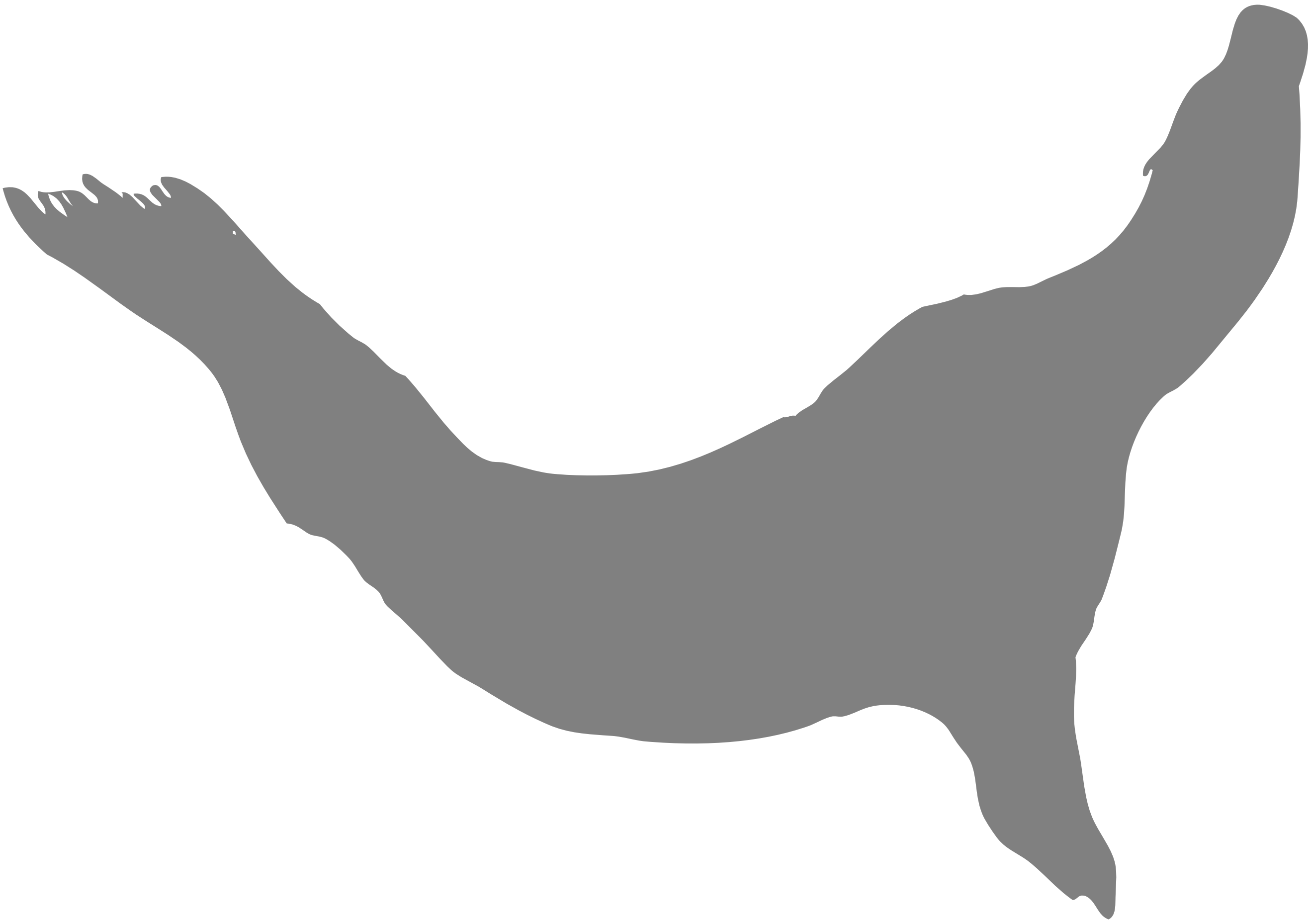
Fundamentals of underwater sound

Report No. 406
May 2008



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1 Sound waves

Sound waves are defined as compressional (or longitudinal) waves that have a frequency that is within the audible spectrum. For humans this covers frequencies from 20 Hz to 20 kHz, but for marine mammals and other species the audible spectrum can extend beyond the human hearing range. Sounds outside the human hearing range are often referred to as infrasound (below 20 Hz) and ultrasound (above 20 kHz).

Compressional waves are mechanical waves that propagate through the interior of the material as pressure fluctuations. A characteristic of longitudinal waves is that the motion of the particles goes back and forth along the same direction in which the wave travels. The rate of change of these pressure fluctuations determines the frequency of the wave.

Figure 1 illustrates the generation of sound waves, and shows how the pressure variations propagate away from the source with a velocity *v*. At the locations where the particles are shown close together, a pressure maximum in the sound wave is found.

Figure 1: Illustrating the generation of sound waves.

There are three other types of mechanical waves that will propagate through solid material: shear, Rayleigh and Lowe waves. In common with compressional waves, shear waves travel through the interior of the material. Both are known as body waves. Rayleigh and Lowe waves travel along the surface of a solid material. Shear waves depend on elastic deformation of the medium in a direction that is perpendicular to propagation. Although most reflection surveys are based upon analysis of pressure waves, seismic sources generate all types of waves in the seabed. The various wave types are separated by their differences in propagation velocity. Only compressional waves can travel through water, and are therefore the only type of waves that needs to be considered in terms of possible impact on marine life.

Fluids, such as air or water, cannot sustain a shear deformation; therefore there will only be compressional waves propagating through air or water. At the water/solid interface however, new wave types will be generated through energy conversion, and shear and surface waves will be present in marine seismic surveys.

Depending on the conditions for generation of the sound wave, they can be either plane waves, spherical waves or something between. Plane waves propagate in an ideal medium with no loss of energy in the direction of the wave propagation. Spherical waves, on the other hand, have an energy decay in the ideal medium that follows a spherical law, that is the energy decreases with the inverse of the distance squared.

Depending on how they are generated and other local conditions, sound waves can also propagate as cylindrical waves, or with other decay factors.

If measurements of sound waves are taken very close to the source they are called near field measurements. Similarly, if taken further away from the source, they are called far field measurements.

The near field is defined as inside a distance r_0, and is determined by the size of the source. For a circular source of area A, the near field will extend to a distance determined by:

$$r_0 = \frac{A}{\lambda} = \frac{Af}{c}$$

where f *frequency of the sound wave*
λ *wavelength of the sound wave*
c *propagation velocity of the sound wave*

Seismic signals have a low frequency, and although the "source area" can be significant, measurements made at distances of over 100 metre will be in the far field. This is normal practice in the geophysical industry.

2 Sound levels

The definition of sound level is not directly given by mathematical equations, but depends on a number of factors, including the intensity of the sound wave, the frequency and the length of the sound exposure, and whether the sound is propagating in air or in water.

2.1 Intensity

The acoustic intensity, *I*, of a sound wave is defined as the average rate of flow of energy through a unit area normal to the direction of wave propagation. The units for acoustic intensity are Joules per second per square metre, which can also be expressed as Watts per square metre.

In some cases it has been stated that the loudness of the sound is determined by its intensity. This is not true in the general case, for loudness and intensity are not synonymous. The loudness of a sound is subjective, and the loudness is in all cases a combined function of both intensity and frequency.

2.2 Pressure

Sound waves are pressure fluctuations, compression and rarefaction of the molecules in the medium through which the sound waves propagate. The unit for pressure is Pascal, equal to Newton per square metre.

The pressure can be measured with a pressure sensitive device such as a microphone (for measurements in air) or a hydrophone (for measurements in water).

Intensity and sound pressure (P) in a plane wave are related through the equation:

$$I = \frac{P^2}{\rho_0 c} \qquad [\text{Watt/m}^2]$$

where ρ_0 *specific density of the medium through which the sound propagates*
c *propagation speed of sound in the medium*

The instantaneous particle velocity, *U*, within the plane wave can be related to the sound wave pressure through the equation:

$$U = \frac{P}{\rho_0 c} \qquad [\text{metre/second}]$$

The displacement amplitude *A*, or particle motion, of a sound wave can be related to its pressure and frequency through the equation:

$$A = \frac{P}{\omega \rho_0 c} \qquad [\text{metre}]$$

where $\omega = 2\pi f$, *and f is the frequency of the wave*

The above formulae hold for both plane and spherical waves when the distance to the source is more than a wavelength at the lowest frequency, often called the far field. If the measurements are taken in small enclosures, it might be difficult to obtain accurate measurements of the sound pressure due to the many reflections from the enclosure walls. In this case the relation between pressure and intensity can only be estimated. However, the relationship between pressure and displacement amplitude will be accurate.

The pressure that represents the lower limit of human hearing (20.4 μPa, corresponding to an intensity of 10^{-12} Watt/m^2, as will be discussed later) will cause a displacement of the eardrum that is in the order of 10^{-9}cm at a frequency of 1000 Hz. This is approximately one-tenth the diameter of a hydrogen molecule.

In many papers on biological acoustics, there seems to be a belief that pressure and particle motion are separate physical phenomena. As shown above, the pressure and the displacement amplitude, or particle motion, in the far field are directly proportional.

2.3 Acoustic impedance

The factor $\rho_0 c$ is called the acoustic impedance, and describes the conditions for sound propagation through the medium. The unit for acoustic impedance is rayl, equal to Pascal second per metre or kilogramme per square metre second. As seen above, the acoustic impedance is the ratio between the pressure and the instantaneous particle velocity ($\rho_0 c = P/U$).

The acoustic impedance is an important factor in all evaluations of sound waves, especially when comparing sound measurements in air and in water. For such evaluations, it is customary to specify the characteristic acoustic impedance as follows:

Air:	*415 rayl*	*T = 20°C and standard atmospheric pressure*
Water:	*1 480 000 rayl*	*Distilled water at 20°C.*

The similarity between Ohm's law for electrical computations and the above equations, where Intensity represents power (Watt), Pressure represents voltage (volt) and acoustic impedance represents resistance (ohm) is a useful consideration for the understanding of acoustic calculations.

2.4 Attenuation factors

The amplitude of seismic waves generally declines with distance from the source. This weakening of the seismic signal with distance is frequency dependent, with stronger attenuation of higher frequencies with increasing distance from the source.

The main factors determining the amount of weakening of the seismic signal with distance are:

2.4.1 Geometrical spreading

From a point source, the sound waves will propagate as spherical waves, the energy of which will decay at a rate proportional with the inverse of distance squared. Many geometrical conditions will cause the waves to propagate with a different decay rate, the other extreme being plane waves where there is no geometrical spreading loss. Cylindrical waves have characteristics that are between those of the plane wave and the spherical wave.

2.4.2 Transmission/Reflection

The pressure waves will be transmitted into the sea bottom and be reflected from the geological boundaries. The transmitted/reflected signals will in some cases have a higher amplitude than the primary signal transmitted only in the water, but due to different propagation paths, the transmitted/reflected signal will not have the same characteristics as a pulse close to the signal source. An elongated pulse from seismic sources at great distances is often the result of a transmission/reflection process.

Due to the attenuation of low frequency sound waves in the water, at great distances the pressure pulse transmitted through the strata below the sea-bottom is often stronger than that travelling through the water. The majority of models that estimate sound levels at distances from a source focus on propagation and attenuation within the water column only. If these models are compared to measured data and used to estimate propagation rates and attenuation factors in water column alone, the results are likely to be in error. This is area that requires further attention in many of the studies that estimates environmental impact from strong sound sources.

2.4.3 Absorption

The transmission loss due to frictional dissipation and heat is an exponential function of distance. Normally, this process is weak in seawater and will only contribute significantly to the losses when seismic waves are propagating within the seafloor and underlying material.

2.4.4 *Scattering*

Reflection, refraction and diffraction from inhomogeneities in the propagating medium cause an apparent transmission loss. Frequency dependence due to destructive interference forms an important part of this weakening of the seismic signal. Since the inhomogeneities in water are very small compared to the wavelength of the signal, this attenuation-effect will mostly contribute when the signals propagate through the sea floor and the subsurface.

2.5 Characteristic differences between air and water

Due to the difference in acoustic impedance, a sound wave that has the same intensity in air and in water, will in water have a pressure that is 60 times larger than that in air, while the displacement amplitude will be 60 times less.

If the pressure is kept the same, the displacement amplitude in water will be 3580 times less than in air.

Another characteristic phenomena of the differences in acoustic impedance are that the air/water interface will act as a very good reflector, the so-called Lloyd mirror. Therefore very little energy will pass this reflector, meaning that sound generated in the water will not pass over to the air, and vice versa.

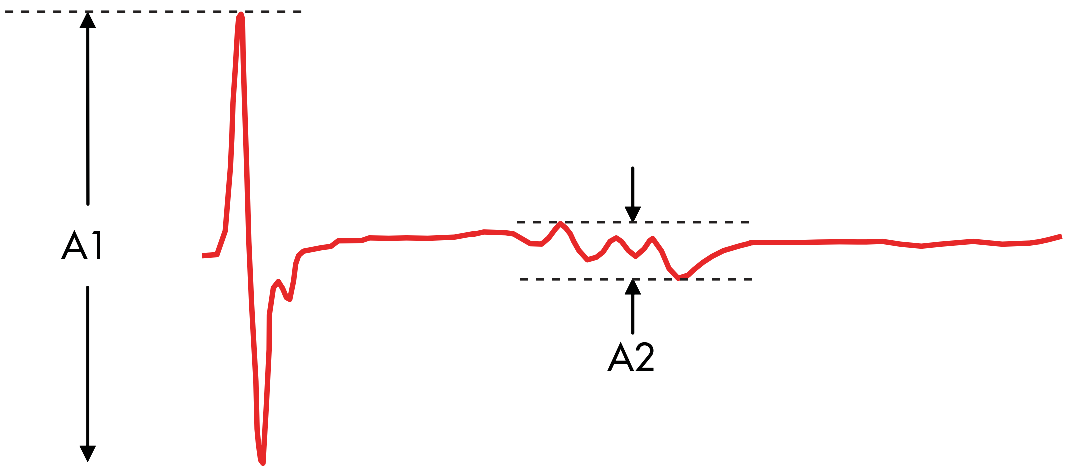
One important aspect of the air/water interface is that sound waves in the water will be reflected with an opposite polarity of the original wave. This means that a compression will be returned as a rarefaction, and a rarefaction returned as a compression. As will be seen later, this is of importance for the evaluation of sound propagation from seismic sources.

3 Measurements of sound

The characteristics of a seismic signal are described by a variety of parametres, both in the time and frequency domain. In the literature, the qualities of geophysical sources (airguns in particular) as well as the impact on marine organisms are defined in terms of these measures.

The main features of a seismic pulse are presented in figure 2. Perhaps the most fundamental measure is the pressure amplitude of the initial pulse. This is commonly reported as the peak-to-peak amplitude A1, and given in barm (*ie* the pressure in bars that would be measured at a distance of 1 metre from the equivalent point source).

Figure 2: The seismic pulse



Following the initial pressure pulse, there will be a "bubble" signal, A2, originating from the volume of air released into the water. The bubble signal is unwanted, and special efforts are taken to reduce this part of the pulse to a minimum.

3.1 The dB scale

Due to the wide range of pressures and intensities encountered in measurements of sound, it is customary to describe these through the use of a logarithmic scale. The most generally used logarithmic scale for describing sound is the decibel scale (dB).

The intensity level, *IL*, of a sound of intensity I is defined as:

$$IL = 10 \log \frac{I_1}{I_0}$$

where I_1 *measured intensity level (Watt/m²)*
I_0 *reference intensity level (Watt/m²)*
log logarithm with base 10

Since intensity is proportional to pressure squared, the decibel expression for sound pressure level (SPL) becomes:

$$SPL = 10 \log \frac{P_1^2}{P_0^2} = 20 \log \frac{P_1}{P0}$$

where P_1 *measured pressure level (Pascal)*
P_0 *reference pressure level (Pascal)*

It is very important to note that the decibel scale is a relative measure, and not a unit for measuring sound. Therefore other units of measurement and reference level can be used instead of the standards indicated above.

3.1.1 Reference levels

For the reference level I_0 or P_0, different values are used for measurements in air and in water.

For measurements of sound in air, the reference level of $I_0 = 10^{-12}$ Watt/m^2 is used for intensity. This corresponds to the lower limit of human hearing at 1000 Hz. Converted to pressure, this corresponds to an effective (root-mean square) sound pressure level of:

$$P_0\,(air) = 20.4\mu Pa\ (or\ 0.0002\mu bar)$$

For sound measurements in water, the pressure reference level is set as:

$$P_0\,(water) = 1\mu Pa\ (or\ 0.000001\mu bar)$$

It is important to note the different reference levels between measurements made in air and in water. The difference between the two is 26dB.

Given a dB value, there is no standard nomenclature that will say whether a measurement is made in air or in water. Therefore, any reference to a dB-value must be carefully checked in order to determine where the measurement is taken, and what reference level is used.

As stated in section 2.5 there is a physical difference between sound in air and in water, and a different reference level is used as stated above. Therefore, in comparisons of sound pressure measurements made in air and in water, a correction factor of 62dB must be added to the air measurements.

4 Signal measurements

Sound levels are measured in many ways, and the abundant amount of research literature on the impact of noise on marine life (fish and mammals) presents data in a variety of ways.

4.1 Spectral analysis

Measurements made for noise studies or the analysis of human hearing are most often carried out in the spectral domain. This implies that the data are transformed from the time domain to the frequency domain, and the results displayed as a function of frequency. These transformations can either be done in processing, or by use of filters. In the latter case, octave-bands are most often used, either 1-octave or ⅓-octave. If data are transformed in data processing, a 1Hz band is most common.

Figure 3: Human audiogram in air (after Kinsler and Frey)

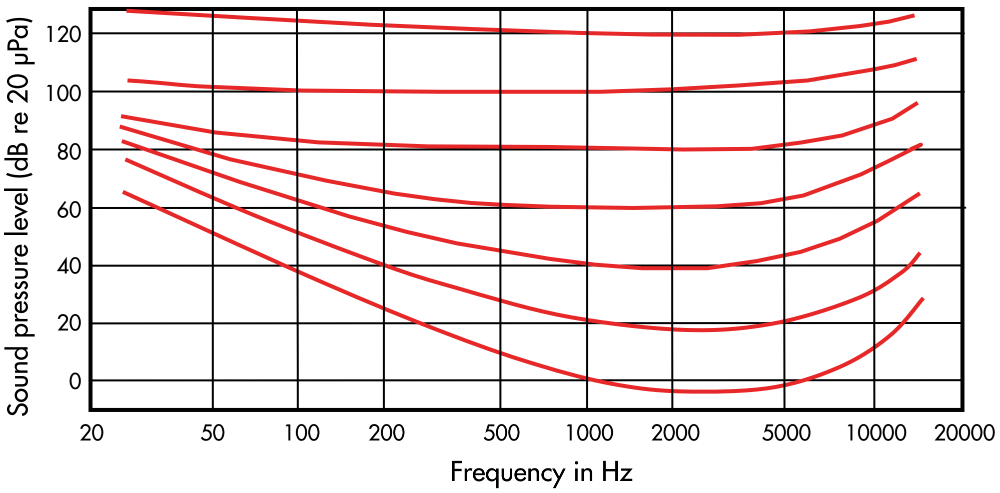
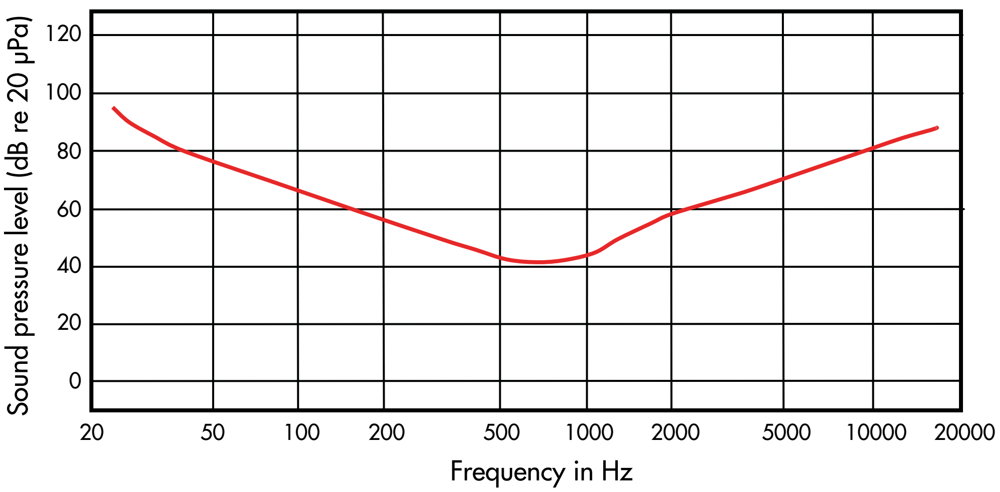


Figure 4: Lower limit of human audiogram in water (after Parvin and Nedwell)



Figre 3 presents a human audiogram in air, and indicates the lower threshold of human hearing. Figure 4 gives the lower limit of human hearing in water. It is important to note that the lower limit of human hearing under water is only 6dB less than in air. The apparent larger difference shown in the figure is due to the acoustic impedance of water. It is also worth noting that the high-frequency hearing of humans is considerably reduced underwater.

Spectral analyses are often done in data processing, using the Fourier Transform method. This technique uses the fact that any signal can separated into a series of sine waves with different frequencies.

The *Fourier transform* of a real, continuous-time signal *x(t)* is a complex-valued function defined by:

$$X(\omega) = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt$$

where ω *real variable (w=2πf, angular frequency given in radians/second) & j=√−1.*

The inverse transform is likewise defined as:

$$x(t) = \int_{-\infty}^{+\infty} X(\omega) e^{j\omega t} d\omega$$

It should be noted that continuous signals will give a line spectrum with a discrete number of frequency components, whereas a transient signal (or a single pulse) will result in a continuous frequency spectrum.

An important parametre of the Fourier analysis is the total energy in a time function *x(t)*, defined as:

$$\| x \|^2 = \int_{-\infty}^{+\infty} | x(t) |^2 dt$$

and the total energy in the frequency domain defined as:

$$\| X \|^2 = \frac{1}{2\pi} \int_{-\infty}^{+\infty} | X(\omega) |^2 dw$$

In studies of underwater sound it is most common to give pressure as a function of frequency in spectral analysis.

Parceval's theorem states a very important aspect of these two ways of defining total energy, namely:

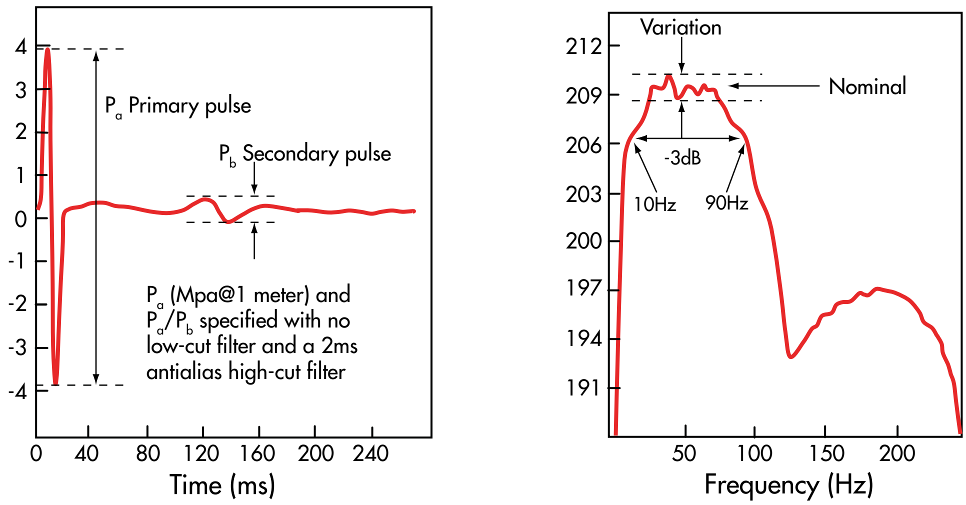
$$\| x \|^2 = \| X \|^2$$

4.2 Broadband analysis

Explosions and most seismic sources are impulsive sources. They are characterised by having a transient output signals, which is a signal with zero power and finite energy. For such signals, it is most suitable to use broadband analysis.

Broadband analyses, as opposed to spectral analysis, are taken over a wider band of frequencies. In the definition of a sound level taken as a broadband analysis, the bandwidth over which the analysis is based should be stated.

Figure 5: SEG standard for seismic pulse definition



Broadband analysis can be undertaken in a number of ways, either as direct measurement of the amplitudes in the time signal, or as a value related to the time signal using a conversion formula.

Impulsive sound, of very short duration, can be given as 0-peak or as peak-peak levels. The first is used in the study of underwater detonation of explosives, and the latter for defining the source strength of seismic sources.

If the positive and negative part of a signal have the same value, the difference between 0-peak and peak-peak measurements will be 6dB.

The Society of Exploration Geophysicists (SEG) has issued standards for the specification of marine seismic energy sources, and Figure 5 gives the parametres that define the source level.

The use of the so-called rms (*root mean square*) notation has gained considerable interest in describing the pressures associated with sound waves. The basis for this notation is measurements of alternating voltages in electrical circuits, but the concept is equally applicable to sound pressure measurements. It should be noted, however, that the rms notation is only valid for continuous signals, and the time gate for analysis should be equal to a full period of the lowest frequency in the signal.

Energy is defined as power times the duration of the signal. The time is easy to measure, whereas the power needs definition, as the analysis may be dependent on the time duration of the signal.

Continuous signals may be analysed using the following formula for the power (as in computation of electrical signals):

$$Power = VI = \frac{V^2}{R} \qquad \text{[Watt]}$$

where V *voltage in volts*
I *current in Amperes*
R *resistance in Ohms*

If the voltage is alternating, it is possible to compute an effective voltage, equal to a fixed voltage that over the time will give the same energy. For a continuous signal, the mean power can be computed from the following formula:

$$Mean\ Power = \frac{1}{T}\int_0^T \left| x(t) \right|^2 dt \qquad \text{[Watt]}$$

where T *time for one period of the lowest frequency in the signal*
$x(t)$ *sample values describing the signal*

From the Mean Power it is possible to define the corresponding effective voltage as:

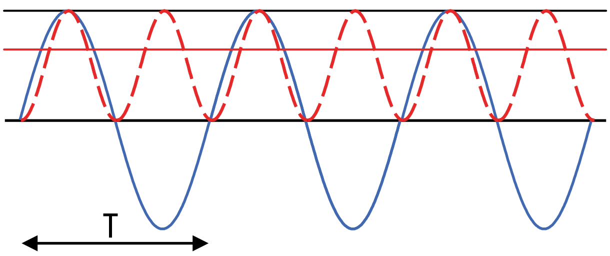
$$V_{eff} = \sqrt{\frac{Mean\ Power}{R}} \qquad \text{[volt]}$$

V_{eff} is often referred to as the root mean square (rms) value of the signal.

The ratio between the maximum amplitude (peak level) and the root-mean-square value (rms level) defines the crest factor for the signal.

As an example, a sinusoidal signal with peak amplitude of 1 (over a resistance R=1) is shown in figure 6:

Figure 6 Illustration of sinusoidal waveforms



Since the signal $x(t) = sin(t)$ is repeating with period T, the signal squared will repeat at an interval of $^T/_2$(from 0 to π), and the effective voltage for this signal becomes:

$$V_{eff} = V_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi}\left|x(t)\right|^2 dt} = \frac{1}{2}\sqrt{2} \approx 0.707$$

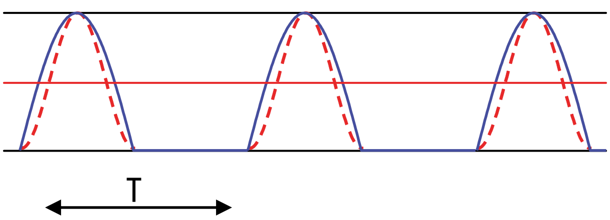
This shows that the crest factor for a sinusoidal signal is:

$$crest\ factor = \sqrt{\frac{V_{\max}}{V_{rms}}} = \sqrt{2}$$

or in decibels the crest factor is 3dB.

If the same sinusoidal signal is rectified (*ie* the negative part of the signal is removed) the waveform will be as shown in figure 7:

Figure 7 Illustration of rectified sinusoidal waveforms



The signal will now repeat at a period of T, but only one half of the period have values that are different from zero. The analysis must, however, be taken over the whole period, as shown in the following formula:

$$V_{eff} = V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\left|x(t)\right|^2} = \sqrt{\frac{1}{2\pi}\left\{\int_0^{\pi}\sin^2(t)dt + \int_{\pi}^{2\pi}0dt\right\}} = \frac{1}{2} = 0.5$$

The crest factor of the rectified sinusoidal signal then becomes:

$$crest\ factor = \frac{V_{\max}}{V_{rms}} = 0.5$$

or in decibels the crest factor in this example is 6dB.

The above analysis can be developed further, and it should be obvious that if the non-zero part of the repetition period becomes small, so will the V_{rms} become very small. For single impulses the V_{rms} will be undefined, and this type of analysis cannot be used for single pulses.

Description of non-sinusoidal signals can be more difficult, as the effective voltage will depend on the duration of the signal as well as the statistical distribution of amplitudes.

The formula for computing the rms value of a statistical varying signal is:

$$V_{eff} = \sqrt{\frac{1}{T}\sum_{0}^{t} x^2 p(x)}$$

where x *sample values of the signal, and*
$p(x)$ *amplitude density (probability for the amount of samples with values between a value x and x+Δx when Δx approaches zero).*
T *duration of the signal analysis window (the signal is assumed to be continuous).*

Random noise (white noise, containing all frequencies) will have an amplitude density that can be described with the normal distribution function (Gaussian distribution), and the rms value of the signal can be computed as:

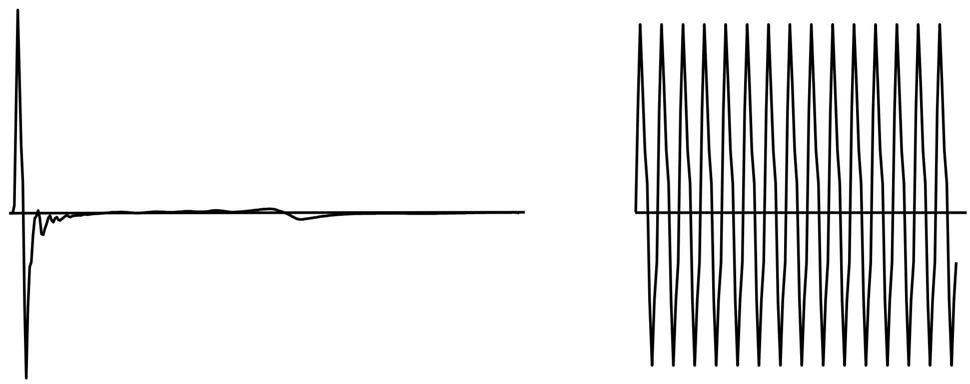
$$V_{eff} = \sqrt{\frac{1}{T}\sum_{0}^{T} x^2}$$

It should be noted that the crest factor for a random signal does not exist, since a true random signal will have amplitudes that approaches infinity.

A popular method for computing the rms-level of signals is to make a histogram of the accumulated amplitudes squared, and define the time T in the above formula as the time between 5% and 95% of the histogram. This is a further approximation to the assumption of random signals, and may lead to gross errors in the analysis.

Furthermore, the method described above is only useful for stationary signals. Impulsive signals, such as airgun pulses, have short duration, and errors in the time estimate may give large errors in this type of calculation of rms levels. Figure 8 illustrates the use of this method on airgun pulses:

Figure 8 Illustration of airgun pulse (left) and resultant "waveform" (right) assumed in computing a "V_{rms}" value with the 5-95 % method.



It should be obvious that the 5-95% method leads to rms-levels that are much higher than the actual signal generated by the airguns.

4.3 Energy flux calculations

The problems in defining sound exposure levels with rms-levels have been widely recognised, and the use of energy flux is gaining much interest. The relationship between rms and energy flux are given by the following equations:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T |\ x(t)\ |^2 dt}$$

$$Energy\ flux\ density = \sqrt{\int_0^T |\ x(t)\ |^2 dt}$$

Hence it is easy to compute one from the other by the simple relationship

$$Energy\ flux\ density = V_{rms} \times \sqrt{T}$$

Computing energy flux in the way described above does not overcome the problems associated with computations of V_{rms}. If continuous signals are being analysed the method is usable, but for pulsed signals it becomes very misleading. For single impulses, V_{rms} is undefined and energy flux calculations as shown above become meaningless. If a series of pulses is analysed the repetition rate is the time separation between the pulses, and this must be the basis for the calculations.

Standards for damage risk criteria (DRC) from repeated exposure of impulsive noises sources use the peak pressure as the basis for evaluation. It is most probable that the zero-peak sound pressure level will be the best for assessing direct physical damage, and it is recommended that this be used in evaluation of possible impact from impulsive sources like airguns.

In some special cases, the total acoustic energy in a pulse can be an indication of "perceived noisiness", and are therefore used in some studies of the impact from seismic surveys on marine mammals.

The acoustic energy in the pulse can be approximated by the equation:

$$E = \frac{P^2 T}{2\rho_0 c} \qquad [\mathrm{Watt{\times}s/m^3}]$$

where P^2 *average pressure squared*
T *time duration of the pulse*

For practical purposes, the time duration T is often taken as the time the pulse has a pressure that is 5% above the ambient noise level.

It must be stressed that measurements of total acoustic energy are very sensitive to the determination of the time T, and are also dependent on the frequency bandwidth used in the analysis. Therefore it may be difficult to compare the dB values obtained from one study directly with those from other studies.

5 Comparison of measurements in air & in water

If a spectral analysis is undertaken with 1 Hz bands used as a basis, an equivalent broadband pressure level can be computed by the equation:

$$PL = SPL + 40 \log W$$

where *PL = broadband pressure level*
SPL = spectrum pressure level
W = effective bandwidth

With the understanding of the dB levels, and the various ways of measuring sound pressure levels, it is possible to establish a table for comparison of the most frequent measurements in air and in water. The following table gives corresponding values for air and water having the same intensities at a frequency of 1 kHz:

Pressure in air re 20μPa/Hz	Pressure in water re 1μPa/Hz	Comments from Kinsler & Frey: Fundamentals of Acoustics
0	62	lower limit of human hearing
60	122	
120	182	threshold of hearing
140	202	threshold of pain
160	222	threshold of direct damage

(the comments quoted from Kinsler & Frey: Fundamentals of Acoustics, 2nd edition, John Wiley & Sons, 1962, page 392, are given as rms-levels for pure tones).

Assuming that the lower limit of human hearing is connected to the pressure of the sound wave, the table shows that in water the lower limit should be approximately 62dB. The direct connection between intensity and pressure allows us to use both when discussing the lower limit of hearing. With reference to figures 3 and 4, this compares well with test-results showing that the limit is 41dB re 20μPa, or 67dB re 1μPa, for an 800Hz signal. (*S.J. Parvin and J.R. Nedwell: Underwater Sound Perception and the Development of an Underwater Noise Weighting Scale, Underwater Technology, Summer 1995*).

At the higher end of the table, the pain/damage level for pure tones in air of 140/160dB (re 20μPa) corresponds to a level in water of around 202/222dB rms (re 1μPa). This corresponds very well with many experiments where is has been shown that physical damage occur to fish (eggs, larvae and fry, as well as larger fish) when the sound pressure level is higher than 230dB peak-to-peak (re 1μPa). It should be noted that at these high-pressure levels non-linear effects occur, and the difference between broadband signals and single frequencies becomes much less than at lower levels. Furthermore, these sound levels are only found in very close proximity to the airguns, and other mechanical factors resulting from the release of high-pressure air, may well have a much larger impact than the direct sound pressure waves.

6 Sound propagation in water

As stated in the introduction, the intensity of spherical waves will be proportional to the inverse of the squared distance from the source. From the relationship between intensity and pressure, if follows that the pressure will be proportional to the inverse of the distance. In practice, the decay rate of a sound wave will be dependent on the frequency, the local conditions such as water temperature, water depth and bottom conditions as well as the depth at which the signal is generated.

6.1 Propagation models

The studies of sound propagation in varying local conditions have been given considerable attention for a long time, and a number of papers have been published on the subject. A thorough treatment is given in *Urick: Principles of Underwater Sound, 3rd edition, Peninsula Publishing, 1983*.

The propagation of sound in the ocean will always be dependent on the frequency of the signal. Most models are developed for high frequency sound, from several kHz and upward. Low frequency sound generated near the sea surface will penetrate into the sea floor, and in practice the conditions will be very similar to spherical spreading. This is of special importance when evaluating the impact of marine seismic surveys. The fact that seismic surveys use the signals reflected from geological boundaries in the sub-surface, indicates that a significant amount of energy has penetrated the sea bottom.

The use of sophisticated models designed for high frequency applications can give misleading results if used to estimate the propagation characteristics of seismic signals, due to limited knowledge of the subsurface conditions. Simplified models of the earth used in combination with techniques for tracing of the sound propagation (ray tracing) might well give a better estimate of the variation in seismic signal strength with distance in may cases. An even more practical method, an possible sufficiently accurate in most cases, is given by the following formulae:

$$SL = A \log(r) - B.r - C$$

Where SL *received pressure level at distance r from the source*
A *wave mode coefficient; for spherical waves A equals 20.*
B *attenuation factor that is dependent on water depth and sea bottom conditions.*
C *fixed attenuation due to acoustic screening; in open water this will be 0.*
r *distance over which the sound has propagated.*

In the above equation, the factor *C* is included for evaluations of sound wave pressure in coastal areas, where it is shown that sound might also be present even if there are small islands in the direct propagation path. In these cases, all sound will travel through the bedrock. In deep water areas the factor *C* can be set to zero.

For high frequency signals, *f* higher than around 1 kHz, more elaborate propagation models must be used.

6.2 Importance of water depth

Variations in water depth will influence the propagation of seismic signals, but to a much lesser degree than the impact on sound waves with higher frequencies.

In publications it has been discussed whether seismic signals in shallow water will follow a cylindrical decay law, which can be expressed as:

$$SL = 10 \log(r)$$

This might be correct for high frequency signals, but the low frequency nature of the seismic signal will cause it to travel through the rocks beneath the sea, and therefore attain a decay rate that is much closer to the deep-water conditions; *ie* a spherical decay law or even stronger attenuation.

6.3 Sea floor conditions

In areas with a very strong acoustic contrast at the sea floor, much of the seismic signals will be reflected back into the water column, and not penetrate into the bedrock. In such cases there might be a lower decay with distance than normally predicted.

It should be noted that seismic surveys carried out in order to map the sedimentary structure under the sea, and therefore, in most cases, the sea floor conditions will be acoustically transparent to the low frequency seismic signals.

It is therefore safe to assume that in most cases seismic signals will penetrate well into the sea floor, and that variations in sea floor conditions will not have a significant impact on sound propagation from seismic surveys.

6.4 "Ghost" reflections

The sea surface acts as a very good "mirror" for the sound waves (the Lloyd mirror effect). This means that the seismic source will have a mirror image, placed at a position that is as much above the sea surface as the source is below. The signal coming from the mirror images will be of opposite polarity to the real source, due to the negative reflection coefficient at the sea surface.

Of the many characteristics of the ghost reflections, the most characteristic is that the primary source and the mirror image will cancel each other at the sea surface, resulting in a rapid decay of the waterborne seismic signal. All observations of seismic energy at significant distances from the sound source must therefore come from reflections, either at the sea floor or in the sediments below. Due to reflection loss, these signals will always have a higher attenuation than would have been estimated from strict propagation modelling of high frequency sound.

7 Special propagation modes

Seismic signals will propagate through the rocks below the sea floor in many different ways. As the energy hits a geological boundary, new wave phenomena such as shear waves and surface waves will be set up. These will propagate away from the source, and will be the origin of new pressure waves that can be detected in the water column.

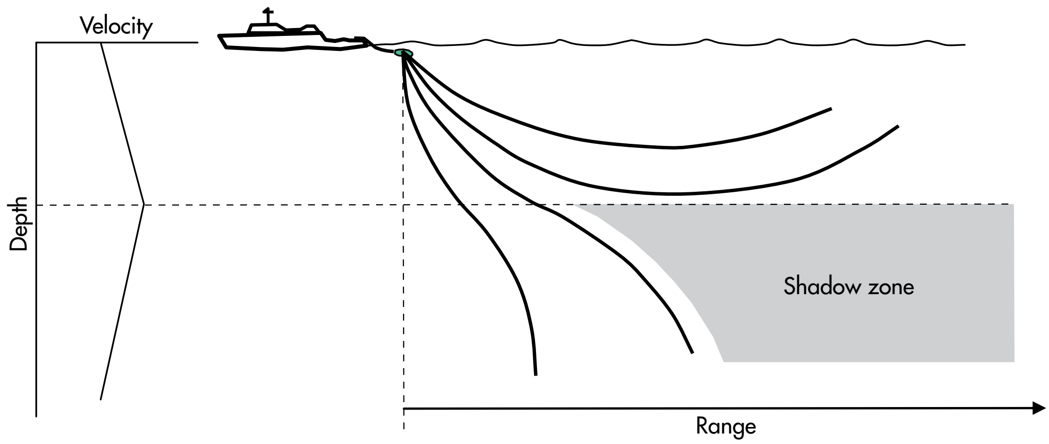
All these mode conversions will mean that the seismic signal loses energy, resulting in stronger attenuation of the signal over distance. However, some conditions might also cause the signal to have lower energy decay, and most noticeable of these are sound channels. It is known that sound may be trapped in the interval between geological layers, and propagate with lower attenuation for great distances. But these conditions in the subsurface are rare, and will not account for stronger seismic signals over distance in the general case.

7.1 Sound channels

In the sea a phenomenon called sound channels frequently occurs. Changes in sound propagation velocity due to temperature and pressure, will form these sound channels at varying depths and with varying thickness. Both these factors will influence how seismic signals are transmitted through sound channels.

Sound channels act like ducts that tend to focus the sound energy, and attenuation in these ducts can be significantly less that normal spherical spreading. Through this mechanism sound can travel over considerable distances.

Figure 9 Mixed layer sound channel (near surface)



Sound channels are often named after their placement in the water column, such as deep sea sound channels, shallow water sound channels and mixed-layer sound channels.

Sound channels will not transmit all frequencies in the same manner. Depending on the thickness of the channel, there will be a cut-off frequency, and sound energy with a lower frequency will not be affected by the channel. The lower cut-off frequency for a near surface sound channel can be estimated by the equation:

$$f_{\min} = 1.76 \times 10^{5} \times H^{-\frac{3}{2}} \quad [\mathrm{Hz}]$$

Using this formula, one finds that a channel thickness of 145m is needed for a frequency of 100 Hz to be transmitted through the channel.

If the sound waves are generated outside the channel, much less energy will enter into this low-attenuation environment, significantly reducing the distance that the sound can travel.

Under conditions when sound channels can form, this will have significant impact on sound propagation. Sound can travel great distances, but there will also be areas in the vicinity of the sound source that little or no sound will reach. Figure 8 illustrates the conditions in a mixed-layer sound channel, clearly showing the "no-sound" areas.

The seismic source will be placed very close to the sea surface, therefore only mixed-layer- and shallow water sound channels can be considered as alternatives for long-range propagation of seismic sound. These channels often have a thickness that prevents low frequency signals from being transmitted through them. With the low frequency characteristics of the seismic source, it is clear that sound channels will not play an important part in the propagation of seismic sound. This is confirmed both by actual modelling and measurements. It should also be noted that most of the energy from the seismic source will travel through the geologic strata below the sea floor, and this must be taken into account when evaluations of signals from a seismic source is measured at some distance.

8 Fundamentals of sound summary

Sound from seismic sources can be recorded over great distances. However, the sound pressure levels are strongly attenuated as the distance from the source increases. Sound pressure levels that may cause physical damage can only be observed within a few metres of the source, but the annoyance level may extend much further.

At distances over 1000 m, the seismic sound reaching the sea surface is dominated by energy that has travelled through the sea floor. This energy has a stronger attenuation than comparable high-frequency signals would have if they travelled in the water-column only.

It is easy to misuse the many different notations of underwater sound, and make comparisons based on dB values that are inconsistent. Great care must be taken in any reference to inferred sound pressure levels based on the source strength and the distance between the source and the observation.

About IAGC

The International Association of Geophysical Contractors (IAGC) is the international trade association representing the industry that provides geophysical services (geophysical data acquisition, seismic data ownership and licensing, geophysical data processing and interpretation, and associated service and product providers) to the oil and gas industry.

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The International Association of Oil & Gas Producers (OGP) encompasses most of the world's leading publicly traded, private and state-owned oil & gas companies, oil & gas associations and major upstream service companies. OGP members operate in more than 80 different countries and produce more than half the world's oil and about one third of its gas.

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