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*Johnston, R. C., Reed, D. H. and Desler, J. F., 1988, Special report on marine seismic energy source standards *: Geophysics, 53, no. 04, 566-575. (* Errata in GEO-53-7-1011)*

Special Report of the SEG Technical Standards Committee[1]

SEG standards for specifying marine seismic energy sources[2]

R. C. Johnston[3], D. H. Reed[4], and J. F. Desler[5]

PURPOSE AND SCOPE

Purpose

The purpose of these standards is to specify, in an easily understood standard form, measurable characteristics of marine seismic energy sources to assist engineers, scientists, and operations managers in choosing, comparing, and/or specifying particular systems for their exploration programs.

Scope

These standards cover equipment used to acquire geophysical exploration seismic data in water-covered areas.

The attributes of the wavelet that radiates to the far field (the far-field signature) are the primary focus of these standards.

Only impulsive sources (explosive or implosive) are covered by these standards. Single-frequency or sweep-frequency sources may be added in the future.

DEFINITIONS

Near-field signature

A near-field signature is an acoustic wavelet whose direct arrival from the marine source is very large (>20 dB) compared with reflections from adjacent boundaries or interfaces. Near-field signatures are usually recorded for a single source or a point source. A point source is one whose dimensions are small compared with the shortest wavelength of interest, $L \ll \lambda$.

Far-field signature

A far-field signature is characterized by a direct wavelet plus its reflection (ghost) from the air-water interface. The ratio of the direct-to-ghost travel distances should approach 1.0. Far-field signatures are usually recorded for an array of sources (a directional source). A directional source is one whose dimensions are of the same order as the wavelengths of interest, $L \approx \lambda$.

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[2] These standards were approved for publication by the SEG Executive Committee on March 13, 1987. We anticipate that revisions and additions will be necessary from time to time. Please address all such suggestions to the current Chairman of the Technical Standards Committee, Ben B. Thigpen, 13914 Nimberly Lane, Houston, TX 77079, or to his successors.

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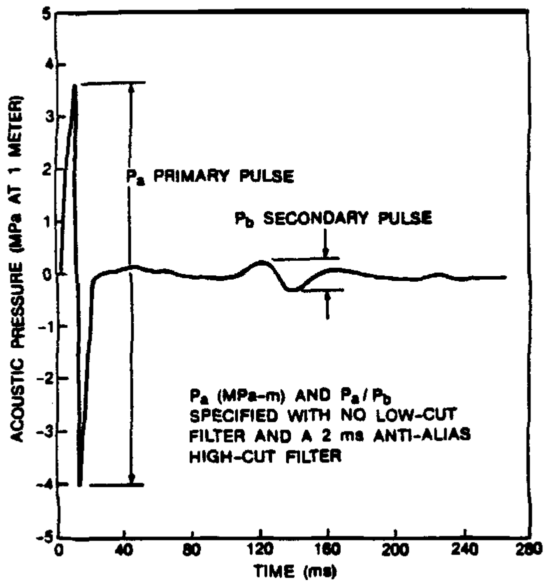


FIG. 1. Far-field signature.

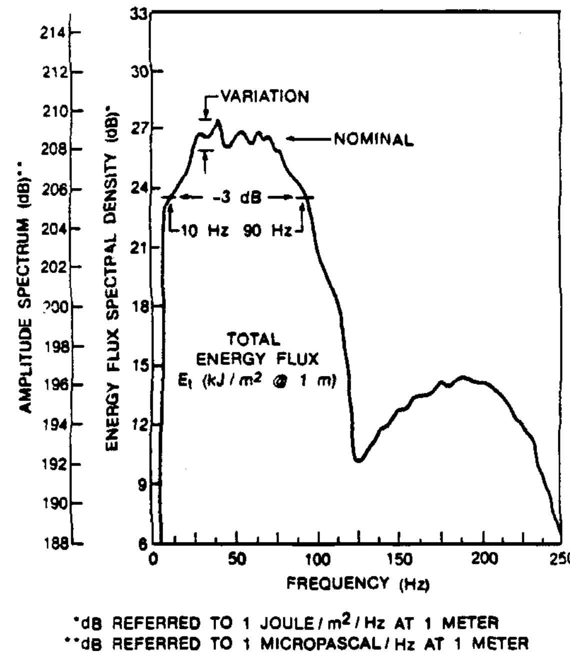


FIG. 2. Energy flux spectral density.

Source strength

Source strength is the maximum acoustic pressure radiated by a marine seismic source measured in MPa-m (megapascals referenced to 1 m) in a stated frequency passband. The zero-to-peak value is used for near-field signatures. A peak-to-peak value is normally used for far-field signatures.

Primary-to-secondary ratio

This attribute is the ratio of the maximum acoustic pressure pulse to the secondary acoustic pressure pulse (precursor for an implosive source and bubble for an explosive source) in a stated frequency passband. Zero-to-peak values are used for near-field signatures. Peak-to-peak ratios are used for far-field signatures. Refer to Figure 1.

Energy flux spectral density

This energy term is the acoustic energy radiated by a marine seismic source measured in J-m/m^2 (joules per square meter referenced to 1 m) in a stated frequency passband, usually 1 Hz. Refer to Figure 2.

Letter symbols

Letter symbols used in this standard comply with those given in American National Standards Letter Symbols for Acoustics, Y 10.11-1953 (R1959), American National Standard

Acoustic Terminology S 1.1-1960 (R1976), American National Standard Preferred Reference Quantities for Acoustical Level, S 1.8-1969 (R1974), and American Society for Testing and Materials Standard Metric Practice Guide, ASTM Designation E 380-79 (also ANSI Z210.1-1976).

Terminology

The terminology used in this standard is based on definitions given in American National Standards S1.1-1960 (R1976) and American National Standard Procedures for Calibration for Underwater Electroacoustic Transducers, S 1.20-1972.

Metrication

In addition to the terminology and letter symbols listed in the references above, the SEG has published a tentative metric standard. This publication, *The S. I. Metric System of Units and SEG Tentative Metric Standard,* SEG Metrication Subcommittee, 1981, should be consulted.

DESCRIPTIVE PARAMETERS

General

Systeme International d'Unites, also known as SI units, are used to quantify physical parameters and acoustic performance. Other units may be given in parentheses but the equivalent SI unit should be given first. Use of prefixes, such as micro, kilo, mega, etc., should be used for convenience in notation.

Physical dimensions

Overall dimensions of an individual source element and the distance between source elements in an array should be provided. The type, location, and specification for near-field source hydrophone monitors, depth gauges, pressure gauges, or any other ancilliary equipment should be provided.

Weights

The approximate weight of individual source elements and the weight of the total array should be given.

Operating conditions

Operating conditions that affect the acoustic performance of the source should be given. Examples for an air-gun array are the pressure, volume, and depth of each air gun, the towing configuration, boat speed, and method of timing the air guns.

Input requirements

Input *power* requirements to operate the source at a stated repetition rate should be given, e.g., standard cubic meters per minute of air required. Input *signal* requirements to initiate the source should be stated, e.g., signal characteristics to operate an air-gun solenoid.

Other parameters

There may be other parameters of importance that should be stated.

ACOUSTICAL PARAMETERS

Far-field signature

The far-field signature is a representation of the acoustic pressure as a function of time. It is characterized as a wavelet that propagates with its surface ghost and whose amplitude is inversely proportional to its distance from the source. An example air-gun array signature is shown in Figure 1. The signature is described by the peak-to-peak primary pulse amplitude, measured in megapascals and referenced to one meter (MPa-m), and the ratio of the primary-to-secondary pulse. The recording frequency passband should be stated, since the peak-to-peak primary pulse amplitude and the primary-to-secondary pulse ratio will be affected.

Amplitude and energy spectrum

The far-field signature should be transformed to the frequency domain and given as an amplitude and an energy flux spectral density plot. The total energy flux integrated to the Nyquist frequency shall also be given. An example spectral representation is shown in Figure 2; it is the transform of the signature of Figure 1. The units are micropascals per Hertz referenced to 1 m (μPa-m/Hz) for the amplitude scale and joules per square meter per Hertz referenced to 1 m from the source [J-m/(m^2Hz)], for the energy flux spectral density scale. The spectral plot shall be scaled in decibels referenced to 1 μPa-m/Hz and 1 J-m/(m^2-Hz).

These scales differ by about 182 dB when nominal values for the acoustic impedance (ρc) of seawater are used, namely,

ρ = 1026 kg/m^3 (the density of seawater)

and

c = 1500 m/s (the velocity of sound in seawater).

The spectral plot is characterized by the nominal value and its variation in the passband between the minus 3 dB points (see Figure 2). An additional parameter may be calculated easily from the energy flux spectral density: the cumulative energy flux as a function of frequency. This parameter is plotted as cumulative energy flux as a percentage of the total energy flux, and may be plotted on the graph with the spectral plot.

MEASUREMENT TECHNIQUE

Philosophy

The measurement technique outlined in Appendix A is intended to serve as a general guideline for acquiring calibrated acoustic characteristics of a marine source. Much of the information is taken from Fricke et al. (1985) "A standard quantitative calibration procedure for marine seismic sources." The intent of this acquisition step is to measure the signature with as much fidelity as possible. This requires measurement specifications which include large dynamic range, low harmonic distortion, low system noise levels, and a linear system response which is known in both amplitude and phase. If these requirements are satisfied in the measurement environment, then the recorded result will be a faithful representation of the original pressure signal.

Requirements

Four items should be considered to meet the requirements of the measurement system:

(1) recording electronics,

(2) system calibration,

(3) proper positioning of the calibrated hydrophone, and

(4) proper source operation during measurement.

Figure 3 illustrates an example acquisition system and the environmental conditions that need to be considered. Other acquisition systems utilizing towed fish and sea floor-based systems are routinely used. See Appendix A for

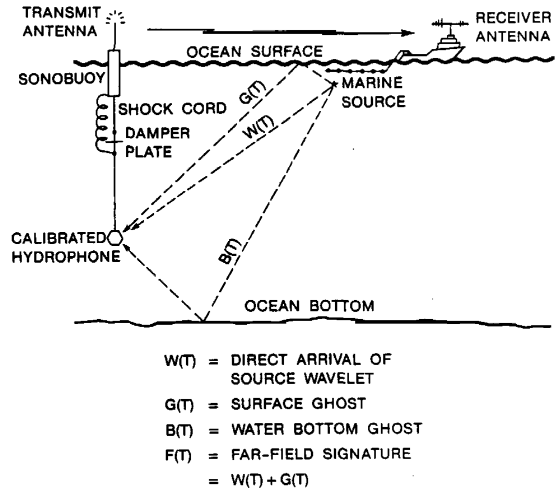


FIG. 3. Sonobuoy acquisition system.

a more detailed discussion of the measurement technique.

PROCESSING TECHNIQUE

Philosophy

Temporal analysis of a source's acoustic performance has traditionally been emphasized. Power spectra have been used, but this method makes quantitative comparisons among sources impossible because power in a transient signal depends upon the window length used in the analysis. The same signal will have different amounts of power depending upon the analysis window. This is also why "power" spectra have always been normalized; if they were not, the same signal analyzed with two different windows would produce different results.

Requirements

A calibrated energy flux spectral density is required to compare performance of sources on a one-to-one basis. The processing technique is given in detail in Appendix B.

Contractor: A
Boat: B
Date of tests: August, 1985
Place: Gulf of Mexico
Array description: 6 strings of 6 guns each
(see layout below)
Nominal array conditions: 123,300c.c.,13.8MPa,
7.5m depth
(7524 cu.in., 2000p.s.i., 24 ft. depth)

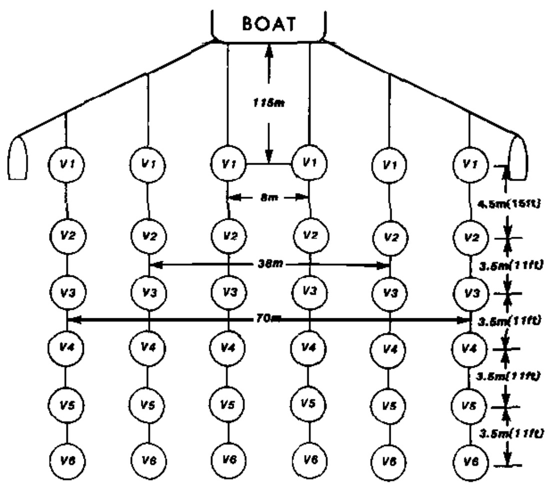


FIG. 4. Source description.

General: 9 passes made along side of Ref-Tek buoy (first 4 passes for total array; each other pass for a different individual gun)

Recording Conditions:

- DFS-V, 120-trace, SEG-D format
- 2 ms sample interval
- Out - 128 (72 db/oct) Hz filter
- Ref-Tek Hydrophone 57

Test Conditions:

- 5 second record, 5 second wait, 5 second record, 5 second wait, etc.
- Figure "8" with 1 mile long straight legs with array fired at 12 second intervals.
- *Array depth = 7.5 m (24 ft)*
- Hydrophone depth = 300 m (980 ft)
- Water depth = 914 m (3000 ft) or greater
- Sea condition = SS2 with 5 knot NW winds

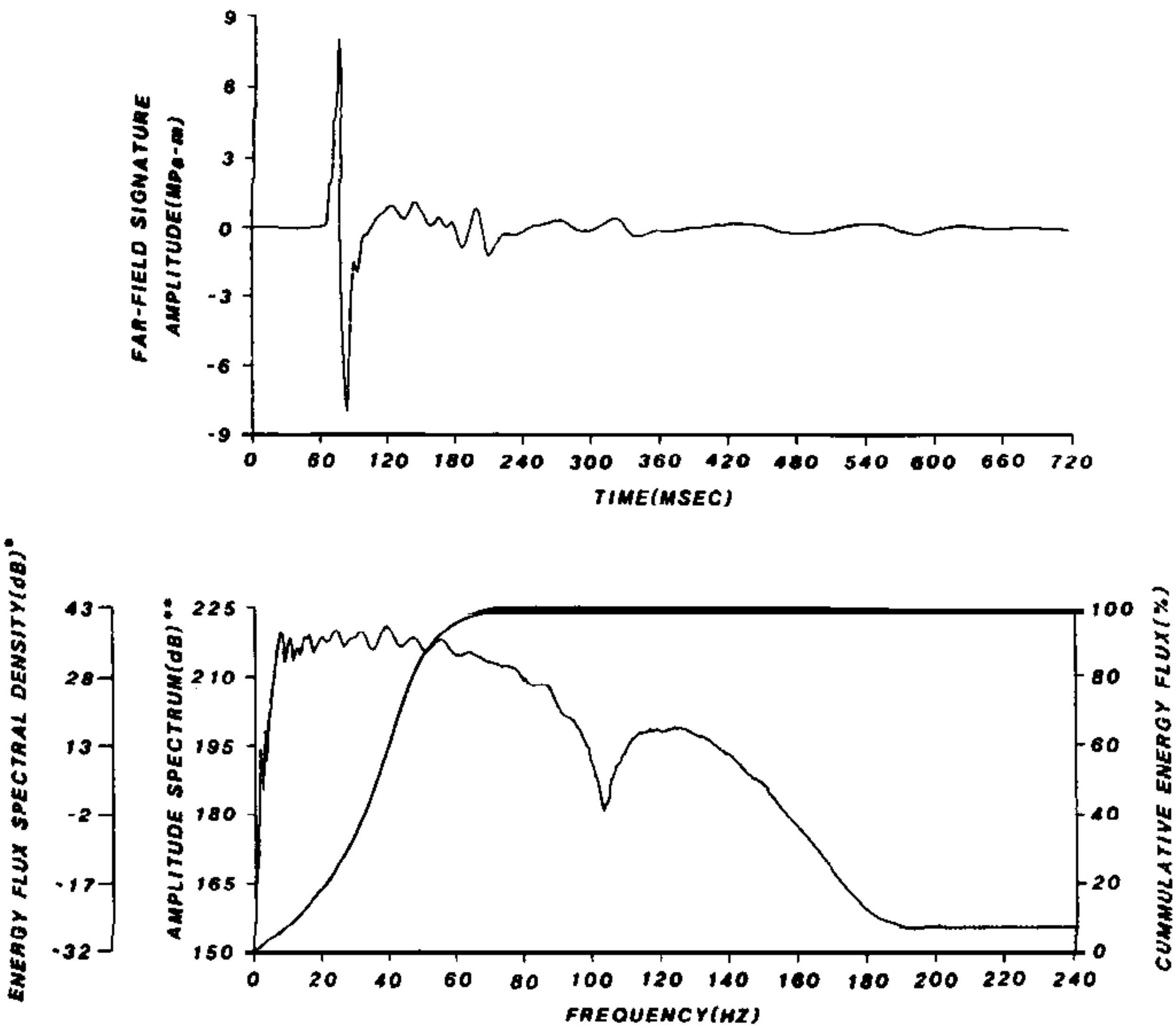
Recorded Data:

- Field tape numbers 1 through 3. Traces 61 and 64 signature data
- Data illustrated in Figure 6 is from FT 1, record 10, trace 61 and is for total array.

FIG. 5. Test conditions.

FILE 10 PEAK TO PEAK 16.03 MPa-m
TRACE 61 PULSE/BUBBLE 7.03

RECORDING FILTER OUT-128(72)Hz



TOTAL ENERGY FLUX = 0.20×10^6 JOULE/M^2 AT 1METER

*dB REFERENCED TO 1 JOULE/M^2/Hz AT 1 METER

**dB REFERENCED TO 1 MICROPASCAL/Hz AT 1 METER

FIG. 6. Results for 12 330 cm^3 (7524 $inches^3$) array.

PRESENTATION OF RESULTS

Minimum requirements

Measurement and processing techniques may vary from those outlined but the results should be presented in a consistent manner. The following data should be considered minimum:

- source description,
- recording instrument specifications,
- test conditions,
- far-field signature, phase spectrum (optional), and energy flux spectral density.

Other data may be shown in a similar format.

Example results

Figures 4, 5, and 6 show the minimum information described above for a particular air-gun array.

REFERENCES

Fricke, J. R., Davis, J. M., and Reed, D. H., 1985, A standard quantitative calibration procedure for marine seismic sources: Geophysics, 50, 1525-1532.

Thigpen, B. B., Dalby, A. E., and Landrum, R., 1975, Report by the subcommittee on polarity standards: Geophysics, 40, 694-699.

APPENDIX A

MEASUREMENT TECHNIQUE

Requirements

The four items that should be considered for the measurement technique are: recording electronics; system calibration; calibrated hydrophone location; and source operation. The use of a digital sonobuoy illustrates requirements of the system but is not the only acceptable technique.

Recording electronics

The recording electronics specifications are satisfied by using, for example, a digital sonobuoy interfaced to conventional seismic digital recording equipment· SEG standards for polarity (Thigpen et al., 1975) should be observed, i.e., a pressure increase should result in a negative number on digital tape.

System calibration

The recording system must be calibrated. A low-distortion signal oscillator, a calibrated digital volt-meter, and a wide-band voltage attenuator are used for the calibration. The digital sonobuoy should be interfaced such that data from the buoy may be received and recorded by the recording electronics. A sinusoidal signal with a measured amplitude and a frequency within the nominal passband is input into the sonobuoy. This signal is recorded and successive records are taken with the input signal attenuated by a specified amount (e.g., 10 dB). This process is continued until a representative range of signal amplitudes has been recorded. The data that result on tape represent sets of counts or values that correspond to input voltages from the oscillator. A calibration constant may be computed from these data, together with the hydrophone calibration. Sensitivity of the hydrophone must be suitable to the anticipated pressure range for the particular source, to avoid clipping of the peak signal· The time delay and the impulse response of the recording system should be determined during calibration of the system.

Calibrated hydrophone location

The proper positioning of the hydrophone in the water column is an important consideration. There are three constraints on correct placement of the far-field hydrophone:

(1) the distance between the hydrophone and the water bottom,

(2) the distance between the hydrophone and the source, and

(3) the depth of the hydrophone.

Each of these constraints is discussed below.

(1) Hydrophone water-bottom distance –

The distance between the hydrophone and the bottom must be such that the source signal is completely received before the water bottom reflection arrives· Figure A-1 illustrates the geometry required to derive an equation relating distance between the source and the bottom to wavelet duration. Equation (A-1) is the resulting equation, represented graphically in Figure A-2 for c = 1500 m/s. Let

$$D \geq \frac{cT}{2}, \qquad \text{(A-1)}$$

where

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

If the criterion established by equation (A-1) is observed, a clean signature will be received before onset of a water-bottom reflection.

(2) Hydrophone-source separation distance –

The hydrophone-source separation constraint must be considered only in the case of source arrays. Ideally a signal generated by the most distant source element in an array must arrive at the receiver simultaneously with the signal 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 will not be satisfied and distortion will occur. Figure A-3 illustrates the geometry of a symmetrical situation and includes an abbreviated derivation of equation (A-2), which defines the minimum separation between the source array and the hydrophone:

$$Z \geq \frac{d^2/4 - (c\Delta t)^2}{2c\Delta t} \qquad \text{(A-2)}$$

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

Equation (A-2) is illustrated graphically in Figure A-4 for Δt = 0.001 s.

For equation (A-2) to be valid, it is important

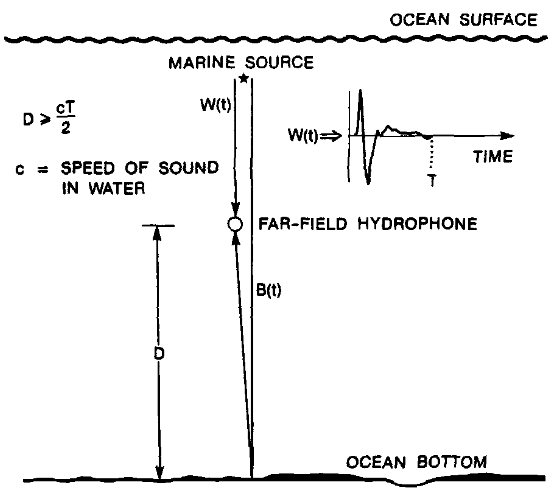


FIG. A-1. Minimum distance between the far-field hydrophone and the ocean bottom.

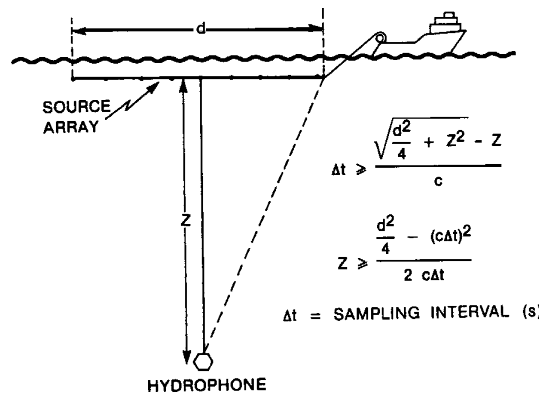


FIG. A-3. Minimum distance between the source array and the far-field hydrophone.

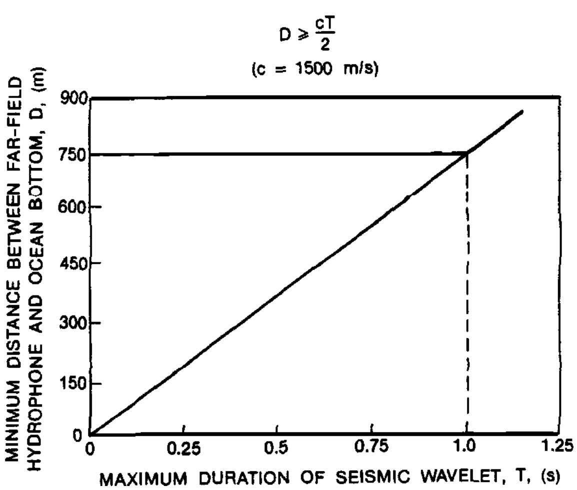


FIG. A-2. Minimum distance between the far-field hydrophone and the ocean bottom as a function of the seismic wavelet's duration.

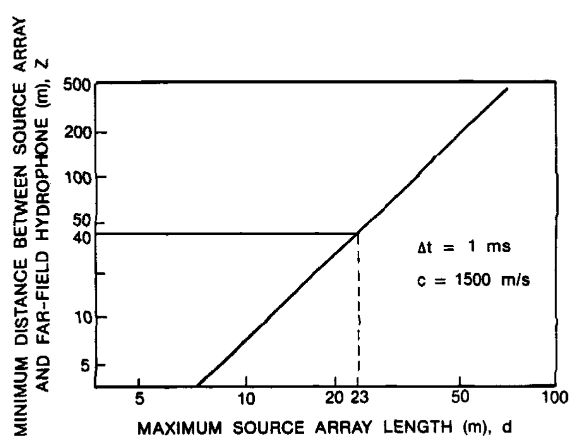


FIG. A-4. Minimum distance between the source array and the far-field hydrophone as a function of the length of the source array.

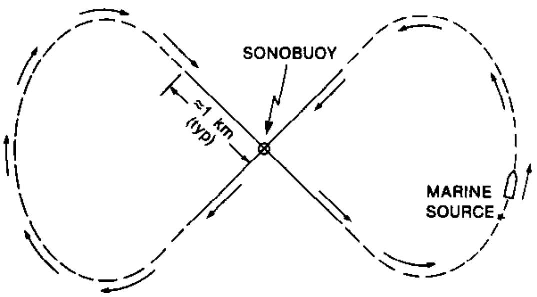


FIG. A-5. Configuration of the dynamic source test.

that the hydrophone be under the center of the source array; this requirement is particularly important for super-wide configurations. Frequently, in practice, this ideal is not attained. Additional calculations should be made for the case of non-symmetric geometry.

(3) Hydrophone depth –

The third and final constraint on the position of the hydrophone is its relationship to the surface of the water. A source ghost signature is produced; when observed from a great distance (i.e., infinity), the ghost appears to have the same amplitude as the emitted pulse but with opposite polarity and is delayed with respect to the original signature. This source ghost is part of the total source signature, which is what the earth "observes" as the source; hence, the ghost is a desirable part of the signature and should be recorded faithfully. If the receiver is not far enough from the surface of the water, the source ghost will not be fully developed. The receiver will see the direct arrival from the source as being larger than the ghost arrival. The difference in amplitude is due to a difference in the travel paths of the two signals. The ghosted arrival has traveled farther and, due to spherical spreading loss, has a smaller amplitude than does the direct arrival. Equation (A-3) expresses the ghosted amplitude as a percentage of the direct arrival amplitude for a given source and hydrophone depth:

$$G = \frac{d_h - d_s}{d_h + d_s} \times 100. \quad \text{(A-3a)}$$

Equation (A-3a) may be rearranged as

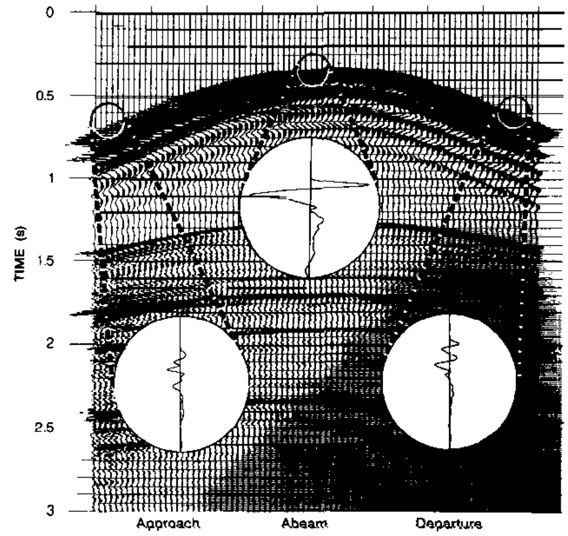


FIG. A-6. Results of the dynamic source test.

$$d_h = \frac{d_s(100 + G)}{(100 - G)} \qquad \text{(A-3b)}$$

where

G = ghost amplitude as a percent of the direct arrival amplitude,

d_h = hydrophone depth (m), and

d_s - source depth (m).

For example, unless the array being measured is very long (greater than 70 m), the depth computed from equation (A-2), with Δt - 0.001 s, will result in a ghost of less than 95 percent. Thus, hydrophone depth normally depends upon how close one desires to approach the idealized ghost of 100 percent.

Source operation

A crucial factor in proper measurement of the source signature is that the sources be operated during the test in their standard operating configuration. This means that they should be fired at their standard pressure, depth, fill time, firing interval, etc. Proper towing speed is a very important parameter. Proper towing speed ensures that the sources are cooled properly and are in proper geometric relationship with the survey vessel. An accurate measurement of the source cannot, in most cases, be taken with the source vessel dead in the water.

Acquisition using the sonobuoy technique

Once the sonobuoy-recording system is calibrated and the hydrophone position is determined, the actual measurement of the source may begin. The buoy system should be deployed and the sources made ready for the test. Successive approach and departure runs past the sonobuoy are made with the sources firing and the buoy-recording system storing the data. Approach and departure paths of 750 to 1000 m should be sufficient to study both the vertical acoustic characteristics of the source and the directivity of the source.

Figure A-5 illustrates a typical experimental configuration. The solid lines indicate firing and recording, while the dashed lines indicate firing the sources only in the event that the sources need to be synchronized through continuous operation.

Results of an acquisition experiment are illustrated in Figure A-6. This figure clearly shows 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 signatures that occur on the flanks of the curve represent signatures in ascension from the vertical and are studied to evaluate the directivity of the source. It is useful to compare calculated direct traveltime from the source to the hydrophone with the time measured at the apex of Figure 6. This comparison allows one to determine how close the source passed over the hydrophone, given that the hydrophone depth and the sea water sound velocity are known. Hydrophone depth may be determined by attaching precision depth gauges. Sonar systems have also been used effectively for determining the relative positions of the source and the hydrophone. Details of these systems are beyond the scope of this document.

APPENDIX B

PROCESSING TECHNIQUES

Requirements

A calibrated energy flux spectral density plot as a function of frequency is required to compare the acoustic performances of various sources.

Energy flux spectral density

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

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

where

$$X(m) = \Delta t \sum_{n=0}^{N-1} x(n) \exp\left[-j(2\pi mn/N)\right],$$

$$m = 0, 1, \ldots, N-1 \qquad \text{(B-1b)}$$

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

Equation (B-1a) produces consistent results for a transient signal no matter what the analysis window length may be, as long as there is no significant noise in the window. Cumulative energy flux and total energy flux are computed from the energy flux spectral density. The cumulative energy flux is interpreted as the amount of energy flux contained by the signal in a frequency band from zero Hz to any particular frequency of interest. Total energy flux is the cumulative energy that is contained by the entire signal over all frequencies. Equation (B-2) gives the cumulative energy flux as a function of the energy flux spectral density:

$$U(k) = \Delta f \sum_{m=0}^{k} E(m), \; k=0, 1, \ldots, N-1, \quad \text{(B-2)}$$

where
U(k) = cumulative energy flux from zero Hz to a frequency of k Δf Hz,
Δf = frequency sampling interval, and
E(m) = energy flux spectral density from equation (B-1a).

Note that *U(N*–1) is the total energy flux and is assigned the symbol U_r.

The cumulative energy flux is conveniently represented as a percentage of the total energy flux; it is the energy flux contained by the signal in a frequency band from zero Hz to any particular frequency of interest. Equation (B-3) is used to compute this percentage. This representation is quite useful in the analysis of individual source characteristics.

$$U_P(k) = \frac{\Delta f \sum_{m=0}^{K} E(m),}{U_T} \times 100, \quad k = 0, 1, \ldots, N-1 \; \text{(B-3)}$$

where $U_P(k)$ is the cumulative energy flux expressed as a percentage of the total energy flux.

Equation (B-2) is used for transient signals that have zero power and finite energy. The nature of source signatures lends them to this class of analysis. If one uses pressure signal values that are quantified to some standard, the resulting energy flux spectral density will also be quantified to the same standard.

To comply with established standards, quantified acoustic source characteristics are represented in SI units referred to a unit distance from the source. The SI units of pressure are newtons per square meter which has been given the name pascal. Scientific underwater acoustics work has adopted the micropascal (10^{-6} pascal) as a reference pressure for all quantitative work. (1 micropascal = 10^{-5} dyne/cm^2 = 10^{-11} bar.)

In addition to the quantification of the acoustic pressure referred to as a micropascal, the source levels are all referred back to a unit distance 1 m from the source. This is done so that sources measured at the various separations between the source and the receiver may all be compared on the same 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.

Processing the data

The calibrated energy flux spectral density may now be computed in a few simple processing steps. A calibration constant relating counts on tape to pressure at the hydrophone can easily be calculated, given the data obtained previously (see the section on system calibration in Appendix A). Check the calibration constant derived from each level of input oscillator signal. If the recording system is linear, each derived calibration constant will be the same. This is the total acquisition system calibration constant.

The next obvious piece of information needed is the distance (in meters) between the source and the hydrophone. As previously discussed in Appendix A, determination of true distance is not trivial, considering the fact that surface currents may move the visible sonobuoy away from a position vertically above the hydrophone. While it is beyond the scope of this document, those skilled in the art will use appropriate techniques to determine a distance (in meters) to be used in referring the pressure of the hydrophone back to a 1 m hypothetical distance. This simply requires multiplying the pressure by the distance (in meters).

Summarizing, the raw data are multiplied by the calibration constant and the source-receiver separation in meters. This results in a calibrated source signature. Application of equation (B-1a) generates the energy flux spectral density. Equation (B-1b) is most conveniently computed using a Fourier tranform. The Fourier coefficients are scaled by the value of the sampling interval. If the resulting values are displayed on a decibel scale, the display will be an amplitude spectrum. If the values are squared and then scaled by ρc, the acoustic impedance, and displayed on a decibel scale, the display will be an energy flux spectral density. The shape of the curve does not change, but the interpretation of the data is seen in a different sense. The amplitude spectrum has units of pressure per unit frequency. In SI units, this would be micropascals per Hz. The energy flux spectral density has units of energy flux per unit frequency. Again in SI units, this would be joules per square meter per Hz. An example of a calibrated spectrum is shown in Figure 2. The two scales on the left show both the amplitude spectrum and the energy flux spectral density.

The total energy flux is calculated using equation (B-2), and the cumulative energy flux is calculated as a percentage using equation (B-3). A final check of the frequency-domain calculations is recommended to obviate any scaling errors. This is simply done by integrating the time-domain signature with the pressure values squared and dividing the result by the acoustic impedance of sea water. The result is the total energy flux and should equal the U_T from the spectral-domain calculations.

ACKNOWLEDGMENTS

Members of the Technical Standards Subcommittee for Marine Source and Detector Standards who contributed to this document are:

C. O. Berglund, Teledyne Exploration Co.

J. Blue, Naval Research Lab., Orlando, FL.

W. A. Knox, Patent Practice, Western Geophysical (retired) Bruce Nelson, Digicon

Chris Walker, while with GECO USA

E. L. Tree, Amoco Research

R. G. Zachariadis, Mobil Research

We appreciate the encouragement given by three former Chairmen of the Technical Standards Committee: L. L. Lenz; D. A. Cavers; and J. G. Morgan. The authors who did the writing are grateful to all the other subcommittee members who reviewed the various drafts and made valuable comments. In addition to those above, industry representatives who reviewed drafts and all the companies who contributed time and resources are gratefully recognized.

Special thanks go to J. R. Fricke, ARCO (retired) now at M.I.T., J. M. Davis, ARCO, and J. P. Lindsey, GeoQuest, for their early lead in marine source measurements.