High-resolution seismic profiling on water

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Abstract
Herein is presented an overview of high-resolution seismic profiling on water. Included are basic concepts and terminology as well as discussions of types of sources and receivers, field practice, data recording and data processing. Emphasis is on digital single-channel profiling for engineering and environmental purposes.

Key words *waterborne – high-resolution – seismic – digital – noise control*

1. Introduction

Reflection seismic profiling has been used throughout most of the 20th century to map deep geologic formations. The method was revolutionized in the late 1950s and early 1960s when digital technology was applied to petroleum exploration. Three decades later digital seismic profiling was being used to image shallow formations for engineering and environmental purposes. The term «high-resolution» seismic profiling was coined at that time. It is a relative term, of course, and since the late 1980s a research program, begun at the University of Utrecht and now continuing at the University of Mississippi, has been directed toward determining just how «high» seismic resolution can be.

2. Basic concepts and terminology

Marine seismic profiling is used over a wide range of scales from deep seismic studies of the Earth's crust to sonic soundings for mapping water depth. It has several characteristics that are common to all scales:

1) The method always uses an energy source that is triggered periodically to produce a pressure wave in the water.

2) The wave propagates away from the source and is reflected at any surface where the seismic impedance is discontinuous.

3) The reflected wave propagates back and is received at one or more locations by pressure-sensitive hydrophones.

4) The path followed by the wave as it travels from the source to the hydrophone location is called the «raypath».

The source and hydrophone(s) are towed from a ship. Each hydrophone produces an electrical signal that is transmitted to the ship via an instrumental «channel». The horizontal distance between the source and any particular hydrophone is called the «offset» of the corresponding channel. If the offset of a channel is negligible relative to the water depth, it is said to be a «zero-offset» channel.

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The signal on each channel is referenced to the instant that the source is triggered. Each triggering of the source is called a «shot». Each recorded signal is called a «trace». Each shot produces as many traces as there are channels.

If the source and hydrophone(s) are towed along a straight course and a zero-offset channel from each shot is recorded on paper, the result is a profile with a vertical dimension of time afte the shot instant, usually called «record time» o «two-way time», and a horizontal dimension o distance measured according to how far the shi travels between shots. An example is shown i fig. 1. Three different types of reflected energ can be seen: a) coherent energy reflected fron bottom and subbottom interfaces; b) incoheren

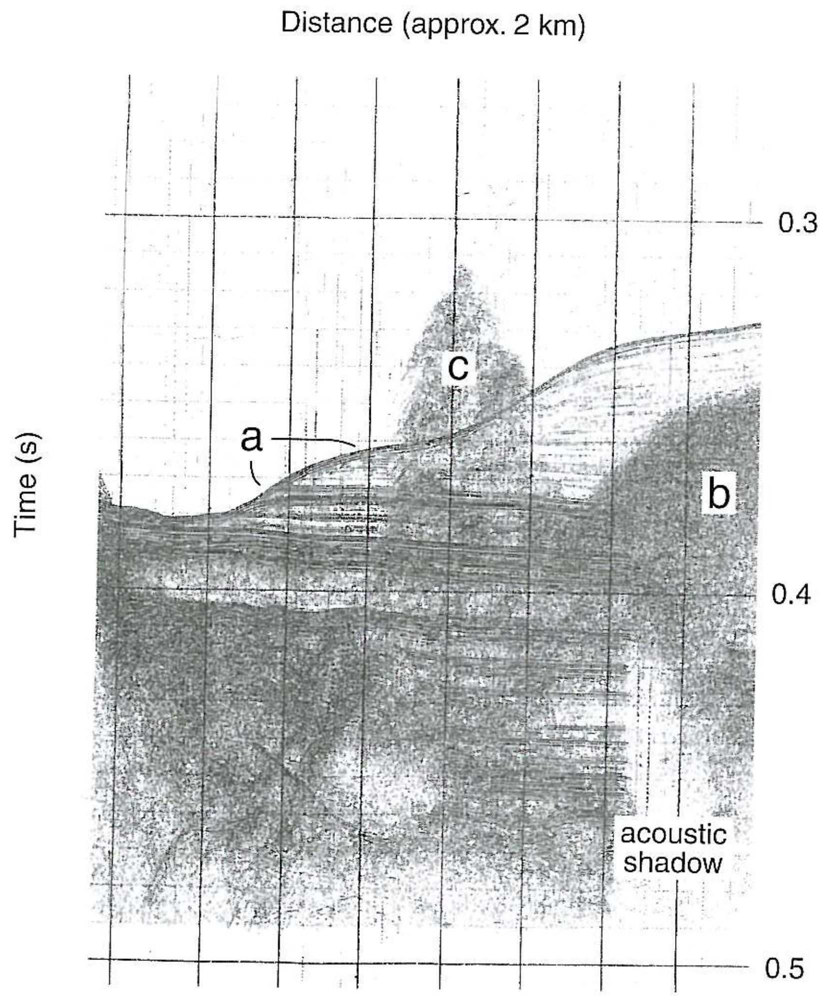

Fig. 1. Example of a high-resolution marine seismic reflection profile. Three different types of reflected energy can be seen: (a) coherent energy reflected from bottom and subbottom interfaces; (b) incoherent energy scattered from gas within the sediment (note the acoustic shadow) and (c) incoherent energy scattered from bedrock out of the plane of the profile.

energy scattered from gas within the sediment (note the acoustic shadow), and c) incoherent energy scattered from bedrock out of the plane of the profile.

For purposes herein, conversion of time to distance is accomplished by multiplying half of the record time in seconds by a speed of 1500 m/s (4875 ft/s), which is within a few percent of the speed of propagation in sea water and most unconsolidated sediments.

Also for purposes herein, a quick-and-easy measure of seismic resolution is taken to be the width of the dominant peak, or trough, of a wavelet. This is about half of the dominant signal period and, for pulses of short duration, corresponds roughly to the minimum layer thickness (in two-way time) that can be discerned on a seismic profile.

A number of the concepts mentioned herein are best discussed in terms of frequency. In order to provide a quick reference, basic concepts concerning frequency domain representations are summarized in Appendix A.

3. Energy sources

There are two basically different kinds of energy sources used for marine reflection profiling; resonant sources and impulsive sources. It is conventional to refer to the signals produced by resonant sources as sonar pulses and to those produced by impulsive sources as seismic wavelets. Pulses produced by either type are characterized according to their frequency spectra, their duration in time and their consistency of shape from shot to shot.

Similar to the statistical entropy of a transmission channel being a measure of the channel's capacity to transmit information (Shannon, 1948), a pulse's capability to resolve detail is indicated by the entropy of its (normalized) power spectrum. In general, for a given pulse duration, the entropy increases and the resolving capability improves as the power spectrum becomes broader and smoother (fig. 2). That capability is realized when the duration of the pulse in time is as short as possible. Resolution also improves as the pulse's temporal shape becomes more repeatable from shot to shot.

The specification of a desired resolution serves to identify which source characteristics are acceptable and, broadly, which sort of source would be appropriate to the use intended.

3.1. *Resonant type*

Resonant sources are piezoelectric devices such as those used in depth sounders, fish finders and subbottom profilers. They produce a pressure pulse whose shape is similar to a portion of a sinusoid, as illustrated in fig. 3. The frequency of the sinusoid is largely determined by the resonant frequency of the piezoelectric crystal. The peaks of the sinusoid (correspond-

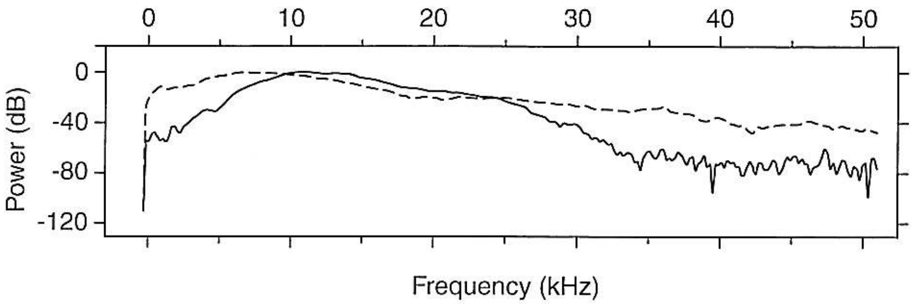

Fig. 2. Illustration of power spectra with different measures of entropy: boomer spectrum (dashed) and sonar spectrum (solid) (adapted from Verbeek and McGee, 1995). The boomer spectrum has a greater measure of entropy than the sonar spectrum.

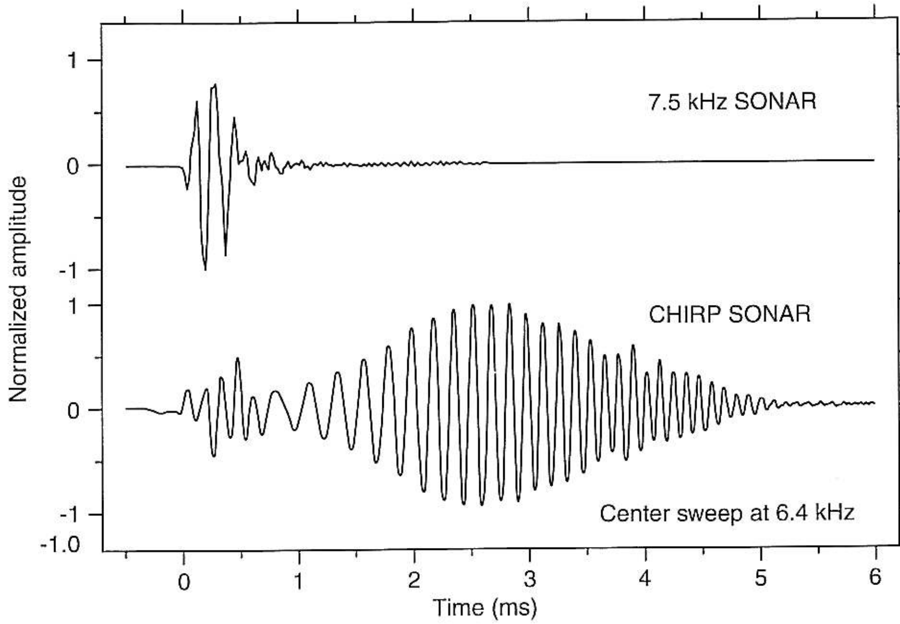

Fig. 3. Examples of resonant source signatures.

ing to pressure greater than ambient) are generated by expansion of the crystal and the troughs (corresponding to pressure less than ambient) by contraction.

Resonant sources are said to be «cavitation limited» because the maximum power that can be transmitted to the water during a single cycle is limited by cavitation at the face of the crystal. Cavitation occurs when the crystal contracts so rapidly that the pressure on its face decreases to a level where the water vaporizes and bubbles form. Increasing the amplitude of crystal oscillation beyond this limit does little to increase the amplitude of the pressure pulse in the water. The only way to further increase the power transmitted to the water is to increase the number of sinusoid cycles which increases the length of the pulse and therefore the layer thickness it can resolve. This limitation represents a major disadvantage of resonant sources.

Another disadvantage is that the polarity of a sonar pulse becomes ambiguous because absorption during propagation distorts its onset. This makes it difficult to distinguish between positive and negative reflection coefficients, thereby seriously degrading the ability to determine sediment parameters. It is possible to reduce ambiguity by combining the technique known as «chirping» , *i.e.* varying the amplitude and frequency of the propagating pulse in a predetermined manner, with full-waveform processing, but this is not commonly done.

The major advantage of using a resonant source is that the pulse shape is well known, which improves its detectability in the presence of noise. Also, resonant sources are often easier to deploy and more maneuverable than impulsive sources.

3.2. *Impulsive type*

Impulsive sources release energy in a sudden burst that, ideally, would produce a signal shaped like a mathematical impulse, or delta function. This ideal is never realized, of course, but the signal generated in the water can be a pulse with a fast onset and a short duration.

Many sorts of impulsive sources are available. The most popular derive their energy from compressed air or electrical discharge. Signal frequencies generated by compressed air sources tend to be lower than those generated by electrical discharge. This is not always true, however, because increasing the operating energy level can reverse that tendency, *i.e.* small compressed air sources can generate higher frequencies than large electrical discharge sources. Figure 4 shows two examples of wavelets generated by impulsive sources.

The main advantage of impulsive sources is that they generate wavelets with broad bandwidths and well-defined polarity. Such wavelets have a substantial capacity to transmit information and are well-suited for digital processing. The principal disadvantage is that the shape of impulsive wavelets is not known as well as that of sonar pulses. Because of this, impulsive wavelets can be difficult to recognize in the presence of noise. Effective use of impulsive sources therefore presupposes adequate control of noise during data acquisition.

4. Receivers

The receivers used in marine profiling are piezoelectric devices which produce a voltage when subjected to deformation. The varying deformation caused by the passage of a pressure wave in the water produces a varying voltage. In resonant-source systems, a single piezoelectric crystal often serves as both source and receiver. In impulsive-source systems, the receiver is separate from the source and is called a hydrophone.

Single hydrophones are used for calibrating systems and recording source signatures, but seismic profiling is usually done with a number of hydrophones that have been combined to form a hydrophone array. The most common array is a line of hydrophones hard wired together so that their signals are summed. It is called a linear additive array. More sophisticated arrays include two-dimensional configurations and arrays in which individual hydrophone signals can be phased (moved in time) before they are summed or, sometimes, multiplied.

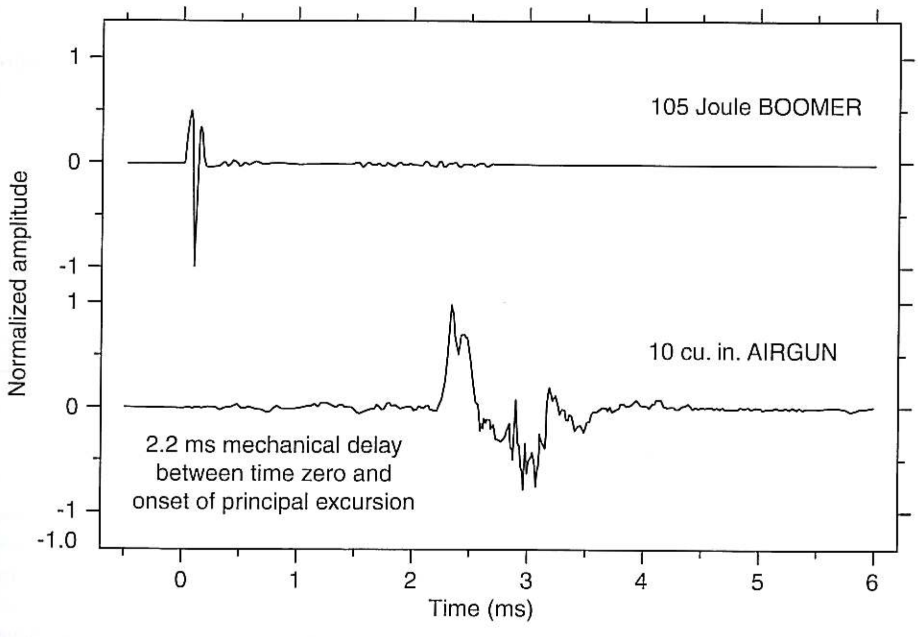

Fig. 4. Examples of impulsive source signatures.

Both the spacing of individual hydrophones and the total size of the array are significant quantities when considering the characteristics of an array. (The same would be true for an array of sources). The principal concern is to avoid configurations that produce interference patterns which degrade the resolving power of the source. Hydrophone spacing is often equidistant, but not necessarily so. Except in some specialized configurations, the distance between hydrophones is usually short compared to the wavelengths of interest.

For additive arrays, the total size of the array should be small enough that all the signals sum in phase. This is the case when ray paths from the source to individual hydrophones are all about the same length, *i.e.* equal within a fraction of the shortest wavelength of interest. In reflection profiling, ray paths of approximately equal length are approximately parallel. Parallel ray paths are described by Fraunhofer diffraction (Born and Wolf, 1959) and the lengths of reflected ray path are approximately equal if the reflector is in the Fraunhofer far field of the array. When profiling on water the closest reflector of interest is the water bottom, thus an additive array should be small enough that the water bottom is in its Fraunhofer far field.

One of the most common profiling geometries, a point source and a linear hydrophone array deployed on the water surface, is illustrated in fig. 5. The length of the array is L and the

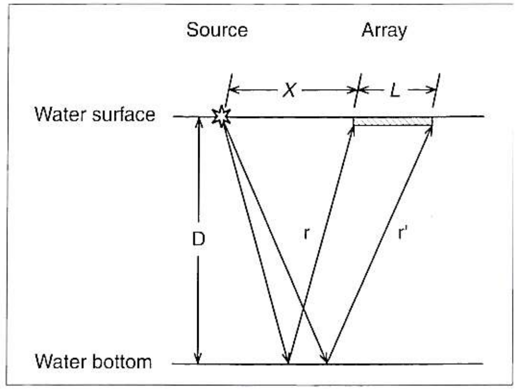

Fig. 5. Reflection geometry for a source offset in line from a linear hydrophone array.

source is offset in line from it by a distance X. The depth of the water is D. The water-bottom reflection ray paths to the nearest and farthest hydrophones are r and r', respectively. It can be shown that, for a signal of wavelength λ, r and r' would be approximately equal if the length of the array is such that

$$L \ll \sqrt{X^2 + 2r\lambda} - X.$$

For zero offset to the nearest hydrophone this reduces to

$$L \ll \sqrt{2r\lambda} = 2\sqrt{D\lambda}.$$

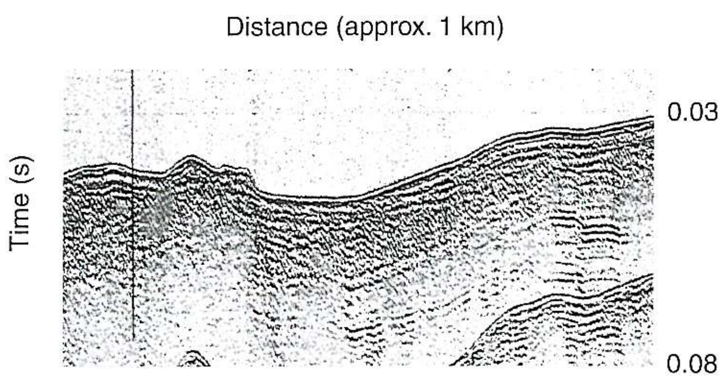

Fig. 6. Example of spatial aliasing due to the hydrophone array being too long. The steeply dipping events than cut across flatter reflections immediately below the water bottom are produced by spatial aliasing.

Since the source signal is transient, its frequency spectrum is continuous and includes all wavelengths. There is a dominant wavelength, however, and it should be possible to resolve layers of thickness about one-half the dominant wavelength. Denoting that half wavelength R and assuming that it is small compared to the water depth, the maximum appropriate array length would be on the order of

$$\sqrt{RD} \quad \text{where} \quad R \ll D.$$

This is a useful rule of thumb and shows that, in order to resolve thinner layers, it is necessary to use shorter hydrophone arrays.

If an array is too long, the data quality is adversely affected by the phenomenon of spatial aliasing. When this happens the eye detects a spurious organization in the data that cuts across and tends to mask legitimate reflections. Spacial aliasing is visible in fig. 6.

5. Source-receiver field geometry

Certain geometrical aspects of source and receiver deployment are important because they affect the resolving power of the signal. Principal among these are the depth below the water surface and the distance between the source and receiver.

5.1. *Depth of deployment*

The depth of deployment is important because the effective signal consists of a primary wavelet followed by a so-called «ghost» wavelet which is the reflection of the primary wavelet from the underside of the water surface. Ghost reflections are opposite in polarity to primary reflections because the underside of the water surface has a negative reflection coefficient.

Ghosts can be generated at both the source and the receiver. Some sources do not generate ghosts because either they do not emit energy upward (*i.e.* boomers) or they disturb the water surface to such an extent that it does not act as a coherent reflector (*i.e.* airguns deployed very shallowly). Ghosts generated at the receiver can be seen on the boomer profile shown in fig. 7 where every reflection comprises two wavelets.

The fact that ghosts are opposite in polarity to the primaries that generate them is illustrated in fig. 8a-c where enlargements of three reflections in fig. 7 are shown. Figure 8a is a reflection from the sea floor, fig. 8b is from 3 ms below the sea floor and fig. 8c is from 17 ms below the sea floor. Figures 8a and c are positive reflections, but fig. 8b is negative. Regardless of reflection polarity, however, the ghost is seen to be opposite to it.

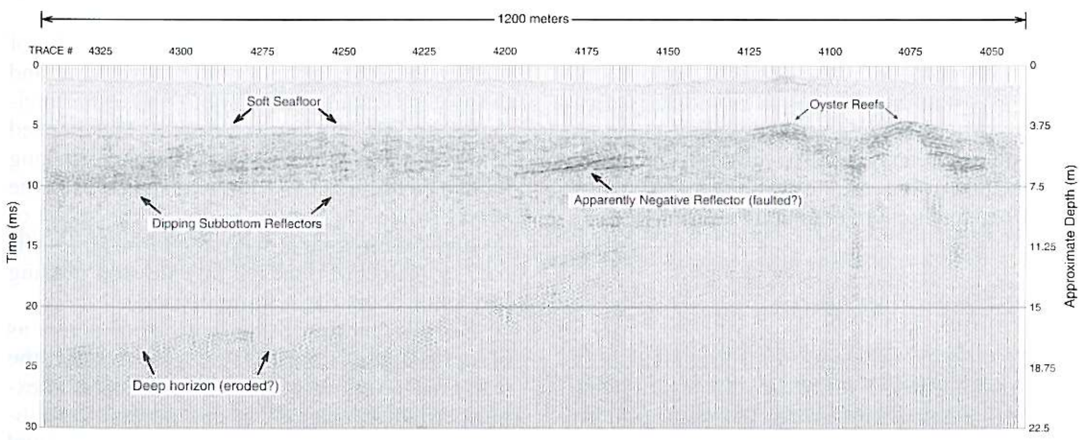

Fig. 7. Example of a boomer profile with ghost reflections generated at the receiver.

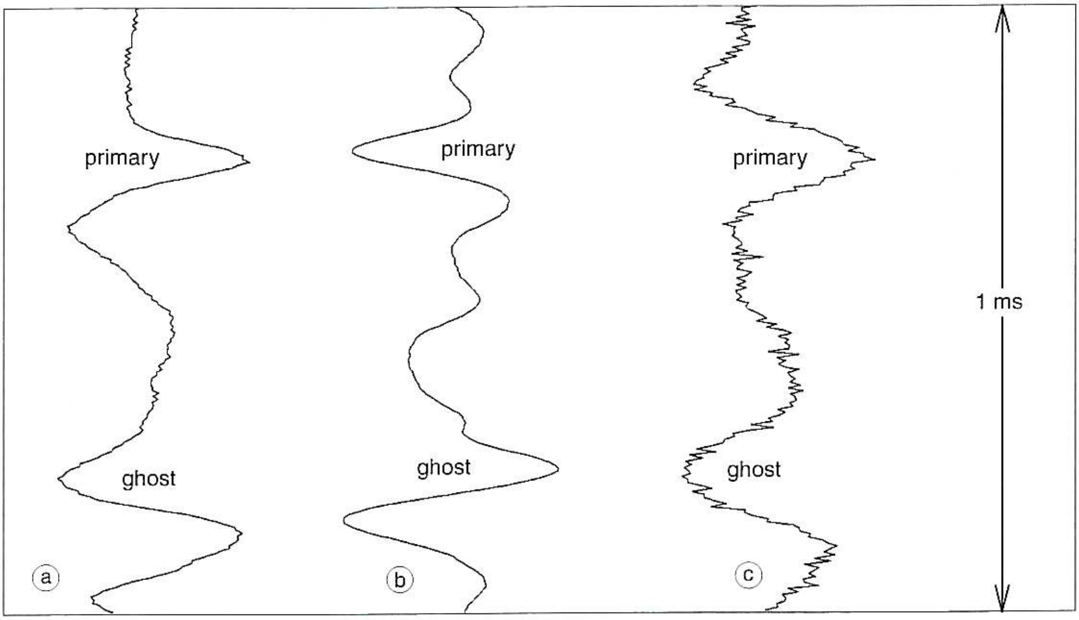

Fig. 8a-c. Enlargement of three reflected pulses, with ghosts, in fig. 7: a) from the sea floor; b) from 3 ms below the sea floor; c) from 17 ms below the sea floor.

Ghosts lag primaries by a time that corresponds to twice the depth of deployment. The ghosts in fig. 8a-c lag their primaries by 0.52 ms, indicating that the hydrophone array was being towed about 39 cm below the water surface. The lag increases as the tow depth increases, thereby increasing the total length of the effective signal and decreasing resolution. Resolution is improved by the depth of deployment being as small as possible. Resolution is also improved by the depth of deployment being as constant as possible because variations in depth, perhaps due to sea state or tow instability, cause the effective signal to change from shot to shot.

5.2. *Source-receiver offset*

The distance between source and receiver is important because it influences the signal power that is transmitted through the water bottom and thus made available for providing subbottom information. If there is no distance between source and receiver, the so-called «zero-offset» geometry, the direction of wave propagation is normal (perpendicular) to the water bottom. This is intrinsic to resonant systems in which the signal is emitted and received by the same piezoelectric crystal. In other systems there is always some offset distance.

As offset distance increases, the angle of incidence between the seismic wave front and the water bottom varies from 0° (normal incidence) to 90° (grazing incidence). If the speed of propagation in the water is constant, grazing incidence occurs at an infinite distance from the source when the bottom is flat. If the speed of propagation increases with depth, nonzero-offset ray paths are concave upward and grazing incidence occurs at a finite distance.

Seismic energy in the water propagates as compressional waves (*P*-waves) because the water has no rigidity. If the bottom material exhibits rigidity, energy transmitted into the subbottom can give rise to both compressional and shear waves (*S*-waves). In general, a *P*-wave inci-

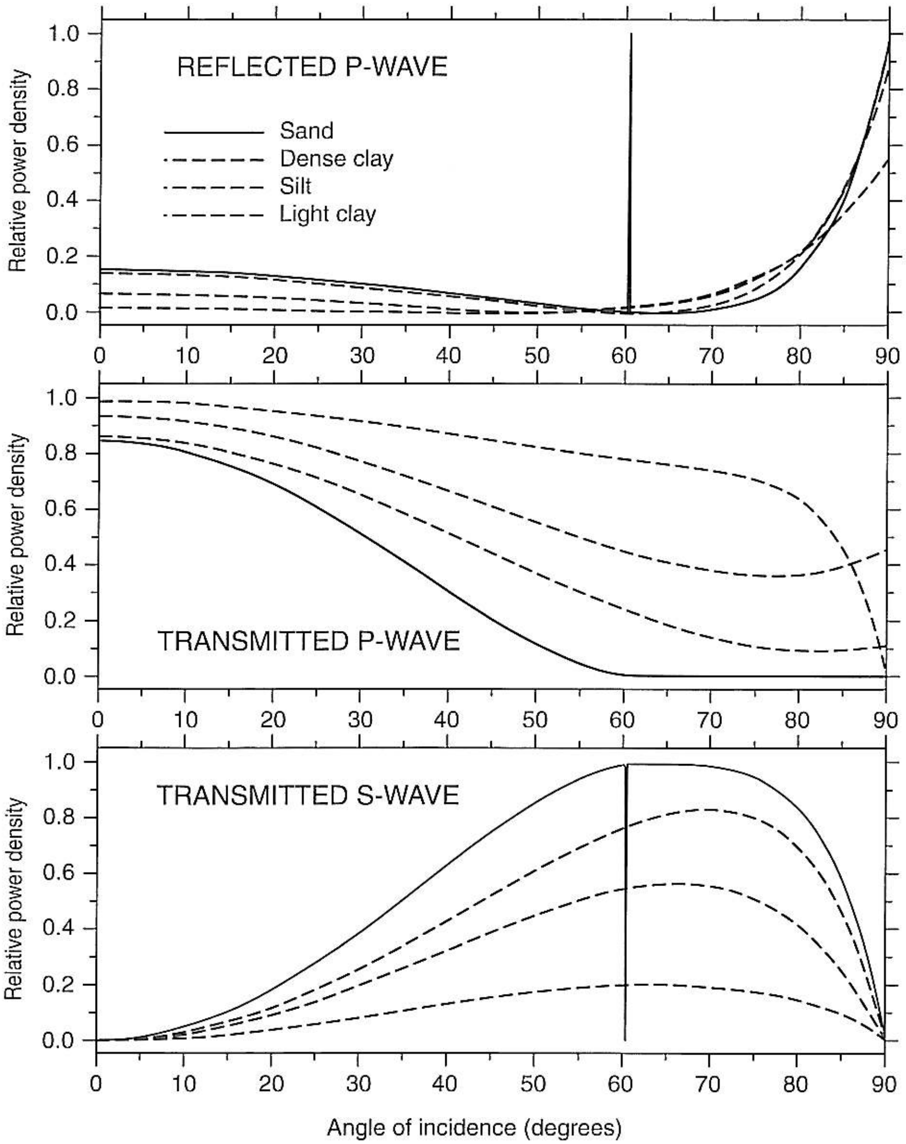

Fig. 9. Power densities of reflected and transmitted waves for a unit P-wave in water incident to typical water-bottom sediments assuming that the ratio of the incompressibility of the sediment to that of the water is 0.9.

dent to the water bottom is partitioned into a reflected P-wave, a transmitted P-wave and a transmitted S-wave. By conservation of energy, the sum of energy reflected and transmitted is equal to the incident energy. Mathematical expressions for ratios of reflected and transmitted energy to incident energy are given by Ergin (1952). Figures 9, 10 and 11 show plots of these for four idealized sediment types and three values of the ratio of incompressibility of the sediment to that

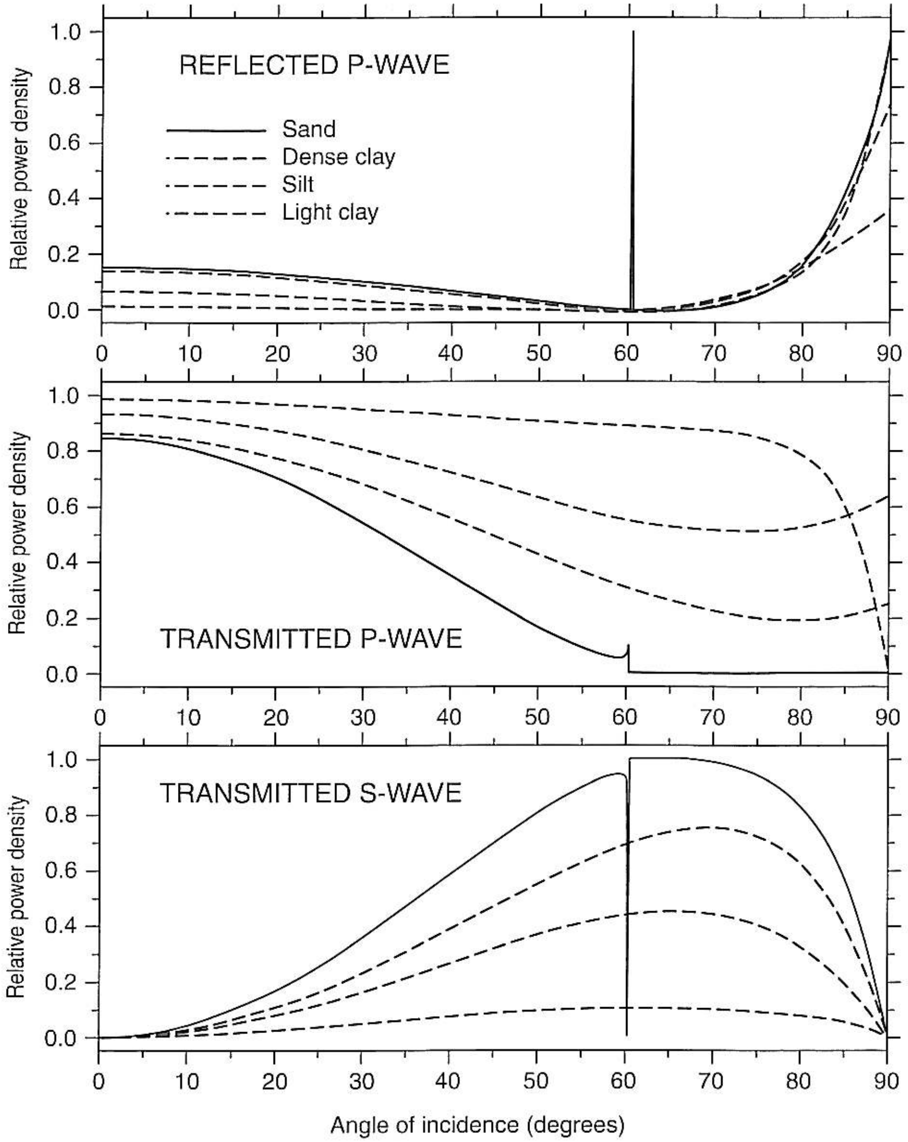

Fig. 10. Power densities of reflected and transmitted waves for a unit *P*-wave in water incident to typical water-bottom sediments assuming that the ratio of the incompressibility of the sediment to that of the water is 1.0.

of the water. It can be seen that the maximum transmitted *P*-wave power occurs at normal incidence regardless of the sediment type and the value of the incompressibility ratio. It can also be seen that the curves are rather flat up to almost 10°, indicating that there is not much loss of transmitted power for small angles of incidence. That is fortunate because there is a practical limit to how small the angle of incidence can be if the source and receiver are separate devices.

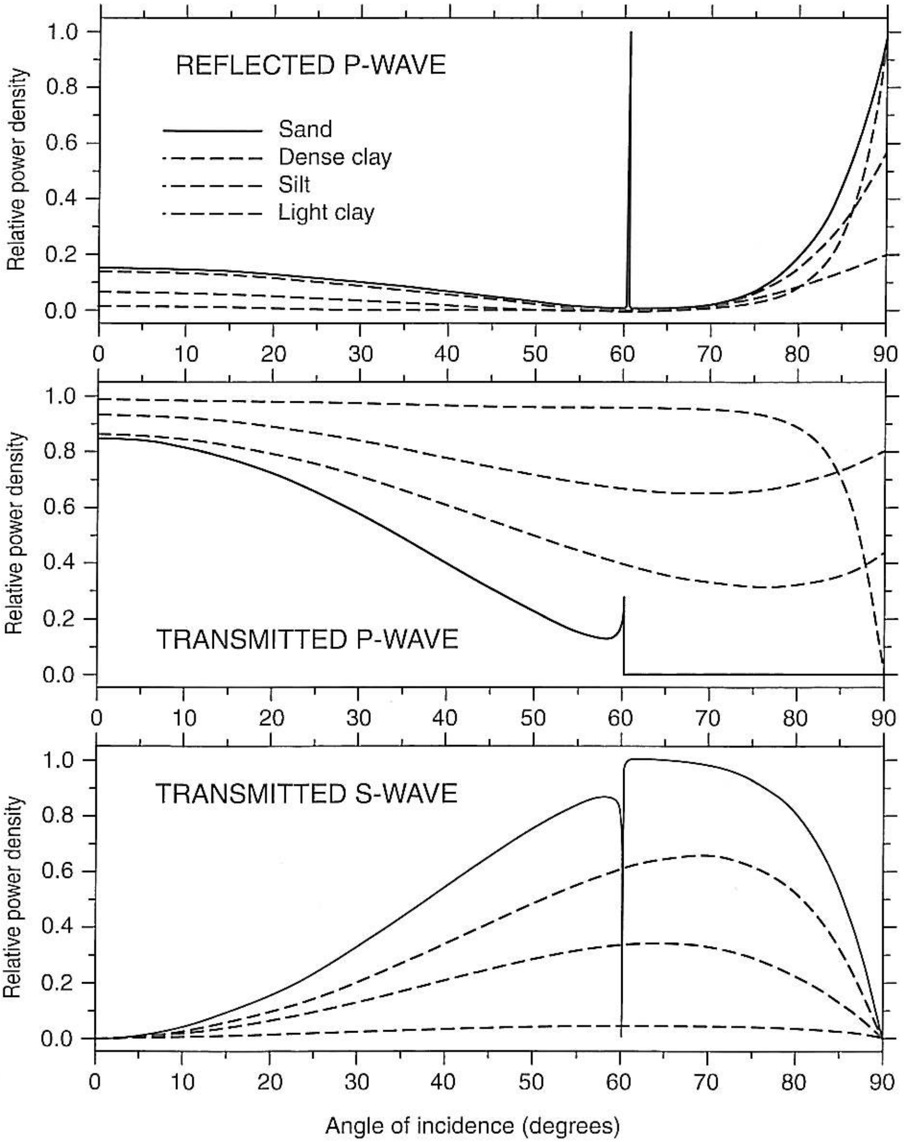

Fig. 11. Power densities of reflected and transmitted waves for a unit *P*-wave in water incident to typical water-bottom sediments assuming that the ratio of the incompressibility of the sediment to that of the water is 1.1.

The minimum feasible offset distance for impulsive systems is usually determined by the level of noise generated by towing the source. When the hydrophone is positioned near the source it picks up the sound of turbulent water which is broadband and cannot be filtered out. As the hydrophone is moved closer to the source, the noise level can become unacceptable and a minimum feasible offset distance is thereby established.

As shown by figs. 9 to 11, it is sufficient if the offset distance is small enough that the angle of incidence at the water bottom is less than about ten degrees. This is the case whenever the offset distance is less than one-fifth of the water depth, assuming constant speed of propagation in the water and horizontal bottom. This is easily checked on a field recording, the time of the direct wave being no more than one-tenth of the time of the water-bottom reflection. It can be difficult to achieve in very shallow water, however, and constitutes a major problem for getting good subbottom penetration there.

6. Controlling noise

Noise can be defined as any recorded energy that degrades resolution. The quality of data obtained from impulsive sources often is reduced drastically due to the presence of noise. In many cases, particularly when the water bottom is unconsolidated sediment, an inability to observe subbottom reflections simply is due to a noise level that precludes the recognition of seismic wavelets. Whenever results are unsatisfactory, the first suspicion should be that noise is responsible, not that there is a lack of penetration or an absence of reflectors. If noise is low, electronic amplification can be increased to permit observation of extremely weak reflections.

The level of noise in a given situation is quantified relative to the level of the signal. The relative quantity is called Signal-to-Noise (S/N) ratio. If the signal and noise occupy different frequency bands, the S/N ratio can be improved by frequency filtering. If they have different spacial characteristics, it can be improved by changing the field geometry. Practical situations are seldom that fortuitous, however. Usually signal and noise are coincident in both frequency and space. The S/N ratio is then improved only by increasing the signal or decreasing the noise.

Increasing the signal is done by increasing the energy level at which the source is operated. Unfortunately, doing so tends to degrade resolution because it increases pulse duration in resonant systems and decreases bandwidth in impulsive systems. The only certain way to increase the S/N ratio while maintaining resolution is to decrease the noise.

Since no realizable data acquisition system can be entirely noise free, the total elimination of noise is not a practical objective. Rather, the objective should be to reduce noise to whatever level is required in order to achieve the desired resolution. Many types of noise contribute to overall noise level, most having sources that are either electrical or operational. The most effective method of reducing total system noise is to approach the problem in a logical manner, source by source. Useful techniques for minimizing sources of noise have been developed during research and practice. Successful utilization of these techniques does require some planning, effort and sensitivity to the problem, however. The procedure is not difficult, but it must be followed rigorously. No source of noise should be neglected because it does not seem to be major. Success in reducing total system noise is usually the result of many small improvements.

6.1. *Reducing electrical noise*

The control of electrical noise requires that all electronic equipment be of good quality and be mutually compatible. It should be well maintained and thoroughly bench checked before being installed onboard the survey vessel. The installation should be closely supervised by a competent technician. Much of the electrical noise encountered in waterborne profiling is associated with grounding and a good grounding procedure must be planned and followed fastidiously. Ground «loops» must be avoided. Since the vessel's ground often fluctuates when shipboard equipment such as pumps, refrigerators, radios, radars, etc. switch on and off, the seismic receiving equipment (hydrophone array, amplifier, recorder, oscilloscope, etc.) should be powered by an isolated supply that is grounded separately. When profiling on salt water the receiving system should be grounded directly to the sea. The sea ground should be heavily weighted so that it tows deeper than the vessel's draft, thereby avoiding zones of fresh water that can accumulate near the surface. (Pods of surficial freshwater often form near shore after an ex-