniques can be adapted to honor and exploit the specific requirements of each geometry, especially orthogonal and areal geometries, leading to a more interpretable end product.

Based on the principles outlined above, this book addresses a variety of issues except for hardware (instruments, sources, receivers), which is not discussed in detail. Following is a summary of each chapter.

Chapter 1. 2D symmetric sampling

This chapter starts with a short summary of 2D symmetric sampling, which is a recipe for optimal sampling of the 2D seismic line. Two-dimensional symmetric sampling is based on a corollary of the reciprocity theorem, which affirms that the properties of the common-receiver gather are the same as the properties of the common-shot gather. As a consequence, sampling requirements of shots and receivers are identical.

Chapter 2. 3D acquisition geometries, their properties, and their sampling

Three-dimensional seismic surveys can be acquired using a number of different acquisition geometries. The most important geometries are areal, parallel, and orthogonal. Each has its characteristic 3D basic subset. If the basic subset is singlefold, it is also a minimal data set. In areal geometry, either shots or receivers are acquired in a dense areal grid. If shots are dense, receivers are sparse, or vice versa. In the first case, 3D common-receiver gathers are acquired. These gathers form the basic subset or MDS of this particular areal geometry.

Parallel and orthogonal geometries are examples of line geometries, in which sources and receivers are arranged along straight acquisition lines that are more-or-less widely separated. In parallel geometry, the (parallel) shot lines are parallel to the (parallel) receiver lines; in orthogonal geometry, shot and receiver lines are orthogonal. The basic subset of parallel geometry is the midpoint line, which runs halfway between the shot line and each active receiver line. The basic subset of orthogonal geometry is the cross-spread, which encompasses all receivers in a single receiver line that are listening to a range of shots in a single shot line. The cross-spread is an MDS with limited extent. The difference in properties of the various acquisition geometries is illustrated by the difference in diffraction traveltime surfaces of the same diffractor for the basic subsets of those geometries.

Fold of coverage can be determined by counting the number of traces per bin; but in crossed-array geometries and areal geometry, fold of coverage can also be counted as the number of overlapping basic subsets of the acquisition geometry. The definition of fold in the latter way can be extended to a definition of illumination fold and image fold.

The periodicity of virtually all acquisition geometries is determined by the two spatial coordinates that are sampled most coarsely in x and y, respectively. The area defined by these two largest sampling intervals is called the unit cell of the geometry. The smaller the unit cell, the smaller the sparsity of the geometry. Each acquisition geometry is also characterized by three aspect ratios: for bin size, unit cell, and maximum offset inline versus crossline. The 3D symmetric sampling of orthogonal and areal geometry is characterized by their aspect ratios, all of which should be equal to one in the ideal case.

For imaging, it would be ideal to have singlefold data sets that extend across the whole survey area but possess a minimum of spatial discontinuities so that they would produce a minimum amount of migration artifacts. These data sets are called pseudo-common-offset-vector (COV) gathers and can be constructed from so-called offset-vector tiles (OVTs). In most geometries, the size and shape of the OVT is equal to the unit cell. In sparse geometries, subsurface illumination is enhanced by reciprocal OVTs (tiles with the same average absolute offset but located in opposite azimuth quadrants).

Depending on the type of process, the basic subsets of each geometry and/or the pseudo-COV gathers may be most suitable as input gathers to various prestack processing steps.

Chapter 3. Noise suppression

Sampling in 3D acquisition is usually not dense enough to record low-velocity noise without aliasing. To reduce aliasing effects, shot and receiver arrays may be used. The arrays can be linear or areal. For a proper choice of arrays, the properties of the noise need to be known. An analysis of the energy distribution of low-velocity scatterers shows that in the cross-spread, most energy is concentrated on the flanks of the traveltime surface and there is less energy around the apex. Linear arrays are sufficient to suppress the energy in the flanks. If there is much undesirable energy coming from all directions, circular arrays can be constructed with a circular response.

It is often argued that arrays are a threat to the signal. However, in most situations, arrays with length equal to the station interval — chosen to allow proper sampling of the desired wavefield — have only mildly negative effects on the signal yet allow successful noise removal by combining array effect and prestack processing. Yet in situations with strong elevation changes or rapidly varying statics, arrays are to be avoided; the acquisition of very high frequencies also requires single-point acquisition.

In a well-designed acquisition geometry, most of the noise can be removed by prestack processing. Nevertheless, it is interesting to see that the stack response of wide acquisition geometries is better than that of narrow geometries with the same fold of coverage.

Chapter 4. Guidelines for designing 3D geometries used on land

The theoretical considerations and observations in the first chapters are translated into practical guidelines for choice of geometry and selection of parameters specifically for orthogonal geometry.

The first part of the recipe for 3D survey design deals with the choice of geometry and its parameters.

The objectives of the survey must be established, and all available information on the survey area — complexity of geology, quality of existing data, etc. — must be analyzed. This analysis may lead to various geophysical constraints that have to be satisfied in the course of the design process.

The choice between orthogonal, parallel, and areal geometry is largely determined by acquisition cost, orthogonal geometry being most efficient on land and parallel geometry in marine data acquisition. Yet geophysical requirements play a role as well, particularly the requirement — especially in complex geology — to illuminate the subsurface from all directions. In that case, orthogonal geometry will be selected not only for land but also for marine with ocean-bottom-cable (OBC) acquisition, whereas areal geometry is most suitable in deepwater situations using sparse nodes (4C receiver units with 3C geophone and hydrophone) and dense shots. The remainder of the chapter focuses on orthogonal geometry.

Knowledge of the area provides a representative velocity distribution to be used at various stages of the design process. The interpreter specifies the main targets, resolution requirements, and maximum dip of the targets so the designer can focus on the requirements of those targets and determine the maximum required frequency.

A 3D symmetric sampling is taken as a starting point to decide on the six main parameters of orthogonal geometry (two station intervals, two line intervals, and two maximum offsets). This simplifies the choice of parameters considerably: the aspect ratio of the bins should always be one (consequently, the station intervals should be equal), whereas the aspect ratios of the unit cell and the cross-spread should be close to one.

The choice of station interval is determined by the maximum wavenumber expected in the wavefield. The preference is for the whole wavefield, but an alternative is the maximum wavenumber of the desired wavefield without noise. In the latter case, it may be necessary to use arrays to compensate for coarse sampling of the noise. The choice of station interval can also be influenced by serious noise or by rapidly varying statics.

The mute function (offset versus time) determines the average fold for all levels where mute offset is smaller than maximum offset. This function may be computed from the maximum acceptable normal moveout (NMO) stretch, or it may be determined from the mute function used in earlier processing. The mute offset for the deepest target determines the choice of maximum offset.

Fold of coverage can be considered a dependent parameter (area of cross-spread/area of unit cell), but it can also be an independent parameter that must be met by a proper choice of the line intervals. Especially in areas with no earlier 3D surveys, it tends to be difficult to make a reasoned choice.

The second part of the recipe deals with the implementation of the designed geometry.

The same nominal geometry may be implemented by a large variety of templates or swaths: the one-line roll template (roll = crossline roll), sources outside the template, full-swath roll, multiline roll with extra receiver lines, and superspread can all be used. The technique chosen may depend on availability of equipment, efficiency of acquisition, and risk of theft or vandalism.

The required extent of the survey area depends on the fold-taper zone (a given for the selected nominal geometry, assuming a closed grid of shot lines and receiver lines) and the fullfold area of the geometry. The fullfold area depends on the area to be interpretable and the migration radius. This radius and the fold-taper zone may overlap partially, depending on data quality.

Obstacles often prevent laying out straight acquisition lines. Spatial continuity then requires the acquisition lines to be smooth. This ensures that common-receiver gathers have similar quality or continuity as common-shot gathers.

The choice of source type depends largely on the type of survey terrain. Sometimes it is necessary to use more than one type of source due to terrain variations. The source strength may have to be tested; in cases where the source strength has to be reduced, repeat sources should be considered for sufficient penetration.

Chapter 5. Marine seismic data acquisition

In marine seismic data acquisition, multisource multistreamer (MC/MC) configurations are usually preferred over stationary receiver systems due to cost considerations. Therefore, streamer acquisition gets the most attention in this chapter.

Many issues that play a role in the design and choice of streamer acquisition are covered, such as influence of boat speed on acquisition parameters, ghost effect, and feathering. The main weaknesses of streamer acquisition tend to be crossline bin size, crossline roll, ghost effect, and feathering. Other weaknesses are the absence of reciprocal OVTs due to end-on acquisition and, for complex geology, the narrow-azimuth (NAZ) distribution.

In the first decade of this century, various techniques have been reintroduced to broaden bandwidth by reducing the ghost effect. All techniques (over/under, dual-sensor streamer, and variable-depth streamer) were proposed or tried earlier but needed technological improvement to become successful.

The NAZ limitation of streamer acquisition can be overcome by using multiazimuth acquisition or wide-azimuth (WAZ) acquisition. Virtually always, WAZ towed-streamer acquisition tends to forsake desirable geophysical requirements because of the very high cost of achieving such requirements. A very interesting WAZ technique is coil geometry.

Simultaneous shooting is a way of reducing the cost of marine streamer acquisition. An interesting application is to simulate center-spread acquisition with a source boat directly behind the streamers. For WAZ acquisition, simultaneous shooting would improve inline sampling, but it would not reduce the large crossline rolls.

Stationary receiver techniques have the advantage that orthogonal and areal geometry are also feasible geometries, next to parallel. These techniques do not suffer from feathering. The main techniques are ocean-bottom cable and ocean-bottom node. The latter is more suitable for large water depths.

Time-lapse techniques for seismic reservoir monitoring can be used with any marine acquisition technique, although stationary receiver techniques tend to show considerably better repeatability, which is a much-needed feature of such acquisition.

Chapter 6. Converted waves: Properties and 3D survey design

Survey design for PS- (or C-) waves is different from P-wave acquisition, owing to the asymmetry of the PS-wave raypath. Differences in PS-wave illumination by minimal data sets of different geometries are much larger than P-wave illumination differences. For instance, a cross-spread with a square midpoint area produces an illumination area with a rectangular shape even for a horizontal reflector. The raypath asymmetry leads to asymmetric sampling requirements for shots and receivers. Shot-sampling interval is determined by P-wave velocity; receiver-sampling interval, by S-wave velocity. A NAZ parallel geometry tends to suffer least from asymmetry effects, whereas orthogonal geometry tends to suffer most. For analysis of azimuth-dependent effects, areal geometry might be the best choice. Processing of orthogonal and areal geometry data has to take into account the spatial discontinuities of the edges of their basic subsets because these edge effects cannot be mitigated by OVT gathers (as for P-wave acquisition).

Chapter 7. Some lowfold data examples

Noise spreads or microspreads are acquired with very dense spatial sampling for an analysis of low-velocity events. A cross-spread with very dense spatial sampling was acquired in The Netherlands. Time slices and cross sections illustrate the 3D behavior of the ground-roll cone and the scatterers inside the cone.

In 1992, the theory of 3D symmetric sampling was tested in Nigeria, where a cross-spread geometry was compared with the standard brick-wall geometry. The test geometry produced better results (higher resolution and better continuity) at target level than the standard geometry. The improvement can be attributed to larger width (maximum crossline offset) of the test geometry and to its better spatial continuity.

Various lowfold migration tests illustrate that under favorable circumstances, very low fold can be sufficient to get acceptable (exploration) 3D prestack migration results.

Chapter 8. Factors affecting spatial resolution

The minimal data sets of the various acquisition geometries also have different resolution properties. The main factor influencing the theoretically best resolution is the stretch effect, caused by NMO. Therefore, zero-offset data potentially have the best resolution. Resolution is not improved by reducing the midpoint sampling intervals while keeping the shot and receiver sampling intervals the same (bin-fractionation technique). Carefully selected "random" coarse sampling may produce fewer migration artifacts than regular coarse sampling; but to eliminate all artifacts, regular dense sampling is best.

Chapter 9. DMO

This chapter is of historical interest; it demonstrates the importance of a clear understanding of the properties of the cross-spread, one of the minimal data sets.

The theory of dip-moveout (DMO) correction was developed for 2D common-offset gathers. Initially, the success of application of DMO correction to 3D data was not really understood. The theory of DMO application to MDSs in general and to cross-spreads in particular dispelled the mystery. The application of existing DMO software to a singlefold data set (cross-spread) revealed serious amplitude and phase artifacts. This prompted improvements in contractor software.

Chapter 10. Prestack migration

Chapter 10 explores the link between data-acquisition parameters and imaging requirements. The basics of prestack migration are covered, with an eye on sampling requirements of the input data. The zone of influence (ZOI) is used to establish migration-apron requirements. Most MDSs have limited extent, leading to edge effects in migration. However, using pseudo-COV gathers constructed from OVTs tends to produce better singlefold images than other singlefold subsets of the geometry.

Appendixes

A few appendixes describe some theory that could not be included satisfactorily in the main text. Appendix C lists some useful formulas that are spread out in the main text.