

## High-resolution common-depth-point seismic reflection profiling: Instrumentation

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### ABSTRACT

Seismic recording hardware must be a deliberately designed system to extract and record high-resolution information faithfully. The single most critical element of this system is the detector. The detector chosen must be capable of faithfully generating the passband expected and furthermore, must be carefully coupled to the ground.

Another important factor is to shape the energy passband so that it is as flat and broad as possible. This involves low-cut filtering of the data before A/D conversion so the magnitude of the low-frequency signal does not swamp the high-frequency signal. The objective is to permit boosting the magnitude of the high-frequency signals to fill a significant number of bits of the digital word. Judicious use of a low-cut filter is the main element of this step, although detector selection is also a factor because detectors have a  $-6$  dB/octave velocity response at frequencies less than the resonant frequency of the detector.

Finally, recording instrument quality must be good. Amplifiers should have low system noise, large dynamic range, and precision of 12 or more bits.

### INTRODUCTION

Critical components in the recording of digital seismic reflection data are the seismometers (geophones), amplifiers, filters which condition the signals, analog-to-digital (A/D) converters, and the digital data storage devices.

Seismographs used for engineering applications commonly have fixed point amplifiers. Floating point and binary gain systems are similar; their basic advantage is that they automatically switch gain as needed. *Ideal dynamic range* is the range (in decibels) from the peak input voltage of the system to the lowest voltage the system can detect. *Actual dynamic range* is the range (in decibels) from the peak input voltage of the system to the system noise level. *Precision* of the signal measurement is determined by the capability of the A/D converter. Most systems have either 8, 12, or 14 bits of precision.

*Significance* is the difference between precision and instrument noise level and is measured in bits of conversion. In *data-enhancement* seismographs, significance is improved by summing repeated measurements.

Filtering acquires an added dimension for high-resolution data acquisition. In addition to being used for noise suppression, low-cut filtering is used to help balance the spectrum of the incoming signal prior to A/D conversion.

A seismometer (velocity geophone), the most commonly used detector, is a wire-coil mass suspended by a spring in a magnetic field. Vibrations of the geophone case cause motion of the magnetic flux lines relative to the suspended coil mass. This motion induces a voltage proportional to particle velocity which is transmitted by wire to the amplifiers. Critical parameters in geophone design include natural (resonant) frequency, damping, coil impedance, sensitivity, harmonic distortion, and parasitic resonances. High natural frequencies are selected for high-resolution work to aid suppression of low frequencies and thereby reduce recorded groundroll and increase the significance of high-frequency information.

Accelerometers are also used as detectors. The design is a mass resting on a piezoelectric crystal. Accelerometers have very high resonant frequencies, typically greater than 1 000 Hz. Response relative to the velocity geophone response is a high-pass filter of slope 6 dB/octave and a 90-degree phase shift. Accelerometers are low-output, high-impedance devices requiring an inline preamplifier to boost signals and reduce impedance. For high-frequency, high-resolution seismic work, it is important to select a detector capable of recording expected high frequencies with integrity.

### FUNCTIONAL CONCEPTS OF THE SEISMOGRAPH

The key to recording shallow, high-resolution seismic reflections is correct use of proper equipment. The equipment and recording parameters used to obtain seismic reflections from a depth of 5 000 m are somewhat different from the equipment and recording parameters used to obtain seismic reflections from 5 to 50 m. We highlight some of those differences and identify and explain some important characteristics of engineering reflection seismographs and geophones.

To the casual observer or to a nonseismologist, a seismo-

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graph with dozens of dials, knobs, switches, and buttons may appear a formidable instrument. In essence, however, a seismograph is like a stereo music system except that the seismograph may have a dozen or more data channels instead of the two or four channels on stereos. Table 1 depicts the conceptual simplicity of a seismograph when compared with a stereo music system. In both cases (1) a motion sensor electronically reproduces the ups and downs of the grooves on a phonograph record or of the motion of the ground surface; (2) the signal is amplified and conditioned to suit the listener or the seismologist; (3) the amplifier output can be saved on magnetic tape; and (4) the magnetic tape can be played back and amplified and conditioned again before "display" through an audio speaker (in the case of music) or as seismograms for the seismologist.

Currently, most music is recorded on analog magnetic tape while most seismic data are recorded on digital tape. There are two distinct advantages of digital tape over analog tape. The most obvious advantage is the ability to perform digital computer processing on data in a digital format. Data quality can be greatly enhanced by modern digital processing techniques. The other advantage involves dynamic range of the recording medium. Analog tape has a dynamic range of not more than 40 to 50 dB. Digital tape is limited in dynamic range only by digital word size and other noise aspects of the recording system as we shall discuss later. In practice, dynamic ranges of 100 to 140 dB are possible with digital tape and modern electronic design. With the advent of digital music recording in the last part of the 20th century, a new generation of people will be provided music of unprecedented quality without a hint of "noise."

It is not really necessary for the seismologist to understand the function of each resistor, capacitor, transistor, and integrated circuit in a seismograph. It is useful for seismologists, and our colleagues—geologists and engineers—to understand the functional concepts mentioned.

### INSTRUMENTATION

Selection of seismic instrumentation is roughly akin to selection of component stereo equipment. The instruments chosen should have combined function and performance characteristics that meet the needs and goals of the user. This requires the user to know what performance characteristics best meet his needs, which is not a trivial task. The objective is to obtain a system to record the quantity and quality of information for either the problem at hand or a suite of problems to be solved. The instrument response characteristics must be designed to match and augment optimally the characteristics of the incoming data and thereby suppress noise and enhance weak aspects of the signal. We define noise as data we don't want and signal as data we do want, i.e., seismic reflections.

Each component of a seismograph can be represented as a filter with particular amplitude and phase characteristics. Amplitude response characteristics define the frequency band-pass nature of the component. Phase characteristics define the signal distortion nature of the component. Some components have negligible effects at seismic frequencies. For instance, wires and cables generally have only resistive losses. Although this affects voltage amplitudes, it does not affect relative amplitude or phase response. Components that affect data quali-

**Table 1. The simplicity of a seismograph.**

Function	Home stereo	Seismograph
Sensor	Phonograph needle	Geophone or seismometer
Signal conditioner	Amplifier with gain, treble, and bass controls	Amplifier with gain, high-cut and low-cut filter control
Storage	Tape recorder	Tape recorder
Display	Speaker	Plotter

ty the most include the energy source, source-earth coupling, receivers, receiver-earth coupling, amplifiers, and filters.

The degree of care required in designing the response of the system depends in part on the resolution of the recording instrument. The merits of a recording system include its precision (number of bits digitized), its noise level, and its dynamic range. The objective is to maximize the significance of all desired frequencies recorded within the signal band-pass. This means the total response of all components combined should be high-pass to counter-balance the low-pass filter characteristic of the earth. The objective is to record a flat band-pass of signal. Hence, rather than requiring a flat instrument response, as some seem to believe, a high-pass instrument response is required.

### DECIBELS AND DYNAMIC RANGE

A mathematical discussion of decibels (dB) can be found in any basic engineering physics book. The decibel is a unit measuring the logarithm of power or amplitude ratio, defined as  $20 \log_{10}$  of the amplitude ratio or  $10 \log_{10}$  of the power ratio. For the purpose of seismology, a few key points and rules-of-thumb must be known. In general, seismologists use amplitude rather than power or energy in their work. The following approximate amplitude relationships are useful:

- (1) an increase of 6 dB in signal approximately doubles the amplitude, 12 dB quadruples it, 18 dB increases it by a factor of 8, and so forth, by 6 dB increments in geometric progression.
- (2) an increase of 20 dB in signal is a factor of 10 in amplitude, i.e., an order of magnitude, and
- (3) an increase of 60 dB in signal is a factor of 1 000 in amplitude or three orders of magnitude, while 120 dB is a factor of a million or six orders of magnitude.

One of the least understood but most important concepts in instrumentation is that of dynamic range. Dynamic range was defined by Sheriff (1973) as "the ratio of the largest recoverable signal (for a given distortion level) to smallest recoverable signal." Before discussing dynamic range in instrumentation, we examine it by discussing the dynamic range of the human eye. Imagine a sinusoidal oscillation plotted on a piece of graph paper such that the peak-to-peak amplitude is 10 cm (roughly the width of a hand) and the frequency is such that one complete oscillation is plotted on the paper. This is approximately the largest amplitude and lowest frequency that can be completely and instantaneously seen by the eye and transmitted to the brain for analysis or opinion when the paper is held about 30 cm from the eye.

Now, visualize a much higher-frequency sinusoidal oscil-

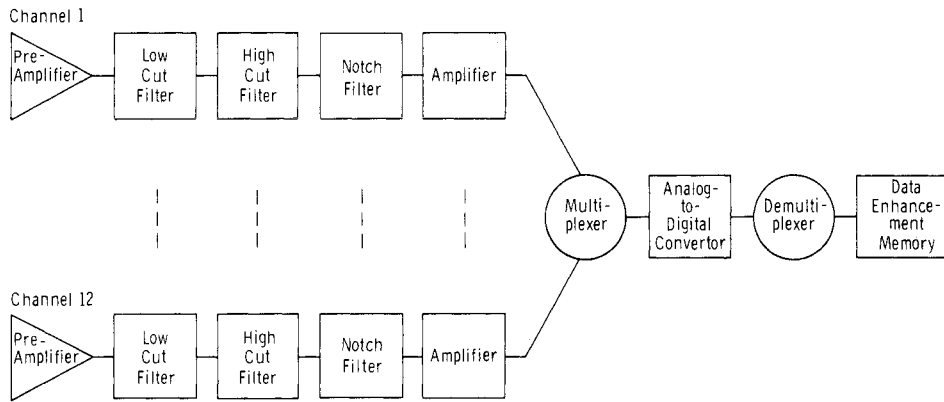


FIG. 1. Schematic of a typical 12-channel, fixed-gain, data enhancement seismograph.

lation with a very small amplitude superimposed on the sinusoid just discussed. The dynamic range of the eye is limited and defined by how small the higher-frequency oscillation can be without being invisible. In practice, this limit is probably about 0.1 mm. The dynamic range of the eye, then, is such that under suitable conditions amplitudes in the range from 0.1 mm to about 10 cm can be transmitted simultaneously to the brain. This represents a dynamic range of 60 dB and is probably an optimistic estimate of human capability.

Because dynamic range of seismographs is related to the number of bits in a binary number in the output of an A/D converter, we can relate the capabilities of seismographs to different dynamic ranges. For instance, many engineering seismographs use eight-bit A/D conversion, with one of the bits reserved for sign (i.e., positive voltage or negative voltage). Since each signal bit represents very nearly 6 dB, the dynamic range of such an instrument cannot exceed 48 dB. Since the dynamic range of the human eye is better than 48 dB, it is likely that a trained seismologist can spot any seismic reflections on a field plot of the digital data from such an instrument.

Consider a seismograph that uses 12-bit A/D conversion, including sign. Such a system potentially has a dynamic range of 72 dB. Because its dynamic range is probably better than that of the human eye, it is possible that seismic reflections may be present on field seismograms in the data that are invisible to the eye. Filtering or other computer processing techniques may allow the seismologist to detect reflections that are not even hinted on field seismograms.

Seismographs with dynamic ranges of 100 dB or more are now available. Considering the foregoing discussion, it is easy to see why some preliminary computer processing must be available on the new, powerful seismographs to allow the engineering seismologist to evaluate the quality of the data in the field. Reflectors may be hidden in such digital data that are a hundred times too small for the eye to see.

#### DIGITAL SEISMOGRAPHS

Various designs of digital seismographs exist, the simplest being fixed-point systems where amplifier gain is preset and constant (Figure 1). Systems come with a preamplifier stage, an analog gain stage, low-cut filters, notch filters, and high-cut

antialias filters for each channel. A multiplexer switches the data channel sequentially to an A/D converter which outputs a binary number proportional to the input voltage.

Such an instrument has several merit factors (Figure 2). The first is its ideal dynamic range. Ideal dynamic range is the voltage range the system can ideally record defined in terms of decibels. All systems have a system noise level given in microvolts. This is a background electrical component noise which masks any smaller input voltage. Therefore, true dynamic range is defined as the voltage range between system noise and the maximum input voltage. A specification of less than 1  $\mu$ V of system noise is excellent.

The number of pieces the A/D converter breaks the signal into defines the precision of the instrument. If it is broken into 12 bits, the instrument is more precise than if it is broken into

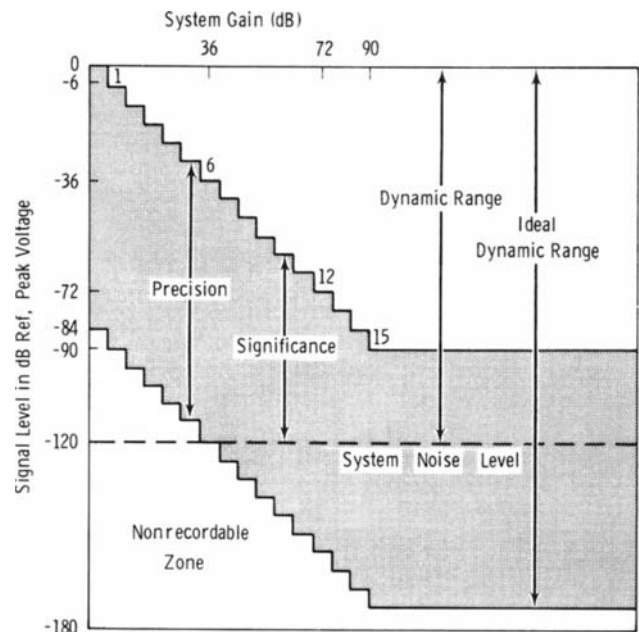


FIG. 2. Merits of a recording system (after Hewitt, 1980).

8 bits. An A/D converter is designed to accept a certain maximum voltage. It is important to amplify seismic signals until the maximum voltages put into the A/D converter are as close to (but not greater than) this value as possible. Using as many of the bits of the digital word as possible increases its significance. The significance of the digital word relates to the number of bits recorded above the system noise level. In other words, to take full advantage of the dynamic range of a seismograph, the amplifier gains should be set as high as possible without saturating signals. A signal is saturated when the largest voltage is too big for the digital word length.

At any specific gain setting a digital system can operate only within a defined input voltage range without the signal being either below the noise level or above saturation. The minimum detectable voltage is the larger of the threshold voltage for the least significant bit or the system noise level. The maximum detectable voltage is the level at which the A/D converter becomes saturated and outputs its largest possible digital number. Signals above the maximum level are truncated digitally in an ambiguous fashion. Clipping circuits limit voltage input to the A/D converter and are typically incorporated into instrument design. Saturated or clipped signals in such a system appear as square waves rather than sinusoids.

Maintaining the significance of the digital number recorded as the seismic signal decays with time requires a variation of gain with time. Programmed gain control (PGC) systematically increases gain with time according to a preset (typically exponential) function. The gain is initially set low so that early large-amplitude arrivals will not saturate the system. As recording time progresses and amplitude levels decay, the gain is increased to maintain a high-voltage input to the A/D converters. PGC circuitry adds to the noise level of the instrument; however, this detriment should be offset by the increased significance of the digital number recorded. Because the gain increase is programmed in a known way with time, true amplitude can be recovered in processing. PGC is not usually available on engineering seismographs.

Automatic gain control (AGC) automatically changes instrument gain according to the average voltage level of the incoming signal. This increase is not systematic and is an unknown function. It therefore causes irrecoverable changes in signal amplitude, and the true relative amplitudes of the recorded signal will never be known. AGC was common on the analog seismographs used in the 1950s.

The systems typically used for petroleum exploration are designed to adjust their gains automatically according to the incoming signal and also to record the gain setting. These are floating-point systems where the number is recorded in exponent-mantissa scientific notation. The output from the A/D converter is the mantissa and the gain setting is the exponent. Binary gain systems were the first of these systems; an example is Texas Instruments' DFS III which is gained in 6 dB increments (single bit shifts). The digital number is recorded as a 14-bit word and the gain is recorded in a 4-bit exponent. With binary gain systems, several (from 15 to 60) calls to shift are required before gain is increased. A single call is needed to decrease gain.

The next generation of floating-point recording systems was the instantaneous floating-point (IFP) system. Only one call is required to increase gain. The Texas Instruments DFS IV and DFS V are examples of such instruments. The gain increment for these instruments is 12 dB (2-bit shift). The TI9000 (DFS I)

and TI10000 (DFS II) are PGC systems, DFS III is a binary gain system, and DFS IV and DFS V are IFP systems.

Most engineering seismographs are fixed-point systems, although production of floating-point systems has begun. Most are also data-enhancing seismographs in that precision is improved by summing repeated measurements. Coherent signal energy is enhanced and random uncorrelated noise is attenuated. An extreme example is that of sign-bit recording. Sign-bit recorders have only one bit of precision, but measurements are commonly enhanced to 16 or more bits by repeated measurement. Data enhancement is a necessary procedure when using low-energy, high-resolution sources.

#### USE OF LOW-CUT FILTERS

In doing high-resolution work, application of low-cut filters prior to A/D conversion is critical, for several reasons. First, the seismic noise environment—wind, traffic, etc.—tends to be low frequency (below 100 Hz). Because high-resolution sources do not have sufficient energy to overcome the magnitude of low-frequency noise, the noise must be attenuated by filtering. Second, seismic sources tend to have more low-frequency energy than high-frequency energy. This imbalance is accentuated by the third factor—that the earth attenuates high frequencies more severely than low frequencies, i.e., the earth is a low-pass filter.

Most elements of the seismic reflection system are working against the generation, transmission, and recording of high-frequency data. The high frequencies received at the geophone can be of such small magnitude compared to the low frequencies that they do not register in the A/D conversion. They are lost in the system noise, or they are smaller than the voltage value represented by the least significant bit of the A/D converter. Applying a low-cut filter can improve this situation by attenuating the low frequencies to a level where their magnitude is comparable to the magnitude of the high frequencies. This technique emphasizes the high frequencies, and such filters are commonly termed preemphasis filters. It is important that instruments used for high-resolution seismic reflection work have analog filters available for this application.

Figure 3 compares the amplitude spectrum of data using a preemphasis low-cut filter with data recorded with the low-cut filter out, which is a broad-band instrument response. The source and detector locations and plants are identical, so information received by the detector was identical. The data were processed identically. The data recorded with broad-band recording parameters are actually more narrow band than the data recorded with the preemphasis filter. There is little significant energy greater than 250 Hz in the data recorded with broad-band instrument response. The low-frequency components of the signal saturated the system and the high-frequency components were insignificant by comparison. The preemphasis filter, on the other hand, attenuated the low frequencies sufficiently that the high-frequency components maintain a relative significance to frequencies greater than 400 Hz.

We now briefly discuss the desired end result of the recording of seismic reflection data. In theory, the seismologist wants a data set in an easily retrievable digital format and, further, the data should contain usable amplitudes of signals of all

frequencies. In practice, it is desirable to have a data set with a relatively flat amplitude spectrum over two to three octaves of frequency. What is really needed, then, for high-resolution reflection work is a flat spectrum from about 100 to 800 Hz or, better yet, from 200 to 1 600 Hz. (However, at this time it is not possible to use frequencies exceeding 1 000 Hz for seismic reflection work, making this example hypothetical.) As the seismologist increases the low-cut filter from 100 to 200 Hz, he must also significantly improve the frequencies in the range between 800 and 1 600 Hz; otherwise, the narrowness of the frequency content in the data set will fall well below the desired three octaves, the data will show "ringiness" on the record sections, and the desired improvement in resolution will be lost.

### THE VELOCITY GEOPHONE

Geophones are motion-sensitive transducers that convert ground motion to an electrical signal whose amplitude is proportional to the velocity of motion. The geophone can be represented by the model in Figure 4. The case of a geophone is fixed to the earth in such a way that its motion will follow the motion of the earth (see Knapp and Steeples, 1986, this issue). The case is part of the support system from which a mass is suspended by a spring. When the earth moves, the mass tends to remain stationary by inertia. To pick up the relative motion between the case and the suspended mass, a magnet is fixed to the case and a pickup coil is fixed to the mass. The relative motion of the pickup coil across the flux lines of the magnetic field induces a voltage proportional to the velocity of motion; hence, the term velocity geophone. Output voltage is not a consequence of the displacement of the case, but rather a consequence of the rate of displacement, velocity.

If the geophone receives an impulse, the spring-suspended mass will oscillate ideally with simple, undamped harmonic motion. Damping factors, air resistance, and losses in the spring and magnetic circuit cause oscillation to cease in time. A shorting, or shunt, resistor placed across the coil leads produces an opposing force which also damps the system. The strength of the shunt resistor controls the degree of damping of the geophone. When the geophone is critically damped, motion created by an impulse very slowly recovers without overswing or oscillation.

Performance characteristics of a geophone include its natural or resonant frequency, sensitivity, dc coil resistance, damping, harmonic distortion, and parasitic resonances. In practice, important factors include its field durability, size, weight, and shape.

Natural frequency,  $f_n$ , is the frequency at which the undamped geophone oscillates. Natural frequency is a function of the spring constant  $k$  and the mass  $M$ ,

$$f_n = \frac{1}{2\pi} \sqrt{k/M}.$$

Natural frequency is also the frequency at which resonance will occur when the geophone is driven by ground motion. The undamped, forced harmonic oscillator has no amplitude bounds at the resonant frequency. For damped systems, the amplitude response at resonance depends upon the damping factor. Figures 5 and 6 show the amplitude and phase re-

sponses for a geophone with various damping factors. Damping flattens the amplitude response and reduces the severity of phase distortion. However, it also reduces geophone sensitivity. Geophones are commonly damped by shunt resistors to about 60 percent of critical damping.

The dc coil resistance  $R_c$  and sensitivity (transduction constant)  $G$  are closely related,

$$G = K \sqrt{R_c}.$$

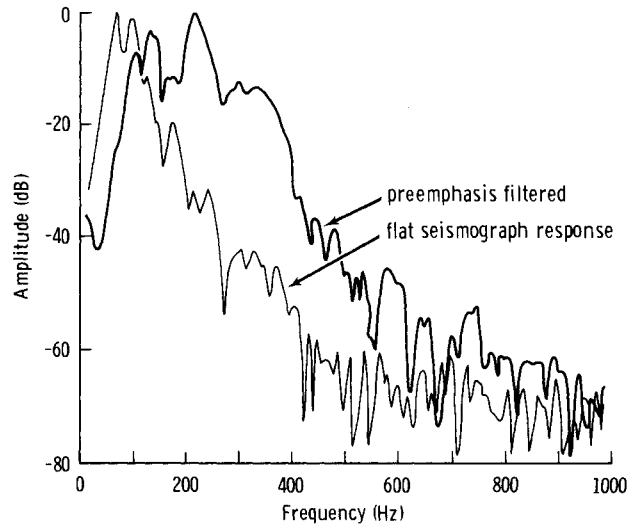


FIG. 3. Normalized amplitude spectra comparing data recorded with a preemphasis, low-cut filter applied prior to A/D conversion with data recorded with flat, broad-band seismograph response (from Steeples and Knapp, 1982).

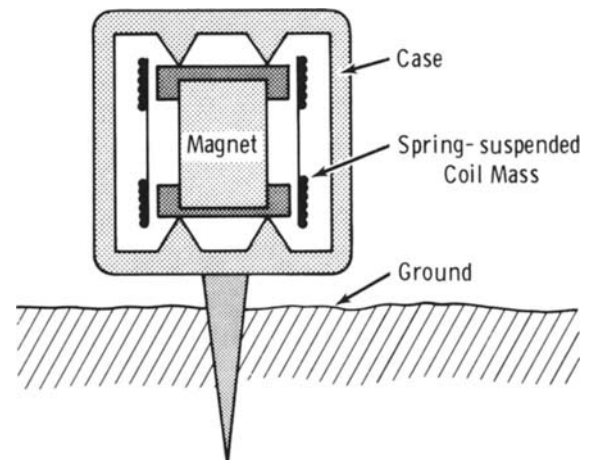


FIG. 4. Schematic of a velocity geophone. The coil mass is suspended from the case of the geophone. The magnet is fixed to the case.

The value of  $K$  is design-dependent. The larger the value of  $K$ , the more sensitive is the geophone.

Harmonic distortion is the result of nonlinearity of the geophone, or divergence of the spring-mass system from Hooke's law. Harmonic distortion in a geophone, which is a design factor, should be small. A typical specification value is 0.2 percent or less total harmonic distortion at the geophone's resonant frequency.

Classically, attempts had been made to use the geophone in the frequency range above the natural frequency because the amplitude response is flat and has little phase distortion. Therefore, design trends were to build geophones with a natural frequency as low as possible. Current attitudes favor using high-frequency geophones because geophone response can be used as a low-cut filter (Figure 5) and because the operating characteristics of a high-frequency geophone with high-

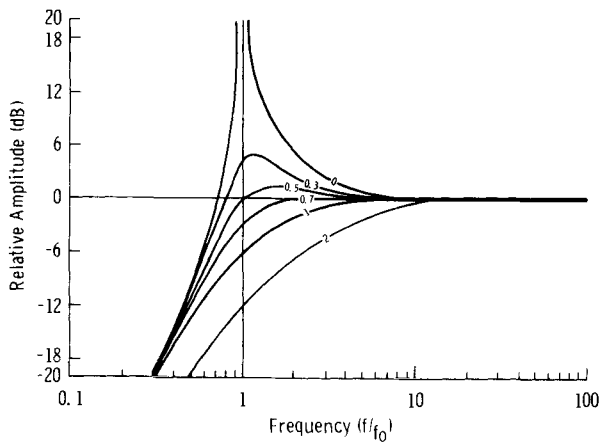


FIG. 5. Universal geophone amplitude response curves, relative output (dB) at constant velocity drive. The different curves are for different damping constants  $h$ .

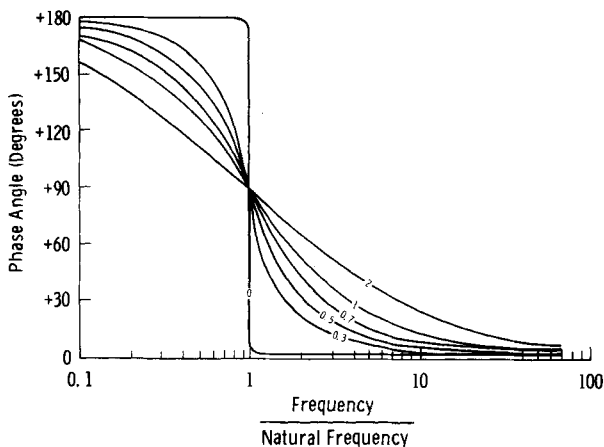


FIG. 6. Universal geophone phase response curves, phase angle between output voltage, and velocity of geophone. The different curves are for different damping constants  $h$ .

frequency data are better than those of a low-frequency geophone recording the same ground motion. Parasitic resonant frequencies are unwanted spurious noise resulting from motion perpendicular to the axis of intended motion (i.e., horizontal motion within a vertical geophone). Parasitic frequency values are a function of geophone design. Designers try to push the parasitic resonances into high frequencies outside the recorded bandwidth. Low-frequency geophones have low-frequency parasitic resonances which can be within the band-pass of high-resolution data. The actual values and character of parasitic resonances depend upon the geophone model and manufacturer. As a rough rule-of-thumb, parasitic resonances at frequencies greater than ten times the natural frequency of the geophone can be expected.

Used as a low-cut filter, the geophone helps suppress low-frequency noise and helps balance the spectrum of the incoming signal prior to A/D conversion. Such preconversion spectral balancing reduces the detrimental influences of the low-pass earth filter, improves the significance of the recorded data, and makes the recording of high-resolution data possible by attenuating to a manageable level the low-frequency signal that would saturate a flat-response recording system.

Choice of the geophone and its configuration is a complex function. Among the considerations are wiring configuration needed, load impedance desired, frequency range of operation expected, and filter characteristics desired. Within these confines choose the geophone that is most sensitive, is damped to about 0.6, has parasitic frequencies outside the data band-pass, has low harmonic distortion, and is field durable.

#### ACCELEROMETERS

Accelerometers respond to instantaneous acceleration of the ground. This means accelerometers have a high-pass response of 6 dB/octave and a 90-degree phase shift with respect to the response of velocity geophones. This response characteristic can be used to advantage in rejection of low-frequency noise and attenuation of large-amplitude, low-frequency signal. Note that the response of a velocity geophone at frequencies less than resonance is that of acceleration. The accelerometer simply has a very high-resonant frequency.

Accelerometers utilize a piezoelectric ceramic transducer with a mass providing the necessary pressure (force/area) to generate a voltage. Pressure (voltage) modulation occurs according to the force of the mass on the ceramic piece as the ground motion accelerates.

Accelerometers have two weaknesses. One is that they are fragile. The ceramic piece breaks with the rough handling typical of seismic field operations. The other is that accelerometers are low-output, high-impedance devices which require an inline amplifier to boost output voltage and to match output impedance to that of the recording system. This contributes to the electrical noise of the system, although the added noise level should be slight.

#### THE RESPONSE OF GEOPHONES AT HIGH FREQUENCIES

At high frequencies the recording of data with good integrity rests critically on the detector used and its coupling to the earth. Lepper (1981) did a comprehensive study of available seismic detectors and their application to high-resolution seismology. He found that most seismometers are not appropriate

for recording frequencies above 200 Hz, and very few can record above 500 Hz with integrity. He pointed out that detectors appropriate for deep petroleum exploration are not appropriate for shallow, high-resolution investigations, and high-frequency geophones and accelerometers appropriate for shallow, high-resolution are not appropriate for deep petroleum exploration. Accelerometers and 100 Hz geophones generally perform well in the 75 to 500 Hz band-pass and also help attenuate unwanted, low-frequency signal. For extremely high frequencies to 1 000 Hz, accelerometers are probably the best suited detector.

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