EXTENDING THE RESOLUTION OF SEISMIC REFLECTION EXPLORATION

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INTRODUCTION

The Problem

Particularly in the United States, it has become very difficult to find prospective land that has not previously been explored for petroleum. Therefore, we must improve our exploration tools so that we can go back over previously explored areas and find fields that were missed in earlier exploration programs. This paper demonstrates how the seismic reflection method — the primary exploration tool — may be improved in resolution by proper field design.

New Developments

The development of new processing techniques and methods of interpretation (Anstey, 1977), as well as the need for better resolution, have made a re-assessment of field techniques essential. The introduction of new field hardware has made many more techniques practical. The new processes — such as wavelet processing and attribute analysis — have made it possible for us to use amplitude, phase, velocity and frequency information in a quantitive way, instead of the traditional approach of using only reflection time quantitatively.

To improve the resolution we must be more careful about retaining high frequencies in data acquisition. The new hardware has made this possible by almost eliminating the limits on numbers of channels, practical offset ranges, and sample rates. Telemetry systems allow any combination of offsets with no degradation of data due to cable resistence and leakage, and with few limitations due to what cables are available. Of course, these new options cost a lot of money, so we must be certain that they are needed. We must also consider what effect our field techniques have on processing costs. Table 1 lists the fifteen field parameters that define the field techniques used for surveys.

1. Far-trace offset
2. Near-trace offset
3. Geophone-group interval
4. Charge size
5. Charge depth
6. Multiplicity
7. Sample rate
8. Low-cut filter
9. Geophone frequency
10. Record length
11. Geophone array
12. Split or end-on
13. Line length
14. Line direction
15. Line spacing

Table 1. Field parameters.

The Traditional versus the New Approach to Parameter Selection

Traditionally, the recording parameters used are "what was used last time" or "what fits the hardware we have available." Field techniques have been generally designed to avoid noise rather than to record reflections, and "what was used last time" may originally have been designed twenty years ago.

This is no longer good enough. Our objective should be to optimize the resolution of reflections of interest. Techniques are practically unlimited by hardware, although often limited by what we can *afford* to do. Because we are now particularly interested in resolution, the effect of field parameters on the reflections must be carefully weighed. Field technique design should be based on the known or predicted characteristics of target reflections.

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The content of this paper is based on Seiscom Delta's Technical Operating Standards. These standards owe much to the exploration philosophy developed by Nigel Anstey and later published in his book (1977). I also thank R.E. Sheriff for many helpful suggestions.

Where comparison shooting is necessary, the comparison must be objective rather than subjective. Designing arrays — which are wavelength filters — merely to exclude unwanted noise is undesirable, because the wavelength range of reflections overlaps the wavelength range of ground roll. Geophone arrays designed to attenuate coherent noise often act as a high-cut filter on reflections (Fig. 8). A further problem with arrays is that the array actually implemented in the field is not the one designed; even if the ground is perfectly level and the geophones are spaced by the jug-hustlers exactly as planned, there is no way of ensuring identical group coupling for all the geophones, and the geophones themselves usually vary in the transduction constant by 5%. In practice, large elevation changes across the array and large irregularities in the spacing are common.

Defining the Problem

Because the traditional approaches to desiging field recording parameters usually result in loss of resolution, the modern approach is first to define as closely as possible the exploration problem that is to be solved, and then to design the field techniques by logical reasoning from this objective. The questions that need to be asked are listed in Table 2. The relationship between the questions that define the problem and the field parameters listed in Table 1 is given in Table 3.

a) Target depth(s)?
b) Reflection quality?
c) Required vertical resolution?
d) Steepest dip?
e) Type of features of interest?
f) Special noise problems?
g) Access or logistic problems?
h) Special processing anticipated?

Table 2. Defining the problem.

Deciding on the target depth seems easy enough, but there can be subtle pitfalls involved. For example, in the Williston Basin it is common practice to use a shallow horizon as a reference plane, which makes the shallow zone important when target depths are being specified.

If the target is a good reflector, less effort will be needed to achieve a satisfactory signal-to-noise ratio than if the target were a weak reflector.

	a Target Depth(s)	b Reflection Quality	c Vertical Resolution	d Steepest Dip	e Type of Features	f Noise Problems	g Access or Logistic Problems	h Special Processing
1. Far-trace Offset	x							
2. Near-trace Offset	x						x	
3. Group Interval			x	x				
4. Charge Size	x		x			x		
5. Charge Depth		x	x			x		
6. Multiplicity		x	x			x	x	x
7. Sample Rate	x		x					x
8. Low-cut Filter	x		x			x		x
9. Geophone Frequency	x		x			x		x
10. Record Length	x							x
11. Geophone Array		?	x			x		x
12. Type Spread						x	x	
13. Line Length					x		x	x
14. Direction					x		x	x
15. Line Spacing					x		x	x

Table 3. Relating the problem to field techniques.

Better resolution is always desirable, but spending money to achieve better resolution than is necessary to solve the exploration problem may not be good economics, and there may be even less point in expending effort to try to achieve a resolution which it is unlikely can be achieved. Because horizontal and vertical resolution are closely interdependent, they should be considered together. There is no advantage in using a 15 m group interval where the highest frequency that can be recorded at the target depth is 30 Hz, because the vertical resolution (¼ wavelength at the highest frequency [Sheriff, 1977]) is about 30 m. In the same situation, it would be an error in the opposite direction to use 134 m for the group interval.

The expected appearance of a feature of interest is important in determining field techniques: it determines which aspects of the data must be retained and which can, if necessary, be sacrificed. For example, if a broad, gentle anticline with minimal closure is expected, long-period static corrections and reflection continuity are of great importance, but if the target is the updip pinch-out of a thin sand or a trap against a small fault, resolution is more important and techniques that smear horizontal variations must be avoided.

Special noise problems can affect almost any field parameter. In general, they tend to force the geophysicist to accept less than he would like to see and to pay more than he cares to pay. Signal-to-noise ratio can be traded for resolution (longer arrays or larger charges) or bought with more field effort (higher multiplicity, more geophones, shorter group interval, deeper shotholes). Knowing in advance any special noise problems helps the geophysicist to either modify his expectations or plan for the extra effort.

Access or logistic problems may limit the range of field parameters that can be used. Permit conditions may limit possible offsets, and the presence of buildings or pipelines may limit charge size.

Sometimes special processing requires a special field design. Migration, which is fast becoming standard rather than special processing, requires that spatial sampling be adequate for the dips and frequencies involved. If the group interval is too long, the choice is between limiting frequencies by filtering, or limiting the dips by restricting the migration aperture. Anstey (1977, p. 497) regards restricting the aperture to less than required by the dip as indefensible. Trace inversion to determine acoustic impedance requires wideband and true-amplitude seismic data. Special processing requirements often demand extra field effort.

Procedure for Determining the Field Parameters

1. *Far-Trace Offset*

The offset to the far trace of the spread should be such that the most important reflection comes in just below the front mute on that trace. For maximum resolution, the front mute usually zeroes data that involve more than 15% trace stretching in the normal-moveout correction; this corresponds to an offset approximately equal to the depth of a reflection at the mute time (Fig. 1). If the offset is too large, the nominal multiplicity is not recorded for the most important reflection, and if the offset is too small, the difference in moveout between primary and multiple reflections is less than it could be, so multiple attenuation is reduced.

2. *Near-Trace Offset*

Similar considerations limit the near-trace offset. It is necessary to ensure that at least single coverage is retained on the shallowest reflection of interest. If the shot interval is larger than the geophone-group interval, the shortest offset in some CDP gathers will be larger than the offset to the near-trace (Fig. 2). As a general rule the near-trace offset should be as short as possible. Sometimes shot-generated noise degrades traces close to the shot, but these may still be more useful than traces recorded at a long offset. Another consideration is that an excessive near-trace offset can give errors in reflection time because of the approximations in the theory of normal move-out corrections.

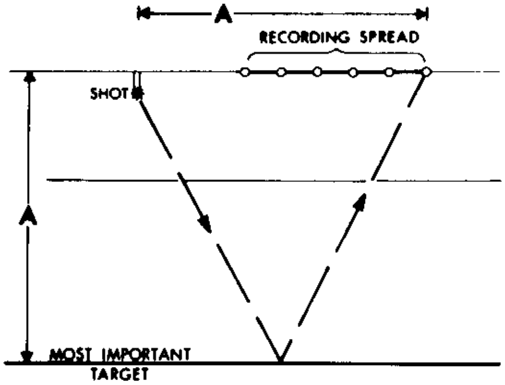


Fig. 1. Far-trace offset.

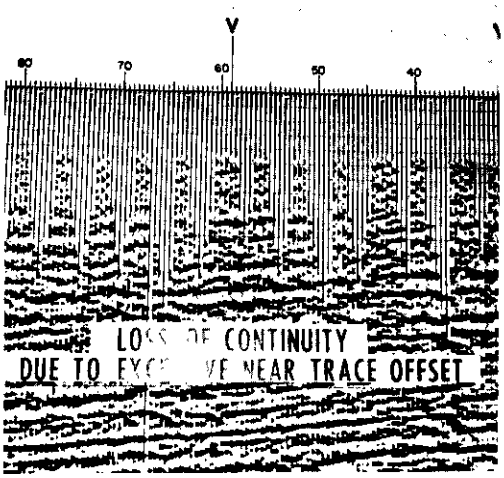


Fig. 2. Loss of shallow data with long near-trace offset.

3. *Group Interval*

The group interval should be chosen to give adequate spatial sampling for migration. This rule should generally be followed for acquisition because migration is now being done on most new data. Even in areas where the reflections are almost flat, migration is often of great use in localizing small faults or attribute changes. Where surface waves are to be attenuated by multitrace processing, the surface waves must be sampled adequately.

The sampling theorem states, "... band-limited functions can be reconstructed from equispaced data if there are two or more points per cycle for the highest frequency present ..." (Sheriff, 1973). In the CDP method the subsurface is sampled at half the group interval, so the shortest reflection wavelength that can be reconstructed is equal to the group interval.

The minimum wavelength component is determined by a reflection's apparent dip and frequency spectrum. Since wavelength equals apparent velocity divided by frequency, the minimum wavelength will occur where the apparent dip is steepest (apparent velocity lowest), and for the highest frequency component.

Even where this reasoning is followed, a common mistake is to use the dominant frequency instead of the highest frequency component, which is often an octave higher (a Ricker wavelet is down about 30 dB an octave above the dominant frequency). The minimum apparent velocity is usually present in the outer parts of diffraction hyperbolae and can be measured on an unmigrated section; this will approach the velocity of the rocks at the depth of the diffracting point. These steeply dipping diffracted data are essential for horizontal resolution (Claerbout, 1975, p. 238). The horizontal resolution is given by dividing the vertical resolution by the sine of the steepest dip angle used for migration:

$$r_h = r_v/\sin a$$

where r_h is the horizontal resolution, r_v the vertical resolution, and a the migration angle. Within the limits of recorded frequencies (see below under "Sample Rate") and practical migration angles (usually 45°), the horizontal resolution is directly determined by the group interval and (with the assumption of resolution = ¼ shortest wavelength) is equal to one quarter of the group interval. For example, for 60 Hz data and a velocity at target depth of 3000 m/s, the vertical resolution (¼ wavelength) is 6.25 m. If migration up to 45° is used, the horizontal resolution limit is 9 m. To record enough samples in a horizontal direction to achieve this resolution, a group interval of 35 m will be needed (to give a stacked trace spacing of 18 m). If the migration is carried out only to a dip of 30°, the horizontal resolution is limited to 25 m and a group interval of 50 m can be used (Fig. 3).

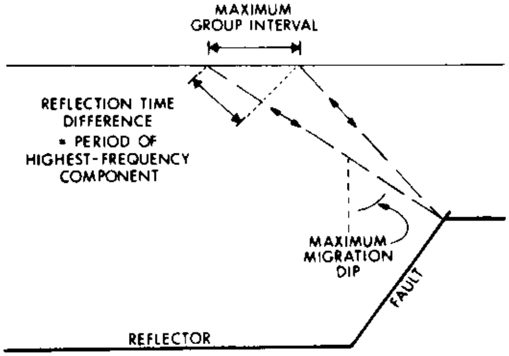


Fig. 3. Maximum group interval.

Diffraction hyperbolae may still be present even where they are not visible on the unmigrated sections. Data spread across the section at an amplitude too small to be seen may become visible when concentrated at a point by migration.

For surface wave attenuation with multichannel filtering there is one sample per geophone group (because the filtering is done before the stack). Again, we need two samples per wavelength. If there is ground roll with frequencies up to 15 Hz and a velocity of 400 m/s, adequate sampling is achieved with a 13 m group interval.

The group interval is a major factor in determining the cost of a survey, both in acquisition and in processing. Once the maximum group interval and the maximum offset have been established, the minimum number of groups is that which will give the required group interval over the required range of offsets. For the example given above, if the 3000 m target is the most important and the shallowest target of interest is 800 m, the minimum number of groups is 62; *i.e.*, (3000 m - 800 m) ÷ 35 m. Because a real system has 60 data channels rather than 62, 60 channels would be used. (Our measurements of frequency, velocity and target depth are not very precise). If 120 channels were available, split spreads could be used to record twice as much data from each shot. A suitable alternative with a 96-channel system would be a 72/24 asymmetrical split spread (see Section 12).

Some quick calculations will show you that most current surveys use inadequate spatial sampling, particularly if attenuation of ground roll by velocity filtering is used. Realistic values for frequency, depth and dip of reflections will usually give a minimum number of groups around 100, while typical ground roll includes components with wavelengths as short as 30 m requiring a group interval of 15 m.

4. *Charge Size*

Most conventional surveys over the past twenty years or so have been overshot. Generally, there has been a tendency to use a larger charge "to be safe" and widespread sloppy line discipline results in more ambient noise than necessary, so that a larger charge is needed to give a satisfactory signal-to-noise-ratio.

It is often argued that there is no geophysical case against overshooting, as it is almost impossible to overdrive an IFP recording system. Figure 4 shows records from shots of five and twenty pounds recorded a few minutes apart into the same spread from the same shotpoint and depth; the larger charge involves loss of high-frequency components, as shown by the lower amplitude from above 45 Hz and the reduction in peak frequency from 36 Hz to 31 Hz. This effect has been investigated theoretically and described in practice by Sharpe (1942) and Ziolkowski and Lerwill (1979). With the demand for better resolution, loss of high frequencies is unacceptable. Figure 5 shows the theoretical change in source-wavelet frequency with change of charge size.

Charge size should be determined by the ratio of shot-generated signal to ambient noise. The acceptable ratio at the target depth varies from about 1:1 where maximum resolution is required in a high mulitiplicity survey, to 10:1 where high-quality data are required but only low multiplicity is practical. Measurements can be

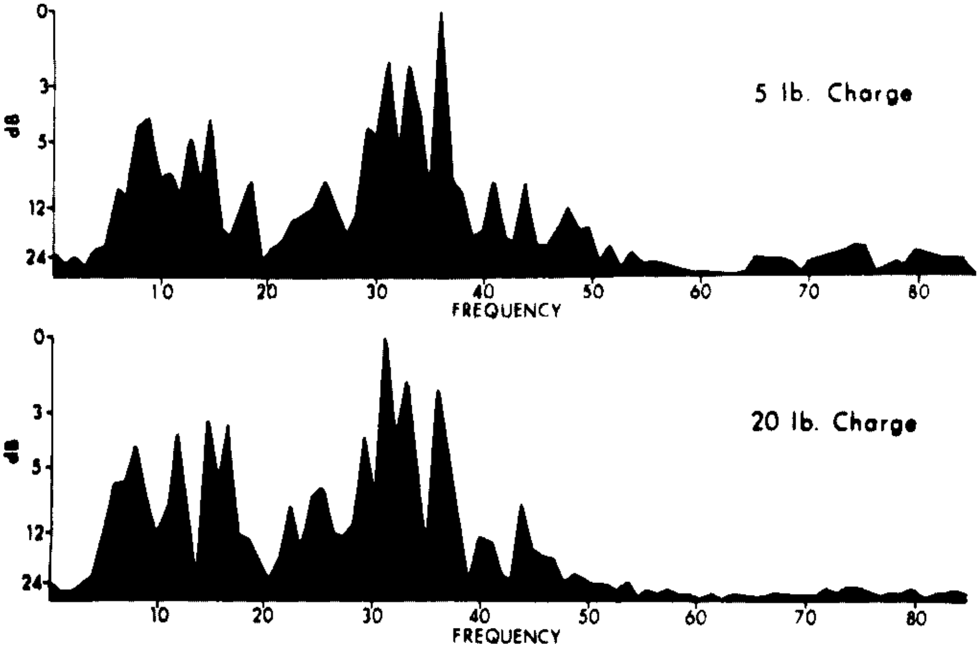


Fig. 4. Effect of charge size on frequency content.

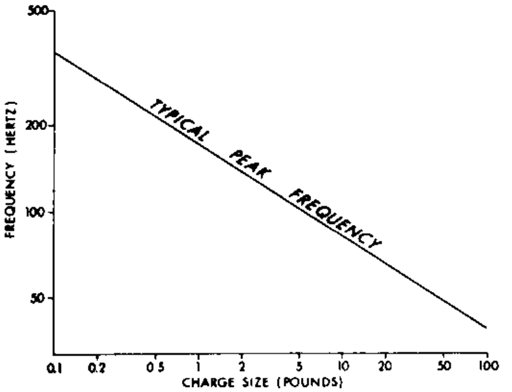


Fig. 5. Theoretical change of frequency with charge size.

made by comparing the signal level at the target depth with the amplitude of the ambient noise recorded before the first breaks. This can be done in the field by comparing trace amplitudes on a "defloat" (true-amplitude) playback.

5. *Charge Depth*

For maximum resolution the energy source must be below the weathering. In many areas there is an additional layer, below the weathering, which contains large velocity irregularities. The shot should be below these irregularities also. This paper considers only conventional surveys: use of any surface source immediately compromises resolution.

A charge depth test will show that, as the depth is increased, the resolution improves down to a depth below the near-surface irregularities. This depth is the optimum charge depth. Further increases in depth do not represent cost-effective expenditures.

6. *Multiplicity*

Multiplicity is a parameter that can be determined only by comparing the quality of sections processed from the same data with different multiplicity (Fig. 6). In general, 600% coverage is the minimum for proper functioning of processing routines that require multiple traces at each CDP. Doubling the multiplicity of coverage gives a theoretical improvement of 3 dB in the ratio of signal to random noise, and possibly better rejection of other noise. As A. A. Fitch has pointed out (1975, p. 109), the improvement expected from the CDP stack is not achieved in practice, so the only way the effect of higher muliplicity can be estimated is to try it. In most areas multiplicities beyond 2400% give only marginal improvements High multiplicities are of most use where targets lie both shallow and deep; the mute reduces multiplicity for shallow targets, so a high nominal multiplicity is needed to retain the minimum needed at the shallow target depths (Fig. 7). For example, if the deepest target (for which the far-trace

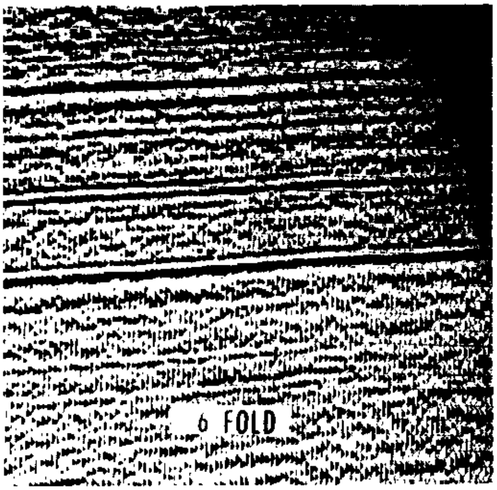
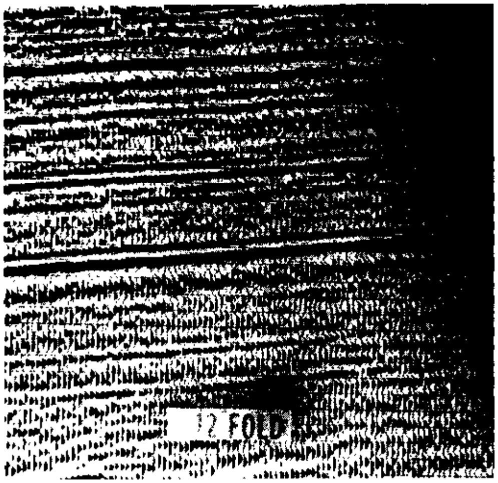


Fig. 6. Comparison of 600% with 1200%.



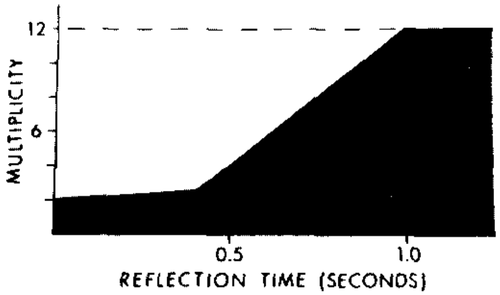


Fig. 7. Reduced multiplicity at early reflection times.

offset is set) is four times the depth of the shallowest target, 2400% nominal multiplicity is probably needed to achieve 600% coverage over the shallow target. As the number of recording channels has already been set, a decision on multiplicity sets the shotpoint spacing in terms of geophone group intervals. Where the number of shotpoints per mile is limited by practical considerations, it is often better to reduce multiplicity below optimum rather than increase the group interval.

7. *Sample Rate*

The sample rate is an important parameter only insofar as it controls the high-cut filter used to prevent aliasing. The high-cut filter should be high enough that the highest frequencies required in the target reflections are not attenuated. The highest frequency required is the frequency needed for the desired vertical resolution, or the maximum frequency of data that can be recorded at a given depth, whichever is lower. The maximum frequency f_{max} that can be recorded at a given depth will vary from area to area, but an empirical guideline is:

$$f_{max} = 150/t$$

where t is the reflection time in seconds.

The traditional approach to alias filters is to attenuate to a level comparable with the converter noise at the Nyquist frequency. For example, the standard alias filter in a DFS V with converter dynamic range of 80 dB attenuates at least 70 dB at the Nyquist frequency. However, this is often an unncessarily cautious approach, and a higher alias-filter frequency can be used without degrading the data (Fitch, 1976, p. 131). If a 72 dB/octave filter down 6 dB at 90 Hz originates from input signal at 160 Hz that has been attenuated 66 dB, it gives a 60 dB separation compared with a genuine 90 Hz signal that has been attenuated 6 dB (while attenuating at the Nyquist frequency (125 Hz) by only 40 dB). With the normal 64 Hz alias filter, the signal is attenuated to 60 dB above system noise at 72 Hz. Thus the 90 Hz filter, which is now available as an option with the DFS V, increases the upper limit of the passband by half an octave. In practice, data can be recorded up to 90 Hz with half as many samples as needed with a conventional alias filter.

Usually the alias filter frequencies on a particular system are fixed by sample rate, so the sample rate is set by picking the alias filter that will pass the required maximum frequency, and using the sample rate that goes with it.

8. *Low-Cut Filter*

Over the last fifteen years there has been considerable emphasis placed on retaining low-frequency information in the seismic signal. This low-frequency information is an important part of a seismic reflection, but retaining it often means using large arrays to attenuate shot-generated noise (such as ground roll). The large arrays attenuate high frequencies, so the signal bandwidth often is being extended on the low side at the expense of signal components on the high side of the spectrum. For maximum resolution, the high-frequency components must be retained, so it is better to reduce ground roll by other methods. One of the simplest is to use a higher low-cut filter, which has the effect of increasing the high frequencies at the expense of the low frequencies. However, a good rule is always to retain two octaves of bandwidth at the target reflections, keeping in mind the limitations the earth imposes on the maximum frequency.

9. *Geophone Frequency*

The choice of geophone natural frequency is related to the choice of low-cut filter. The geophone frequency is the major factor that limits the bandwidth at the lower end of the passband (-6 dB at ½ the geophone frequency and -24 dB at ¼ geophone frequency). The low end of the passband is extremely important, as pointed out above, but as excessive low-frequency energy can use up too much of the dynamic range of the recording system (ground roll may be 40 dB above signal level), geophones with a high enough natural frequency to reject most of the high-amplitude shot-generated noise such as ground roll may be required. For example, ground roll that is 24 dB above reflection amplitude with 8 Hz geophones will be the same amplitude as reflections if 28 Hz geophones are used. Otherwise, the geophone frequency should be as low as practical to retain bandwidth in the octave sense. As manufacturers have found that it is difficult to make geophones rugged enough for field use at a practical price if the frequency is lower than about 8 Hz, most geophones in use have a natural resonance in the 8 to 10 Hz range. Where wideband recording is used, spurious resonances in the 150-250 Hz range can be a problem with these low-frequency geophones.

10. *Record Length*

Record length is usually set by allowing a very generous margin beyond the deepest reflection. This is a safe practice, but it may be uneconomical as number of channels and sample rates increase. Generally the record should extend beyond the deepest reflection or diffraction of any interest for a time equal to twice the length of the longest operator to be used in processing. If migration is used, the termination of events at the end of the record can produce noise a long way up the section.

11. *Geophone Array*

There are two approaches to geophone array design: design to attenuate specific coherent noise trains, or design to attenuate all coherent energy except the desired signal. The first approach is the one that has generally been used in the past, when geophone arrays were the main technique available to attenuate noise, and the one about which most of the papers on the subject had been written, starting with one in the first volume of "Geophysics" (Klipsch, 1936) and culminating in papers such as Smith's (1956). Designing arrays to cancel a specific noise wavelength is now almost standard procedure: the first shooting in a new area includes a noise analysis, and the geophone array is designed to cancel the highest-amplitude coherent noise. Typically, an array is designed to strongly attenuate ground roll with a dominant frequency of 7.7 Hz and a velocity of 305 m/s (the figures are taken from an East Texas example [Fig. 8]). Such an array will be 6 dB down at a wavelength of about 8 m. The minimum apparent velocity of a reflection in the area at the target depth of 2 seconds is about 2500 m/s, at which velocity a 40 m wavelength is 31 Hz. This means that if an array designed on the basis of the noise analysis were used, frequencies above 31 Hz would be attenuated in the places where apparent velocities were low. At 2.0 s it should be possible to record reflections with components as high as 75 Hz, and certainly shallower reflections (if of interest) will have higher components. Thus, in this case, the use of an array designed around the noise is undesirable if maximum possible resolution is desired.

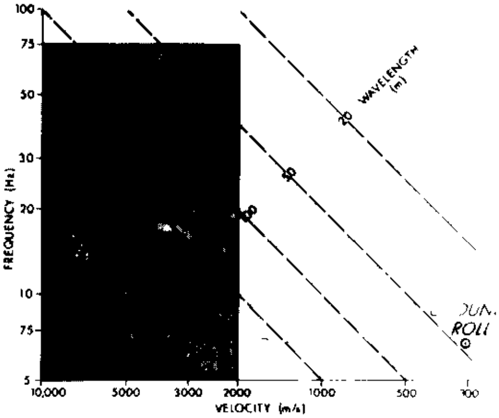


Fig. 8. Ground-roll wavelengths overlap reflection wavelengths.

For maximum resolution, geophone arrays are best designed by the second approach, using the apparent velocities and frequency content of the target reflections to design an array to attenuate as wide a range of wavelengths as necessary without significantly affecting the reflections. The shortest wavelength component in a reflection is the highest frequency component at the lowest apparent velocity, which usually (because of moveout) is the shallowest reflection of interest on the longest offset trace on which that reflection is usable. The wavelength of this reflection component can be estimated by measuring the apparent velocity and estimating the maximum frequency component from the reflection time. An array should have the first null on its response at a wavelength shorter than this wavelength. The array will then have little over-all effect on the desired signal.

Geophone array design theory generally assumes all geophones are identical, equally coupled, and laid out on level ground exactly as specified. The reality is almost always otherwise (Fig. 9); Newman and Mahoney (1973) said that pattern design must be taken "with a pinch of salt". Even where ground conditions are ideal and the array is laid out exactly as planned, the geophones are only equal in output to a tolerance of 5%. Weathering variations across the array may be 10-20 ms or more, and only ±2 ms difference constitutes a 62 Hz filter (Fig. 11). In practice, the variations in spacing are large. The spacing shown in Figure 9 is taken from actual measurements in an unannounced spot check on an array laid out by an experienced recording crew in moderately rugged terrain. The nominal array was twelve geophones in line at 6 m intervals, but measurements of twenty-four consecutive arrays gave a mean spacing of 6.05 and a standard deviation of 1.53 m. The average length of the groups was close to the specified figure, because the first geophone of one group was at the same point as the last geophone of the previous group.

The static-correction variations resulting from elevation and weathering changes across an array are harder to measure, but a high-resolution survey shot with single geophones at 15 m intervals shows the magnitude of such variations. The final surface-consistent static corrections for part of this survey are shown in Figure 10.

If this line had been shot with a conventional array with a group length of 45 m, there would have been up to 23 ms variation in the static correction across the array, and a mean variation of 12 ms. There were similar variations in amplitude response: up to 10 dB, with a mean of 5.7 dB.

Because of limitations in the application of array theory, in most surveys there is little point in going beyond the following considerations, which are very similar to those advocated by Telford *et al.* (1976, p. 306-307):

1. Effective length of array is shorter than the shortest wavelength component in the reflections of interest.

2. The spacing of elements within the array is less than the wavelength of the shortest wavelength coherent noise, or more than the radius of coherence of ambient noise, whichever is smaller.

If there is coherent noise within the recorded spectrum with an apparent wavelength equal to the element spacing, it will not be attenuated by the array, so the spacing should be short enough to prevent this. Most treatments of array

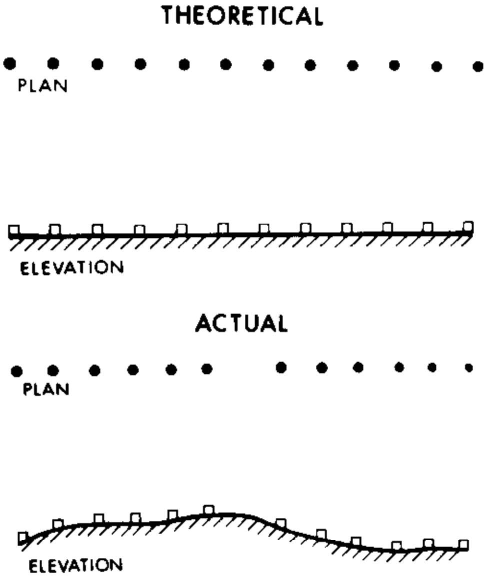


Fig. 9. Array theory — and reality.

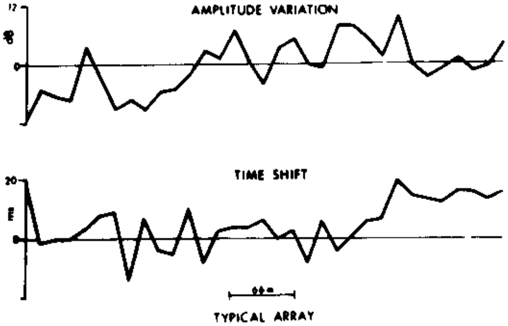


Fig. 10. Short-period amplitude and static variations.

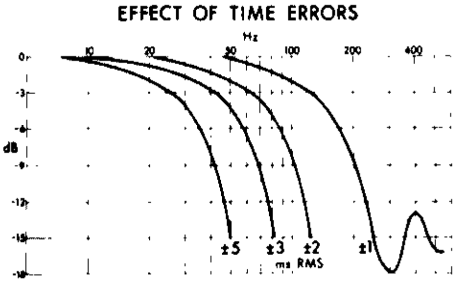


Fig. 11. Effect of time errors on arrays.

design assume that each element in the array is driven by the same ground movement, delayed in time according to the velocity and the geometry. However, this applies only to coherent movement that has the same amplitude across an array. An equally important function of an array is to attenuate ambient noise, which is usually noncoherent. The attenuation of noncoherent noise depends on the noise being different at adjacent detectors, so there is no advantage for ambient-noise attenuation in putting array elements so close to each other that locally generated noise is the same at adjacent elements.

Occasionally, weighted arrays may be used to achieve more attenuation of noise in the reject band (roughly, the wavelength range from the effective array length to the interval between elements). The improvement, however, is rarely what is expected. Newman and Mahoney (1973) point out that the maximum attenuation actually achieved is much the same regardless of the type of array, being about 30 dB in the presence of 10% errors. One disadvantage with weighted arrays is that planting geophones together to give weight reduces the ambient-noise cancellation. Where ambient-noise cancellation with an in-line array is insufficient, additional geophones can be used in an areal array (without either exceeding the array-length limit set by the reflection wavelength, or using a spacing less than needed to record independent ambient noise). Coherent shot-generated noise travelling across the line, sometimes a problem, can be reduced by an areal array, but it is usually impractical to lay out arrays whose cross-line dimensions are comparable with the long wavelengths often associated with cross-line components. Nevertheless, areal arrays are certainly of practical use for attenuating cross-line noise in some areas, such as West Texas.

For recording frequencies over about 75 Hz it is usually necessary to abandon geophone arrays and use single geophones. This is because the uncertainties in time delay from geophone to geophone within an array act as a high-cut filter (Fig. 11).

12. *Off-End or Split?*

A choice must be made between using off-end (end-on) shooting and split-spread shooting. The near- and far-trace offsets and group interval have already been defined by the target depths and the required resolution. The number of channels of data recorded with each shot can be doubled by recording a split spread. The resultant doubling of multiplicity should not improve attenuation of shot-generated noise such as multiple reflections and ground roll, because the traces in each CDP gather can be paired, each pair differing only in having shot and detector interchanged. Although the reciprocity principle says that the members of each pair should be the same, often a buried single shot is being interchanged with an array of geophones on the surface, so they will not be quite identical. In fact, a major advantage of split spreads is that, for dipping reflections, the geophone array is at the updip end of the reflection path on half the traces regardless of dip direction. (With off-end shooting, where there is significant dip and the geophone array is longer than the source array, the spread should be updip of the shot.) The benefit of the increase in multiplicity from the split spread is thus greater than simple theory would indicate. Of course, the ambient noise on reciprocal traces will be unrelated, so a 3 dB improvement in signal-to-ambient-noise ratio can be expected. One alternative that is rarely used, the asymmetrical split spread (*e.g.*, 12-36), is particularly suitable where both shallow and deep horizons are targets, because it gives increased shallow multiplicity compared with off-end shooting, and longer far-trace offsets than a symmetrical split. It is also useful when the offset and group-interval requirements do not match the number of channels available.

13-15. *Additional Considerations*

Three of the most important recording parameters are not usually thought of as such; these are line length, line orientation, and line spacing. The line length is often shorter than required for solving the exploration problem, particularly where migration is done. This serious error occurs commonly on the Gulf Coast. As a general rule, the line should extend beyond the area of interest a distance equal to the depth of the deepest target. If a target is 15,000 ft deep and the area of interest is one mile wide, a line should be seven miles long to allow for migration to an angle of 45°. As migration is essential for maximum resolution, this rule should always be followed if resolution is important (Fig. 12).

Line orientation relative to geological structure is the most important single field parameter in reducing the uncertainty in the geological interpretation of a seismic profile. A more reliable interpretation can be made of a dip line than of a strike line or one oblique to the dip, and conventional migration depends on the assumption that the line is in the dip direction.

Anstey points out that the optimum line arrangement for detailing a circular feature is not a rectangular grid, but a set of radial lines with a square joining the outer ends (Fig. 13).

Line spacing required to answer an exploration problem varies with the type of problem. For a reconnaissance survey, the line spacing should be small enough that a feature of interest cannot be missed. For detailed surveys, the dip lines should be spaced closely enough for the variation in strike direction to be sampled adequately. These sampling requirements are the same as those for any continuously varying data: two samples per wavelength for the shortest wavelength components. Because variations in the strike direction are often gradual, the shortest wavelength components may be quite long, but where the strike changes rapidly, the dip lines must be closer together. The test for whether line spacing is close enough is whether contouring can reasonably be done in more than one way. If the interpreter has trouble deciding where contours go between lines, the lines are too far apart. When the resolution of seismic lines is improved, it is reasonable to expect that closer line spacing will be needed to take advantage of the available resolution.

Strike lines perform two functions: they confirm the correlations between dip lines, and they demonstrate that the dip lines are indeed dip lines; where not required for these functions, the effort can be expended more profitably on dip lines. In some areas where the direction of dip varies with depth or where strike changes rapidly, the distinction between dip and strike lines may not be clear. The sampling requirements may then be the same in all directions: this leads to a requirement for three-dimensional recording.

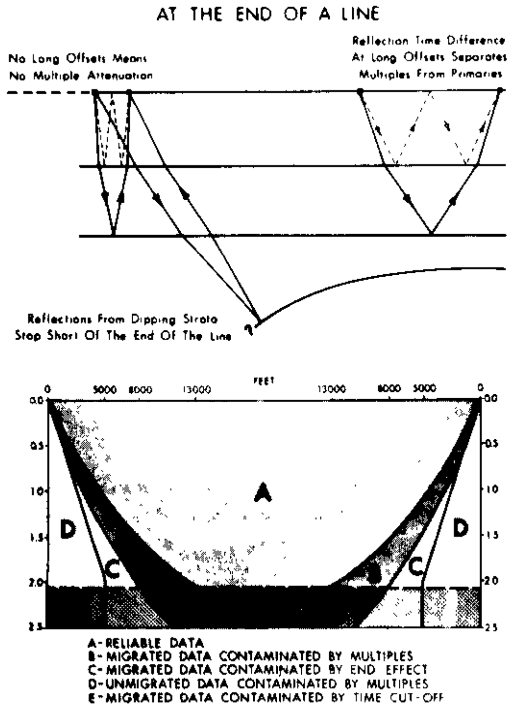


Fig. 12. Effects at the end of a line.

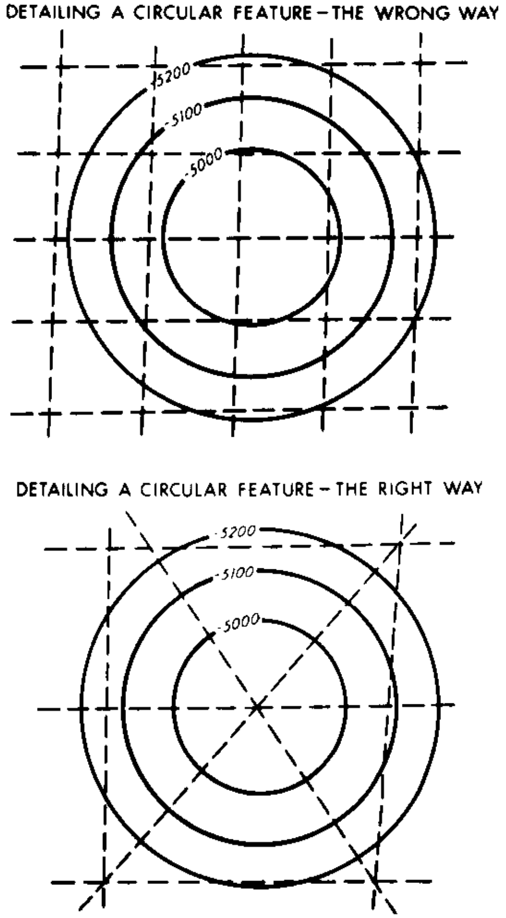


Fig. 13. How to detail a circular feature.

ECONOMICS

So far, we have considered what we would like to do optimize resolution. Following these principles will give a set of parameters that are balanced, all parts being aimed at solving the exploration problem. Before production shooting starts, we must ask whether we can afford it (that is, whether the benefits of doing it this way outweigh the cost) or whether the field techniques can be modified so that the exploration problem can be solved at lower cost. Sometimes the cost of a seismic survey may be so high that it is cheaper to leave the problem unsolved (*i.e.*, risk a dry hole) than carry out the survey, but more often the cost of a seismic survey is so small compared with the cost of a dry hole that even a small chance of solving the problem justifies the survey.

Even if the cost of optimum techniques can be justified, it is still good business to reduce costs as far as possible without endangering the solution to the exploration problem. Costs can be reduced at the expense of resolution (longer group interval, shallower shots) or of signal-to-noise ratio (shallower shots, lower multiplicity, fewer geophones, etc.). It may be sound economics to use less than "state-of-the-art" equipment and techniques (Anstey, 1977, p. 622). However, a seismic survey that does not solve the exploration problem is usually a complete waste of money, so cutting costs must be done only with a full appreciation of the geophysical consequences.

One important cost consideration is to plan techniques in advance, so that the right equipment is on site and a minimum of time is wasted on experimental shooting. In most areas, the only experimentation needed is to determine optimum charge size and depth. Most other parameters are set by the required information — and presumably we know what we are looking for.

CONCLUSION

The purpose of this paper has been to demonstrate that proper seismic survey design for maximum resolution is a systematic, reasoned process, beginning with an adequately defined exploration problem. The design recognizes the close interrelation between acquisition, processing and interpretation. Compared with traditional field techniques, a survey designed for maximum resolution will have much shorter group intervals, more recording channels, shorter arrays and smaller charge sizes.

In view of the increasingly wide range of field parameters available and the increasing demand for improved resolution, it is essential that the purpose of a survey be clearly and completely defined before the acquisition parameters are set, and that design of these parameters be based logically on the defined objectives. To achieve this end, the planning, acquisition, processing and interpretation must be considered as one continuous sequence, not as the series of discrete specializations it has become today.

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