Impact of Seismic Surveys on Marine Life

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The possible impact of marine seismic surveys on marine life has been of great concern for many years. In the beginning of the last decade the debate in Norway centered on the impact that these surveys could have on fish, more recently an international concern has been over possible impact on marine mammals.

The current discussion is, however, characterized by a confusion over sound level terms and measurements, as well as an apparent misunderstanding of the nature of the seismic signals. This paper will give a review of the most important terms relating to underwater sound, and to the nature of impulse sound as it may impact marine life in general.

Sound levels: The character of a seismic signal is quantified by a variety of measures, both in the time and frequency domain. Factors such as peak pressure and how quickly the pressure increases (or decreases) determines the quality of the seismic data, but is also of significant importance for the evaluation of possible impact the signals may have on marine life. This will later be discussed in detail.

The pressure output from the source is measured in Newton/m^2, or Pascal (Pa), but is most often given on a decibel scale.

Intensity and effective sound pressure (P_e) is related through the equation:

$$I = \frac{P_e^{\,2}}{\rho_0 \mathrm{c}}$$

Where: ρ_0 is the specific density, and
c is the propagation speed of sound

This gives the basis for the decibel scale for sound intensity or pressure as:

$$dB = 10\log\frac{I_1}{I_0} = 20\log\frac{P}{P_o}$$

Where: I_0 is the reference intensity level (watts/m^2) and P_0 is the reference pressure in Newton/m2 (Pascal)

$\rho_0 c$ is often referred to as the Characteristic Impedance of the medium. A value of 415 is used for air and 1.54 x 10^6 is the standard value for seawater.

Sound intensity, or pressure, will cause an amplitude displacement of the molecules that is given by:

$$A = \frac{1}{\omega}\sqrt{\frac{2I}{\rho_o c}} = \frac{P}{\omega \rho_o c}$$

The lower limit of hearing for the human ear corresponds to an intensity of I = 10^{-12} watt/m^2, corresponding to a pressure level of 20.4 µPa. This value is used as the reference pressure P_o for acoustic measurements in air. In water the reference pressure P_o is 1 µPa. The difference between these reference pressures is 26 dB.

In water, due to the much higher specific acoustic impedance, similar sound intensities will have different pressure associated with them, the factor being in the order of 61, which corresponds to a difference of 35.6 dB.

Correcting for the difference in reference level, and the specific acoustic impedance, 62 dB must be added to the measurements in air to compare with measurements taken in water.

The following table gives some corresponding values for air and water having the same intensities at a frequency of 1 kHz:

Pressure in air re. 20 µPa	Pressure in water re 1 µPa	
0	62	hearing threshold
60	122	office environment
120	182	feeling threshold
140	202	threshold of pain
160	222	threshold of direct damage

(The comments in the table above are quoted from Kinsler & Frey: Fundamentals of Acoustics, 2nd. edition, 1962, page 392, and the levels given are frequency spectral levels).

Assuming that the lower limit of human hearing is connected to the intensity (and therby the pressure or the amplitude displacement as given by the equations above) of the sound wave, the table above shows that in water the lower limit should be approx. 62 dB. This compares well with test-results showing that the limit is 41 dB re 20 µPa, or 67 dB re 1 µPa, for an 800 Hz signal. (S.J. Parvin and J.R. Nedwell: Underwater Sound Perception and the Development of an Underwater Noise Weighting Scale, Underwater Technology, Summer 1995).

Sound Measurements: Sound levels are measured in many ways, such as:

RMS-levels: The Root mean Square, or the equivalent to a static pressure having the same power.

0-p: Zero to peak, or the maximum value measured from the zero-line

p-p: Peak to peak, or the maximum negative-to-positive measurement or the signal. This is the standard for specifying airgun signal levels.

Frequency spectrum gives the pressure as a function of frequency.

Other methods involve the computation of an equivalent signal, using a variety of mathematical schemes. This technique is often used by studies in the USA on possible impact of seismic signals on marine mammals. It should be noted that the computation of the equivalent signal is difficult, and therefore this type of measurements must be used with great care.

The abundant amount of research literature on the impact of noise on marine life (fish and mammals), give their data in a variety of ways, with differing measurements and reference pressure. In most cases, however, the units and measurements are not specified, making it difficult to compare results from one paper to another. Furthermore, when reference is made to papers where proper specifications are given there is a strong tendency to misinterpret the values and thereby make false comparisons. It should be stressed that specification of units used and method of measurements is essential for publications on environmental impact of high intensity sound.

To compare 0-p levels with RMS-levels one must add 3 dB (assuming sinusoidal signal, higher if noise is considered), and for comparison with p-p levels the addition will be 9 dB. Many of the other methods used will require even higher dB-value corrections for direct comparisons to be made. Spectral measuremnts (as is common for most noise analysis) a summation must be made over all the single frequencies contributing to the broadband signal. Within the seismic bandwith this means that a correction of apprx. 40 dB must be made for comparisons of spectral levels to peak-to-peak measurements.

To place seismic signal levels in perspective, the pressure of a low level background noise (spectral level) is above 60 dB re 1 µPa (10 - 100 Hz). This corresponds to gentle wave action and little wind. In periods of inferior weather, the low frequency background noise increases to 90 - 100 dB re 1 µPa. Heavy ship traffic generates higher levels of background noise.

Marine vessels generate significant noise, and the output from large tankers can be well above 170 dB rms re 1 μPa @ 1m, and the output from active trawlers will be 150 – 160 dB rms re 1 μPa @ 1m. Whales can generate signal levels exceeding 180 dB re 1 μPa @ 1m.

The signals from airguns are given as peak-to-peak (p-p) measurements, and they range from 210 to above 250 dB p-p re 1 μPa @ 1 m. (Comparable to spectral level of 170 - 210 dB per Hz re 1 μPa @ 1 m.). Chemical explosives detonating in the water column will have peak pressure levels upwards of 270 dB re 1 μPa @ 1m, for charge sizes of 1 kg. However, chemical explosives are not used in seismic operations today.

The computed source level depends on the frequency range over which the acoustic pulse is measured. Seismic airgun arrays are frequently measured over the bandwidth 0 to 125 Hz or 0 to 250 Hz. There may be a slight underestimation of the total energy by these bandwidths, but for the airguns the error is small since the output above 250 Hz is limited. It is clear, however, that the output from airguns extend well into the kHz-band, but with much reduced pressure level.

Sound propagation in water: The study of sound propagation in varying local conditions has been given considerable attention for a long time, and a large number of papers have been published on the subject. A comprehensive 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 used. Most models are developed for high frequency sound, upwards in the kHz-range. Low frequency sound will penetrate into the sea-floor, resulting in a propagation that follows the law of a spherical wave. This is of special importance when evaluation the impact from marine seismic surveys. Another important factor is the depth at which the signal source is placed. Most studies of sound propagation use the standard "source depth" of 18 or 91 meter, whereas the seismic source is placed at 4 – 5 meter depth. This implies that the impact of the surface reflection is much more important, resulting in significantly more attenuated sound than would result from a deeper source.

Sophisticated models for sound propagation may not be necessary in the evaluation of possible impact of seismic surveys. Due to the "spherical spreading" nature of the signals (with the source close to the water surface) and the attenuation of the signals in the geological strata below the sea bottom, a more simple model can be used.

A practical formula for evaluating the sound pressure at a given distance, r, from the seismic source can be given as:

$$P(r) = P(s) - A\log_{10}(r) - Br - C$$

Where: P(r) is the Measured sound pressure at distance r, P(s) is the Source level, A is the Propagation type attenuation factor (A = 20 for spherical waves, for seismic waves in open waters the value may be as high as 25), B is a Range dependent attenuation (in the order of 2 – 5 dB per Km.) and C is a Fixed attenuation due to obstacles (in open sea this is 0)

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

The water depth and the sea floor conditions will influence the propagation of the seismic signals. But as the seismic signal is low frequent and the source is placed close to the sea surface, the sound pressure at significant distance from the source is dominated by the signals that have traveled through the subsurface. Standard underwater sound pressure modeling may therefore not be the right method for assessing the impact of seismic sources at larger distances.

The well-known ghost reflections (signals from the mirror image of the source) play an important role in the assessment of sound propagation in the ocean. Due to the phase characteristic of the source and its mirror image, they will cancel each other at the sea surface, resulting in a rapid decay of the waterborne seismic signal.

Sound channels frequently occur in the ocean, and sound generated in these will propagate for considerable distances. Although many consider these significant also for seismic signals, it should be stressed that the low frequency nature of the seismic signals, and the shallow towing depth of the source, little energy will be generated that can be propagated through sound channels.

A general observation is that seismic signals tend to be attenuated with a factor that is somewhat stronger than given by spherical spreading, regardless of waterdepth, temperature- and bottom conditions. It is therefore easy to overestimate the sound pressure levels at significant distances from seismic sources, giving wrong impression of the possible impact these will have on marine life.

Environmental Impact of Marine Seismic Surveys: Since 1970 several studies have been published documenting the sensitivity of fish and marine mammals to high level sound. A thorough treatment of this was given at a workshop in Halifax, Nova Scotia (Greene et al, 1985), and in a report published by the UK Offshore Operations Association (UKOOA) (Turnpenny and Nedwell, 1994). The most comprehensive study, however, is given in the book by Richardson et.al (Richardson, W.J., Greene, Jr. C.R., Malme, C.I. and Thompson, D.H.: Marine Mammals and Noise. Academic Press, Inc., San Diego, California. 1995.) An exhaustive reference list is given in the latter two references, and they are recommended for anyone with a further interest in these topics.

The use of sound for communication, navigation and sensing is well documented for both fish and marine mammals. More than 50 fish families have sound producing species, and all marine mammals are vocal underwater.

The frequencies used by marine species vary over a large frequency spectrum. Whales generate strong signals with frequencies of 20 Hz and upwards, while other marine animals generate sounds for echolocation purposes reaching frequencies above 100 kHz. Fish normally generate sounds in the range 50 - 3000 Hz.

The frequency range of the seismic signals coincide with the audiogram of many marine species, and may therefore interfer with their normal behaviour.

High level sound may impact marine mammals in different ways. If the sound is really high, and of significant duration, it may cause physical damage such as permanent hearing losses. Lower sound levels may cause hearing temporary treshold shifts, and may certainly influence the ability to communicate and navigate.

Impulsive sound will also have an impact on fish and marine mammals, but the effects of this type of sound is less well studied, as most studies have been performed using continuos or intermittent noise of considerable duration. From experiments in Norway using both airguns and explosives, it was reported that after only one exposure, little or no damage could be observed even after very high sound levels. Several exposures were needed in order to cause observable damage. Unfortunately the studies concentrated on damage, and the "no-damage" findings from single exposures are not often included in the final report.

Direct physical damage from airguns has been studied on fish eggs and larvae in a number of reports. It is confirmed that at level of more than 230 – 240 dB p-p re 1 µPa is necessary for physical damage to occur. (Weinhold and Weaver, 1973; Kostyvchenko, 1973; Dalen and Knutsen, 1987; Greene et. al, 1985; Holliday et al, 1987; Kosheleva 1992; Falk and Engel, 1992; Evans and Nice, 1996 etc) All these show that massive physical damage only occur within 1 - 2 meter from the airguns.

Changes to the behavior patterns of fish and marine mammals are potentially the largest impact caused by marine seismic surveys.

A large amount of controlled scientific experiments have been performed, studying the effect seismic activities have on the behavior of fish and marine mammals. These are documented as reports (Engås et al, 1993; Pearson et al, 1992), or given as reviews of current knowledge on the subject (Turnmpenny and Nedwell, 1994, Richardson et al, 1995).

In a report from the Scottish Fisheries Research Services, it is shown that fish will continue to swim towards active airguns. The normal response to the sound impulse is a short side skip, followed by a return to normal swimming in the direction of the gun. Sound pressure level at the fish was in the order of 220 dB p-p re 1 µPa.

The studies on marine mammals use direct observations, often from airplanes, or through analysis of their vocalizations and position as determined by hydrophones.

Many of the reports on behavioral change caused by seismic surveys are difficult to compare, since the measurement methods and units used are not documented properly. Unfortunately, there is no clear rule for defining the sound levels that will inflict behavioral change, which leaves the interpretation of the various reports highly subjective.

Characteristics of impulse noise: The impact of impulsive sound on humans has been studies extensively, especially in regard to impulse noise from weapons. Based on these studies recommendations on daily exposure maxima is developed, and those given by CHABA for use in the USA is shown in figure 1.

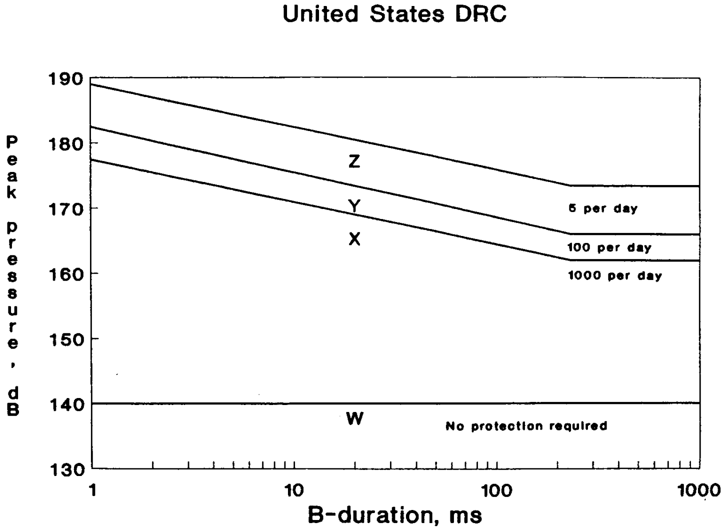

Figure 1, The CHABA recommendation for impulsive noise on humans.

Some regulatory institutions require that the sound level from seismic surveys reaching marine mammals should never be more than 180 dB rms. re 1 µPa. There is no specification as to the duration of this exposure, or the number of impulses allowed if the noise is intermittent. It is therefore reasonable to assume that sound levels below 180 dB rms. re 1 µPa represents a level that is not dangerously high for the animals, regardless of the duration of the exposure.

A sound pressure level of 180 dB rms. re 1 µPa corresponds to 190 dB p-p re 1 µPa if one use the conversion factors for sinusoidal signal. Noise signals will have an even higher number.

By comparison, the CHABA specifications for impulse noise on humans, shown in figure 1, states that below a level of 140 dB (0-p re 20 µPa) "no protection required". Converted to the water environment, this represents 202 dB 0-p re 1 µPa, or 208 dB p-p re 1 µPa. The CHABA specification compares well with the level of 180 dB rms. re 1 µPa, provided one assumes that marine mammals have a lower threshold of hearing that is about 20 dB below that of humans and that the audiophysiological dynamic range is about the same.

If one assumes that the seismic source have a source strength of 250 dB p-p re 1 µPa, the analysis above would give a safe distance from the airgun array of 1 km (60 dB loss due to spherical spreading).

The CHABA specifications indicate that if the number of impulses is less than 1000 per day, the acceptable sound level is increased by 20 dB, reducing the distance to 100 meter. A seismic vessel normally fires the seismic source every 25 meter, or 40 times over 1 km. This must mean that, unless the animals deliberately follow the seismic vessel, a maximum of 40 impulses is emitted before the distance between the animal and the vessel is greater than the safe distance.

The use of the CHABA figures can be taken further, as the impulse sound level can be increased even more if there are only a few impulses.

The output of an airgun array of 250 dB p-p re 1 µPa is only a theoretical value valid vertical below the airgun array, and it is used for seismic data analysis only. Due to the physical dimensions of the airgun array, sound generation is spread over an area, and nowhere within the array will the pressure level exceed 235 dB p-p re 1 µPa. The physical size of the airgun array will also result in a significantly reduced output in the horizontal direction.

This analysis should make it quite clear that a seismic vessel operating at 10 km/h can not really represent a physical danger to marine mammals, regardless of distance.

Concluding Remarks:

Airgun operations cause little direct physical damage to fish at distances greater than 1 to 2 m from the source. It is evident that fish respond to sounds emitted from airguns. Reactions to the sound impulses are reported at levels from 180 dB re 1 µPa, but the measurements and the full extent of the reactions are unknown.

Due to the avoidance behavior, there should not be any physical damage to free swimming fish caused by the airguns.

The catch rate in close proximity to surveys can be affected, but the reduction in catch rates is, however, not expected to be long lasting. The reason for reduced catches is probably the fact that fish dive to the bottom or they disperse when exposed to high level sound.

It is standard industry practice to “ramp up” the airguns when starting a seismic survey, in order to "warn" the fish and marine mammals in the area.

Marine mammals are clearly reacting to the seismic signals at ranges of a few km., but the reactions may well be due to curiosity rather than a direct negative effect on the animals.

Current research on possible impact of seismic surveys on marine life appears to neglect the literature on impulse sound on humans. Using this material may change some of the current restriction on marine seismic in sensitive areas.

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