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GEOPHYSICS

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A standard quantitative calibration procedure for marine seismic sources

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ABSTRACT

Marine source evaluation has traditionally been a subjective and qualitative study. This is particularly true in the case of source spectral characteristics. As a result, source evaluation, development, and array design based on seismic energy over a specified frequency band have been impossible. Further, the transient nature of source wavelets lends itself to energy analysis rather than the traditional relative power analysis. The methodology required to achieve a calibrated quantitative estimate of marine seismic source energy is detailed here.

The procedure involves two steps. First, a calibrated high-fidelity measurement of the source signature is required; and second, an analysis of the signatures by a suite of computer algorithms designed to extract quantified measures of amplitude and energy is necessary. Results of the analysis include a time-domain signature calibrated in American National Standards Institute (ANSI) units of pressure and a frequency domain spectrum calibrated in ANSI units of energy flux. These results provide figures of merit for evaluation of individual source characteristics (e.g., energy flux over seismic bandwidth, and total source energy). Additionally, the results provide data for a quantitative comparison of any two or more sources. Illustrative examples of source studies are included.

INTRODUCTION

A calibration technique for marine seismic sources which emphasizes quantitative spectral analysis has been developed. The technique condenses the acoustic characteristics of a source into a format which is easy to understand. With this tool the geophysicist may evaluate any given source in a precise, quantitative manner.

Seismic mapping of high-resolution structural and stratigraphic targets requires knowledge of source spectral content and source energy level. Traditional source evaluation techniques which emphasize peak-to-peak amplitude and primary-to-bubble ratio do not address these measures directly. Primary-to-bubble ratio is only a qualitative evaluation of the spectral content of a source, and peak-to-peak amplitude (often used as a measure of energy) is a function of recording bandwidth. In contrast, the technique presented here generates consistent spectral amplitude levels regardless of the recording bandwidth.

Three fundamental elements form the calibration procedure: acquisition, processing, and interpretation. Each element is discussed in detail below.

ACQUISITION

Overview

Every seismic source has a characteristic acoustic signature. The intent of the acquisition phase is to produce a high-fidelity measurement of this characteristic signature. High-fidelity recordings demand system specifications including large dynamic range, low harmonic distortion, low system noise levels, and a linear system response. If these requirements are satisfied by the measurement system, then a faithful representation of the original pressure signal is recorded. To meet these requirements, four items must be considered: the recording electronics, system calibration, proper positioning of the calibrated hydrophone, and proper source operation during measurement. A digital sonobuoy with a receiver interfaced to a digital seismic recording instrument provides the

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high-quality of recording electronics that is needed. This hybrid system satisfies the required dynamic range, harmonic distortion, system noise, and linear response. The system calibration provides a constant that relates pressure levels in the marine environment to numerical values on the recording medium. Proper positioning of the hydrophone eliminates source-related noise and harmonic distortion that could be introduced in the actual measurement process. Of course, proper source operation is essential for a successful signature measurement.

A diagram of the overall acquisition system is shown in Figure 1. Each of the four items and how they contribute to the desired high-fidelity recording are discussed separately and in detail. Smith (1975) presented background discussions regarding system calibration and hydrophone position.

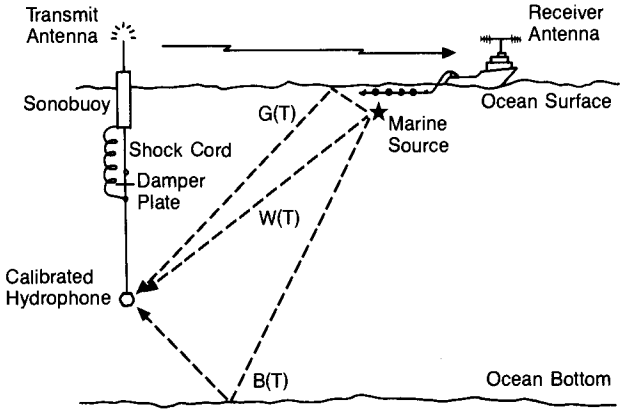


FIG. 1. Schematic representation of sonobuoy acquisition system: $W(t)$ = direct arrival of source wavelet, $G(t)$ = surface ghost, $B(t)$ = water-bottom reflection, $F(t)$ = far-field signature = $W(t) + G(t)$. $F(t)$ is the desired signal and $B(t)$ is to be avoided.

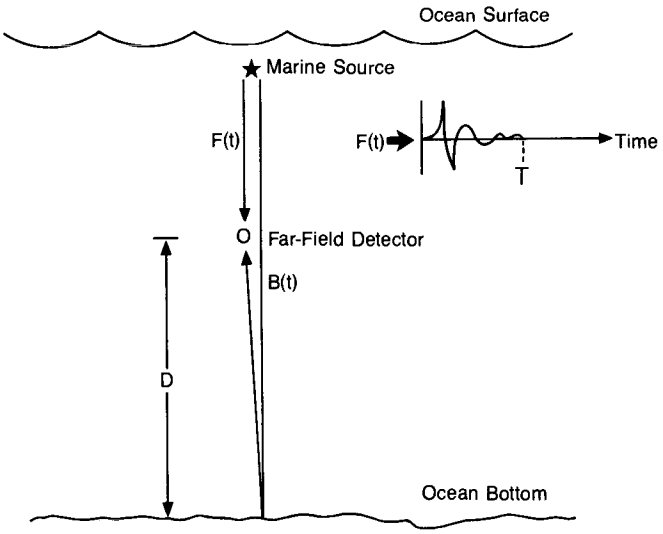


FIG. 2a. Minimum distance between far-field detector and ocean bottom. Schematic representation of hydrophone placement. $D \geq cT/2$ where c is the speed of sound in water and T is wavelet duration. Again, the bottom reflection $B(t)$ is to be avoided.

Recording electronics

Recording system components include a calibrated hydrophone, a digital sonobuoy/receiver system, and a digital seismic recording instrument. Each component must conform to the stated system specifications. In addition, the entire set of components when used together must meet the same standard. A hydrophone (we recommend calibration at the Naval Research Laboratory, Underwater Sound Reference Division, Orlando, Florida or similar facilities) converts the acoustic signal generated by the source into an electrical signal that is coupled to a digital sonobuoy. The ratio of output voltage to input pressure is the hydrophone sensitivity. This ratio should be constant over a broad range of frequencies and hydrostatic pressures. Electronics in the buoy sample and digitize the signal in floating point format to preserve dynamic range. Using an FM radio link, the buoy transmits data to a digital receiver on board the survey vessel where the data bit stream is interfaced to the seismic recording electronics. Each of these three components is designed to meet the strict tolerances required for high fidelity and, if interfaced properly, the entire recording system meets the same specification.

System calibration

Calibration of the recording system is done as part of the field experiment. A low-distortion signal oscillator, a calibrated digital voltmeter, and a wide-band voltage attenuator are used. The hybrid sonobuoy/seismic recording system should be set up on deck in the instrument room. A sinusoidal signal in the seismic band with a measured root-mean-square (rms) amplitude is coupled to the sonobuoy. This signal is recorded and successive records are taken with the input signal attenuated by specified steps (e.g., 10 dB). The process is continued until a representative range of signal amplitudes is recorded. The data on tape represent sets of counts or values that correspond to input voltages from the oscillator. As discussed later, a system calibration constant may be computed from these data. This constant is used to calibrate the source signatures recorded later.

Hydrophone positioning

Proper positioning of the hydrophone in the water column helps to keep the system noise level, as well as the system distortion, low. Three constraints on correct placement of the hydrophone are (1) the distance between the hydrophone and the water bottom, (2) the distance between the hydrophone and the source, and (3) the hydrophone depth.

Hydrophone/water-bottom separation.—The distance between the hydrophone and the bottom must be such that the source signature is completely received before the water-bottom reflection arrives. Figure 2a illustrates the geometry required to derive equation (1) which relates distance between the receiver and the bottom to wavelet duration. This equation is represented graphically in Figure 2b for c = 1 525 m/s. The relationship is

$$D \geq cT/2, \tag{1}$$

where

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T = wavelet duration (s),
c = speed of sound in water (m/s), and
D = minimum distance between source and bottom (m).

If the criterion established by equation (1) is violated, the signal quality will be degraded due to an increase in system noise and an increase in harmonic distortion. These problems are introduced if a water-bottom reflection or any subbottom reflections contaminate measurement of the source signature.

Hydrophone-to-source separation.—In the case of source arrays as opposed to point sources, a source-receiver separation constraint must be considered. Signals generated by the most distant source element in an array must arrive at the receiver simultaneously with signals generated by the closest source element. In digital recording systems "simultaneously" may be interpreted as occurring within one sampling interval or less. If the receiver is too close to the array, this requirement is not satisfied and distortion occurs. Figure 3a illustrates the source-receiver geometry and includes an abbreviated derivation of equation (2). That is,

$$Z \geq (d^2/4 - (c\Delta t)^2)/2c\Delta t, \tag{2}$$

where

Z = minimum separation between source and hydrophone (m),
d = maximum lateral extent of array (m),
c = speed of sound in water (m/s), and
Δt = sampling interval (s).

Equation (2) defines the minimum separation between the source array and the hydrophone as a function of array length and Δt, the sampling interval.

In Figure 3b the minimum value of Z is plotted with respect to d for the case when $\Delta t = 0.001$ s and $c = 1\ 525$ m/s.

Hydrophone depth.—A source signature's ghost is produced at the water-air interface and, when observed from a great distance (i.e., infinity), it appears to have the same amplitude, opposite polarity, and a slight delay with respect to the original signature. This source ghost is part of the total source signature and is what the earth "observes" as the source: hence, it is an integral part of the signature and should be recorded faithfully. If the receiver is not far enough from the air-water interface, the source ghost is not fully developed and the receiver sees the direct arrival from the source as being larger than the ghosted arrival because of the difference in the travel paths of the two signals. The ghosted arrival has traveled farther and, therefore, has a smaller amplitude due to spherical spreading loss with respect to the direct arrival. Equation (3) expresses the ghost amplitude as a percentage of the direct arrival amplitude for a given source and hydrophone depth. Thus

$$G = 100(D - d_s)/(D + d_s) \tag{3a}$$

which may be rearranged to produce

$$D = d_s(100 + G)/(100 - G), \tag{3b}$$

where

G = percent ghost,

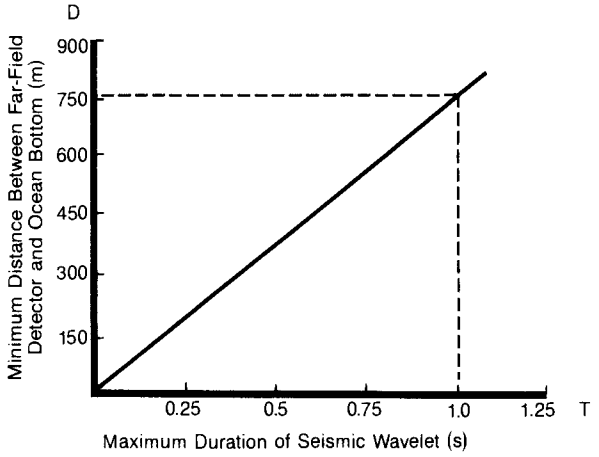


FIG. 2b. Minimum distance D as a function of wavelet duration T for $c = 1\ 525$ m/s. The dotted line indicates that for a wavelet duration of 1.0, the minimum distance between the far-field detector and the ocean bottom is slightly over 750 m.

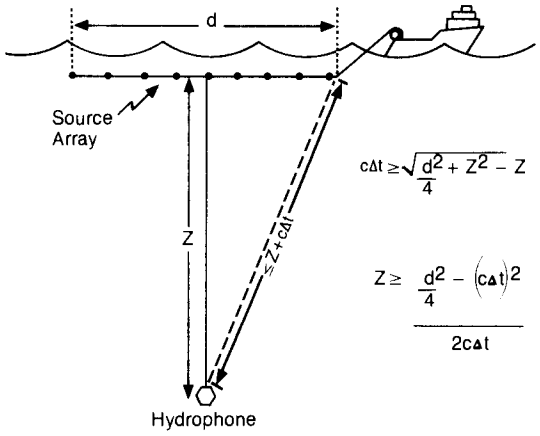


FIG. 3a. Minimum distance between source array and far-field detector. Schematic representation of hydrophone placement. The minimum distance Z must be such that signals from the closest source element and signals from the farthest source element arrive within one sampling interval Δt. c is the speed of sound in water.

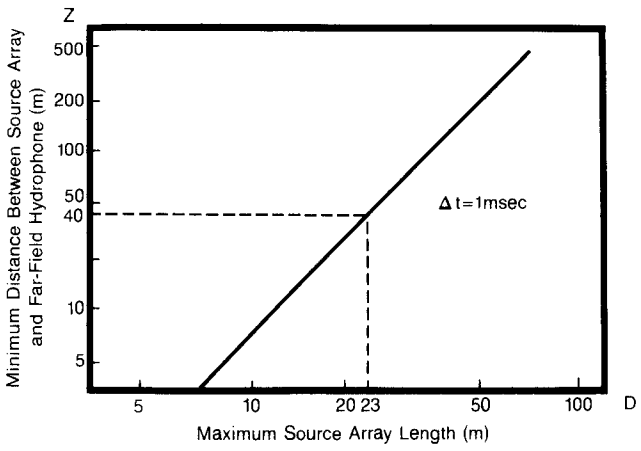


FIG. 3b. Minimum distance D as a function of source array length d for $c = 1\ 525$ m/s. The dotted line indicates that for an array length of 23 m with a sampling interval of 1 ms, the minimum distance between the source array and far-field hydrophone is 40 m.

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D = hydrophone depth (m), and
d_s = source depth (m).

Unless the array is very long, the minimum depth computed from equation (2) will not result in a fully developed ghost as determined by equation (3a). Thus, hydrophone depth is normally constrained by ghosting requirements, as dictated by equation (3b), and not by source array length, as expressed by equation (2). (Note, however, that D is the actual hydrophone depth while Z is the source-hydrophone separation or $D - d_s$, the hydrophone depth minus the source depth.)

Source operation

Once the sonobuoy and recording system is calibrated and the hydrophone position determined, actual measurement of the source may begin. The buoy system is deployed and the sources are readied for the test. A crucial factor in proper measurement of the source signature is that the sources must operate during the test in their "standard operating configuration." They should be fired at their standard pressure, depth, fill time, firing interval, etc. Proper towing speed is an important parameter in that it ensures a proper geometric relationship between source elements. Accurate measurement of the source in most cases is not possible with the source vessel dead in the water. Once everything is operating properly, the tests may begin.

Successive approach and departure runs past the sonobuoy are made with the source firing and the buoy and recording system storing the data. Approach and departure paths of 750 to 1 000 m should be sufficient to study the vertically directed source wavelet and the directivity pattern of the source. Figure 4a illustrates a typical experimental configuration. The solid lines indicate firing and recording, while the dashed lines indicate firing the sources only when the sources need to maintain synchronization through continuous operation.

Results of a typical acquisition experiment (Figure 4b) show the approach and departure of the source past the sonobuoy. The signatures of greatest general interest occur at the apex of the hyperbolic curve and represent the vertically directed signature. Those that occur on the flanks of the curve represent signatures ascending from the vertical and are studied to evaluate the directivity of the source.

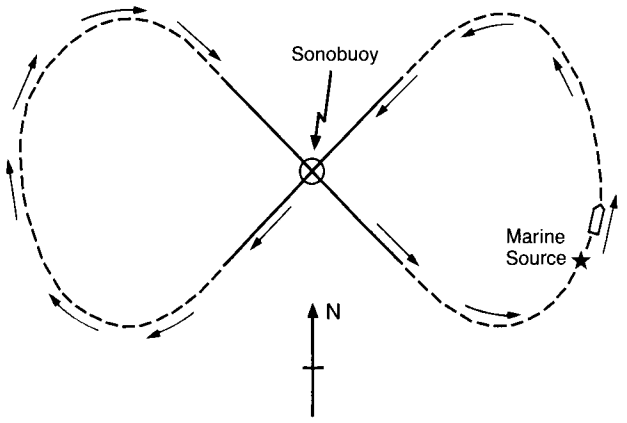


FIG. 4a. Signature acquisition traverse. Schematic representation of vessel maneuver. Solid lines represent acquisition and dotted lines represent periods of maneuvering and maintenance of source synchronization if necessary.

PROCESSING

Philosophy

Spectral analysis.—As noted in the Introduction, temporal analysis has historically been emphasized in marine calibrations. Spectral analysis, however, has not been completely ignored and has traditionally resulted in a display called a "power" spectrum. In reality, most of these power spectra are normalized or relative acoustic power flux spectral densities with the peak values set at 0 dB. The distinction between power flux versus power derives from the fact that pressure signatures are measured at one location rather than on a spherical surface around the source. If real power is desired, then an integral over a surrounding spherical surface must be computed.

A second point concerns how most modern "power" spectra are calculated. The Fourier transform technique generally used for this type of analysis implicitly assumes a repetition of the signal being analyzed. The repetition is assumed to be periodic with a period equal to the analysis window length. However, severe repercussions occur when computing a quantified power flux spectral density of a transient signal. The Fourier transform equations for quantified power flux spectral density are expressed as

$$P(m) = \frac{1}{\rho c N \Delta t} |X(m)|^2, \quad m = 0, 1, \ldots, N-1, \tag{4a}$$

where

$$X(m) = \Delta t \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi m n}{N}}, \quad m = 0, 1, \ldots, N-1, \tag{4b}$$

and

$X(m)$ = Fourier coefficients,
N = number of samples in the analysis window,
$x(n)$ = digital samples of time series,
$P(m)$ = power flux spectral density,
ρ = density of water,
c = speed of sound in water,
and
Δt = sampling interval.

Because the squared coefficients of equation (4a) are normalized by N, the "power" of a transient signal in a large window is less than the "power" of the same signal in a small window, assuming both windows wholly contain the signal. This implies that one signal has different amounts of power depending upon the analysis window and is also why "power" spectra have always been normalized. If they had not been normalized, the same signal analyzed with two different windows would have produced different answers.

Transient source signatures actually have zero power, since power in the strict definition involves a time integral from minus to plus infinity. Acoustic source signatures, however, do have energy. They are zero-power, finite-energy signals which is the key to proper signature spectral analysis. Instead of computing a true quantified power flux spectral density (that should be zero for all frequencies), a quantified energy flux spectral density is computed. This is expressed as

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$$E(m) = \frac{1}{\rho c} |X(m)|^2, \quad m = 0, 1, \ldots, N-1 \tag{5a}$$

where

$$X(m) = \Delta t \sum_{n=0}^{N-1} x(n) e^{-j \frac{2\pi mn}{N}}, \quad m = 0, 1, \ldots, N-1, \tag{5b}$$

and

$X(m)$ = Fourier coefficients, while
$E(m)$ = energy flux spectral density.

Note the absence of $N\Delta t$ in the denominator of equation (5a) compared to equation (4a). This difference produces consistent spectral amplitudes for a transient signal regardless of the analysis window length.

Also note that for any given signal in an analysis window there is a unique amplitude spectrum, a unique energy spectrum, and a unique power spectrum. For transient signals both the amplitude and the energy spectra are invariant with respect to window length if the window completely contains the signal. Therefore, either the amplitude spectrum or the energy flux spectral density quantitatively defines the spectral

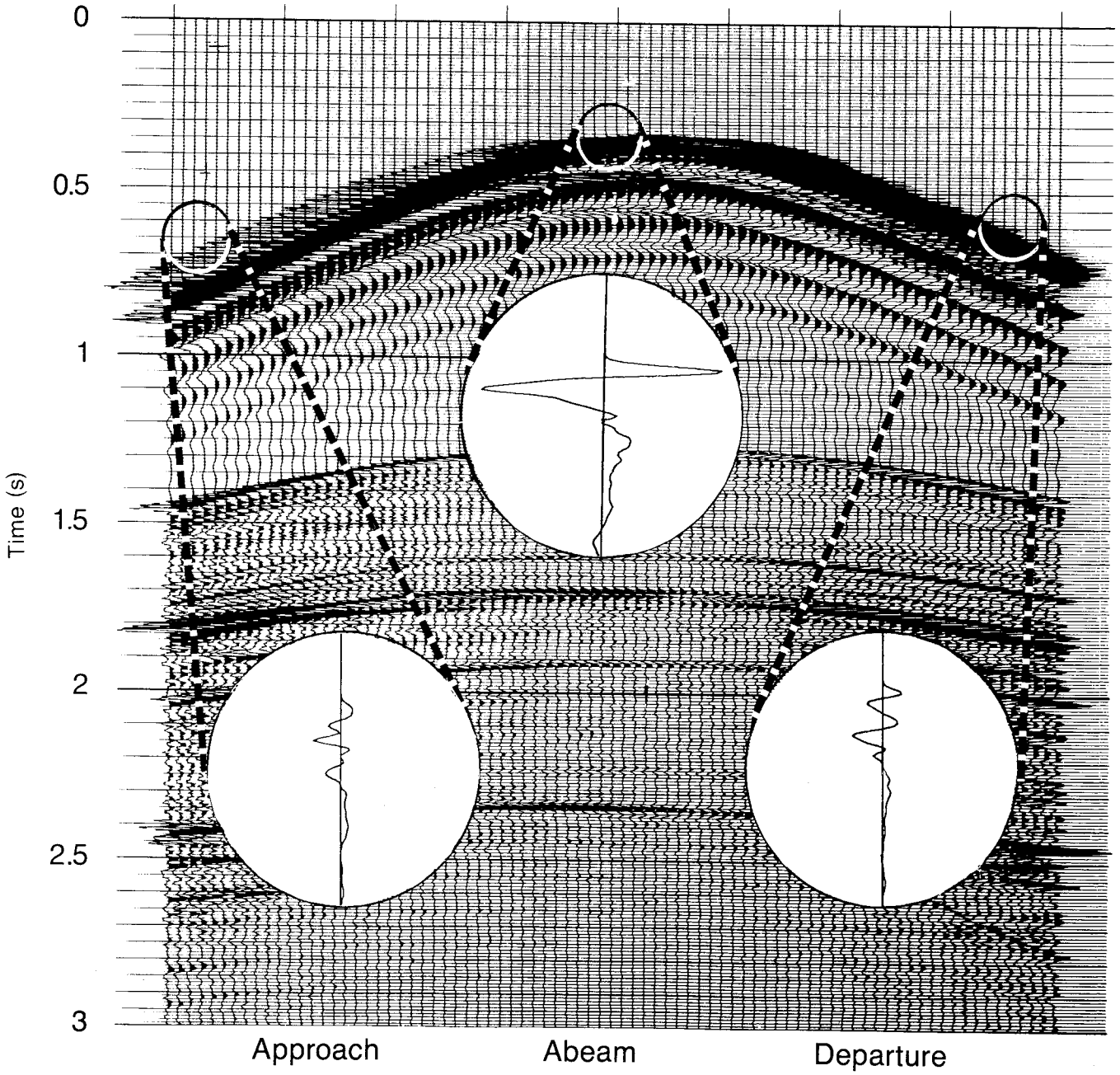


FIG. 4b. Results of a typical traverse. Notice the signature is completely recorded before the water-bottom arrival occurs. Note the difference in the signatures taken at the three locations of approach, beam, and departure.

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characteristics, and either may be used with equal validity for transient signals (assuming a constant acoustic impedance). The power spectrum of a transient signal actually analyzes the "apparent" power and varies with respect to the length of the window chosen for analysis.

From the energy flux spectral density, cumulative energy flux and total energy flux are computed. The cumulative energy flux is interpreted as the amount of energy flux contained by the signal in a frequency band from 0 Hz to any particular frequency of interest. Total energy flux is the cumulative energy flux contained by the entire signal over all frequencies. Cumulative energy flux as a function of the energy flux spectral density is given by

$$U(k) = \Delta f \sum_{m=0}^{k} E(m), \quad k = 0, 1, \ldots, N-1, \tag{6}$$

where

$U(k)$ = cumulative energy flux from 0 Hz to a frequency of $k\Delta f$ Hz,
Δf = frequency sampling interval, and
$E(m)$ = energy flux spectral density from equation (5a).

Note that $U(N-1)$ is the total energy flux and is assigned the symbol U_T.

A convenient representation of cumulative energy flux is a percentage of the total energy flux; thus

$$U_p(k) = \frac{\Delta f \sum_{m=0}^{k} E(m)}{U_T} \cdot 100, \quad k = 0, 1, \ldots, N-1, \tag{7}$$

where

$U_p(k)$ = cumulative energy flux expressed as a percentage of the total energy flux,

and the numerator is equal to $U(k)$ from equation (6). As shown later, this representation is quite useful in analysis of individual source characteristics.

Briefly, equation (4) is used for signals that are stationary and have finite power and infinite energy, while equation (5) is used for transient signals with zero power and finite energy. The transient nature of source signatures dictates the use of equation (5) for analysis rather than equation (4).

Calibration.—If pressure values quantified to a given standard unit are used, the resulting energy flux spectral density will also be quantified to the same standard unit. To comply with established standards, quantified acoustic source characteristics are represented in units referenced to a unit distance from the source. The ANSI unit of pressure is 1 newton per square meter (N/m^2) which has been given the name Pascal (P). Scientists in underwater acoustics use a micropascal (10^{-6} Pascal, μP) as reference pressure for all quantitative work (Urick, 1975). This unit is also used here. (Note, 1 μP = 10^{-5} dyne/cm^2 = 10^{-11} bar.) Joules per meters squared (J/m^2) are used as the standard unit of energy flux. In addition to quantification of acoustic pressure in units of micropascals, the source levels are all referred to a unit distance 1 m from the source. This is to compare sources measured at various separations between source and receiver on an equal basis. In referring the signal level back to 1 m from the source, a simple spherical spreading loss $1/r$ is assumed and removed; r is the distance between the receiver and the source in meters. The calibrated energy flux spectral density of a given source signature may now be computed. Information required in addition to the recorded signature is: first, a calibration constant relating pressure at the hydrophone to counts on tape; and second, the distance between the source and the receiver. Given these two values, the calibrated energy flux spectral density is computed.

Processing sequence

Calibration constant.—System calibration is performed to estimate a constant that converts the counts recorded on tape back to volts input into the system, i.e., the sonobuoy. Sinusoidal calibration signals recorded in the field generate corresponding sets of values on tape. The ratio of the rms input signal to the rms count level produced on tape yields a calibration constant for the recording system. When this ratio is combined with the hydrophone sensitivity, the result is a constant that relates units of pressure to counts on tape. This total acquisition system calibration constant may be used to convert values recorded on tape to actual pressure levels detected by the hydrophone in the water.

Source-receiver separation.—Because there is a high probability of surface water currents in the marine test area, we may expect a nonvertical hydrophone cable and hence a slightly shallow hydrophone depth. In most cases the hydrophone is only a few meters shallower than expected. A good estimation of depth may be made with a pressure transducer in close proximity to the hydrophone. In addition, source-receiver separation may be confirmed through transit times computed from the difference between shot time and the arrival time at the hydrophone. Knowing this interval, and with an estimate of the velocity of sound in water, a distance may be computed. These estimated distances should agree closely with measured and expected receiver depths. Note that the survey vessel must pass as close to the buoy as possible. Otherwise, estimates from the transit times will be greater than the measured and expected depths, in which case the estimates from the transit times should be used because they are more accurate.

Spectrum calculation.—Given the system calibration constant and the source-receiver separation, a calibrated energy flux spectral density may be computed. The raw data are multiplied by the calibration constant (in units of megapascals/count) and the source-receiver separation (in meters). This results in a calibrated source signature, an example of which is shown in Figure 5. The application of equation (5) generates the energy flux spectral density for the source. Equation (5b) is most conveniently computed using a Fourier transform. If the Fourier coefficients are converted to units based on micropascals and displayed on a decibel (20 log) scale, the result is an amplitude spectrum. If the coefficients are then squared, divided by ρc (the acoustic impedance), and displayed on a decibel (10 log) scale, the result is an energy flux spectral density. There is no difference in the shapes of the two curves, but the units change. The amplitude spectrum has units of pressure per unit frequency [micropascal/hertz (μP/Hz)] while the energy flux spectral density has units of energy flux per unit frequency [Joule/meters^2/hertz ($J/m^2/Hz$)

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at 1 m]. Amplitude values expressed in dB (20 log) referred to a μP/Hz at 1 m are 182 dB greater than the equivalent energy values expressed in dB (10 log) referred to J/m²/Hz at 1 m, assuming a constant ρc equal to 1.539×10^6 Kg/m² · s.

An example of a calibrated spectrum is shown in Figure 6. Scales on the left correspond to both the amplitude spectrum and the energy flux spectral density. Unless stated otherwise, it is assumed that any source-related amplitudes are referenced to 1 m from the source.

INTERPRETATION OF THE CALIBRATED SPECTRUM

Three items of interest in a calibrated spectrum are: (1) spectral amplitude, (2) total energy flux, and (3) energy flux distribution with respect to frequency. Probably the most obvious, easily understood attribute of any source spectrum is its magnitude. When expressed as decibels referred to a micropascal/Hz, the amplitude spectrum peak usually lies near 200 dB, depending upon the source. Another useful spectral characteristic is total energy flux. Generally, this figure ranges from 10^2 J/m² to 10^4 J/m², again depending upon the source. As a rough estimate, the ratio of total energy flux for two sources is approximately proportional to the square of the ratio of the peak-to-peak amplitudes for the same two sources, given similar wave shapes and recording bandwidths.

Information about total energy flux leads to the question of how the energy flux is distributed over frequency, or more precisely, what is the cumulative energy flux as a function of frequency. As an example note in Figure 6 that the cumulative energy flux, expressed as a percentage of the total, builds up to almost 100 percent near 150 Hz. The curve is virtually linear from 10 to 50 Hz, which might indicate a good low-frequency, deep-penetration source. In general, a linear cumulative energy flux curve results from a flat spectrum and an impulsive source. A stair-step cumulative curve indicates a lack of energy in certain frequency bands. Frequently the steps are caused by source ghosting notches as defined by equation (8):

$$f_n = c/(2d_s), \tag{8}$$

where

f_n = frequency of ghosting notch (Hz),

c = speed of sound in water (m/s),

and

d_s = source depth (m).

If the stair-step cumulative energy flux presents a problem, a change of source depth might help.

Phase spectra may also be interpreted and are interesting to study for source evaluation. However, they do not require a quantified study because phase is the arctangent of a ratio of amplitudes and the ratio cancels any effect of calibration. Since the importance of phase has been discussed extensively in the literature (for example, Oppenheim and Lim, 1981) and since the interpretation of a "quantified" phase spectrum is the same as that of a "normalized" phase spectrum, the subject is not discussed further.

SOME USES OF THE SOURCE CALIBRATION TECHNIQUE

Quantified spectral data may be utilized in a variety of ways. They are interpreted and used directly, as in the previous section, or they may be used for further analysis. Perhaps the most immediate application of the calibration technique is in source evaluation and selection for seismic surveys. These spectra allow the geophysicist to determine if a given source meets certain criteria for a specific exploration target.

These criteria may include spectral amplitude over a given frequency band or presence or absence of energy at a specific frequency. Study of the source characteristics in a quantified fashion could improve the chances of success in any given exploration task.

Source calibration techniques may also be applied in the area of source development. Any time a new source is introduced, a quantified spectral analysis of its acoustic characteristics should be studied. This provides information about the individual source as well as information about the source in comparison to others previously analyzed. If a new source development is undertaken to improve characteristics of an existing source, the best way to gauge the improvement precisely is through quantified spectral analysis.

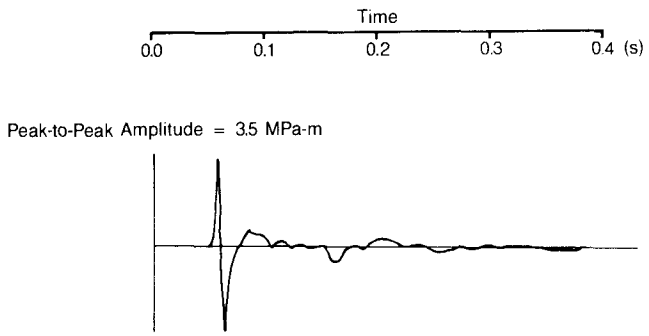


FIG. 5. Typical air gun array response. The amplitude is in calibrated units and is corrected to a reference distance 1 m from the source.

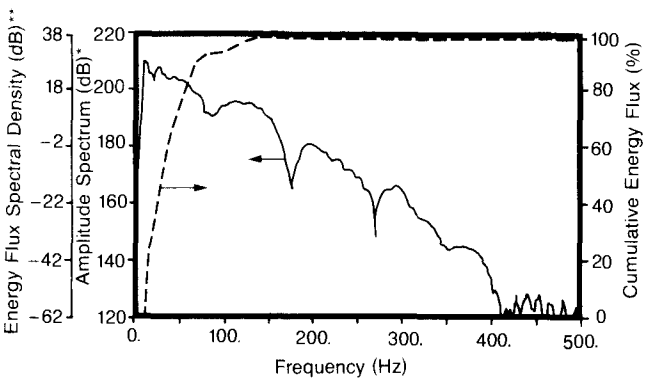


FIG. 6. Typical calibrated spectrum. The amplitude spectrum (*) is referenced to 1 μPa/Hz at 1 m. The energy flux spectral density (**) is referenced to 1 J/m²/Hz at 1 m. There is a difference of 182 dB between these two scales for the ocean acoustics case.

Another, more sophisticated use of the technique in source development is in the study of source efficiencies. Conversion of potential energy to acoustic energy in seismic sources is not an efficient process (usually 0.1 to 4 percent). Source efficiency is analyzed in a number of ways; the efficiency of energy conversion from total potential energy to total acoustic energy radiated in a sphere around the source may be analyzed. Because we did not measure the total acoustic field surrounding the source, this type of efficiency cannot be computed. Even if we had measured the entire acoustic field and could compute the efficiency, the figure may not be of interest because the vertically directed signature is considered most important. Thus, a more appropriate measure of efficiency for our purposes is the ratio of acoustic energy flux generated by the source in the vertical direction to the total potential energy available to the source. This type of efficiency has units of percentage per unit area (percent $/m^2$) and may be referred to as efficiency flux in the vertical direction. Physically, efficiency flux represents the product of total source efficiency and the directivity index of the source. For an omnidirectional source, efficiency flux and efficiency are identical. For arrays which have nonuniform directivity patterns, efficiency flux is different from the source efficiency. Based upon these concepts, a source study may include an analysis of efficiency flux in the seismic frequency band. As an example, we know that as source systems have increased in size and capacity over the years, the magnitude of handling problems has increased. Studies of efficiency flux for various source options and improvements determine which source system delivers the most energy for a given level of handling difficulty.

SUMMARY AND CONCLUSIONS

Traditional source evaluation techniques emphasized peak-to-peak amplitude and primary-to-bubble ratio. This type of evaluation is no longer adequate for studying seismic sources in light of modern exploration targets which include high-resolution structural and stratigraphic formations. Successful mapping of these targets requires a greater understanding of source energy level and frequency content than was required in the past. Traditional methods studied these source characteristics rather indirectly. A new source calibration method was proposed which studies frequency content and source energy level directly and quantitatively. The proposed method is based upon a study of the source energy flux spectral density.

To obtain the energy flux spectral density for a source, we first obtain a high-fidelity recording of the acoustic source signature. These data are processed to extract the energy flux spectral density. From this spectrum and the calibrated signature, a geophysicist can select sources for surveying purposes based upon quantitative measurements of the acoustic source characteristics. In addition, the quantitative measurement of source energy level and frequency content may be used for source development.

REFERENCES

Oppenheim, A. V., and Lim, J. S., 1981, The importance of phase in signals: Proc. of the Inst. Electr. and Electron. Eng., **69**, 529–541.
Smith, S. G., 1975, Research note: Measurement of airgun waveforms: Geophys. J. Roy. Astr. Soc., **42**, 273–280.
Urick, R. J., 1975, Principles of underwater sound: McGraw-Hill Book Co., 13–15.

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