Chapter 8

Data Acquisition

This chapter describes the principal ways in which data acquisition affects the seismic data processing effort. This includes information about array effects, aperture, aliasing, and the physical arrangement of the acquisition methods themselves.

The most frequently asked question about seismic data acquisition may be about the optimum approach to acquire the data. Fundamentally, this is a question about the geometry and sampling rate of the receiver array, but it easily expands to include what source we should use, what microphones we should employ, whether or not we should use geophone sub-arrays, how big our aperture should be, and, finally, what temporal and spatial sampling rates we should select. In the spatial sense, we have always acquired seismic data digitally. We never had continuous (analog) sampling in space; analog data was only acquired in time.

The answers to these questions are mathematically and physically clear. For each source, the receiver array should consist of point receivers (no arrays) densely sampled over a wide aperture array encompassing a large square area. The source, however it is formed, should be a point source (no arrays) generating energy uniformly in all directions. For maximum benefit, there should be full source-receiver reciprocity; that is, for each receiver position, there should be a source, and for each source there should be a receiver. Hopefully, this chapter will make the reason for these statements clear.

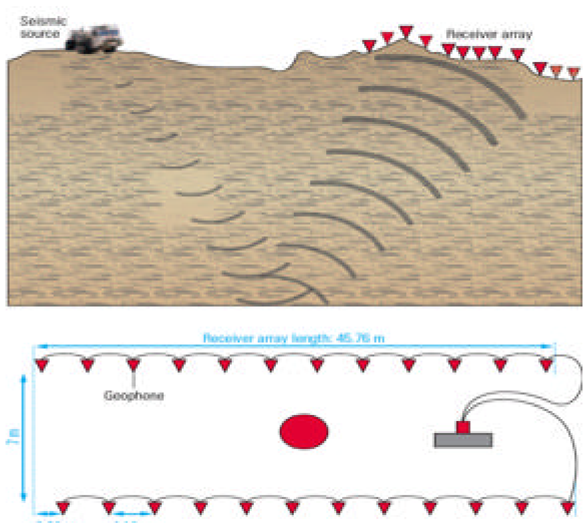
Unfortunately, there are many reasons why the mathematics and physics are almost always ignored—primarily, economics and practicality trump correctness. Furthermore, faced with budget limitations in an era when oil was relatively easy to find, little or no consideration was given to the underlying mathematical assumptions. Many geophysicists assumed that mathematics, including the wave equation, did not apply to the seismic acquisition process. Arrays were designed to control perceived noise, but frequently depressed the dip response. Fancy acquisition geometries were designed to reduce costs, but resulted in data sets that could not image geologic objectives. Illumination studies were conducted in an attempt to determine the impact of any given acquisition style, but, because they were often based on one-way equations or rays, the studies had no real impact on the solution—such studies can be fairly meaningless since complicated waveforms exist in even relatively simple geologic environments.

In contrast, mathematics does not lie. Mathematics, physics and a tremendous amount of empirical evidence suggests that imaging is a complex process almost totally controlled by the degree to which mathematical assumptions are honored. While we will not go into the mathematics in detail, we hope to provide a reasonable clarification of why we should acquire data in a precise, mathematically-correct manner. We will show that acquisition schemes can and should be modified to meet implicit assumptions.

Array Effects

Instead of recording single, non-overlapping shots into straight-line arrays, acquisition became one in which each shot was recorded by a line of receivers laid out on either side of the central shot. When receivers are laid out on only one side of a source, the resulting acquisition is said to be single ended. Figure 8-1 shows a typical single-ended acquisition, where a modern land vibrator provides the energy source causing the subsurface wavefield and its reflection. Receiver arrays record the response.

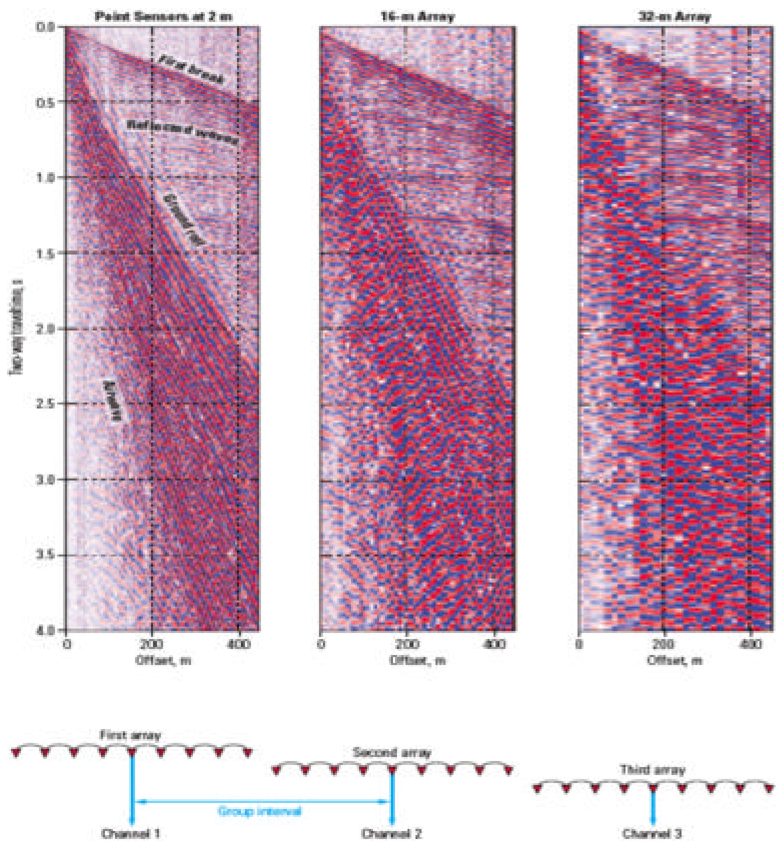
Figure 8-1. Schematic of typical multi-fold, single-end seismic recording process



The bottom part of this figure shows how receiver arrays can be arranged and summed to produce a single trace. The output of this sub-array forces us to recognize that each trace can be affected by the array response. Although such arrays were supposed to reduce noise when it was not economically feasible to record the full output at each location, the mathematics says we should record and image using all receivers.

Array effects are rarely considered as part of the overall acquisition-data processing-imaging methodologies. In fact, the underlying mathematics is based on the assumption that each receiver is a so-called point receiver, but this assumption is wrong when an array is involved. Figure 8-2 demonstrates the smearing that arrays cause. The three images show the effect of recording every trace, a group of 8 traces, and a group of 16 traces. Note the considerable blurring caused by the mixing. While it appears to improve continuity and reduce noise, the net effect tends to be unwanted dip reduction.

Figure 8-2. The effect of seismic arrays.



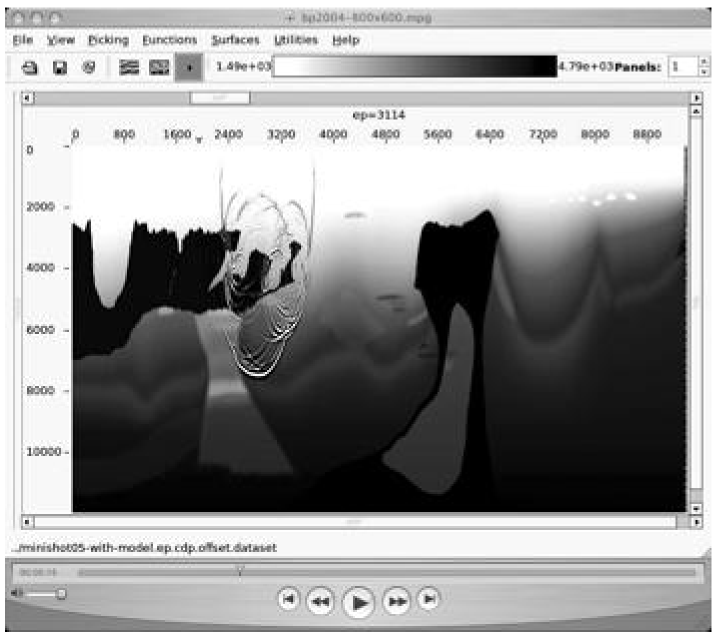
Among other things, smearing can reduce the dip response of the recording system and thereby seriously decrease the quality of the ultimate image. Although it seems like a good idea to use arrays, and, when steep dips are not an issue, it seems to make sense, that is never really the case. The use of arrays is a fundamental violation of the mathematical assumptions in all cases. Today, it is probably possible to record all the receivers. The affect of any given array can be emulated in the processing stage, so applying it in the field seems to be unnecessary and it is perhaps a big mistake.

Aperture

Figure 8-3 (courtesy of BP) provides an example of the kind of Earth model that you might see in the Gulf of Mexico. This model represents a typical salt imaging problem. Given that this model is a reasonably accurate representation of the subsurface, several facts are clear:

- every conceivable type of wave propagation will occur;
- since sea level represents a free-surface, every type of multiple will be evident;
- proper imaging will require that data acquisition be performed with a sufficiently wide aperture to capture a sufficient set of reflectors.

Figure 8-3. A complex model for data synthesis. Model courtesy BP, Modeling movie courtesy Panorama Technologies.

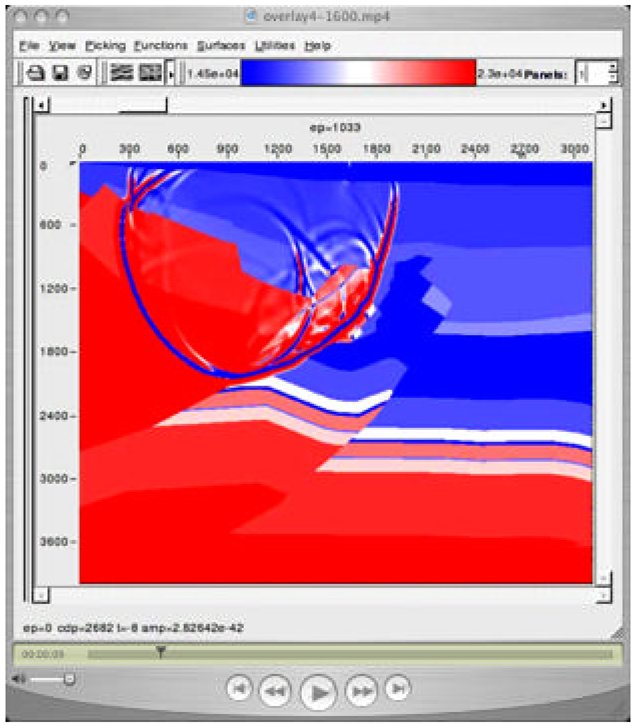


What modeling says is that producing an optimum image requires long offsets, long recording times, and small surface increments. What this means in three-dimensions is that we must use dense areal arrays as opposed to narrow-azimuth towed streamers. Another issue that is not fully appreciated is the importance of low frequencies. Full appreciation of this statement will become clear through the rest of the book.

Because it is from a Gulf of Mexico salt setting, many people conclude that the example represented by Figure 8-3 is of little value in a more worldly view of exploration. They say this kind of problem is simple to solve, and so should not be of much interest in the larger scheme of things. As we will see, this is far from the case. The salt-sediment contrast is on the order of 1.5 to 1, and a contrast this large is extremely difficult to handle for many of approximations used to produce imaging algorithms.

Figure 8-4 provides an example of the kind of complex geology we find on land. This perceived Oklahoma subsurface model from an over-thrust area in the southwestern part of the state faithfully represents a granitic overthrust in a very complex geologic setting. Once again, modeling tells us that to properly image subsurface structure, it is absolutely necessary to acquire long offsets and times. Thus, in both land and marine, satisfying mathematical assumptions means that acquisition arrays must be composed of point receivers, they must be areal in extent, and they must be densely sampled.

Figure 8-4. A complex model for data synthesis. Model courtesy Chesapeake Energy, Modeling movie courtesy Panorama Technologies.



The rocks are hard, the near surface velocity is highly variable, and it is not unrealistic to assume that the true Earth model should really include anisotropy. Again, all waveforms are present in the simulation, and unraveling them requires that, to the extent possible, all waveforms be used in the imaging.

A big difference between imaging land and marine data is the lack of water cover for land data. When water is present, it is relatively easy to figure out what the near surface propagation parameters should be since it is not necessary to rely on the recorded data to determine the velocity of water. When water is not present, we must estimate the near surface velocity structure (compressional and shear) from the data itself, but this is very difficult to do because the number of traces that can be used to do this is highly restricted by the acquisition parameters. Sufficient offset is seldom available to do even simple semblance-based picking. What modern methods need is data that are fit for purpose; data must contain the information necessary to permit accurate estimation of the Earth model.

Aliasing

Aliasing happens when the frequency of repetition is too fast for the true nature of the repetition to be recognized. For example, everyone who has ever watched an old American Western movie has seen wagon wheels, maybe like those in Figure 8-5, spin diametrically opposed to the direction of travel (backwards). This occurs because the thirty-frame per second sampling rate of the movie camera is incapable of resolving the faster rate of the wheel spin. The net result is that the wheel appears to spin at a slower rate in the wrong (backwards) direction.

Figure 8-5. Wheels alias when in motion.

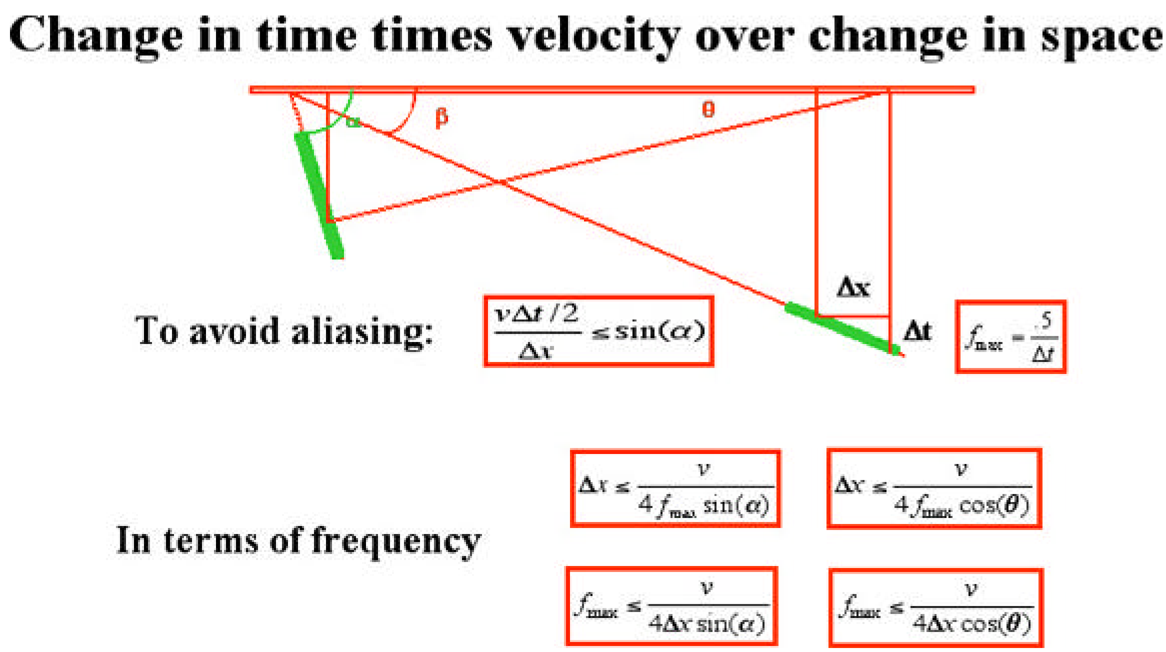
For our purposes, spatial aliasing in seismic exploration makes it impossible to correctly distinguish and image dipping events at their true position and angle. Many people argue that the mathematics of sampling is incorrect because they believe that if the human eye can recognize the correct pattern, the more mathematical migration algorithms should also be able to do so. But our brains make the event appear continuous, and handles it from there, while discrete mathematics cannot do this. The mathematics of discrete migration algorithms make strong demands on what kind of data they can handle because they cannot make the data continuous before they process it. Consequently, both acquisition design and the imaging algorithm must take aliasing into account. In some cases, the algorithm can be designed to handle any aliasing problem or issue automatically and directly. However, when this is not the case, aliasing must be avoided during the acquisition process itself. The elimination of aliasing ensures that dipping events are imaged as optimally as possible.

Data acquisition parameters play an important role in subsequent imaging exercises, while imaging algorithms vary considerably in their sensitivity to acquisition parameters. Understanding the impact of acquisition parameters on imaging techniques is the key to producing superior images.

Many geophysicists believe that there is some magic level of sampling, or that the sampling rules seemingly demanded by acquisition and processing are unnecessarily strict. The basic idea that the human eye is better than the computer at being able to see through under-sampled data is probably true. However, ensuring that any given imaging application produces the most optimum results limits both the kind and style of the acquisition method. For the most part, data must be sampled sufficiently finely to ensure that the imaging algorithm can image target objects without loss of dip or image quality.

Figure 8-6 provides simple, conservative formulas relating the important parameters that affect the relationship of dipping reflectors at their true subsurface position to their apparent dip on a two-dimensional seismic recording when the source and receivers are coincident and the velocity is constant. The relationship between apparent dip, as specified by a change in time versus a change in space, coupled with Shannon's sampling theorem, tells us when to expect and how to handle potential aliasing caused by spatial sampling intervals.

Figure 8-6. Aliasing Formulas



The trigonometric *sine* function of the true dip of the subsurface event turns out to be the ratio of half of the relative change in two-way time of the event at its apparent position, Δt, to the spatial range over which the time change takes place, Δx, multiplied by the assumed constant velocity of sound in the medium.

After this simple concept is understood, it is straightforward to use the Nyquist relationship between time sampling and frequency to rewrite the basic formula in terms of frequency. The Nyquist relationship states that a signal must be sampled at a rate greater than twice the highest frequency component of the signal to accurately reconstruct the waveform; otherwise, the high-frequency content will alias at a frequency inside the spectrum of interest.

Note that fixing any three parameters in the variety of formulas rewriting the basic formula produces provides a bound for the fourth. In 3D, it is important to do the calculations based on the largest spatial interval in the data set, Thus, if we want to make sure that we can image a given set of dips at a given frequency and velocity, we must make sure that the data has been recorded at the correct spatial spacing, or we must migrate it at the proper sampling interval.

You should understand that these are conservative formulas. The fact that velocities vary helps the imaging process because, in this kind of medium, ray bending improves the ability to image steeper dips. In precise mathematical terms, note that:

(8-1)
$$\frac{\partial t}{\partial x} = \frac{\Delta t}{\Delta x} = \frac{2\sin\alpha}{v}$$

We all claim to understand the idea that when we sample a signal at a fixed even increment, the resulting set of samples can be used to reconstruct the original signal completely, but only up to a fixed frequency determined by the sampling rate (that is, the Nyquist frequency). Thus, if we sample at 250 samples per second (in other words, 4 milliseconds per sample), the highest possible frequency we can record correctly is 125 Hz, or exactly half the sampling rate. Note that in this case, the Nyquist frequency is determined equally from 250 or half of 1.0/.004. Thus, 125 = 1.0/.008. A similar equivalence is available for surface sampling parameters. If lines are spaced at 100 meters, the spatial Nyquist frequency in the line direction is 1.0/200. This Nyquist frequency specifies the maximum wavenumber or wavelength that can be safely recovered from the surface sampled data in the line direction.

Figure 8-7 shows a schematic of a single plane monochromatic wave front traveling at a slight angle relative to the vertical. The wave front on the right is recorded in time, while that on the left is recorded in depth. The wave front in this case is propagating in a constant velocity medium and is characterized by its vertical and horizontal wavenumbers, or their reciprocal wavelengths. The vertical wavenumber, k_0, is completely determined by the frequency, w, and the velocity, v. In contrast, the horizontal wavenumber, k_x, is impacted by the angle of propagation. Later, we will see that this dependence on angle can be used to specify a simple migration algorithm.

Figure 8-7. Wavenumbers

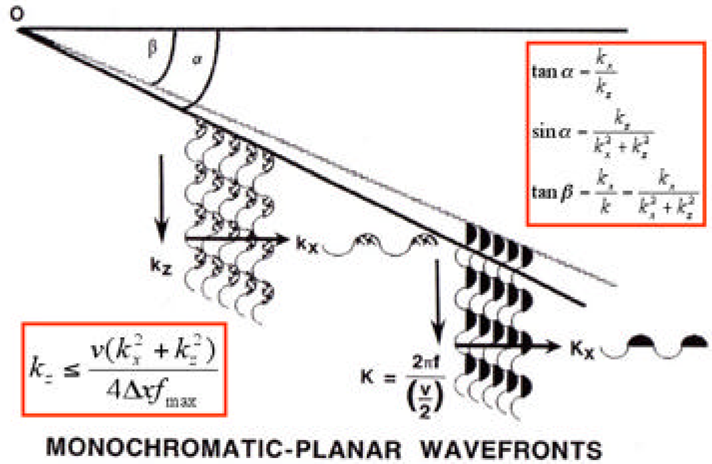
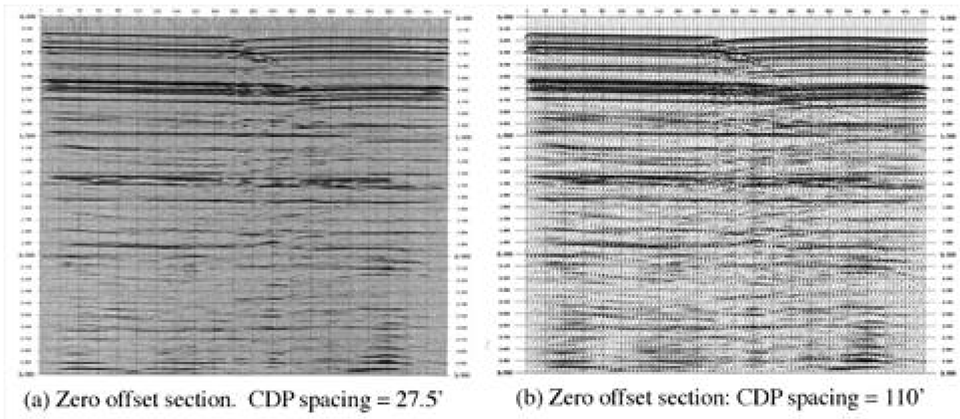


Figure 8-7 also shows the relationship between monochromatic wavefronts true dip. The figure shows how the trigonometric functions relating apparent dip to true dip are expressed in the frequency domain. The most important formulas say that the sine of the true dip angle, α, is equal to the tangent of the apparent dip angle, β.

It is important to note that in the real world, this means that we must consider measured seismic data to be digital in character, since the sources and receivers are at discrete locations. Since modern data is also digital in time, reflection seismic processing today is purely digital. Since wavenumbers of plane waves carry information about the angle of propagation, this suggests that there will be some issues with regard to the aliasing of dipping subsurface reflectors. The impact of aliasing on our ability to image subsurface events will be discussed in subsequent sections.

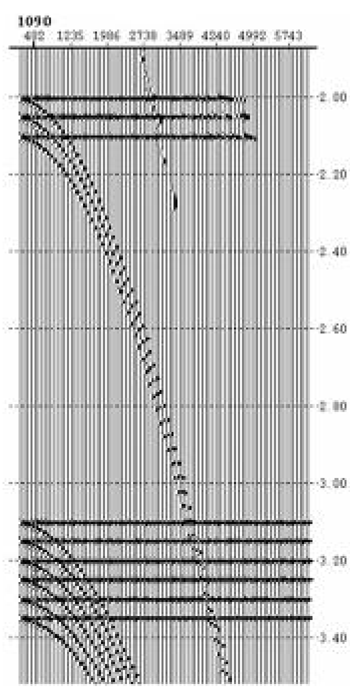
Aliasing appears in many ways. Figure 8-8 demonstrates the appearance of aliasing on zero offset sections. Here we see the difference between sampling at 27.5 feet and 110 feet. The figure on the left at 27.5 feet is clearly less aliased than the one on the right at 110 feet; that is, the section on the left has been sampled sufficiently finely to almost completely eliminate all aliasing for this level of dip. The section on the right was constructed by simply eliminating traces from the one on the left. Evidence of aliasing is represented by the grainy appearance and by the areas where events that follow some hyperbolic-like trajectory appear more like a single flat event.

Figure 8-8. Aliasing when the data are flat.



The synthetic CDP in Figure 8-9 is a normal moveout corrected CDP or midpoint gather with both flat and hyperbolic arrivals. It demonstrates a form of aliasing that occurs when the moveout of an event is so strong that the recorded spatial sampling cannot handle its rapidity adequately. This means that events can be aliased in offset even when all dips are perfectly sampled in space. This figure shows a synthetic (raytraced) CDP with multiples that are aliased in offset. While the human eye has no difficulty recognizing the pattern of these events, many noise suppression and migration algorithms will treat these events in a predictable, but incorrect manner. For example, a Radon transform is not be able to completely remove the event from the record.

Figure 8-9. Offset aliasing.



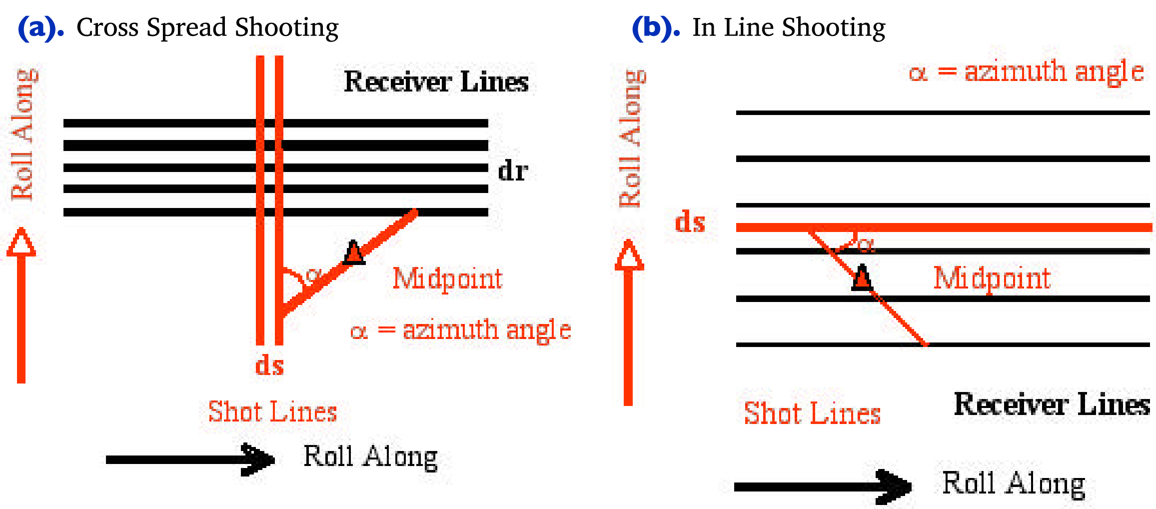
Modern Acquisition Geometries

This section describes the physical structure of the commonly used methods of acquiring seismic data over land and water environments.

Cross and Inline Spreads

Modern 3D land acquisition takes many forms. Figure 8-10(a) shows a typical cross-spread acquisition where shot lines are perpendicular to receiver lines. As the acquisition progresses, the entire pattern is rolled along to cover a large area. This represents true 3D acquisition with large azimuth variation.

Figure 8-10. Modern Land Acquisition



While the data from this kind of acquisition can still be sorted into the usual gathers, it can also be sorted into what are called common azimuth gathers. While this type of shooting produces uniform surface coverage, at least in terms of common midpoints, it usually does not fully satisfy underlying mathematical requirements.

Figure 8-10(a) shows the geometry of source lines relative to receiver lines for what is called cross-spread acquisition. Figure 8-10(b) shows acquisition for inline shooting. A grid of receiver lines records the output of sources aligned along source lines. The source lines are separated by *ds* and the receiver lines are sampled every *dr*. Both the source lines and receiver grids are rolled-along to achieve uniform surface redundancy. Part (b) shows a typical inline land acquisition geometry. This style is clearly reminiscent of typical 2D split-spread acquisition, and, in fact, the only real difference is that multiple parallel receiver lines recorded each shot response. Like its cross-spread cousin, inline acquisition produces data sets with uniform surface coverage. Because the number of recording lines is small, it usually only produces narrow azimuth data.

As was the case for our split-spread acquisition, each gather from either of the recording geometries in Figure 8-10 can be migrated independently of any other similar gather. Thus, we can conceive of migrating common azimuth volumes for detailed illumination comparisons. Note that this kind of acquisition produces five dimensional data since there are two coordinates for the source, two coordinates for the receiver, and one coordinate for time. The most important point is that widely spaced lines are good for quick coverage but are bad for spatial sampling.

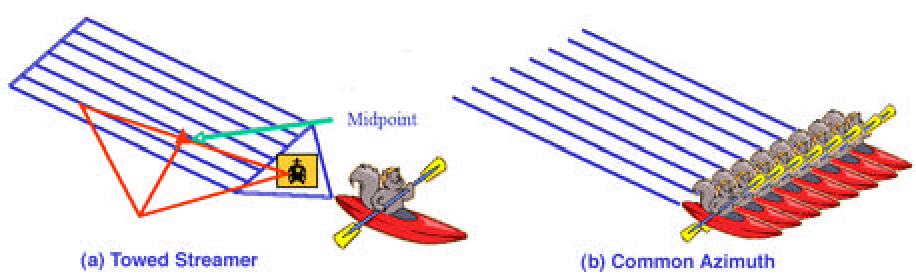
Sampling will become an issue later when we discuss its impact on high resolution migration algorithms. Although this style of sampling can generate many different azimuths, each azimuth is poorly sampled, meaning that, in some cases, azimuth migration cannot be performed.

CATS, NATS, and WATS

Marine data acquisition has evolved from single cable, single source acquisition to multi-cable multiple source, multiple boat and even ocean bottom (OBC) configurations that can record long offset data in record time. Again, redundant coverage can be sorted into any of the orders discussed in old-fashioned, split-spread shooting.

Figures 8-11(a) and 8-11(b) show current common azimuth towed streamer (CATS) and narrow azimuth towed streamer (NATS) geometries. There are typically 1 to 20 streamers spanning a cross-spread length from 0 to 2000 or 3000 meters. The geometry on the left has many receiver streamers, while the common azimuth geometry on the right has only one streamer. Although impossible in normal applications, the streamers in the single-ended marine experiment are never really straight. For migration purposes, the cross-spread width should be as large as possible.

Figure 8-11. Schematic of typical towed multi-streamer marine acquisition.



Towed streamers containing a few hundred receivers record data every time the sources, usually air guns just behind boats, like those shown in Figure 8-12, are fired. Because of boat movement, recording time is usually limited to at most 10 to 15 seconds. Receivers in each streamer data are very finely sampled in each dimension. Cable spacing is rarely more than 100 meters with the number of cables ranging between 1 and 20. The number of traces per shot is large while the shot density per unit area can be relatively low. Although this kind of geometry has been used for many years and has proven to be reasonably good for advanced imaging techniques, it is still somewhat far from what the mathematics and physics demands. An important issue with this approach is cable feathering caused by water currents, which usually means that it is not possible to achieve the precise common azimuth form shown in the right half of Figure 8-11. Since most of the algorithms we consider must be run on a grid, traces may have to be regularized to that grid to ensure algorithm accuracy and final image quality.

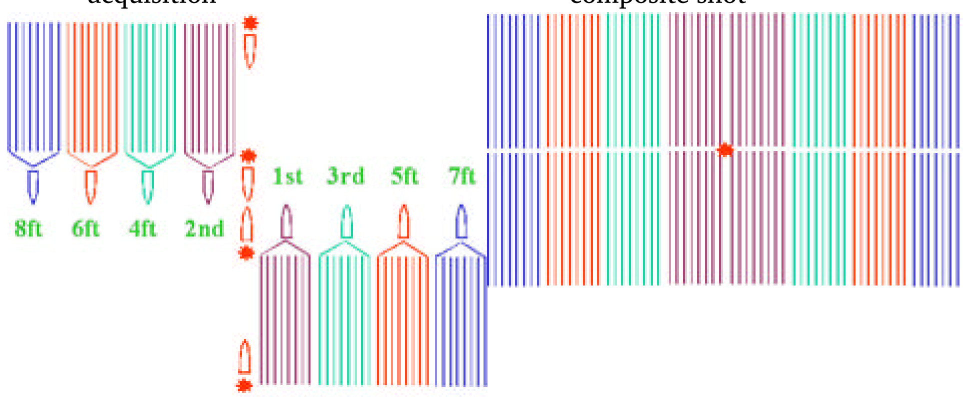
Figure 8-12. Petroleum Geo-Services (PGS) boats in operation. Note the towed streamers and the triangular shape of the Ramform boats.

Figure 8-13(a) and (b) show a wide angle towed streamer (WATS) acquisition and composite shot. In WATS schemes, gunboats make multiple passes over the same shot line. One gunboat is placed at the head and to one side of the receiver array and the other is on the same side at the end of the array. The boat towing the receiver array parallels the gunboats, but traverses an every widening path in accordance with each pass of the source boats. Part (a) shows double gunboats recorded by a single eight streamer receiver boat to achieve shot centered receiver arrays. Four or more wider receiver swaths may have to be recorded to produce sufficient data to produce receiver arrays with areal coverage, as indicated by the surface coverage in the composite shot layout in Part (b). The WATS technology may be the first marine acquisition scheme that actually honors the mathematical assumptions underlying seismic imaging algorithms.

Figure 8-13. The geometry of wide azimuth towed streamer acquisition.

(a). Wide azimuth towed streamer acquisition

(b). Wide azimuth towed streamer composite shot

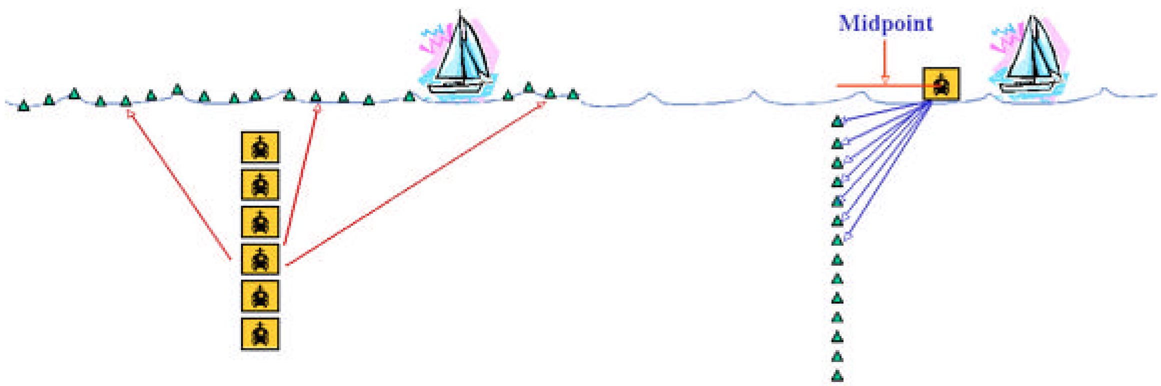


The composite shot in Figure 8-13(b) can contain a huge number of receivers. This figure was constructed based on the assumption that the receiver boat could effectively tow just eight streamers. Utilization of receiver boats towing 16 or more streamers would cut the work load significantly while still producing a composite shot that is much closer to the true mathematical ideal. When 8,000 meter streamers are separated by 100 meters, eight streamer WATS shots have an areal extent of approximately 6,000 meters by 16,000 meters but could certainly cover an area 16,000 meters on a side. As shown by BP, these types of acquisitions do, in fact, produce data sets fully capable of imaging complex subsurface geology.

Vertical Cables (VC)

Vertical cables, as shown in Figure 8-14, are just that. Receivers are actually placed along a vertical cable suspended at a fixed surface location either by sea anchors or by a tether attached to the ocean bottom. Usually source and receiver reciprocity is used to change the acquisition process into an equivalent one where the sources are assumed to be along the cable and the receivers on the surface. While vertical cable acquisition is certainly capable of generating the equivalent of the composite shots of WATS, this particular approach has never achieved its promise, probably because of the inability to keep the cable in a fixed and completely vertical position. Furthermore, processing common receiver gathers as if they were common source gathers is much more computationally efficient than processing common-shot gathers.

Figure 8-14. Marine Vertical Cable Acquisition.



Ocean Bottom (OBC)

Since gunboats can shoot in a virtually unlimited set of locations, OBC acquisition can generate areal array shots quite easily. In Figure 8-15, receivers are laid on the ocean bottom and sources are located on the surface in gun boats like those shown in Figure 8-16. The receivers on the ocean bottom can be organized into a grid or as a small set of cables similar to those used on the surface. The grid can be positioned on the bottom by a remotely operated vehicle, by a manned submersible, or by simply allowing the cables or receiver unit to sink to the bottom. Wireless communication can be used to accurately locate the receivers when in position.

Figure 8-15. Schematic of a typical ocean bottom acquisition.

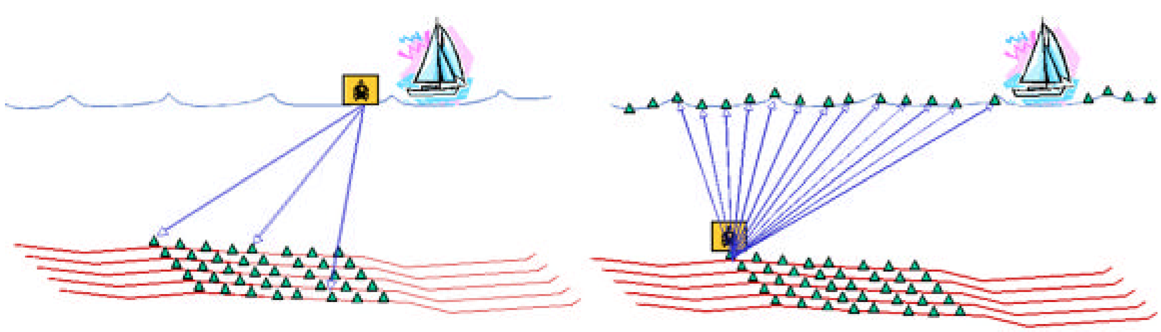
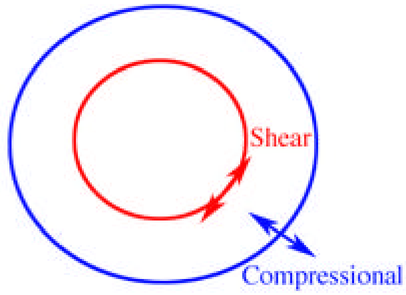


Figure 8-16. Fairfield gunboats near shore. OBC acquisition removes many restrictions on where source boats can sail.

Because the sources are at the surface, the gun boat can move in any direction desired. As a result, many azimuths can be recorded during the acquisition session. Data from the receivers can be recorded on the gun boat or on another boat especially designed for recording and processing. If sea-floor cables are used, this acquisition can be very similar to orthogonal shooting on land. The basic difference is that the source boat can move in any desired direction and consequently can generate full azimuth surveys. Usually source-receiver reciprocity is used to view a common-receiver gather as a single shot, making source spacing and density extremely important. Because receivers are actually on the ocean bottom, this data usually must be preprocessed almost as if it was land data. Certainly, receiver coupling or lack thereof, and the consequent amplitude differences must be addressed and eliminated or at least suppressed.

Regardless of how they are generated, seismic wavefields are the result of particle motion in the medium. Figure 8-17 shows two types of motion: compressional and shear. The red wavefront particles are vibrating tangentially to the wavefront as part of a shear wave. In a medium where velocity varies with angle (that is, an anisotropic medium), there are two orthogonal shear waves. Shear waves do not propagate in a fluid or gas. Particles on the blue wavefront vibrate perpendicular to the wavefront in the ray direction and consequently are part of a compressional wave. Perhaps the best example of a compressional wave is sound in air. Particles in air are compressed and rarified as the wave front progresses. Compressional waves travel in virtually all fluids and solids. Shear waves in solids generally travel at about 60% of the speed of compressional waves. Typical speeds of compressional waves are 330 m/s in air, 1450 m/s in water and about 5000 m/s in granite.

Figure 8-17. Shear versus Compressional waves



Shear waves are much more difficult to visualize than compressional waves. A good way to think of shear propagation is to consider a deck of cards. It is quite easy to slide the cards in the deck against each other and so generate a wave that propagates through the deck from one end to the other. While this is not necessarily how such waves propagate in the earth, the existence of shear propagation is not in question. Since shear waves cannot propagate in water, it is impossible to record shear waves in the water layer, but this does not mean that marine recordings do not contain shear wave information since all recordings, both land and marine, contain converted wave data. Seismic data from land and OBC data can both contain direct shear reflections, but data recorded in water contains only shear-related compressional waves that are direct conversions from shear to compressional at the water-ocean-bottom interface.

Practical acquisition of OBC data, as shown in Figures 8-18, 8-19, and 8-20 takes several forms. Whether the receivers are cables, as shown in Figure 8-18, or individual units like those shown in Figures 8-19 and 8-20, the primary objective is to place the receivers on the ocean bottom at precisely known locations, but this is not always easy to do. For example, cables are usually towed and then dropped, but even with radio sensors, it is not always possible to determine their exact ocean bottom position. The units in Figures 8-19 and the more modern version in Figure 8-20 contain computer systems that can accurately determine position and relay the information back to the recording instruments. In addition, they have sufficient local storage to record several shot responses before they must transmit the data to the primary storage system.

Figure 8-18. Ocean bottom layout and acquisition. This figure shows the cables and sensors used to acquire data from ocean bottom cables.

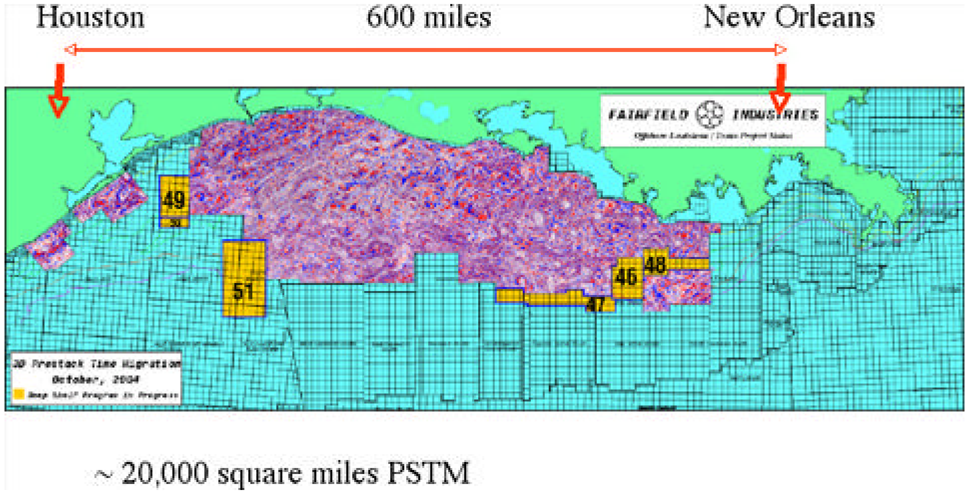
Figure 8-19. This figure shows boxlike ocean bottom receivers being deployed overboard (bottom left and top right) in both deep and shallow marine environments. The top left composite demonstrates that source boats can operate close to shore and platforms.

Figure 8-20. Fairfield Industries' latest ocean bottom recorder contains four phones and all the electronics necessary to record source-responses.

The secondary objective of OBC recording is to ensure that each component of the OBC receiver is correctly oriented. Each OBC phone contains a hydrophone, two shear phones, and one accelerometer. The two shear phones must be level and their orientation fixed relative to the rest of the receiver units. Consequently, they are gimbaled and adjustable based on each unit's digital compass. Clearly, OBC acquisition is difficult and potentially expensive.

Regardless of which acquisition method is employed, the net result are data volumes that are truly massive. Figure 8-21 shows a single time slice through 20,000 square miles of prestack, time-migrated Gulf of Mexico data with an average redundancy of about 90. Simple back of the envelope calculations suggest that the size of this data volume is several hundred terabytes or more. One can easily imagine ocean bottom acquisitions more than four times as large as this one.

Figure 8-21. This figure shows a time slice from a prestack time migration that essentially covers the Gulf of Mexico Continental shelf. (Image courtesy of Fairfield Industries.)



Data Acquisition Summary

The usual seismic sound fields we record are due to what we frequently consider to be point sources. As they propagate into the Earth, they radiate in all directions. The normal to the propagating wave front at any given subsurface location points in the direction of what you can think of as a ray. Since the propagation is normally not constrained with regard to direction, this normal can point in any direction consistent with the sound speed in the medium through which the field is propagating. If the normal points upward, it is an upward traveling wave; if the normal points downward, it is a downward traveling wave. Clearly such fields change directions at 45 degrees, and they become purely horizontal waves at 90 degrees.

If we arbitrarily assume that what was recorded only propagated upward, much of the true wavefield will not be properly imaged unless the assumption is true, but it should be clear that this kind of assumption cannot possibly be true. Nevertheless, the assumption that wavefields travel only in the upward direction is a major part of the migration/inversion/imaging algorithm set.

Note that while the Earth permits wave motion in all directions, migration algorithms may or may not be able to handle these motions. Table 8.1 summarizes the type of algorithms that are currently used in practice. We will consider each of these types of waves and how they impact the imaging process in the rest of the book.

Table 8.1. Wave Motion Hierarchy

Wave Motion	Wave Type
Waves move in all directions	Two-way wave motion
	Turning waves and rays
Waves move is almost all directions	Almost two-way wave motion
	Limited turning waves and rays
Waves move upward only	Propagation angles less than 90 degrees
	No turning waves or rays
Waves move downward only	Propagation angles less than 90 degrees
	No turning waves or rays

The measurement of seismic waves is accomplished using a variety of receivers or phones. These devices can measure the velocity of particle motion (accelerometers), pressure changes (marine geophones), and even the two shear waves. Modern OBC data is usually acquired using all four of these devices. Note that, although each class of phone records only data of that type, it also records all waves that converted from one form to another. Thus, unraveling, migrating, or imaging these data is only possible if they are all handled together. This is still a daunting task, even with today's massive computer power. The following list summarizes the type of microphones in use today.

- Accelerometers—Particle Velocity
- Geophone or hydrophone—Vertical Pressure change
- Shear Horizontal
- Shear Orthogonal