Report for

Norwegian Oil Industry Association (OLF):

Seismic Surveys Impact on Fish and Fisheries

by

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1 Summary

The purpose of this report is to give an overview of possible impact that seismic surveys may have on fish and fisheries.

In order for the reader to get an understanding of the operational characteristics of seismic surveys and of underwater sound generation and propagation, both these themes are covered in more detail.

Studies have shown that physical damage to fish caused by the sound from seismic sources can only occur in the immediate vicinity of the airguns, in distances of less than a few meters. Adult fish will flee from the strong sound, but eggs and larvae may be affected by the signals. However, it is concluded that the impact of airguns on fish eggs and larvae will only account for a mortality rate per day of less than 0.018% (worst case scenario, 0.0012% on average), which is insignificant compared to the natural mortality rate of 5 – 15 % per day for most species at that life stage.

Seismic surveys will have an impact on the behaviour of fish, but the reported magnitude of this impact is variable. Norwegian reports claim an effect out to more than 33 km, whereas studies in Australia indicate that no behavioural change could be observed at distances over 2 km. Research in Scotland shows that the fish studied appeared to have stronger avoidance reactions to the visual impact of a plume of air and mud then from the airgun sound pulse.

A study from the Faroe Islands shows that although 75% of the fishermen interviewed claim a detrimental effect on fishing in the neighbourhood of seismic activity, there is no evidence of this effect from study of the logbooks. The actual effect of seismic surveys on fishing may therefore be within the “noise level” of the natural variations that impact fishing and catch rates.

The impact of seismic surveys on the most sensitive periods of fish, during spawning or migration to spawning areas, will be dependent on the actual distance of behavioural impact. Based on the available data the safe zone should be set to a few kilometres.

None of the available reports document a lasting effect on fishing or fish stock as a result of seismic surveys.

2 Seismic surveys

2.1 Introduction:

Seismic surveys are the main tool used by the oil industry in locating hydrocarbon accumulations several kilometres down under the surface of the earth. The seismic data that arises out of these surveys can be used to map the reservoirs and define possible drilling targets several thousand meters below the surface.

The type of data needed varies with the different stages of the work in a license, from early exploration to the development and depletion of the resources in a field. It must therefore be expected that the same area may be covered with many seismic surveys, as they all meet various purposes.

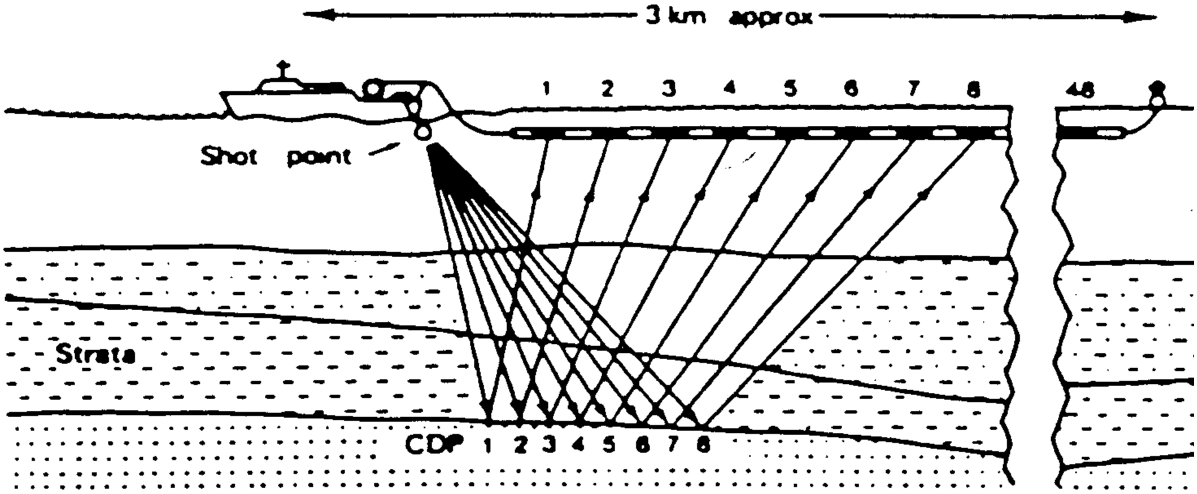


Figure 2.1.1.

The basic principle of seismic surveys is illustrated in Figure 2.1.1. A strong sound pulse is sent out from the seismic source towed behind the survey vessel. This pulse is reflected from the boundaries separating the geological layers in the subsurface, and the reflected signals are recorded by many hydrophones towed in a cable several kilometres long. Generally speaking, the system operates as a large echo sounder.

By recording the reflected signal at many points along the cable, it is possible to process the data and thereby remove noise and unwanted signals, in addition to the presentation of the final data in a form that makes it suitable for interpretation.

The reflection points at each strata boundary (CDP-points) from many Shot points are combined in the subsequent processing in order to achieve the required final seismic data.

2.2 Operational characteristics

The seismic surveys can be performed as either reflection or refraction surveys. Reflection surveys are predominantly used by the oil industry; the refraction survey method have only have limited use by universities for scientific purposes. Either method requires that the seismic vessel follow predetermined paths that are selected based on the objective of the survey and the geology in the area. This operational requirement leads to restrictions in the vessels manoeuvrability and calls for very good cooperation with fishing vessels and other marine traffic in the area.

The two-dimensional (2D) method is relatively cheap, and is today mostly used in the very early stages of exploration in an area. Three dimensional (3D) seismic surveys will give a much more comprehensive coverage of the area, and are always used following a discovery and at the later stages of exploration. Repeated 3D surveys (often called 4D or time laps surveys) are used to map the production of hydrocarbons in a field, a technique that have contributed significantly to increased production from the reservoirs.

All marine seismic surveys are sensitive to the weather conditions. Rough seas will increase the ambient noise level, making the recorded data useless for processing. Shipping and other marine activity will also generate underwater noise that may make parts of the recorded data unusable, a situation that requires the data to be reshot, which will extend the time required for the seismic operations.

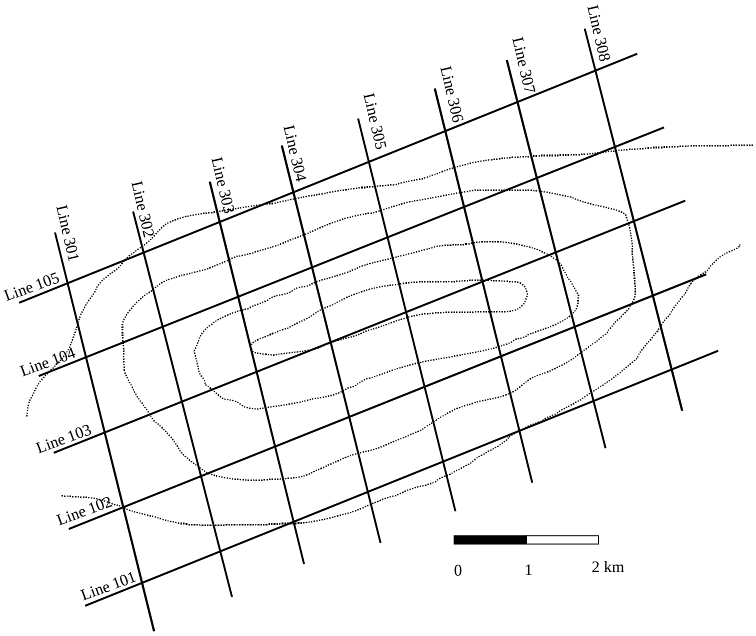
Special methods are used in shallow water areas, and in areas with restricted access such as fields with infrastructures, but a detailed discussion of these falls outside the scope of this report.

2.2.1 2-D surveys

2-D surveys are designed with a number of single long lines, or lines that form an open grid, with spacing of 1 km or more as illustrated in fig.2.2.1

In standard 2-D recording little information is gained about the true position of the reflecting points in the subsurface. For instance, in such cases where the horizons have the shape of a valley with steep flanks, many reflected signals will be received from these flanks, which cannot be assigned to the reflecting points perpendicular to the survey line. Another weakness is the uncertainty that arise from the gaps between the lines, a factor that often leads to misinterpretations of the data.

One source and one hydrophone cable is used for 2D surveys. The seismic source is set up to give as strong a signal as possible, and this source is normally fired every 25 meters, or every 10 seconds.



2.2.2 3-D surveys

3-D recording and processing techniques have found an ever-increasing application in the petroleum industry, specifically for the more complicated geological structures and for delineation of structural traps. Repeat 3D seismic surveys (often called Time Lapse Surveys) are used for reservoir studies and the mapping of remaining hydrocarbon reserves.

The advantage of 3-D recording is that information about the subsurface is taken from a dense grid covering the area, thereby providing information about the true position of dipping horizons or complex geological structures not obtainable with 2-D surveys.

In 3-D surveys the vessel sails along parallel lines, in order to record data onto a regular grid, with cell dimensions of 25 x 25 meter or 25 x 37.5 meters being frequently used. Fig. 2.2.2 shows a typical layout for a 3D survey. The grid cells must be small enough to allow for detailed data processing along both axis of the grid. Each time the source is fired, the recording system will record data for 6 to 8 seconds.

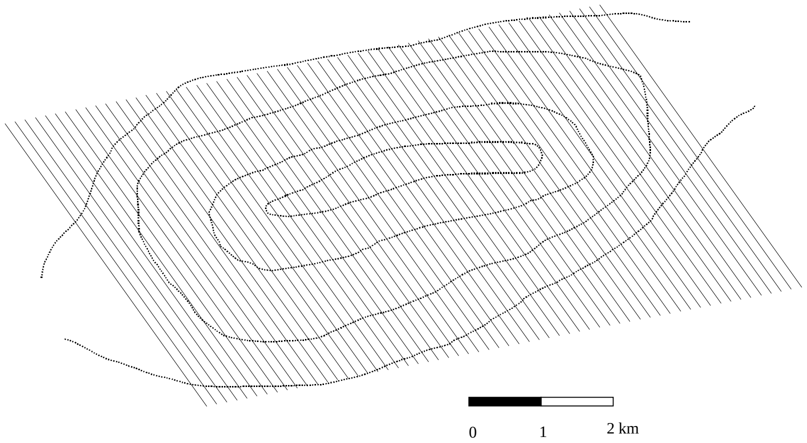


Figure 2.2.2. 3D grid over structure map

Modern seismic vessels used for 3-D surveys are capable of recording many lines in each traverse of the prospects. This is achieved by towing a number of hydrophone cables, and by using two seismic sources fired alternatively, so called flip-flop. When this technique is used, each source is fired every 50 meters.

In 3D surveys, with multiple sources and hydrophone cables being used, each traverse of the seismic vessel will be spaced from 200 to 500 meters, depending on the parameters used. The minimum time between two adjacent lines will be 8 - 12 hours, but due to operational considerations, there can be many days between the recordings of adjacent lines. This results in a significant lower amount of "seismic" disturbance being emitted out into the ocean environment.

2.3 The seismic equipment:

2.3.1 The seismic vessel:

For the seismic surveys, a specially equipped vessel is used, operating as a complete, self-contained geophysical laboratory, carrying all equipment and supplies necessary for round the clock operations.

The vessel is also equipped with all necessary communication equipment for efficient operations anywhere in the world.

The instrument room is the heart of the seismic vessel. Here is where all the instruments for recording the seismic data, control of the seismic source and the hydrophone streamer and the main navigation equipment are located. Links between these units are essential for operations of all seismic surveys, and having all personnel in one location simplifies the communication between the operators of the various instruments. Today’s seismic vessel is also equipped with a large computer centre for processing of the recorded data.

The back deck is another important part of the seismic vessel. A large open space is required for handling of the airguns and the hydrophone streamers. This handling included deployment and recovering the equipment, as well as necessary maintenance and repair. The back deck arrangement will vary from vessel to vessel, but in principle they are all very similar. The airgun arrays are configured as long strings, and when not in the water they are hanging form beams at the back deck roof. The streamers are stored on large reels, with additional reels available for spare streamer parts or even whole streamers.

In addition to the storage facilities, the back deck contains special equipment for deployment and recovery of both airgun arrays and streamers. The safety aspect is always given careful considerations, in order to have safe operations even in adverse weather conditions.

The large compressors needed to supply the airgun arrays are often located close the engine rooms, for ease of operation by the onboard mechanics. Onboard machinery is of critical importance to a seismic vessel. Not only is large power needed in order to tow all the in-water equipment; but also noise generated by the engines and propellers also need to be as low as possible. With purpose built seismic vessels great care is taken into the overall design of vessel hull and machinery to ensure quiet operations.

Positioning of the vessel and the equipment towed in the water is important, and systems used will give the position of each part of the equipment with an accuracy of better than 5 meters. For the overall positioning of the vessel, satellite-positioning systems, such as Global Positioning System (GPS) or shore-based radio positioning systems are used. To achieve the required accuracy, GPS will be used in "differential" mode (DGPS). Acoustic positioning systems are used for positioning of the equipment in the water; often combining this with DGPS or radio based systems on floats in order to give surface reference points and thereby improving accuracy.

Normal operating speeds of the seismic vessel when performing seismic operations are 4.5 to 5.5 knots, equivalent to approx. 10 km/hour (2.7 m/s).

2.3.2 Seismic sources

Marine seismic surveys have been performed since the 50's, and in the beginning chemical explosives was used as the sound source. During the 60's new seismic sources have been developed that are much safer to use, and that have much less environmental impact. Although the airguns are used for nearly all seismic surveys performed today, two other sources will be briefly discussed, due to their special reputation in the industry.

2.3.2.1 Airguns

The airgun is today the preferred source for marine seismic surveys. Other sources, such as the Water-gun, Vaporchock or Maxipulse (chemical explosives) have been used in the past, but are now considered obsolete. They will therefore not be considered in this report.

The operating principle of the airgun (the Bolt airgun system) is shown in figure 2.3.1. High-pressure air, of about 140 atm. is supplied continuously to the airgun. In the charging state, this will force the piston downward and fill both chambers with compressed air. The total area of the upper piston is slightly larger than the lower, and this will keep the piston in this closed position, ready for firing.

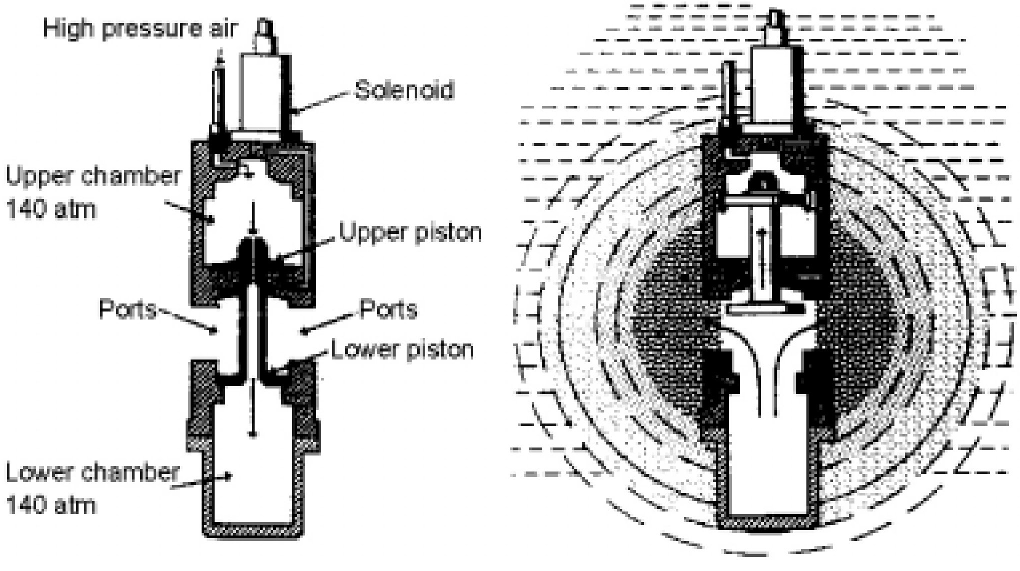


Fig. 2.3.1: Operating principles of an airgun

When the airgun is triggered, the solenoid valve is opened electrically, and releases air to the lower side of the upper piston. The net forces acting on the piston will now force it upwards, and the compressed air is released through the ports. This rapid outflow of air will push the water away from the airgun and create the pressure wave used as the seismic signal.

The amount of air released into the water is determined by the volume of the lower chamber, and this will range from 0.5 to 10 litres.

In order to increase the total emitted energy, several airguns of differing sizes are mounted together in arrays. Such airgun arrays may consist of 10 to 30 airguns or more, and have a total volume of up to 100 litres.

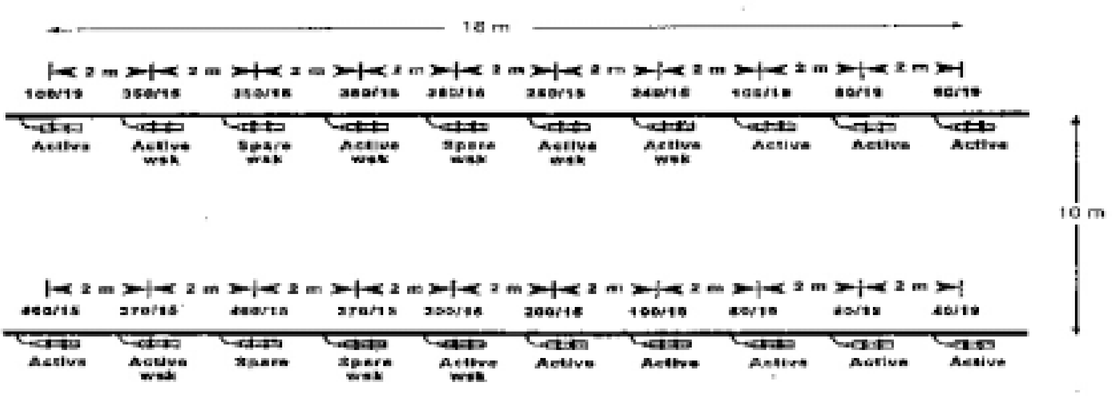


Fig. 2.3.2: Layout for 3180 cu.in.airgun array

Another advantage of arrays is the ability to direct the energy downward into the seabed. All airguns in the array will be fired such that the peak pressure from each one coincide when measured vertically under the centre of the array. Due to the lateral separation of the guns, destructive interference will reduce the pressure at points away from the vertical axis. The resultant pressure will be dependent on the frequency, and also vary with the angle away from the vertical axis.

Typical layout for an airgun array of 3180 cu.in. is shown in figure 2.3.2, and the resulting signal (amplitude as a function of time) is given in fig. 2.3.3.

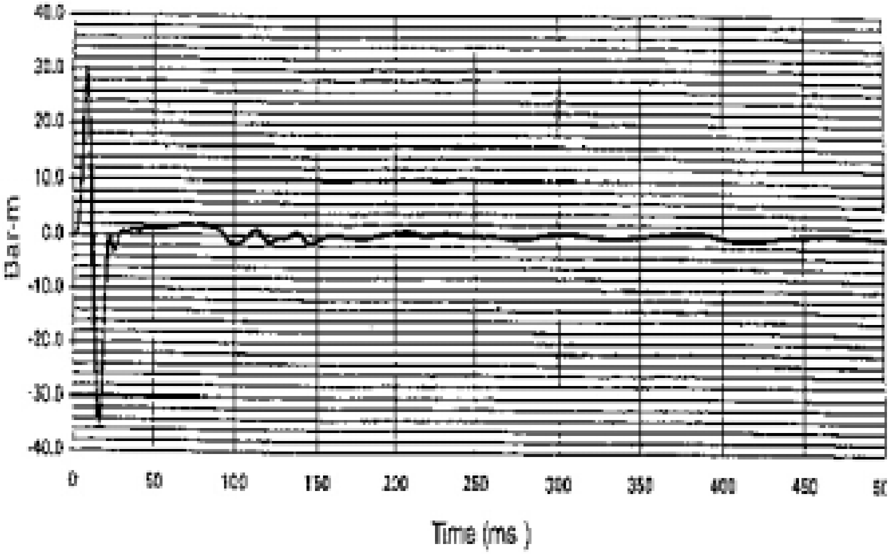


Fig. 2.3.3: Pulseform from seismic array

This airgun array have a total amplitude (peak to peak) of 257 dB re 1 uPa @ 1 m, corresponding to a maximum spectral pressure amplitude of 210 dB/Hz re 1 uPa @ 1 m. It should be noted that due to the separation of the airguns the maximum pressure within the array will not be greater than slightly more than that of an individual airgun, and not to the total pressure given for the array.

The frequency spectrum will be dependent on the depth at which the airguns are deployed. Due to the very high acoustic impedance of the sea-air interface, this act as a mirror, and there will be a "ghost" array with source level equivalent to the one of the seismic array itself. The mirror effect will change the phase of the "ghost" signal, and destructive interference will strongly attenuate the frequencies where the two signals are of opposite phase. Shallow deployment will give broader bandwidth, but total energy output will be reduced. Normal operating depth for airgun arrays is 5 - 7 meters.

The primary output of the airguns and the airgun arrays have most of the energy in the frequency bandwidth of 10 to 200 Hz. Fig. 10 shows the spectral characteristics of the airgun array from fig. 2.3.4.

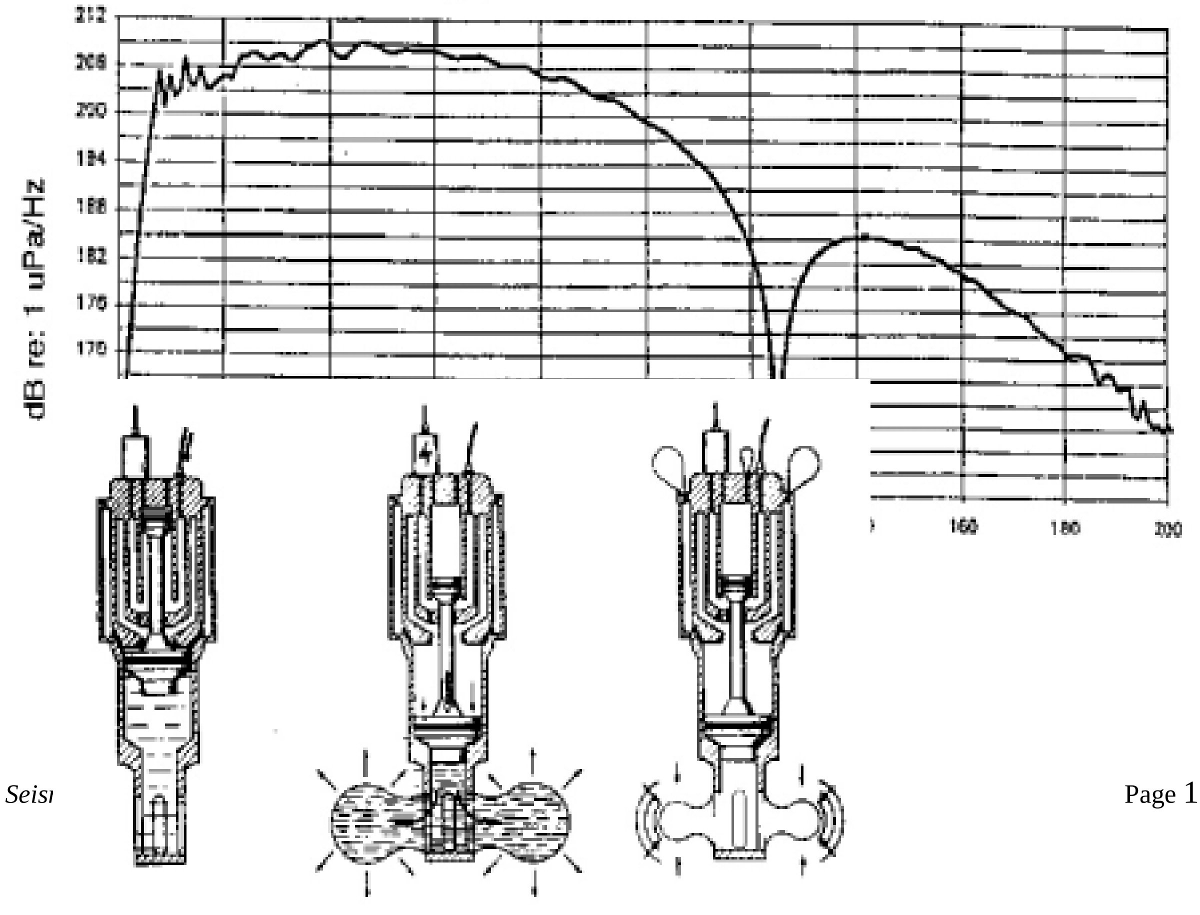
The design of source arrays are done by combining several airguns with different chamber volume, and releasing the air such that all primary signals are synchronous, while the bubble comes at different times and thereby cancel each other.

2.3.2.2 Waterguns

The waterguns held a considerable interest as a seismic source for many years, but today they are used only for very special purposes. In the North Sea and surrounding areas, the waterguns have not been used for seismic surveys after 1995.

Fig. 2.3.4. Spectral characteristics of an airgun array

Fig.



2.3.5: Operating principles of the watergun.

Although the waterguns are normally driven by air, a design based on hydraulic power is also available. In both cases the operations is significantly different from that of the airgun, as can be seen from fig. 2.3.5.

When the watergun is fired, the shuttle will drive a slug of water out through the ports, with such speed that a void is created in the surrounding water. When this void collapses, the acoustic output signal is created. The first pulse from a watergun is therefore a pressure decrease, in contrast to the airguns that creates a pressure increase.

The "strength" of the watergun signal is dependent on the design of the firing chamber and the pressure of the air supplied. Normally, the air pressure is 2000 psi, or approx. 140 atm.

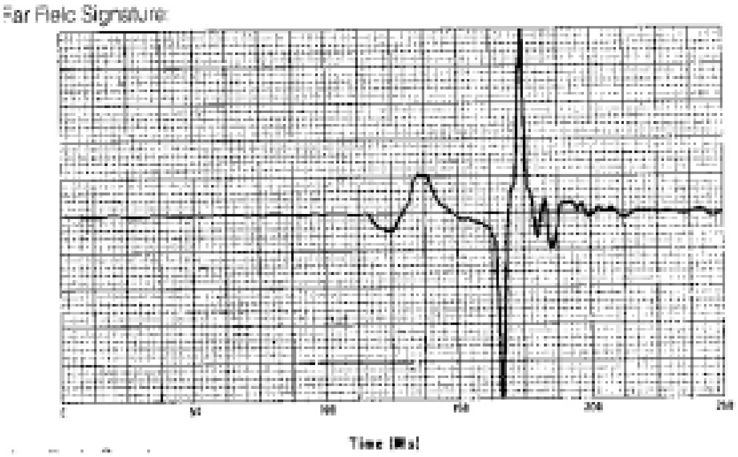
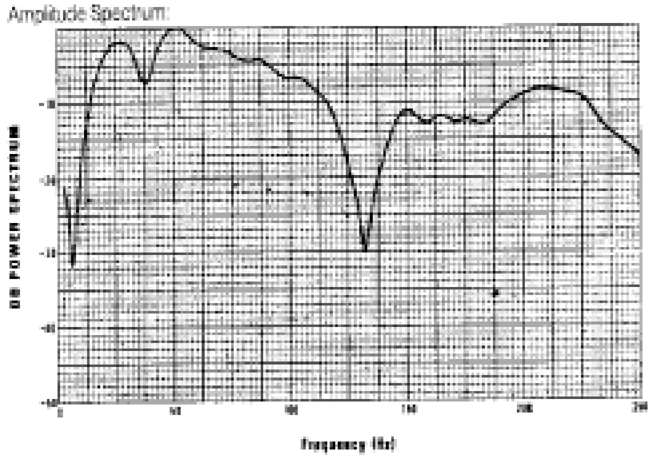


Fig. 2.3.6. Far field signature from a single watergun

The far field signature from a single watergun is given in fig. 2.3.6. The peak-to-peak pressure in this case is 5.8 barmeter (235 dB re 1 µPa-m)



Characteristics of this signature is the pressure coming from the rapid outrush of water through the portholes. This precursor to the main signal is clearly seen on the figure. The corresponding amplitude spectrum is shown in fig. 2.3.7.

The watergun does not contain a bubble-pulse, and therefore it is easier to build large arrays with significant power output. But the precursor is an undesired element in the signal, and reduces the usefulness of the watergun as a seismic source.

The spectrum is considerably wider than that of the airgun, with only 10 dB reductions at 200 Hz. The notch at 130 Hz is the result of the surface interference as the watergun is in this case at 6 meter depth.

Waterguns are well suited for use in arrays, for stronger signal and improved focusing of the sound energy downwards. Each element has the characteristics needed for a good resultant output signal and no special design criteria are needed in the design.

The directivity from an array of waterguns are similar to an airgun array, although the signal waveform can be different.

2.3.2.3 Marine vibrators

An alternative to using a sharp pulse as the seismic signal one can generate a long tone with changing frequency. This is done by a marine loudspeaker, or a vibrator. The reason for calling this sound source a marine vibrator is the similarity with the equivalent source used for land seismic surveys, where a vibrator is used to generate the mechanical waves used for the seismic survey. The marine vibrator can sweep over a frequency range from 10 Hz upwards of 200 Hz, and the tone will be of several seconds in length.

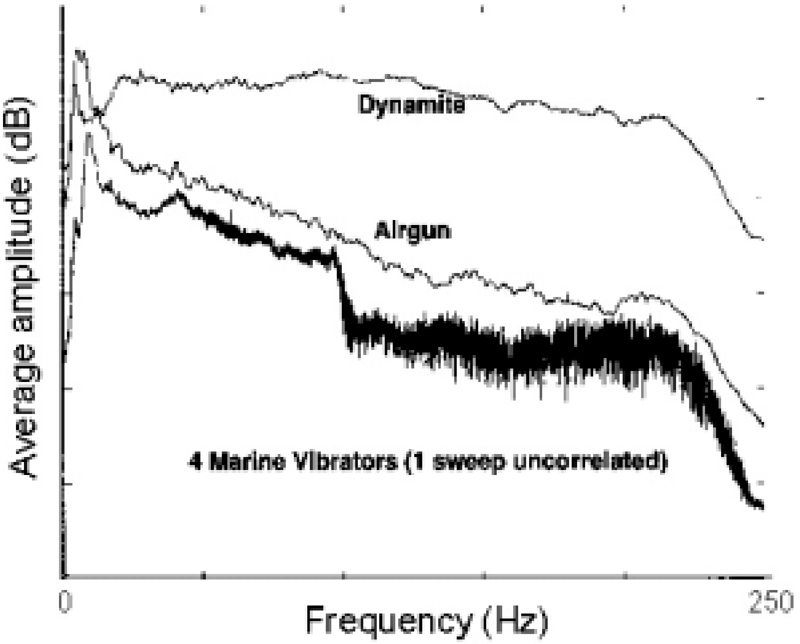


Fig. 2.3.8: Spectral characteristics of the marine vibrator.

The instantaneous pressure resulting from the marine vibrator will be lower than that of an airgun, but the total acoustic energy transmitted by the source will be quite similar due to the extended duration of the signal.

The output from a marine vibrator is a tone that sweeps through the required frequency spectrum. Fig. 2.3.8. gives the spectral characteristics of the marine vibrator.

Marine vibrators are easy to control and the use of multiple units in an array is essential in order to increase the total output from the source.

However, due to lower output at low frequencies, the marine vibrator, cannot substitute for the airgun array in seismic surveys.

2.3.3 The hydrophone cable

The seismic signal, reflected by the many boundaries in the subsurface geology, is received by the hydrophone cable, and fed back to the recording instruments on the seismic vessel. The hydrophone cable is often 3000 to 6000 meters long, and is constructed as many groups of hydrophones. The spacing between the groups can be 25 meters or shorter, dependent on the purpose of the seismic survey. Each group contains many hydrophones, spaced less than 1 meter apart.

The hydrophone cable must be towed at constant depth, normally between 6 to 8 meters. This is achieved by filling the cable with kerosene, so that it is neutrally buoyant. To compensate for minor adjustments, Automatic Cable Levellers, or "birds" are used. These devices are attached externally to the cable, and have "wings" controlled by a pressure sensitive device that forces the cable to be at the right depth.

The end of the hydrophone cable is marked with a tail buoy, the purpose of which is both to give a warning to shipping about the presence of the cable in the water. Additionally, the tail buoy acts as a platform for surface positioning systems so that the location of end of the cable can be monitored.

The hydrophone cable is not considered to be of any environmental hazard.

3 Fundamentals of underwater sound

3.1 Sound waves

Sound waves are defined as compressional (or longitudinal) waves that have a frequency that is within the audible spectrum.

Compress ional waves are mechanical waves that propagate through the interior of the material as pressure fluctuations. 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 determine the frequency of the wave.

Fig. 1 illustrates the generation of sound waves, and show how the pressure variations propagate away from the source with a velocity *v*. At the locations where the particles are shown close together, one will find the maximum pressure of the sound wave.

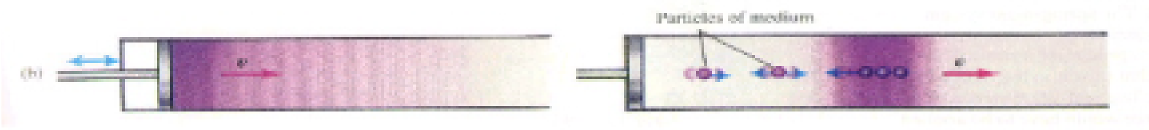


Fig. 3.1: Illustrating the generation of sound waves.

There are three other types of mechanical waves that will propagate through solid material. In addition to the compressional waves, shear waves travel through the interior of the material, and both are known as body waves. Rayleigh and Lowe waves travel along the surface of the 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, but in most analysis of the compressional waves, the other wave types appear as strong noise.

Fluids, like air, can not sustain a shear deformation, therefore there will only be compressional waves that propagate 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 also 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.

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

If measurements of the 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 boundary between these two are defined as the distance r_o at which the difference between the centre and the periphery of the source equals $\lambda/2\pi$. For a circular source of area A, the sound waves at distances greater than:

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

where f = frequency 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 meter will be in the far field. This is normal practice in the geophysical industry.

3.2 Sound levels

The definition of sound levels are not directly given by mathematical equations, but depends on a number of factors, like 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.

3.2.1 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 meter, which can also be expressed as watts per square meter.

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

3.2.2 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 meter.

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:

$$I = \frac{P^2}{\rho_o c}$$

where ρ_o is the specific density of the medium where sound propagates
c is the 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:

$$U = \frac{P}{\rho_o c}$$

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

$$A = \frac{P}{\omega \rho_o c}$$

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

The above formulas hold for both plane and spherical waves, under normal conditions. 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 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 frequencies 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 two separate physical phenomena. As shown above, the pressure and the displacement amplitude, or particle motion, are directly proportional.

3.2.3 Acoustic Impedance

The factor $\rho_o c$ 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 meter or kilogram per square meter second. As seen above, the acoustic impedance is the ratio between the pressure and the instantaneous particle velocity.

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 rayls	T = 20^o C and standard atmospheric pressure
Water:	1.480.000 rayls	Distilled water, otherwise as for air.

The similarity between the above equations and Ohm's law for electrical computations should be evident.

3.2.4 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:

3.2.4.1 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.

3.2.4.2 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 be stronger 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 if often the result of a transmission/reflection process.

3.2.4.3 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 significantly contribute to the losses when seismic waves are propagating within the seafloor and underlying material.

3.2.4.4 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 is very small compared to the wavelength of the signals, this attenuation-effect will mostly contribute when the signals propagate through the sea floor and the subsurface.

3.2.5 Characteristic differences between air and water

Due to the difference in acoustic impedance, a sound wave that have 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 is 60 times less what it would have been in air.

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

Another characteristic phenomena of the difference 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.

3.3 Measurements of sound

The character of a seismic signal is quantifies by a variety of measures, both in the time and frequency domain. In the literature, the quality of geophysical sources as well as impact on marine organisms is defined in terms of these measures. The schematic seismic pulse presented in fig. 2, defines some of the more important factors. 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 (i.e. the pressure in bars that would be measured at a distance of 1 meter from the equivalent point source).

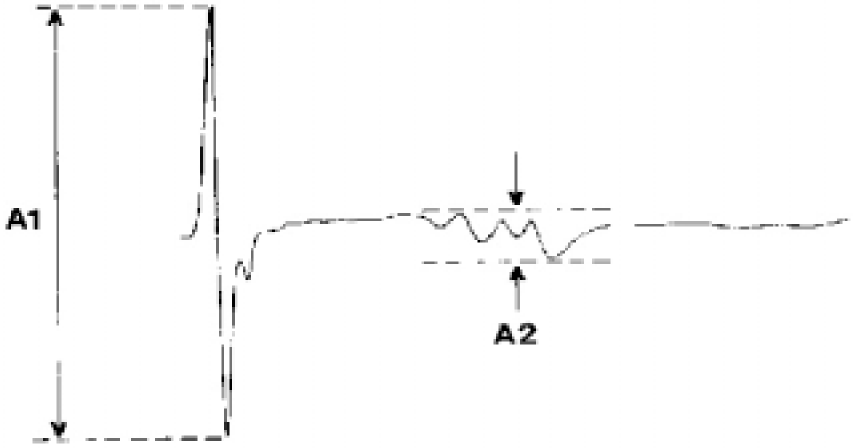


Figure 3.3.1: The seismic pulse

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.

3.3.1 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

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

where I_1 is the measured intensity level (watts/m^2)
I_0 is the reference intensity level (watts/m^2)
log means the logarithm with base 10

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

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

where P_1 is the measured pressure level (Pascal)
P_0 is the 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.

3.3.1.1 Reference levels

For the reference level I_o or P_o , different values are being used for measurements in air and in water.

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

P_o (air) = 20.4 µPa (or 0.0002 µbar)

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

P_o (water) = 1 μPa (or 0.000001 μbar)

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

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.

3.4 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) give their data in a variety of different ways.

3.4.1 Spectral analysis

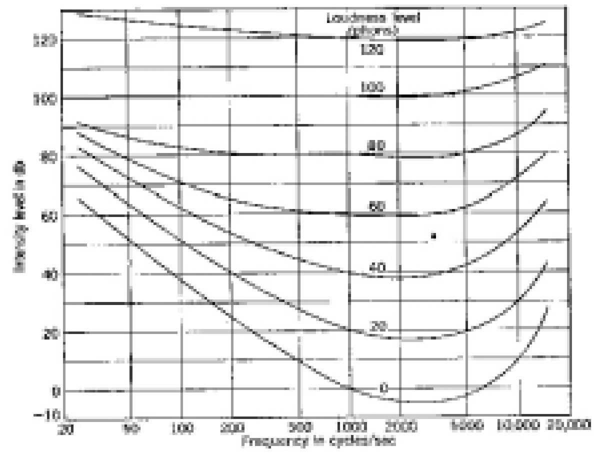
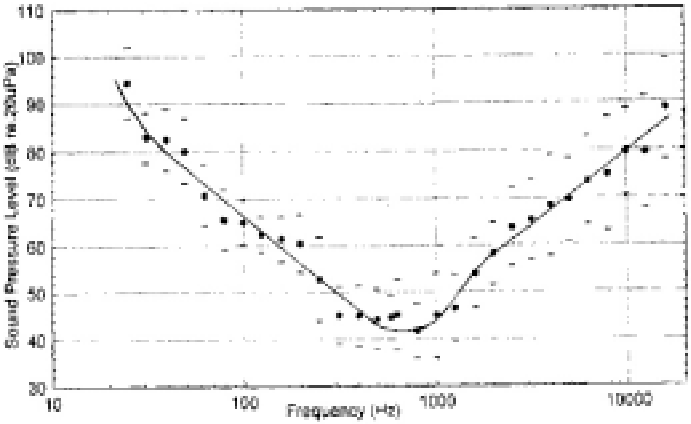


Figure 3.4.1: Human audiogram in air (from Kinsler & Frey)

Measurements made for noise studies or the analysis of human hearing are most often done in the spectral domain. This implies that the data is transformed from the time domain to the frequency domain, and the results displayed as a function of frequency. Although narrow frequency bands can be used in these analyses, such as 1/3-octave bands, the use of 1 Hz bands are most often used.

Fig. 3.4.1 gives the human audiogram in air, and indicates the lower threshold of human hearing. Fig. 3.4.2 gives the lower limit of human hearing in water.



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

3.4.2 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.

Figure 3.4.2: Threshold of human hearing underwater (from Arvin and Nedwell)

frequencies. In the definition of a sound level taken as a broadband analysis, one should also include the bandwidth over which the analysis is made.

Broadband analysis can be made in a number of ways, either as direct measurement of the amplitudes in the time signal, or given 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.

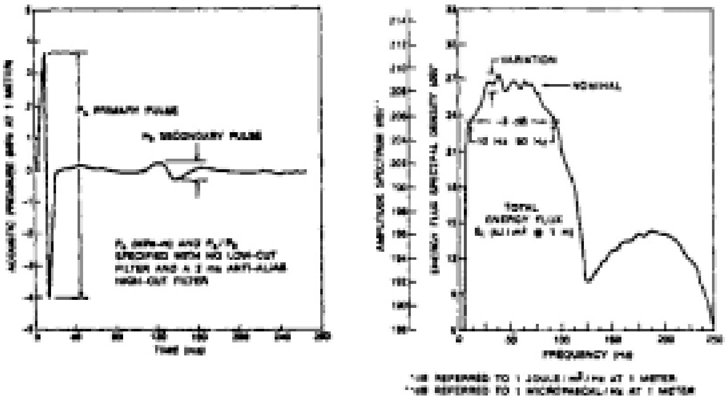


Figure 3.4.3: SEG standard for definition of the seismic pulse.

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

The Society of Exploration Geophysicists has issued standards for the specification of marine seismic energy sources, and fig. 3.4.3. gives the parameters that defines the source level.

For narrow-band signals, but also for broadband description of noise signals, the root-mean-square (RMS) value of the signal is used. The RMS-value is computed as the average of the squares of the instantaneous values that make up the signal.

$$RMS = \frac{1}{N}\Sigma\left(x^2(t)\right)$$

where N = number of samples taken from the signal
x(t) = sample values

for sinusoidal signals, the relation between rms and peak value is:

$$RMS = \frac{Peak}{\sqrt{2}}$$

This implies that the difference between the 0 - peak value and the RMS-value is 3 dB.

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:

$$E = \frac{P^2T}{2\rho_o c}$$

where P^2 is the average pressure squared
T is the 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 is very sensitive to the determination of the time T, and is 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.

3.5 Comparison of measurements in air and in water

If the spectral analyses are done with 1 Hz bands 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 20 μPa/Hz	Pressure in water re 1 μPa/Hz	
0	62	lower limit of human hearing
60	122	
120	182	threshold of feeling
140	202	threshold of pain
160	222	threshold of direct damage

(the comments are quoted from Kinsler & Frey: Fundamentals of Acoustics, 2nd. edition, John Wiley & Sons, 1962, page 392. The levels given are RMS-levels for pure tones).
Assuming that the lower limit of human hearing is connected to the pressure of the sound wave, the table show that in water the lower limit should be approx. 62 dB. The direct connection between intensity and pressure allows us to use both when discussing the lower limit of hearing. With reference to Fig. 3.4.1 and 3.4.2, 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).

At the higher end of the table, one find that the pain/damage level for pure tones in air of 140/160 dB (re 20 μPa) corresponds to a level in water of around 202/222 dB rms (re 1μPa). This corresponds very well with many experiments where is has been shown that physical damage to fish (eggs, larvae and fry, as well as larger fishes) will occur at a sound pressure level of around 230 dB (re 1 μPa). 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.

3.6 Other noises

Although the main purpose of this paper is to discuss underwater sound generation in relation to seismic surveys, a short description of other man made noise will be included

Active sonar is a common source of noise in the ocean. In evaluating the sound levels made by sonar equipment, it is important to note that the levels given include the effect of source directivity. This implies that if the source is highly directive, as is the case with many fish-finding sonar, the sound generated will only be heard within the narrow beam set up by the equipment. The attenuation factors are still the same as described earlier, with a 20 log(r) factor for the geometrical spreading.

3.6.1 Military

The military use of chemical explosives is well known. Testing of weapons normally takes place in restricted areas, and will only have impact in those local areas that are cleared for this type of activity. Destruction of mines sometimes has to be taken in shore areas close to fish farms or other environmental sensitive areas. From time to time this can create a problem, but the total impact will be small.

A larger potential problem is the use of sonar signals, especially the high power low frequency sonar (such as LFAS, Low Frequency Active Sonar), with reported maximum pressure level of over 230 dB re 1 µPa. The details concerning the definition of this source level are not given, and the directivity factor is unknown, therefore it is difficult to fully assess the long distance sound propagation.

Lower power, high frequency sonar might also have an impact on marine life, especially on those marine mammals with an extended high frequency hearing ability.

Possible impact from military activity on marine life requires detailed knowledge of signal source characteristics, frequency range, total transmission time and other factors relating to the transmitted signals.

Further discussion of sound propagation resulting from military activity is outside the scope of this paper.

3.6.2 Fishing

Fishing vessels create a significant amount of noise; especially trawlers that need high engine power to tow the trawls through the water.

The noise from a typical fishing vessel will have a spectral level of 150 - 160 dB re 1 µPa/Hz at 1 meter distance. This is a continuous signal, and can therefore not be directly compared to the pulses used in a seismic survey.

The sonar signals from fishing vessels will also be heard by marine mammals and fish, when they are within the narrow beam transmitted by this equipment..

3.6.3 Shipping

Shipping will create noise very much the same way as fishing vessels, and use echo sounders the same way. The noise is to some extent a function of vessel size, and the large super tankers can have a noise output of 170 - 180 dB re 1 µPa/Hz at 1 meter.

The considerations given above for fishing vessel sonar should also be taken with regards to the sonar and echo sounders used by shipping.

3.6.4 Scientific investigations

The Acoustic Thermometry of Ocean Climate (ATOC) program uses low frequency signals with an output level of 195 dB re 1 µPa. The ATOC signal source is normally deployed at significant water-depth, and the propagation from these sources is not directly comparable to seismic signals. The possible impacts on marine life from ATOC have been treated in many papers over the last years.

Marine scientific investigations also rely on sonar to a large degree, and the same considerations as given for fishing above are relevant for scientific surveys.

All analysis of man-made noise involves making other types of noise. It must, therefore, be evaluated carefully which disturbance is most detrimental to the subjects being tested. On one occasion it has been stated directly that the monitoring programme was more harmful than the seismic survey being evaluated.

3.7 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.

3.7.1 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 through 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, 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 proper spherical spreading. This is of special importance when evaluation the impact from marine seismic surveys. The fact that seismic surveys use the signals reflected from geological boundaries in the sub-surface, indicate that a significant amount of energy has penetrated the sea bottom.

The use of sophisticated models designed for high frequency underwater use when evaluating the propagation of seismic signals can therefore be very misleading. Simple earth models used in combination with the ray tracing techniques might well give a better estimate of seismic signal strength with distance.

A practical formula for estimating the sound level from low frequency sources is the following:

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

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

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 island in the direct propagation path. In these cases, all sound will travel trough 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.

3.7.2 Importance of water depth

Variations in the 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 frequent nature of the seismic signals will cause these to travel through the rocks beneath the sea, and therefore attain a decay rate that is much closer to the deep-water conditions, i.e. a spherical decay law or even stronger attenuation.

3.7.3 Sea floor conditions

In areas with a very strong acoustic contrast at the sea floor, much of the seismic signals will be reflected back to 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 are done 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 frequent 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.

3.7.4 "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 what would have been estimated from strict propagation modelling of high frequency sound.

3.8 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 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, and results in stronger attenuation of the seismic signals over distance.

Some conditions might also cause the signals 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 in general account for stronger seismic signals over distances.

3.8.1 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. This way, the sound can travel over considerable distances.

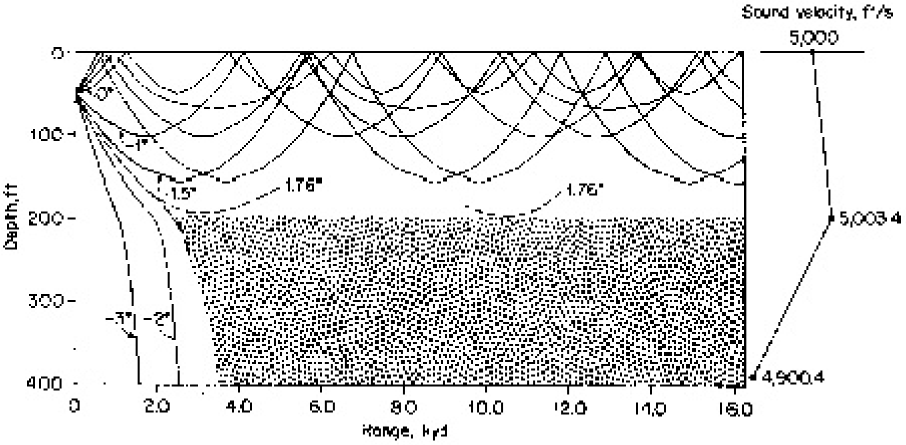


Fig. 6.1 Ray diagram for sound transmission from a 50-ft source in a 200-ft mixed layer. Rays are drawn at 1° intervals, with 1.5° and 1.76° added, for the profile at the right.

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. Further discussion of the characteristics of these are not included in this paper.

Sound channels will not transmit all frequencies the same way. 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 can be estimated by the equation:

$$f_{\max} = 1.76 * 10^5 * H^{-\frac{2}{3}}$$

where H is the height (or thickness) of the sound channel.

Figure 3.8.1: Shallow sound channel.

U [illegible] ency 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. Fig. 3.8.1 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 should be obvious that sound channels will not play an important part in the propagation of seismic sound. This is confirmed both by actual modelling and measurements.

3.9 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 meters from the source, but the annoyance level may extend much further.

At distances over 1000 meter, the seismic sound reaching the sea surface is dominated by energy that have 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 do not match. Great care must therefore be taken in any reference to inferred sound pressure levels based on the source strength and the distance between the source and the observation.

4 Environmental impact on fish and fisheries

The environmental impact of seismic surveys has been studied for many years by a wide variety of organizations. In the early days of seismic shooting, when chemical explosives were used as the seismic source, the physical impact was most noticeable. Today's use of airguns is much more environmentally safe, and the direct damage is not considered an environmental problem. Possible impact on the fish behaviour is, however, still open to discussion between the parties.

Many studies on the topic of environmental impact of seismic activities on fish and fishing appear to have a bias against seismic activity. Lack of understanding of the underlying physical principles of sound in water, and limited knowledge of the nature of seismic operations in general, often leads to unrealistic "worst case scenarios". When such reports are referred to, the background material are omitted and the conclusions taken as normal occurrences. This is a problem that needs addressing specifically in order to improve the dialog between the parties.

Hopefully, this report can be used as a basis for more detailed discussion over the possible impact that seismic surveys may have on fish and fisheries, a discussion that should lead to a improved understanding of a very important topic.

4.1 Direct damage

A number of studies have analysed the conditions leading to direct damage on fish from high-level sound. Unfortunately, most of the studies have not documented the sound levels in a consistent way, and the results are therefore difficult to compare.

As a general rule, physical damage is highly dependent on the characteristics of the sound impulse. The following factors must be described:

Peak pressure level
Rise time of the pressure increase
Decay time of the pressure wave

At the Workshop on Effects of Explosives use in the Marine Environment, Halifax 1985, Larson concluded that mortality can occur when the sound pressure pulse has a peak pressure exceeding 229 dB re 1 µPa (275 kPa), and the rise- and decay time is less than 1 msec. Detonations of chemical explosives are needed in order to reach such rise- and decay times. Airguns will have a much slower rise time, and are therefore not as dangerous with regards to potentially lethal damage.

The specified output from airgun arrays will, however, often be higher than the level of 230 dB given above. In this context it is important to remember that the specification of airgun output is that of a notional source, measured at a distance away from the array and computed back to a distance of 1 meter from the centre of the array. Due to the physical dimensions of the array, the maximum sound pressure level that can be measured at any point within or close to the array will never be higher than approximately 6 dB more than the output from a single gun. In practice this means that the maximum level will be in the order of 232 dB μPa (zero-to-peak).

Dalen et al (1996) studied the impact of airgun arrays on fish stock levels, and concluded that “the mortality rates and damages are limited to distances of less than 5 meter from the airguns, with most frequent and serious injuries at distances of less than 1.5 meter.” The report further states that, on a stock level, this damage would only account for a mortality rate per day of less than 0.018% (worst case scenario, 0.0012% on average), which is insignificant compared to the natural mortality rate of 5 – 15 % per day for the exposed species.

With regards to fish, it can therefore be concluded that direct physical damage resulting from exposure to high level sound from seismic airgun arrays is not an issue that requires special mitigation.

However, the study concludes that care must be taken in the sensitive periods, and seismic surveys should be avoided in areas of spawning or fish migration for between spawning areas. A comment to this conclusion will be given later.

4.2 Behaviour impacts

Fish in a wide area around the seismic vessel may hear the sound field from a seismic airgun array. The reaction to this sound is, however, very variable and will probably depend on many other factors than those coming from the seismic operations.

Fishermen have for many years claimed that seismic operations will impair the fishing in a large area around the seismic vessel. Despite this, active fishing is often observed from the seismic vessels. There are also reports of fishermen getting larger catch rates if they follow in the immediate track of the seismic survey. The reason for this could be that the fish will move closer to the sea bottom when scared by the seismic sound, leading to higher concentration of fish in the area covered by bottom trawling.

A number of recent studies on the behaviour impact on fish from seismic surveys in general show that the effect on seismic may be limited, and that the alleged impairment of fishing may not be as severe as claimed by the fishermen. Some of these studies will be discussed in more detail below.

4.2.1 Tromsøflaket

In the report “Effect of seismic shooting on catch and catch-availability of cod and haddock”, Fisken og havet nr. 9 - 1993, Engaas et al. claimed that the reduction in catches were about 70% in the area of the seismic shooting, with significant effects in the entire study area of 40 x 40 nautical mile.

The study was done by means of fishing trials using trawl and longline, in addition to extensive acoustic mapping of the fish distribution before (7 days), during (5 days) and after (5 days) the seismic shooting. The fishing was done with standard commercial fishing gear.

Trawl fishing included 62 hauls before, 67 hauls during and 60 hauls after seismic shooting, and longline fleets of 56 before, 40 during and 35 after the seismic operations.

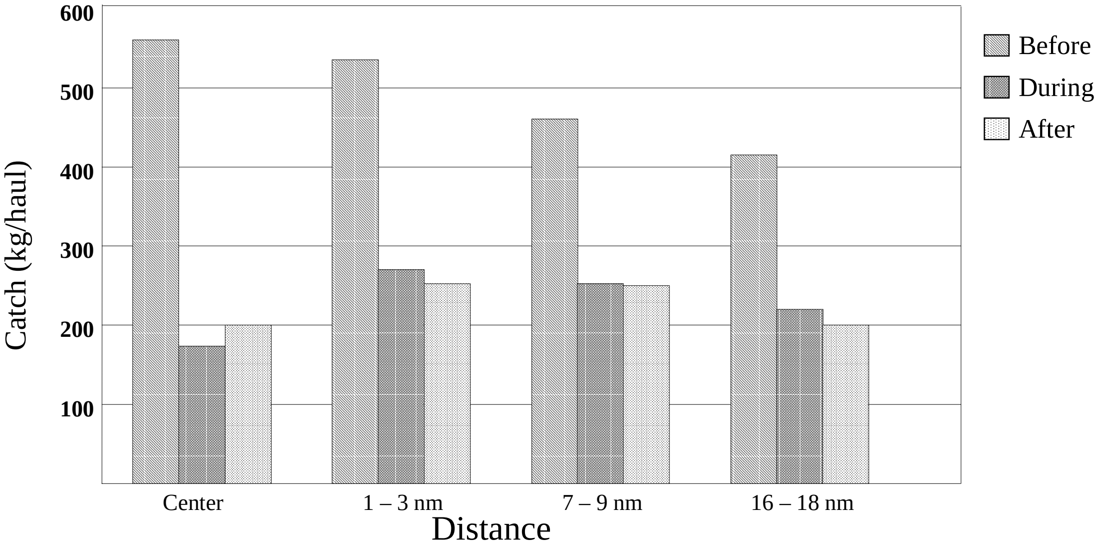
Within the area of the fishing, and during the same period, the fish distribution was mapped and abundance estimated by crisscrossing the area along transects out to 20 nautical miles. Samples of the acoustically registered fish were taken with a standard sampling trawl.

The seismic shooting was performed in the centre of the entire study area, and covered an area of 3 x 10 nautical miles. This operation was performed in accordance with standard industry practices for 3D surveys.

The catches by trawl and longline consisted primarily of cod and haddock, with cod as the dominant species.

Fig.4.2.1.shows the results from trawling as presented in the report. In the centre area catch rates were reduced by 70%, and overall the catches after start-up of seismic shooting was halved compared to the initial trawl hauls.

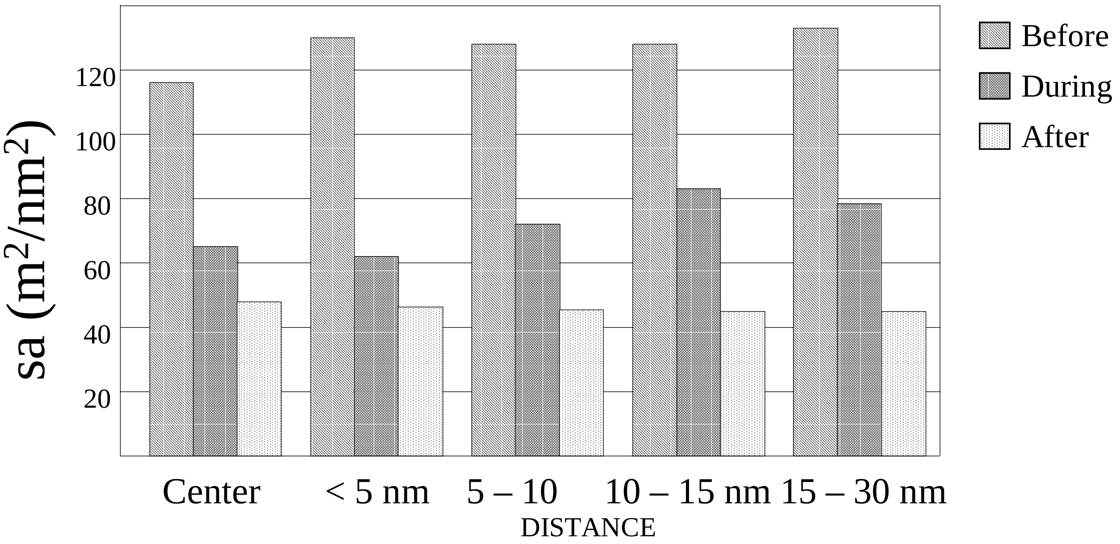
Fig. 4.2.2 shows the total acoustic density of fish during the project period, and the same general reduction in abundance can be seen.



Average trawl-catch rate for cod before, during and after shooting, arranged by distance from the shooting area (Redrawn from fig. 4.2.1. in the original report)

Figure 4.2.1

The study presented in Fisken og Havet nr. 9 – 1993, is a very comprehensive and thorough study of the possible impact of seismic surveys on the behaviour of fish.

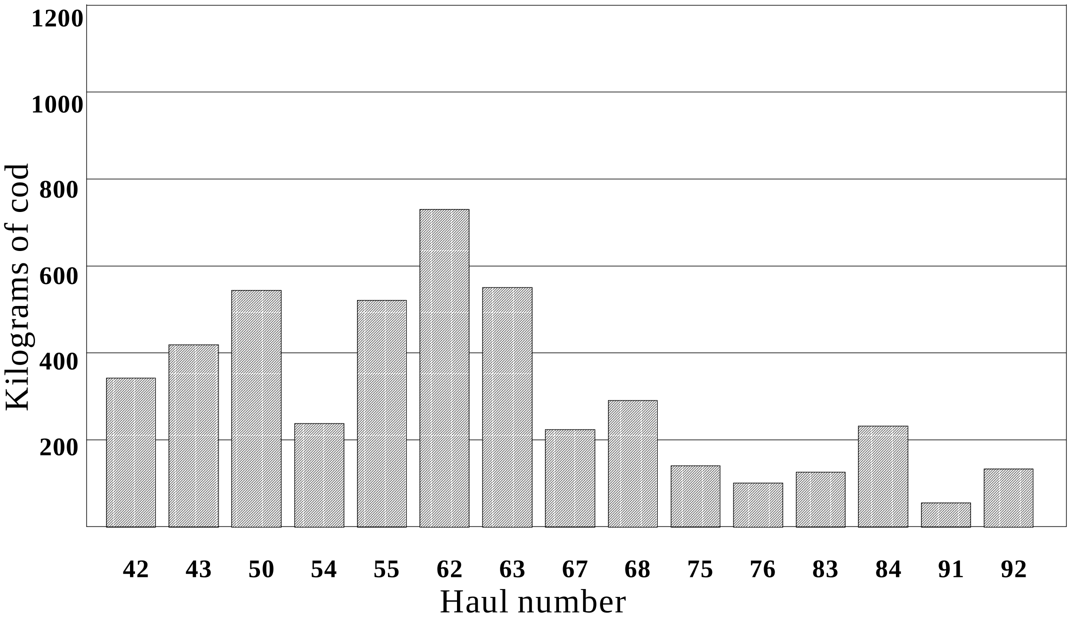


Total acoustic density distrubuted by distance from the shooting region before, during and after shooting (redrafting of fig. 4.1.6 in the original report)

Figure 4.2.2.

In the statistical analysis of the catch results the study groups the data into quite large time periods, namely those of “before”, “during” and “after”. Hence, more detailed variation in the abundance of the fish cannot be analysed.

However, the report have figures that show the catch rates for each trawl haul during two days before and two days after start-up of seismic shooting. These figures are shown here as figures 4.2.3 to 4.2.6 respectively.

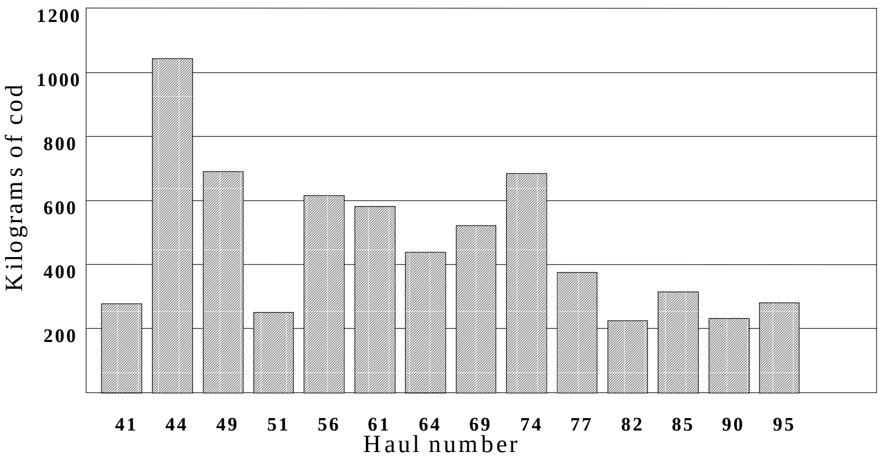


Catch rate for cod at distance 0 (within the shooting area) the last two days before and first two days after the start of shooting (Redrawn from fig. 4.2.13 in the original report).

Figure 4.2.3

At distance 0 (within the shooting area) a distinct reduction can be seen between hauls 63 and 67, the point at which shooting started.

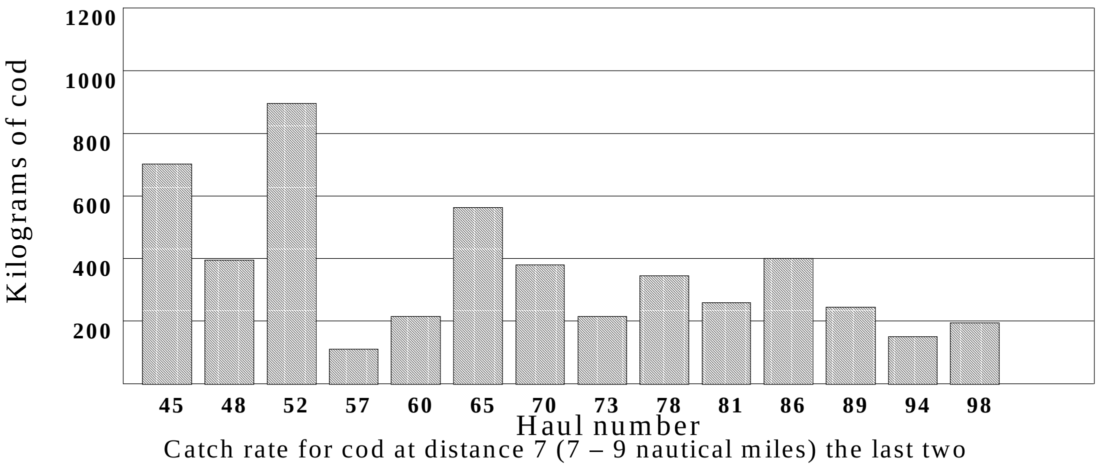
At distance 1 (1 – 3 nautical miles) it is difficult to determine a distinct change in the catch rates between the various hauls. During the four days covered by the figure, there is a clear trend of reduced catch rates throughout the period, without a clear break at the start of seismic shooting.



Catch rate for cod at distance 1 (1 – 3 nautical miles) the last two days before and first two days after the start of shooting. (Redrawn from fig. 4.2.14 in the original report).

Figure 4.2.4

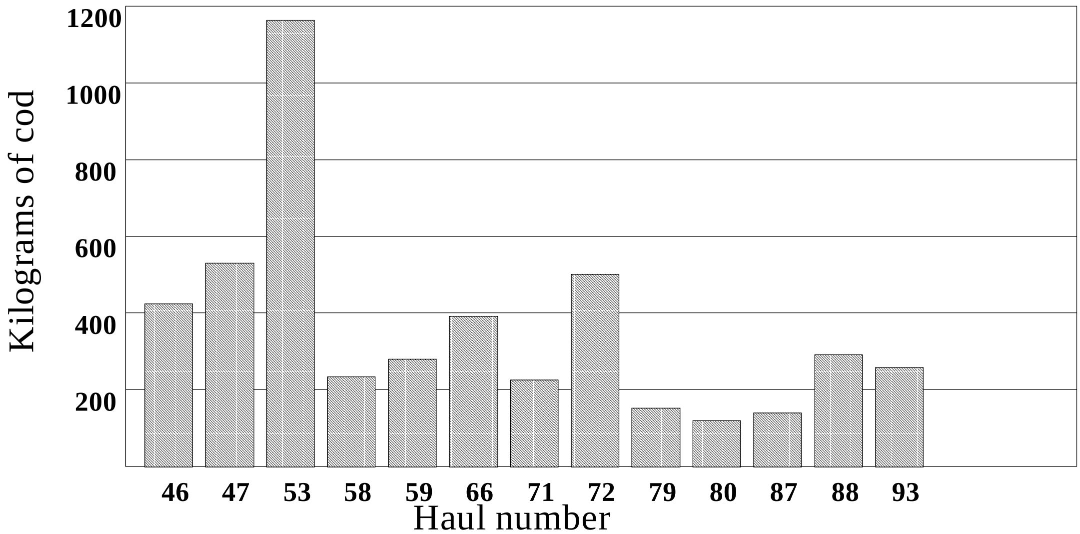
The conditions at distance 7 (7 – 9 nautical miles from the centre) shows the same trend at the figure above. The most obvious trend is a decline in catches rates throughout the period, without an obvious change at the start-up of seismic shooting that occurs between hauls 65 and 70.



Catch rate for cod at distance 7 (7 – 9 nautical miles) the last two days before and first two days after the start of shooting. (Redrawn from fig. 4.2.15 in the original report).

Figure 4.2.5.

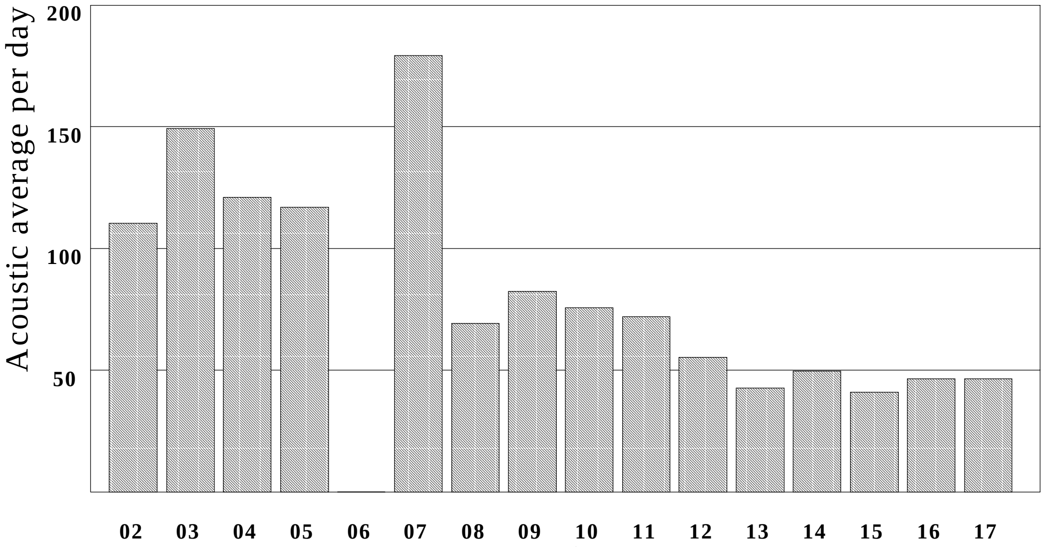
At distance 16 (16 – 18 nautical miles) the picture remains the same. It is difficult to determine that there is a clear change in the catch rates at the start-up of shooting which happens between hauls 66 and 71.



Catch rate for cod at distance 16 (16 – 18 nautical miles) the last two days before and first two days after the start of shooting. (Redrawn from fig. 4.2.16 in the original report).

Figure 4.2.6.

Based on these figures it may also be concluded that the scaring effect of fishing probably had a stronger impact on the catch rates then the start-up of seismic shooting. The conclusions given in the original report, and repeated in many subsequent papers by the same authors may therefore not be entirely in agreement with the data from the original experiment.



Average daily acoustic quantity, independent of position, throughout the whole period, 2 – 17 May 1992. The gap in the data for May 6 is due to a meeting with the seismic vessel. (Redrawn from fig. 4.1.13 in the original report.

Figure 4.2.7.

In addition, the average daily acoustic quantity of fish, independent on position, throughout the whole period of the study, is shown in fig. 4.2.7. From the acoustic measurement of the total quantity of fish in the area, it should be evident that there may be a gradual decline over the whole period, not an abrupt change when the seismic survey started.

4.2.2 Scotland (1998)

The Marine Laboratory of the Fisheries Research Services, Aberdeen Scotland, in the report "The sound of a triple "G" seismic airgun and its effect on the behaviour of marine fish." (Wardle et.al, 1998) studied the effect of seismic pulses on fish and invertebrate species living on an inshore reef. The study used a cluster of three guns, and included TV films as well as tracks of tagged fish, one week before, during and four days after a seismic triple-G airgun was deployed and fired.

The study shows that fish was observed swimming from a point within 1.5 meter from the airgun towards the TV camera apparently undamaged. This fish was exposed to a peak sound pressure of 229 dB re 1 μPa.

The only prolonged flight reaction observed was from fish approaching the airguns placed at the seabed; where the air bubbles also produced a very visible, large sand cloud. It appears as if the fish has a stronger reaction to visible effects than to the sound levels produced by the airguns.

All fish observed while the airguns were firing showed a skip to one side, called a "C-start". Following this reaction to the seismic sound pulse, the fish continued with their previous activity. There was no signs of disorientation or other possible effects of the high-intensity sound that the fish was exposed to. The population of fish around the inshore reef behaved normally, apart from the C-start, throughout the period of the study.

The conclusion from this study is that there is no immediate behavioural impact on fish following seismic shooting in the area. Admittedly, the fish exposed in this study were a local group in an inshore environment, and the results may not be directly transferable to conditions in open waters where commercial fisheries take place. However, the indication is that fish are not easily scared away from their home habitats.

4.2.3 PGS herring study (Norwegian Sea, 1999)

A special study of the impact of seismic surveys on distribution, abundance and migration of herring took place in the Norwegian Sea centered around the position 64^{o} 10" N, 4^{o} 30" E. (Slotte et al. 1999). During a 1999 PGS seismic survey, the Institute of Marine Research, Bergen used acoustic methods to map the density of fish, mainly herring and blue whiting.

Estimates of total biomass of herring within the set security zone during the first part of the study (Survey 1) amounted to 95 000 tonnes, significantly lower than the set risk threshold level of 225 000 tonnes. Therefore no special restrictions were set on the performance of the seismic survey.

The estimates of blue whiting was 192 000 tonnes, the species that turned out to be the most abundant in the area.

Conclusions drawn from the study are that the large-scale distribution of both herring and blue whiting systematically showed lower abundances after periods of seismic activity. However, there was no convincing, significant evidence of direct scaring effects from the shooting within the study area. The observed impacts indicate less reaction than previously observed in cod and haddock, as described above. The report states that the data from this study were not collected under strict experimental regimes and are therefore of limited value regarding firm conclusions on short term impacts on pelagic fish.

The figures presented in the report show a clear avoidance of the area immediately following the seismic vessel, but the mapped distribution over the whole area is very variable and makes it difficult to confirm the conclusions drawn by the authors.

4.2.4 Faroe Island (1999)

Fishermen on the Faroe Plateau have expressed concern that seismic surveys may have an adverse impact on their fisheries. In 1999 the Faeroese Fisheries Laboratory undertook to study the topic, with a comprehensive interview with individual fishermen and a statistical analysis of catch rates from logbook data. The fishing and seismic activity in 1997 was used to analyse the effects on fisheries, as this was the last year in Faeroese waters that no announcement of seismic activities were announced to the fishermen.

In the report “Effects of Seismic Activities on the Fisheries at the Faroe Islands” Jacupsstovu et. al. (2001) describes the study and states that from the logbook data it is not possible to document any effects of seismic activity on the fishing catches. However, 75% of the fishermen, coming from all vessel groups, claim that in areas with seismic activity they observed an effect.

The authors state that it is very difficult to have an unbiased response to the question through an interview process, but the number of observations are numerous and represent the whole range of demersal fisheries in the Faroe Islands. They therefore conclude that it must be accepted as a fact that seismic activity affects the fisheries although it has not been possible to verify this from logbook data.

The report also states that it is not possible from the logbook data to distinguish between any long or short-term change in the catch rate that could be linked to seismic activity in the same area in time and place. This does not mean that there are no effects from the seismic activity, one can only say that the natural variations in catch rate are so large that they mask any effect of seismic activity that may exist.

A firm conclusion is, however, that the seismic activity on the Faeroese territorial waters in 1997 did not have any lasting effect on success in the demersal fisheries nor on the fish stocks.

4.2.5 Australian study 1996 – 1999

A comprehensive study “Marine seismic surveys – a study of environmental implications” by R.D. McCauley et.al., describes the results from a program initiated and sponsored by APPEA from March 1996 to October 1999. The program consisted of a number of activities that described the airgun as a sound source, the sound propagation from this source and the potential biological effects of a seismic survey including observations and experiments on humpback whales and fish. In general the study covers the responses in relatively shallow waters (<150 meter).

The study gives the sound levels as “rms”, where the time gate is set to 1 second. Therefore, the results may not be directly comparable to other uses of “rms”-values where a shorter time gate is used.

The study found that fish will have a threshold of increased swimming behaviour at distances of 1 – 3 km from a 3D seismic survey. Captive fishes showed a generic fish “alarm” response at an estimated 2 – 5 km from the seismic source, and that the threshold for initial increases in swimming behaviour may be at distances of 1 – 2 km

The authors point out that any potential seismic effects on fishes may not necessarily translate to population scale effects or disruption to fisheries. For many fish species any behavioural changes or avoidance effects may involve little if any risk factor.

4.2.6 Sand eel (Tobis) (Norway North Sea, 2002)

The possible impact of seismic surveys on sand eel (Tobis) has for years been a concern among Norwegian fishermen, and in 2002 a study was performed in order to investigate possible impact on sand eel from seismic surveys. The study in location N 57^o 12,5’ and E 05^o 19,1’ done by the Institute of Marine Research, Bergen during the month of May, 2002, involved acoustic monitoring of sand eel abundance, grab samples to find sand eel buried in the sand, behavioural studies of sand eel in cages as well as a review of the fishing activity in the area.

The acoustic monitoring showed an increasing amount of sand eel during the study period. The lowest readings were before seismic operations started, and the overall highest abundance was found on May 19, four days after the end of the seismic activity. This may indicate that that the amount of sand eel increased significantly after the seismic operations was terminated, but may also indicate that other fish species migrated into the area. The report points out that schools of herring may explain the increase in acoustic recordings, as the herring will give an acoustic backscatter of about 10 times that of similar schools of sand eel.

The conclusion from the acoustic monitoring is that there is an increase of sand eel, and possibly other pelagic schooling fish, in the experimental area after the end of seismic operations.

Grab sampling was done in order to test the hypothesis that the sand eel would be scared and bury deeper than it could survive due to lack of oxygen, however, none of the grab samples showed any dead or paralysed fish before or after shooting.

In order to analyse possible mortality due to the sound pressure pulses resulting from the seismic operations, and to observe the sand eel under influence of seismic signals, some sand eel were placed in cages measuring 2.0 x 1.8 x 2.0 meter. In all 6 cages were used, 3 in the experimental area and 3 in a control area about 40 km southeast of the seismic centre.

The mortality was similarly high in both sets of cages, being around 35%. As there is no significant difference between the experimental area and the control area, it can be concluded that the seismic operations did not cause increased mortality of the sand eel in the cages.

A plastic inspection window allowed video filming of the fish in the cage, and post-mission analysis included visual inspection of more than 40 hours video recording. The fish remained calm in the cages for a long period, but when the seismic vessel had shot half of the lines close to the cages a slight increase in tail beat frequency was seen. The tail beat decreased when the distance to the seismic vessel increased. Some irregular swimming was also observed on many individual fishes during the seismic shooting period. A behaviour described as a C-start like response was observed, but there is no correlation between these observations and the arrival of the seismic pulses. The video recording also confirmed that the sand eel did not frighten and took refuge in the sand during the seismic shooting.

Fishery statistics reveal that there was a reduction in the reported landings on the two days after the shooting, on May 16 and 17, but this may be caused by the closing of the Norwegian landing sites on Norwegian National Day May 17. The landing of sand eel catches from the experimental area increased significantly after the two day decline, but was followed by a new decline some days later. This makes it difficult to interpret the reduced landings as a direct result of the seismic operations in the area.

Satellite tracking of the fishing vessels show that most of the vessels increased the distance to the experimental area after the seismic operations, but the change in distribution pattern might appear random.

The report clearly shows that sand eel has no direct negative reactions to seismic shooting resulting in increased mortality. Possible reactions to the seismic signals may be enhanced by the fish being confined to cages, and with no correlation between the reported startle responses and the arrival of seismic pulses it is difficult to conclude that the seismic operations have direct impact on the behaviour of the sand eel. The fact that the video recording showed schools of sand eel outside the cages and that the acoustic abundance mapping showed an increase of fish in the experimental area after the seismic operations may also indicate that sand eel has little or no reaction to seismic operation even in close proximity to the main fishing grounds.

5 Summary comments

Recent studies on the impact of seismic surveys on fish have shown that there is negligible direct physical damage, but that there may be a behavioural change in the vicinity of the seismic source.

The radius of the affected zone is dependent on many variables, like the local physical conditions of the sea, the food supply for the fish and the behavioural pattern of the fish present. Fish with natural habituation will be more steadfast than shoals of fish migrating through an area. Therefore it may be difficult to accurately determine the exact impact of seismic on the behaviour of fish.

Contrasting the conclusions in the IMR studies from 1992-93, many studies find that the maximum distance from seismic surveys that cause behavioural impact on fish is limited to less than 2 km. Reinterpretation of figures from the IMR study, as shown above in paragraph 4.2.1, may support this conclusion.

Media coverage and anecdotal evidence have led to a strong belief among fishermen that seismic activity will interfere with fishing in a negative way. Most fishermen will claim that a bad fishing day is just bad luck, but if this same day follows in an area of seismic activity, they will argue that the seismic activity is the reason for the low catch rates.

Studies on the behavioural patterns of fish in areas with seismic survey activity are most often performed in close cooperation with fishermen. The interpretation of the results of the studies may therefore in some cases show a bias towards the fishermen assumptions rather than a more neutral conclusion of the often very vague data.

There is no doubt that seismic shooting does affect the behaviour of fish in the area close to the seismic vessel. The magnitude of this effect may, however, be within the noise level of all natural stimuli for the fish, and will not lead to long term changes in average catch rates or to the size of fish stocks in general.