

**Exploration gazière et pétrolière du golfe du Saint-Laurent :
Revue sommaire sur les impacts potentiels**

ANNEXE 1

Rappel d'acoustique marine

préparé par

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1.0 Introduction

The use of geophysical techniques in the exploration for hydrocarbons, i.e. the identification and delineation of possible target zones that may have economic gas or oil potential, will invariably involve the use of acoustic energy for remote mapping of deep geological stratigraphy. This is because acoustic energy propagates very well through the materials that make up the earth's upper surface.

Seismic exploration in a marine setting as on land, involves the use of short impulses of acoustic energy that excite an echo response from deep geological structures. The recorded responses are processed and collated and presented as seismic sections for geological interpretation.

This complete process is called seismic reflection surveying and in the marine environment, depending on the particular targets zones of interest, a seismic survey can range in scale from single small boat, day long operations to multiple, special purpose ocean going vessels operating for month long missions.

The nature of sound propagation through natural materials is very complex and as in all propagation problems, certain loss processes are always present. In order to utilize the seismic reflection principal to map the geological structure that may support hydrocarbon reserves, high-energy sound pulses have to be generated, and small echoes detected and recorded. On land, this is a relatively simple operation and though large chemical explosives are often used to generate the required sound pulses, the effects on the environment are localized and relatively easily controlled and monitored. However, in a marine setting the intervening water layer separates the sea surface, where the data collection activities takes place, and the seafloor where the interesting target geology begins.

Although the water column is an effective coupling medium, more complex techniques have to be used at sea both to generate sound pulses on a repetitive basis and to detect the resulting echoes. Thus marine geophysical activities are extensive, costly and highly technical when compared to land exploration. However, once a marine survey operation is in place and underway, a large area can be fully surveyed in a relatively short time period.

It is the nature of sound in the ocean to spread out in all possible directions away from the generation point. Unfortunately it is not possible to direct all this sound downwards. Although modern surveying equipment is directional to some extent, a portion of the acoustic energy will propagate horizontally. This means that all life forms in the water column and on the seafloor adjacent to the track of the survey vessel will be subject to a pressure wave that is repeated at regular intervals. This outward going pressure wave will naturally decrease in amplitude with time and distance suggesting that areas close to the primary source will be subjected to higher pressures than regions farther away - in all directions. However, in recent years, the effects of this sound exposure on benthic life and both fish and marine mammals in the water column has come under scrutiny by scientists, regulatory bodies and the public at large. This concern has lead to much research into the effects of seismic waves on all marine life.

In this brief report it is not possible to fully discuss all environmental aspects associated with marine seismic exploration. Various reports and publications have been relied on heavily for relevant information. It is suggested that these reports, some with executive summaries that are listed in the bibliography, be made available to all interested parties. Together they contain hundreds of technical and scientific references to all aspects of seismic/environmental interaction.

This submission however will attempt to define and discuss some of the relevant seismic terminology, data collection methods that are presently in use in marine exploration and areas of research so that all interested parties will be able to relate to the acoustic and environmental issues. It will also discuss briefly mitigation measures that are used in some jurisdictions.

2.0 Discussion of the Marine Seismic Technique

The seismic reflection profiling technique has been used for over 40 years in various forms for hydrocarbon exploration, engineering and research purposes. All variations of this technique, however, whether on land or in the marine environment, utilize the:

source – transmission path – echo generation– return transmission path - receiver

configuration and invariably the amount of energy stored and emitted impulsively by the seismic source is proportional to the amount of penetration required. This is because of the various energy loss processes that naturally occur during the transmission of sound energy through both the water column and the earth's geological strata. These loss processes such those due to spreading, coupled with absorption, are range and frequency dependent. Losses also occur at all the reflection and transmission boundaries and in some cases from internal scattering processes within a geologic unit. Because the conversion efficiency from one form of stored energy to acoustic energy for most seismic sources is low, 1 – 5%, a much larger input energy has to be dissipated initially that would initially appear necessary.

Figure 2.1 shows a simple marine arrangement for seismic profiling. Acoustic energy emitted by the source travels in all directions and a portion is reflected from plane surfaces forming the boundaries between different earth materials. This energy travels back towards the receiving array. The receiving array converts the resulting echoes to electrical signals for subsequent recording and display.

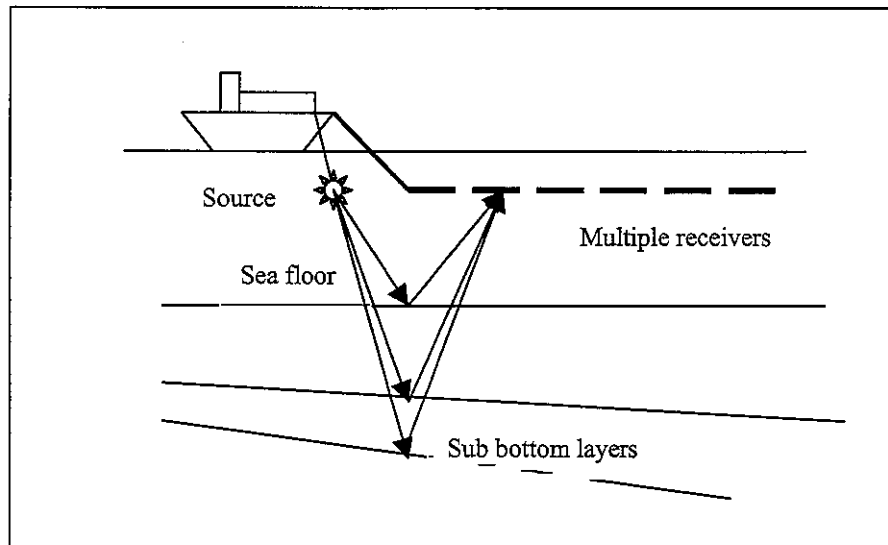


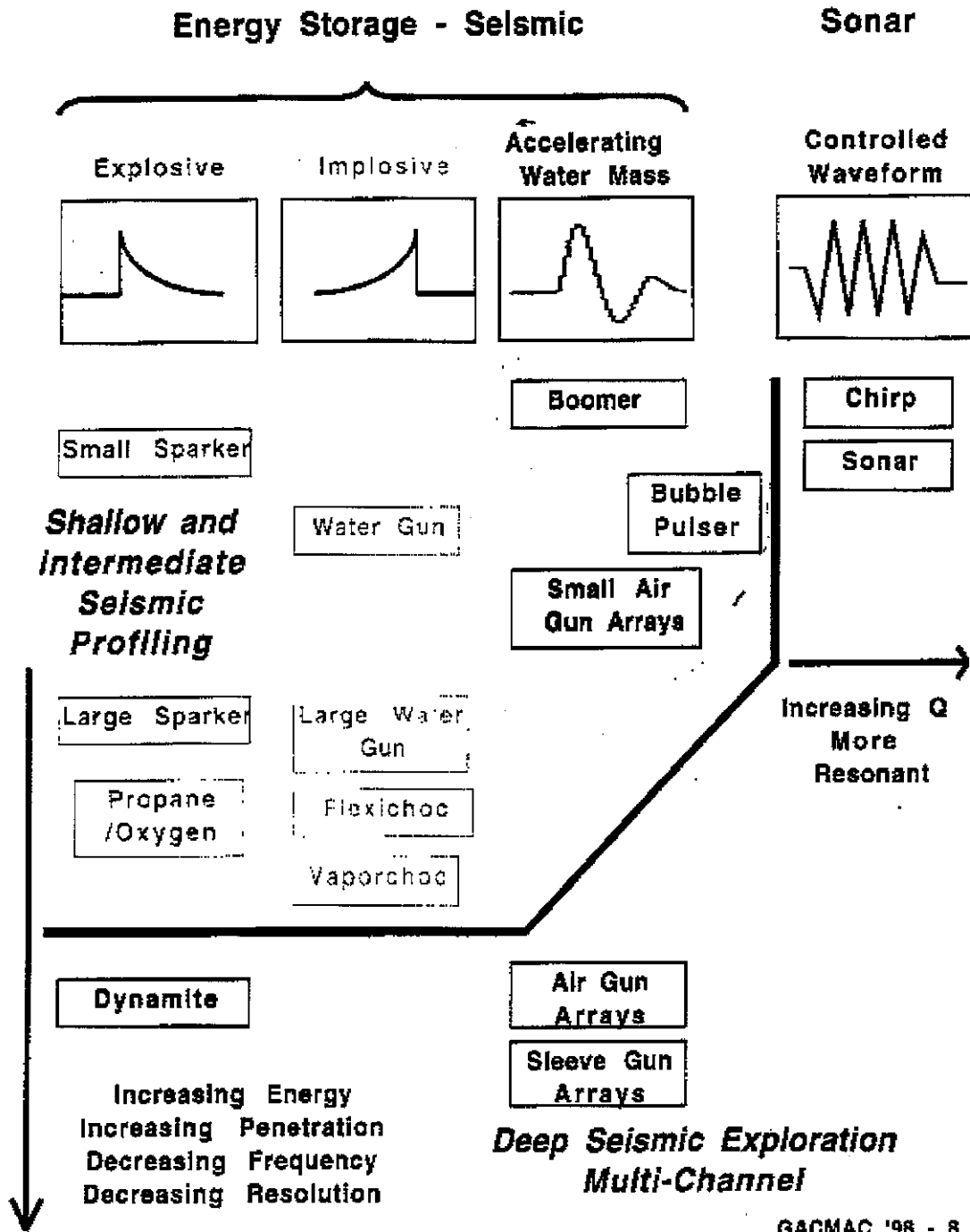
Figure 2.1 Basic arrangement for marine seismic data collection

In order to map potential economic hydrocarbon-bearing structures that may extend 10 km below the sea surface, large acoustic, low frequency, wide band, high energy sources are required.

Figure 2.2 summarizes the range of source options presently in common use for seismic profiling. In this figure, the larger and more powerful sources are to the bottom right and the high-resolution sources for shallow targets are to the top right of the seismic groups.

For a variety of reasons mainly to do with reliability, consistency in performance and flexibility in operations, airgun and sleeve gun type sources have dominated the deep marine seismic sector since chemical explosives were phased out in the 1980's for environmental and operational reasons. Both of these sources use high-pressure air to produce an acoustic impulse.

A Selection of Seismic Sources



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Figure 2.2 Selection of seismic sources used for most seismic ventures

2.1 Airgun Operation

Figure 2.3 shows the operation of a single airgun. High-pressure air at about 2000 psi is stored in a chamber that is sealed by a moveable piston. On command from a fire controller, an electrical pulse actuates the solenoid and releases a volume of high-pressure air into the surrounding water generating an expanding bubble of air.

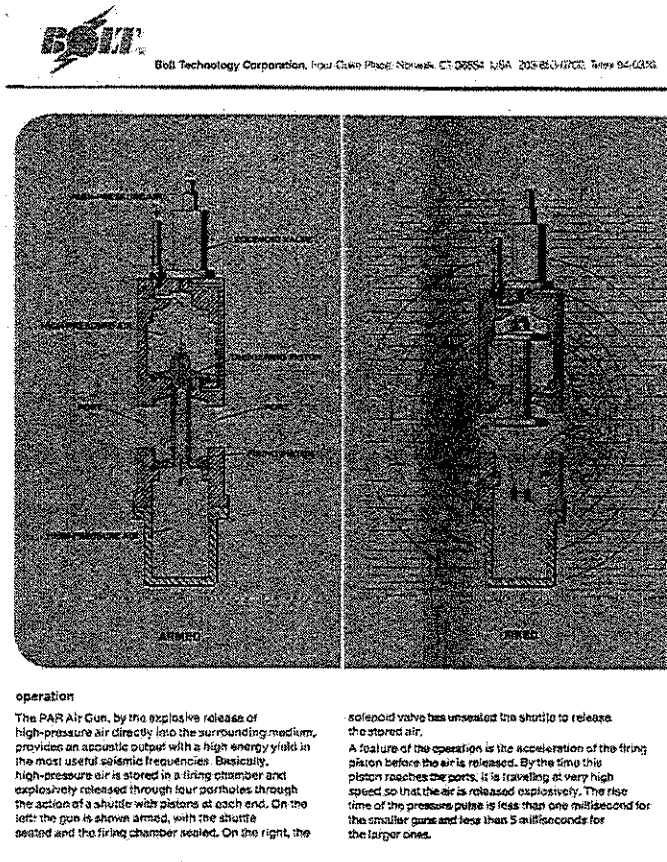


Figure 2.3 Basic operation of an airgun seismic source. From reference 6.

The rapid expansion of air is similar to popping a balloon, a loud sound is created when the air inside a balloon is quickly expelled into the atmosphere. For any airgun, the amplitude (or loudness) of the seismic (acoustic) signal is a function of the volume and pressure of the air inside the cylinder and the cylinder's depth under the water surface. The larger the cylinder volume and the higher the internal air pressure, the greater the intensity of the sound.

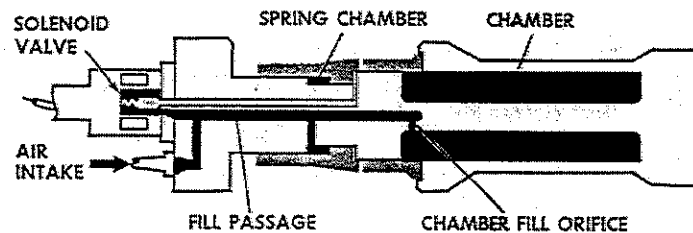


Figure 2.4 The modern sleeve Gun

In simple terms, the firing of an airgun generates an oscillating bubble in the surrounding water. At the time of firing, the pressure of the air inside the cylinder far exceeds the outside pressure in the surrounding water. This difference in pressure causes a bubble to rapidly expand in the water around the airgun. It is this initial bubble expansion that generates the relatively broadband seismic pulse, i.e. the “pop” as from a burst balloon. Because of the momentum of the bubble expansion, the bubble continues to grow until the air pressure inside the bubble becomes less than the surrounding ambient water pressure. At that point the bubble will start to collapse. At some time during this collapse the pressure inside the bubble will again become greater than the pressure outside. The bubble will then start to expand again. This expansion/collapse cycle will continue until the bubble reaches the sea surface and vents to the atmosphere. Given that energy is lost during each cycle, the system behaves as a damped oscillator, producing smaller and smaller bubble pulses with each oscillation. Figure 2.4 shows the latest form of air gun, the sleeve gun, which offers a better pulse shape and greater reliability than the air gun shown in Figure 2.3

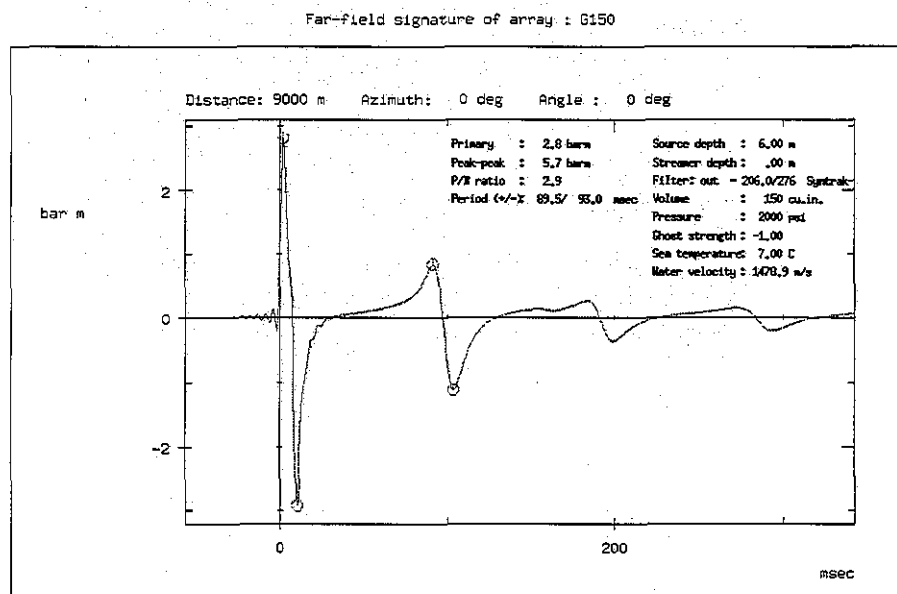


Figure 2.5a Far field pressure signature of a 150 in³ air gun

Figure 2.5a shows an “on-axis” far-field pressure impulse generated by a 150 in³ (2.45 L) airgun charged to 2000 psi (136 bar) and measured directly beneath the air gun at some distance away. Figure 2.5b gives the spectral content of the impulse. The plot of pressure versus time, referred to as an airgun’s **pressure signature**, illustrates the bubble oscillation process. This signature shows the first, or primary, positive pressure pulse due to the initial expansion of the bubble. This has a peak amplitude A, of 2.8 bar-m. The following negative pulse, referred to as the “ghost”, is due to the reflection of the initial pulse at the sea surface, and the subsequent damped oscillating bubble pulses are referred to as the “bubble train”.

As mentioned, the “ghost” pulse is due to the reflection of the primary pulse at the sea surface. Mainly because of the large difference in density between air and seawater, the sea/air interface acts like a perfect ‘mirror’ to pressure waves arriving from beneath. These pressure waves essentially “bounce” off the interface and are reflected back down. As the water air interface represents a “soft” reflecting surface, the phase of the reflected pulse is opposite to that of the incident pulse, i.e. the phase is changed from positive to negative contributing the negative part of the primary pulse.

The gap or notch in the spectrum {Figure 2.5b) is a function of the depth of the airgun and is one operational parameter that can be varied to optimize the outgoing pulse shape and spectral content. It

corresponds to the negative ghost mentioned previously. Changing the charging pressure will also change the form of both the pressure signature and spectrum.

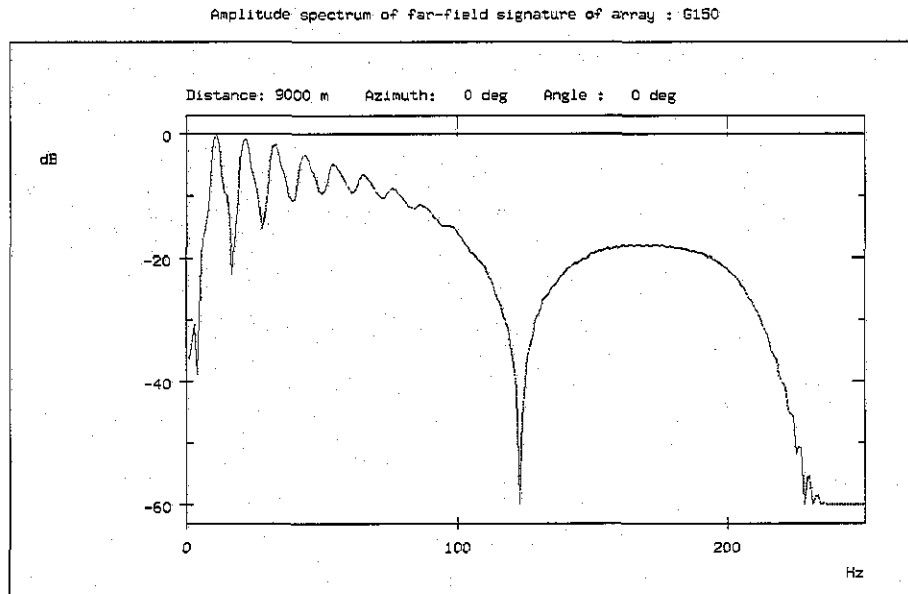


Figure 2.5b Spectral details of the Far field signature shown in Figure 2.4a.

For a given internal air pressure and depth below the surface, the peak amplitude A and bubble oscillation period of an airgun's signature are proportional to the cube root of the volume V of air in the airgun.

$$\text{i.e.} \quad A \propto V^{1/3}$$

In practical terms this relationship states that the volume of a single airgun would have to be increased by a factor of 8 in order to produce a factor of two increase in the pressure amplitude of the seismic pulse.

2.2 An airgun array

Rather than using a single larger airgun to produce a more acceptable impulse, commercial seismic contractors invariably use an array of smaller volume air guns configured in a way that will enhance the primary pulse but minimise the effects of the later bubble pulses. Figures 2.6a and 2.6b show the far field (distant) signature and spectrum of an air gun array comprising of an arrangement of 30, 90 and 60 in³ airguns positioned at a depth of 6 m. The total volume being 3090 in³.

It will be noticed that the farfield amplitude of the primary pulse is much greater than that produced by the single 150 in³ gun and the relative amplitude of the bubble pulse is much less. The peak amplitude has increased by a factor of 20, approximately equal to the ratio of the two volumes. Although pressure measurements are made at some distance from the guns, the amplitudes are scaled back to a reference distance of 1m. This technique is commonly used in comparing different seismic sources and is considered later in more detail.

The advantages then in using an array of smaller airguns rather than one large gun is that a more ideal and higher amplitude pressure pulse can be produced from a given amount of stored energy. There is also the added bonus of the ability to "tune" the array to improve the pulse shape and to reduce the bubble pulses by changing operational depth and operating pressure. However, perhaps the most important

improvement is the concentration of the emitted sound in an optimum downward direction that, from an environmental aspect, is very positive attribute. Although more costly and complex, an array of small airguns adds reliability, flexibility in performance and efficiency in the use of compressed air.

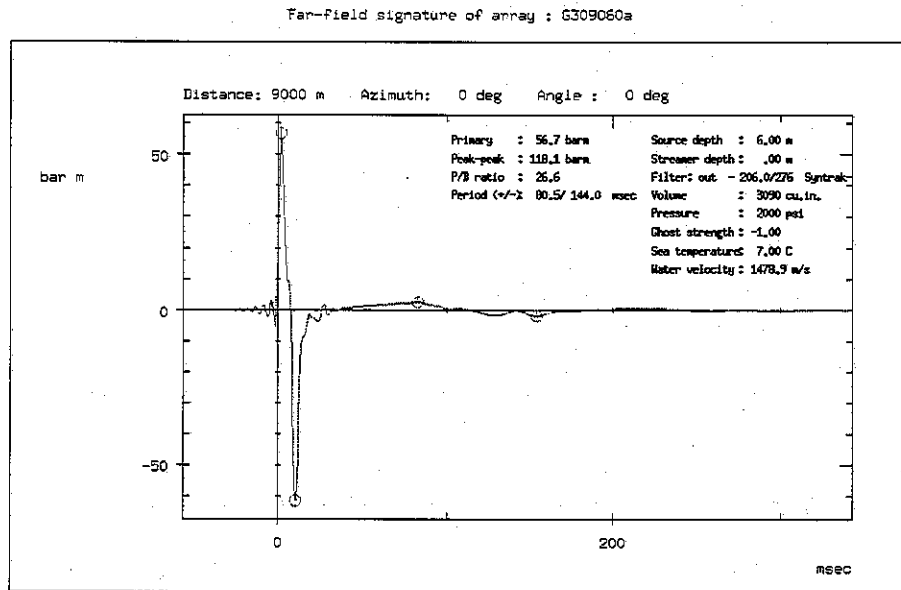


Figure 2.5a Far field signature of a multiple 30, 90, 60 in³ air gun array.

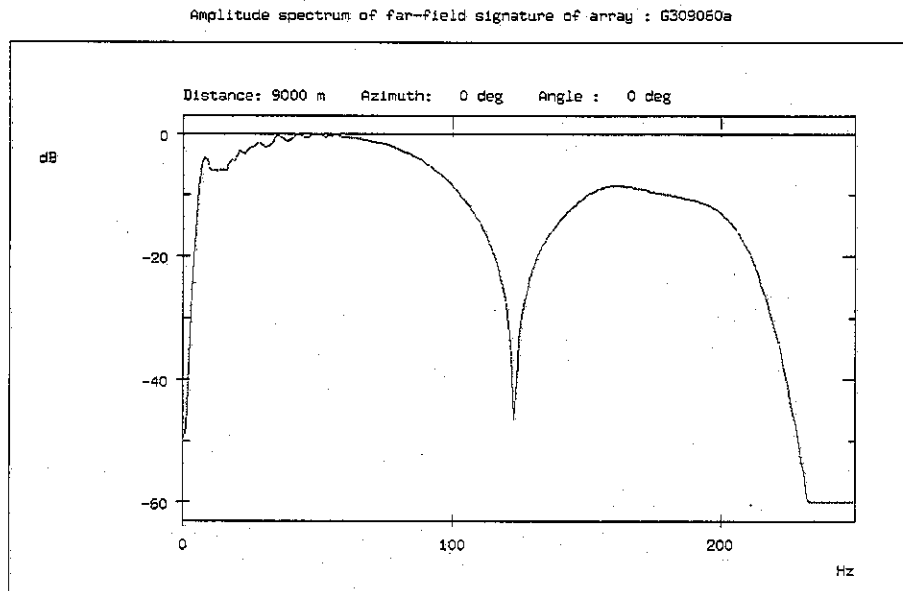


Figure 2.5b Spectral details of the Far field signature shown in Figure 2.5a.

2.3 The Concept of Reference Pressure and Reference Distance

There are several methods of describing a pressure scale in underwater acoustics and it is necessary for all workers in the field to be aware that different sectors of industry and research groups use different units.

The airgun pressure signatures shown in Figures 2.5 a and 2.6 a have a pressure axis that is given in bar - metres which introduces a concept of a reference distance for comparing signatures. This is the traditional convention used in the seismic industry where pressures are measured in bars conforming to the old CGS¹ standard of units. However, the use of the Systeme International (SI) units is used almost exclusively for all other areas of underwater acoustics and with this system the μ Pascal (μ Pa) is the reference pressure. The relationship between the two reference pressures is given below.

$$1\mu\text{Pa} = 10^{-11} \text{ bars.}$$

Thus it is obvious that the μ Pa is a much smaller unit of pressure than the bar. It is convenient that a logarithmic scale be used to accommodate the large range of pressures that can be encountered in ocean acoustics. The μ Pa has been adopted as a reference pressure because all useful pressure levels, when converted to decibels will be positive.

Thus a pressure of 1 μ Pa converted to a decibel notation is $20 \log_{10} 1/1$ dBs (decibels) = 0 dB//1 μ Pa.

A pressure of 2 μ Pa converted to a decibel notation is $20 \log_{10} 2/1$ dBs (decibels) = 6 dB//1 μ Pa.

A pressure of 10 μ Pa converted to a decibel notation is $20 \log_{10} 10/1$ dBs (decibels) = 20 dB//1 μ Pa.

The units qualifying these measurements, dB//1 μ Pa indicate the measurement is in decibel form referenced to 1 μ Pa. This is also seen in literature as dB ref. 1 μ Pa.

It is erroneous and often confusing to present a decibel form of any pressure or of any other variables without the reference information being given. All decibel calculations are derived from a ratio of similar quantities with the denominator as the reference value. A measurement in decibels (dB) is therefore unit-less.

In these conversions we see that a doubling in pressure amplitude is equal to an arithmetic increment of 6 dB. Conversely, a halving of a pressure amplitude is equivalent to a decrement of 6 dB. Also increasing a pressure by a factor of 10 is equivalent to adding 20 dBs.

Thus a pressure of 1 bar when converted/referred to 1 μ Pa $= 20 \log_{10} 10^{11} / 1$ dB
 $= 220$ dB//1 μ Pa.

Theoretically, the decibel notation is relevant only for continuous signals such as sine waves and random noise. However, in the seismic industry, peak pressures are often quoted in decibels with respect to a reference distance.

It is also customary to add the suffix **Level** to a decibel quantity. Thus a seismic signature with a zero to peak pressure of 1 bar-m will have a **Sound Pressure Level (SPL)** _(o-p) of 0db //1bar@1m or 220 dB //1 μ Pa@1m. A pressure of 1 bar is approximately 1 atmosphere.

Since the measurement of the any seismic signature will depend on the distance from the source that the measurement is made, it is necessary to refer all measurements to a standard distance. The generally accepted method for signature measurement is to assume an omni-directional point source with ideal spherical spreading as the mechanism for the change in pressure amplitude with distance (and time). When a loss free medium is assumed this will mean that the fall off in pressure with distance from a

¹ CGS system - Centimetre, Gram, Second

source will be inversely proportional to distance since acoustic intensity (watts/m^2) obeys the inverse square law.

In order to compare pressure signatures for different situations, it is therefore necessary either to quote the range at which a signature was measured or to use a linear multiplier to refer a signature to a reference distance. For underwater acoustics the reference distance is normally 1 metre.

If, for example, we measure a pressure signature at a range of 25 metres from a source, we can refer this measurement to 1 metre by multiplying the pressure signature by 25. The pressure coordinates will then be in bar metres or $\mu\text{Pa}\cdot\text{m}$ as appropriate. Conversion to logarithmic form can then be undertaken.

Similarly, if we have another signature measurement made at 10m and we wish to compare the two sources, we can refer this signature to 1m by multiplying this pressure coordinate by 10. These two referred signatures can then be plotted on the same pressure scale for direct comparison.

As an example, for the pressure signature shown in Figure 2.5a, the primary positive peak pressure is shown as 2.8 bar metres.

This can be given as a $\text{SPL}_{a(o-p)} = 20 \log_{10} (2.8/1) \text{ dB//1bar @ 1m} \equiv 8.9 \text{ dB//1bar @ 1m}$

If we want to refer this pulse to μPa , then the $\text{SPL}_{(o-p)} = 2.8 \times 10^{11} \mu\text{Pa m}$ or $228.9 \text{ dB//1}\mu\text{Pa @ 1m}$.

Note that decibels are always added, never multiplied.

For the large air gun array shown in Figure 2.6a, the peak positive pressure is given as 56.7 bar-m thus the

$$\text{array SPL}_{b(o-p)} = 20 \log_{10} (56.7/1) \text{ dB//1bar @ 1m} \equiv 35 \text{ dB//1bar @ 1m} = 255 \text{ dB//1}\mu\text{Pa @ 1m}$$

2.4 Airgun Signature Characterization

There are several features of a pressure impulse that are important for full characterization. Thus far we have considered only the primary peak positive excursion of the pressure signature. There is also the negative excursion, the pulse duration and the shape of the pressure pulse. There are also the two reference parameters identified above, the reference pressure and the reference distance. As we will see later there is also another reference parameter, that of time. All these features can be expressed in decibel notation.

It is particularly important when using the decibel notation that all references are identified and, for comparison purposes the same. If this concept is not strictly adhered to, then gross errors in calculation and understanding can occur.

In characterizing the amplitude of a pressure pulse such as Fig. 2.5a, we have several measurement options:

- The zero – primary positive pressure Peak value (**o-p**)
- The primary positive pressure peak value to negative pressure peak value or peak – peak (**p-p**)
- The **rms** or root mean square value.

In addition, for comparing the energy content in pulses of different duration, a time reference has to be introduced. This creates another reference parameter:

- The Sound Exposure Level (**SEL**) always in decibel format.

For example, two pressure signatures can have the same peak pressures but one may have a duration of 100 μ s as is the case with boomer high resolution profiler sources and maybe 20 ms as is the case with a medium size airgun. If signatures from these two sources were quoted only as $(p-p)$ or $(p-p)$ then their SPL values in decibels would be the same, however, their energy content would differ by a factor of 200. It has been customary in the underwater acoustics field relating to animal physiology to use a descriptor called the Sound Exposure Level (SEL) which attempts to relate total energy in a pulse rather than peak amplitudes.

The SEL is equal to the rms value of an impulse averaged over a time duration of 1 second rather than the pulse duration itself. Since SEL is always in decibel form, calculating it is equivalent to modifying the rms decibel format by adding

$$10 \log_{10} T_p/1 \text{ dB where } T_p \text{ is the overall pulse duration.}$$

For example the overall pulse duration in Figure 2.5a is approximately 20 ms. therefore the SEL would have a numerical value equal to the rms level (dB) + 10 $\log_{10}(.02/1)$ dB

$$\begin{aligned} \text{Therefore SEL} &= \text{rms level (dB)} + (-17) \text{ dB} \\ &= \text{rms level (dB)} - 17 \text{ dB} \end{aligned}$$

(If the pulse duration were 1 second then the SEL level in dB would equal the rms level in dB.)

2.5 Pulse Shape

One final attribute exhibit by airgun signatures is that of shape. This can be accommodated by the rms calculation which can only be calculated numerically except in the case of standard pulse shapes, e.g. a truncated sine wave or a triangular wave or as an SEL.

In Figures 2.7a and b we can summarize all the decibel attributes for several waveform shapes including the typical airgun signature shown in Figure 2.5a.

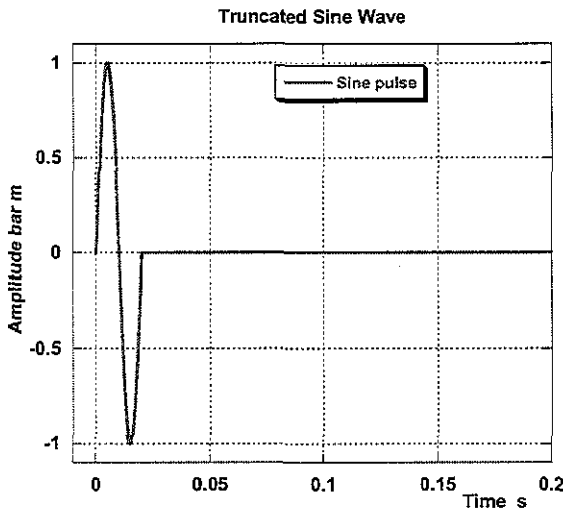


Figure 2.7 a Truncated sine Wave

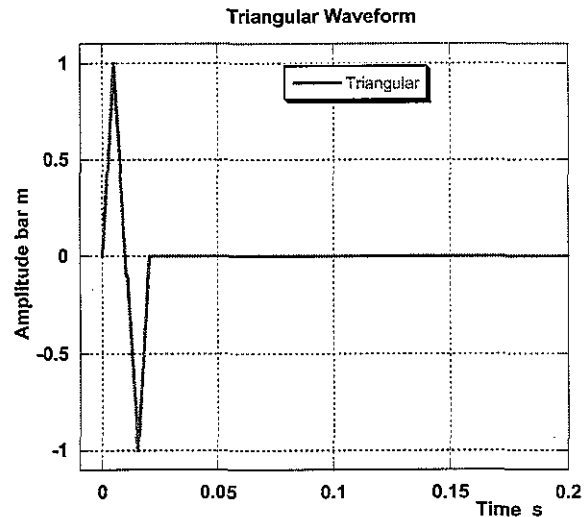


Figure 2.7 b Triangular wave.

Table 2.1 compares the various attributes of two waveforms each by the 4 alternative methods.

The SPL $(p-p)$ of the airgun signature shown in Figure 2.5a (5.7 Bar@1m) is used as a reference level for amplitude.

The triangular waveform, which better matches the signature of an airgun, has a **rms** attribute 1.7 dB lower (-1.7) than the equivalent truncated sine wave. The **rms** value of real airgun signatures are often lower than this value in the range (-5 to -10 dB) with respect to the truncated sine wave. This 1.7 dB reduction is reflected also in the SEL. It is obvious that in using decibel attributes it is important to fully define all the reference levels used.

Waveform Attribute	Sine Tp=20ms	Triangular Tp=20ms	Typical Air Gun 150 in ³ Tp=20ms	Boomer (sine) Tp=0.1ms
SPL (p-p) @ 1 m	0 dB	0 dB	0 dB	
SPL (o-p) @ 1 m	-6 dB	-6 dB	-6 dB	-20 dB
SPL rms @ 1m	-9 dB	-10.7 dB	-16 dB	-23 dB
SEL dB// @ 1m	-26 dB	-27.7 dB	-33 dB	-63 dB

Table 2.1 Comparison of decibel attributes for a truncated sine wave, a triangular waveform, The peak-peak value of the airgun signature Figure 5.a is used a reference pressure.

A typical SPL(o-p) for a boomer source would be 0.6 Bar. This is approximately -20dB with respect to the peak to peak pressure of the 150 in³ air gun. The boomer pulse width would be about 0.1ms. The SEL adjustment for such a source can be calculated directly by $10 \log_{10}(0.1ms) = -40$ dB with respect to the rms value.

2.6 The Airgun Array Concept.

In section 2.1 it was observed that an array of smaller guns offers many advantages in producing a more consistent and appropriate pulse shape for seismic exploration. However, to reach much greater target depths higher SPL's may be required. This can be achieved by using several arrays each consisting of several airguns as shown in Figure 2.8.

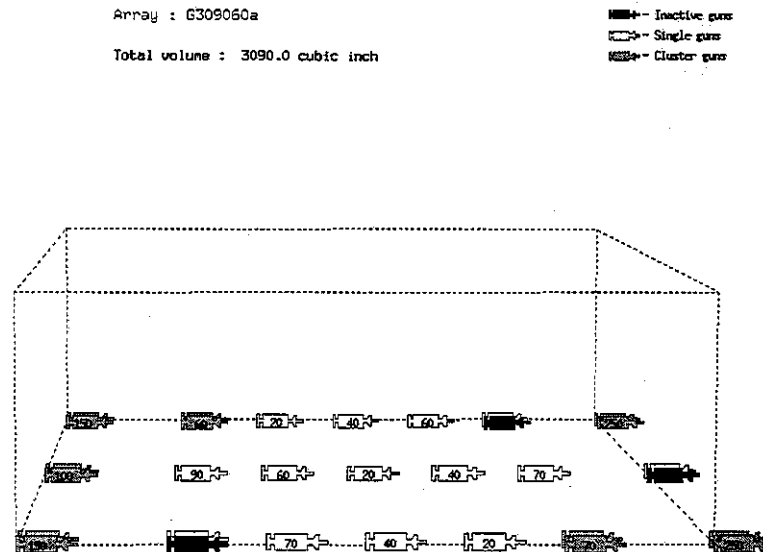


Figure 2.8 Typical air gun array for deep exploration seismic profiling.

The effect of configuring a multi-airgun array is to give directionality to the acoustic energy, higher output amplitudes and the ability to tune the airguns for a particular pulse shape. Figures 2.9a show the spectral amplitude contours for the airgun array in the horizontal plane at a frequency of 50 Hz.

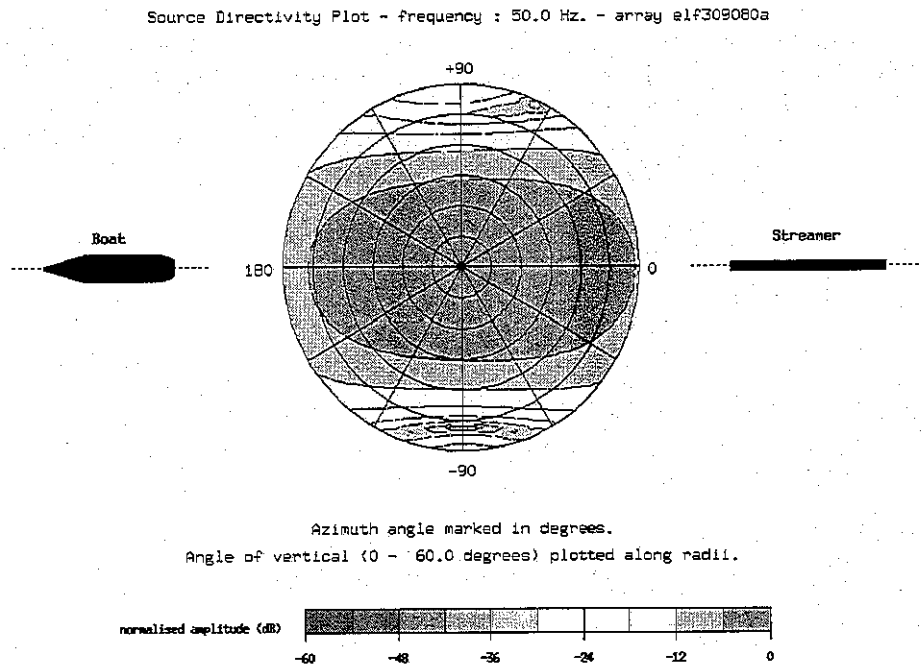


Figure 2.9a Directional characteristics of an airgun array in the horizontal plane

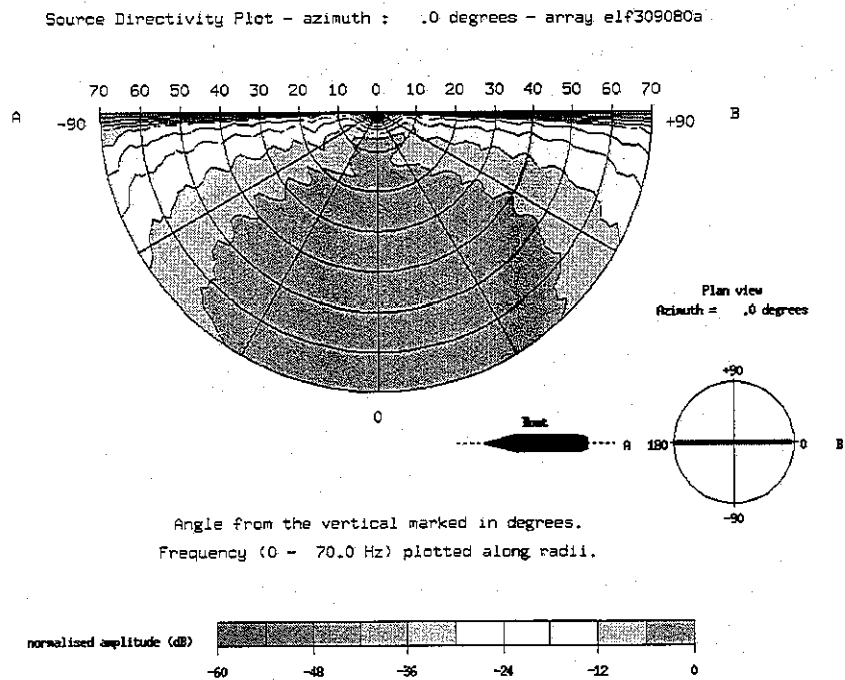


Figure 2.9b Directional characteristics of an airgun array in the vertical plane in the towing direction

The directionality diagrams show that in the vicinity of the array at least, energy transmitted in the horizontal direction is very much reduced. However, in the vertical direction the pressure pulses from all the guns reinforce each other and increases the Sound Pressure Levels substantially.

Note that in Figure 2.9a the spectral amplitude information is plotted in the horizontal radial direction at the peak spectral frequency of 50 Hz with respect to the vertical (on-axis) direction. The spectral level in the along-track direction is -6 dB at -60° from the vertical whereas in the across-track direction (azimuth = +/-90°) the -6 dB contour is at an angle of -30° from the vertical. This indicates that more of the energy is concentrated in the vertical direction in the +/-90° azimuth directions.

At the 60° (Outer) circle, i.e. 30° to horizontal, the spectral amplitude at +/-90° azimuth bearings is about -24 dB with respect to the on-axis level. At shallower angles (circles not shown), the spectral amplitudes would be decreased further.

In Figure 2.9b, a spectral amplitude display in the along-track vertical direction is presented for a frequency of 50 Hz. This display shows the directional information in the along track direction in a vertical plane. The contours indicate that at 30° from the horizontal, the spectral levels at about -6 dB from the on-axis direction, and at 20° and 10° from the horizontal the spectral amplitudes are -12 dB and about -20 dB respectively relative to the on-axis levels.

This directional information is very useful for far-field pressure mapping but is normally not available from seismic contractors. A different method can be used.

2.9 Estimating the Near and Far Field responses of an airgun array on the main vertical axis

The spectral information presented in Figures 2.9a and 2.9b have been generated from far field measurements of array output measured at various off-axis positions. The pressure field close to array does not continue to increase towards the reference position (say 1m) but averages out at a pressure close to that of the individual airguns. Reference 4) summarizes the near/far field effect by indicating that only at distances in the far field do the phases of the various airguns align to increase the net pressure level. This near-far field transition distance is shown in Figure 2.10 as a relationship with frequency. The higher the frequency, the greater the transition distance is from the array. Only at distances beyond this far field limit. (In this case 15m for a frequency of 50 Hz) can the array can be assumed to be a point source.

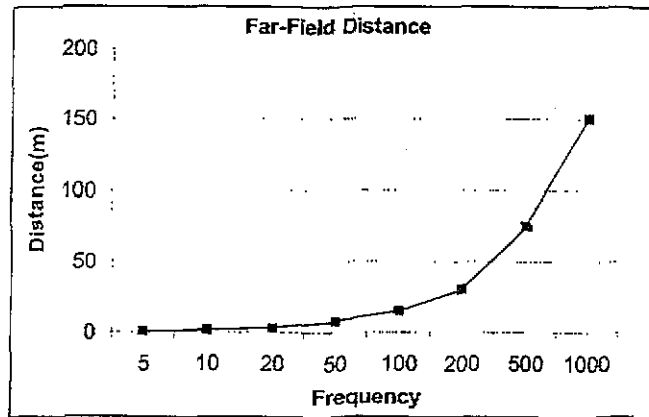


Figure 2.10 Near-Far Field distance against frequency for a large array.

Reference 4) also continues:

“Since the far-field distance is frequency-dependent, the point source model produces pressure values that over-estimates the real values in the near-field vicinity of the array. The higher the frequency, the higher the over-estimate of pressure level appears.”

2.9.1 Non-Point Source Response

Up to this point, the discussion has been framed in terms of a point source response. That model does not hold for the response of seismic airgun arrays. Referring to the plan view diagram for the airgun array, it can be seen that a measurement taken at any point in the immediate vicinity of the array will be influenced more by those guns close to the measurement point than by guns farther away. Again, it is very important to understand that the full array amplitude as reported in bar-m (or dB re 1 μ Pa @1m) is never realized in the water. That means no life form would be exposed to the pressure levels quoted at 1m from the theoretical point source of an air gun array.

However, if animals get close to the array they could be exposed to pressures expected from individual airguns which is not insignificant.

A point source response is a convenience that only has validity in the *far-field* of the array. The term *far-field* refers to the distance from the array where the acoustic output appears to be coming from a single point source and contributions from all guns arrive simultaneously.

The *far-field* distance is a function of frequency by; $d = f * a^2 / c$ where d is the far-field distance, f is frequency, a the maximum aerial dimension of the airgun array, and c the speed of sound propagation in the water. "

The graph shown in Figure 2.11 gives the estimated on-axis $SPL_{(0-p)}$ against range (vertical) for an airgun array response with an $SPL_{(0-p)}$ 6dB lower than shown in Figures 2.5 a,b and Figures 2.6 a,b. Using a peak response frequency of 62 Hz, and the array dimensions of 20 x 25 m, the Near field/far field transition distance R_c is $20 \times 25 \times f/c \text{ m} = 20 \times 25 \times 62/1475 = 21\text{m}$.

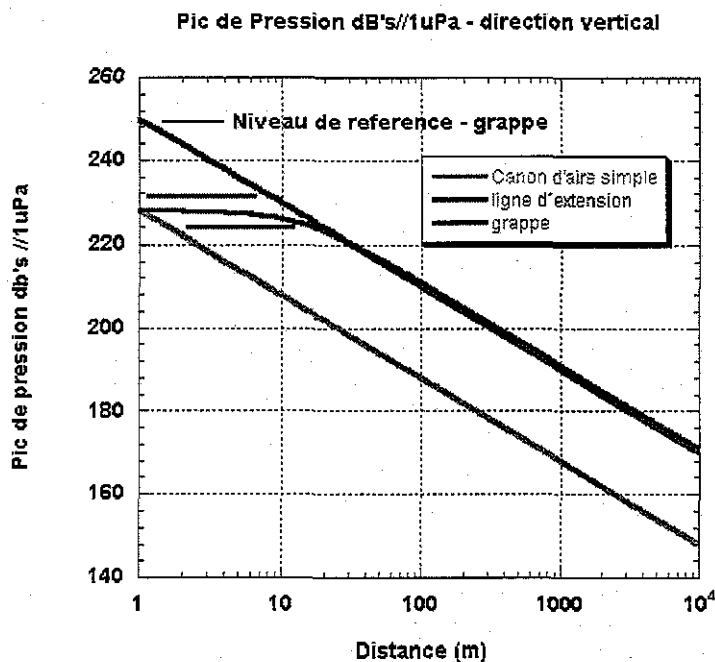


Figure 2.11 Estimated Near/Far field amplitude against on-axis distance for airgun array

In Figure 2.11, the on-axis response for the array (green) is compared to that of a single gun (red), both referenced to 1m. This graph indicates that at a distance closer to the source than R_c (21m), the actual pressure levels are approximately the level of a single gun. This is the near-field region of the array. However, when referred to a distance of 1m, the reference value (250dB) will overestimate the actual near field pressures by about 22 dB.

Reference 4) summarizes the airgun array performance by making 4 points:

- 1) Most of the broadband energy emitted from an airgun array is concentrated close to the vertical direction.
- 2) In the array's near-field, pressure amplitudes will be significantly less than estimated from a point source extrapolation.
- 3) The pressure amplitude rapidly diminishes at emission angles greater than 65° to the vertical.
- 4) Coherent high frequency energy generated by airgun arrays is generally less than 300 Hz.

2.8 Introducing Transmission loss

It is important to note that the main direction of interest in seismic exploration is downward and although some attempts are made to direct sound in this preferred direction, as discussed above, there is inevitably, some leakage of sound directed at low horizontal angles where transmission is unconstrained. It is this energy that is the target of much research by scientists who are addressing for environmental effects. Estimation of a pressure field in the vertical direction is relatively simple. This is not so in the horizontal direction.

If we have to determine the pressure amplitudes at remote horizontal distances from a known source we have to know how the amplitude of a signal changes with range. Earlier we assumed that the output from a source spreads out spherically and this gives a simple relationship in linear terms $P_r = P_o/r$ where r is the range of measurement in terms of the reference distance $r_o = 1$. In logarithmic terms this is $20 \log r/r_o$ for spherical spreading.

Thus for a doubling of distance the pressure falls by a factor of 2 giving a Transmission loss of 6 dB. For increasing distance by a factor of 10 the spreading loss is 20 dB, (See Figure 2.11 for vertical propagation). However, in a situation where spherical spreading does not take place, i.e. where transmission is constrained by boundaries, for example in shallow water, the $1/r$ factor will cease to be relevant. Figure 2.12 outlines the normal shallow water case where the range R is well in excess of the water depth. This ideal model assumes the no other losses such as absorption or boundary losses occur.

When R is very much greater than the water depth the spreading pressure field changes into cylindrical spreading with a spreading law of $10 \log_{10} R$. In the transition zone the spreading law is somewhere between the two and can be taken as $15 \log_{10} R$. In other words at similar ranges, the expected pressure levels in a bounded region will be higher than those where boundaries do not exist.

This simple model however, does not include absorption and scattering effects of the sea-surface boundary, the sea floor, inhomogeneities in the water column and the frequency dependant absorption of sound in the water column.

In estimating more accurately the pressure amplitude relationship with distance, these boundary conditions effects have to be included in the transmission loss model. However, this is a vast subject and most of the research work until recently has been undertaken for defense purposes. This work often involves the use of complex mathematical models to simulate a real situation.

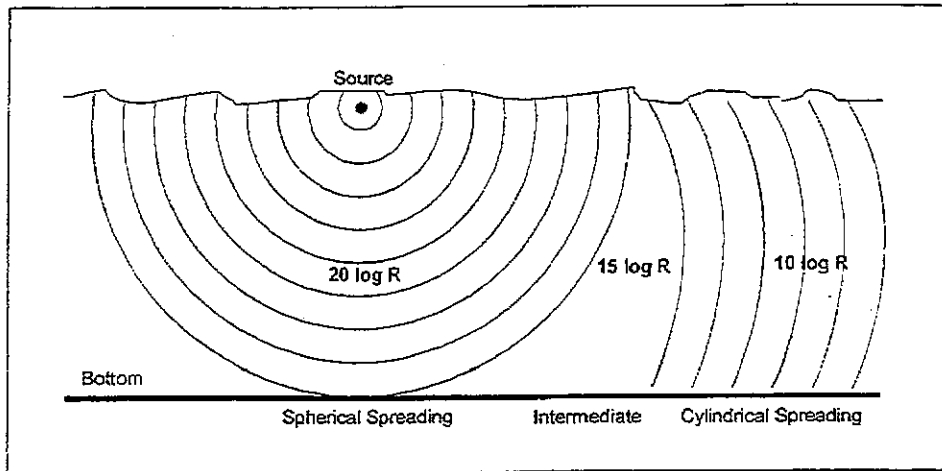


Figure 2.12 Simple transmission loss model for a bounded water half space.

Several of the reports in the Bibliography consider in detail the effects of the boundaries on long range transmission. However, in terms of estimating the transmission loss for a particular region of the seafloor, there are invariably insufficient data available to fully describe the sea surface, seafloor and water column for accurate predictions to be made. Figure 2.13 gives the high and low frequency transmission loss curves for an area to the south of Sable Island, approximately parallel to the coastline.

Figure 1-1. Sable Bank Track S1

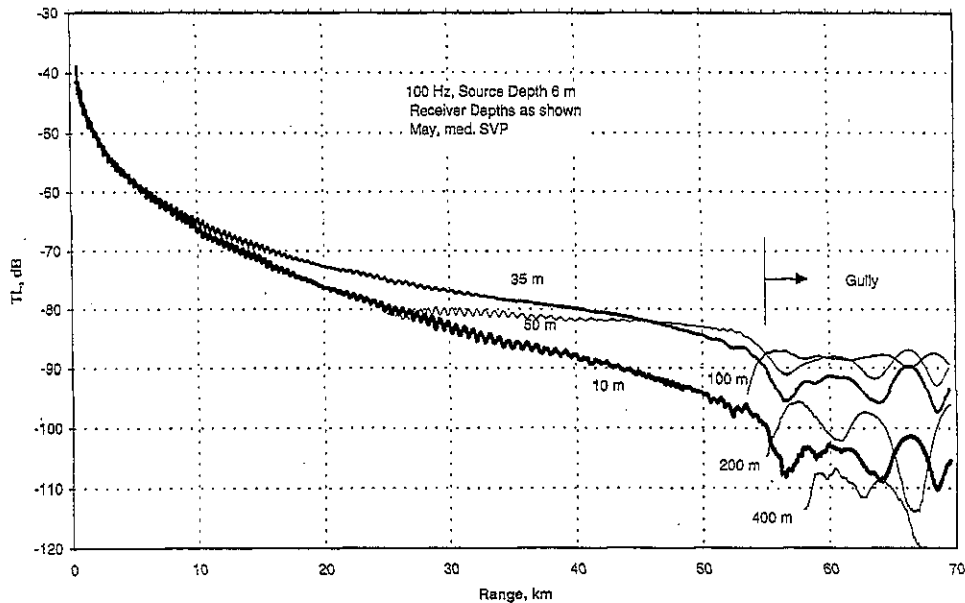


Figure 2.13 Transmission Loss curves for a region to the south of Sable Island. Linear Range. Reference distance, 1m. From Reference (1).

It is seen that horizontal transmission is very much affected by the (vertical) position of the source and receiver in the water column. This is due to channeling of sound caused by (seasonal) variations in the acoustic properties of water bodies and is particularly noticeable at long range. Using these curves with a source would enable estimates of sound pressure levels at remote horizontal distances to be made providing directional information is available. For example, if the far field main axis SEL of an airgun

array was 222 dB//1 μ Pa@1m , with a directivity factor of -18 dB, then the SEL at 10m depth and 25 km range would be 222 -18 - 80 = 124 dB//1 μ Pa.

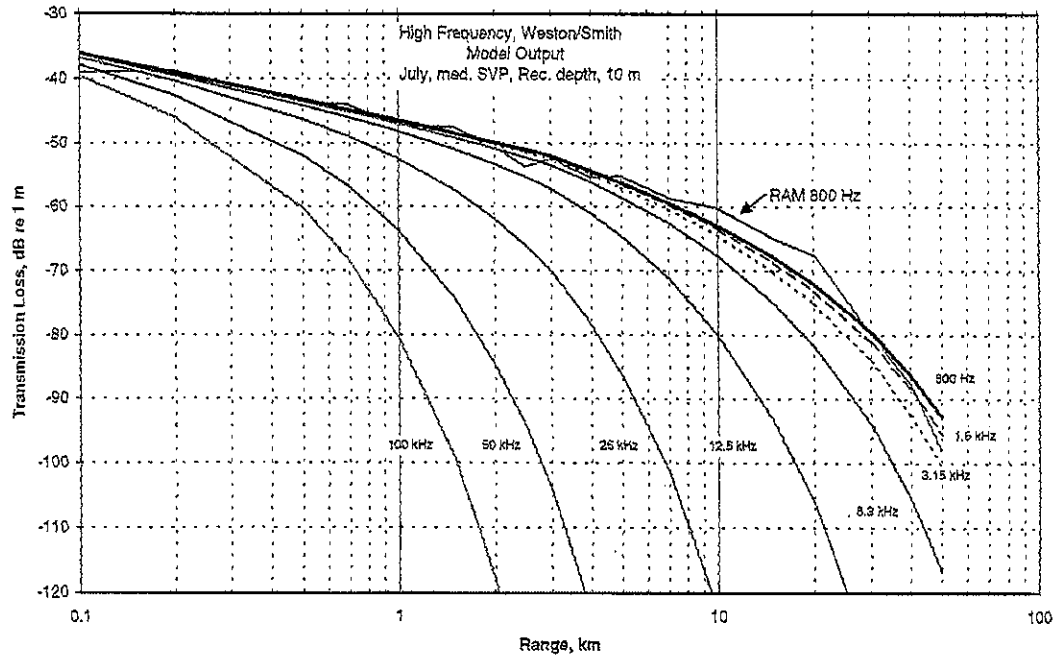


Figure 2.14a Transmission loss against range for sea water in an area south of Sable Island, heading $\cong 80^\circ$. High frequency Case, Reference distance 1m.

Figure 14. Sable Bank Track S1

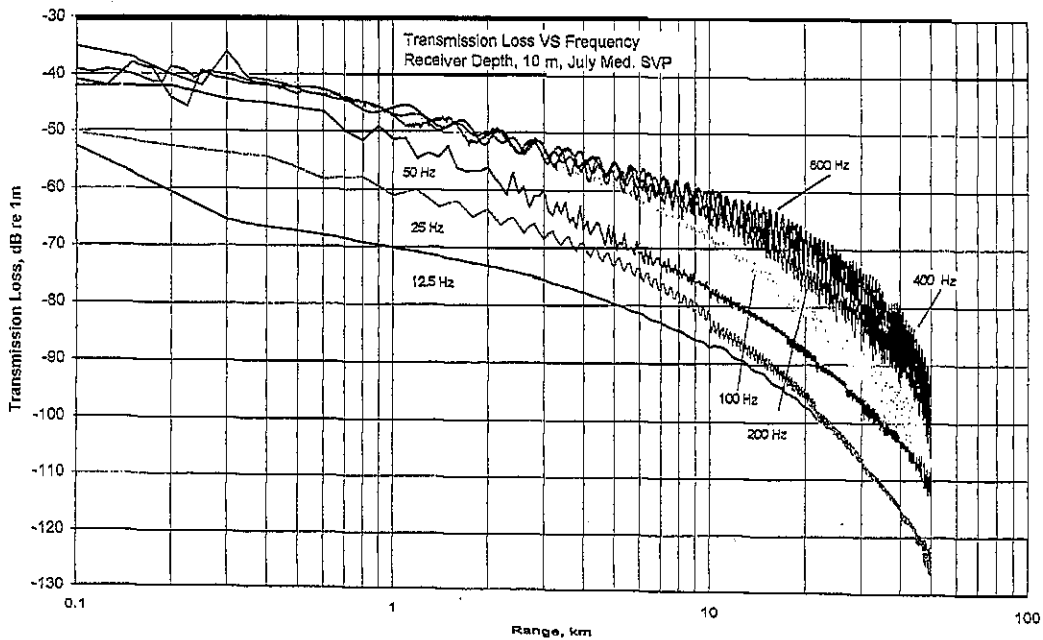


Figure 2.14b Transmission loss against range for sea water in an area south of Sable Island, heading $\cong 80^\circ$ Low frequency case, Reference Distance 1m

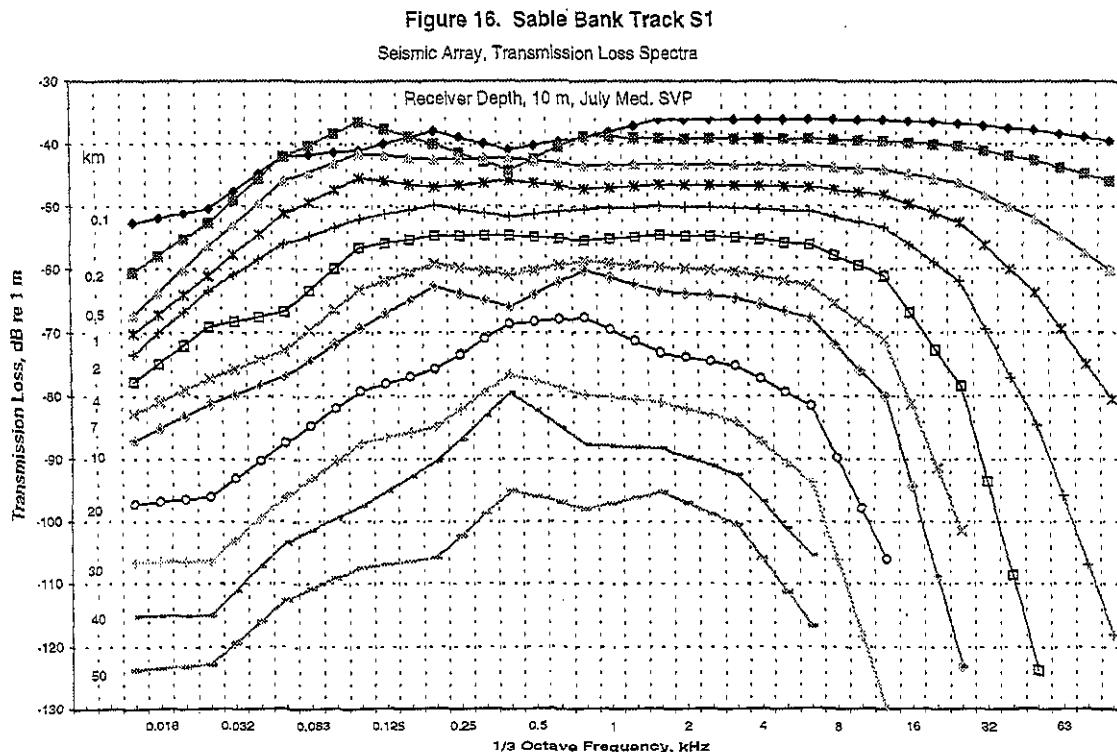
Figures 2.14a and 2.14b shows measured transmission loss plotted in a Log range format for both high and low frequencies for different frequency bands. At the lower seismic frequencies shown in Figure 2.14b, the effects of sound absorption in the water are not as evident as for the higher (sonar) frequencies shown in Figure 2.14a. Figure 2.14a also gives the results of the RAM model used to predict transmission loss. In this case, because the boundary information is well documented, the predictions at least at 800 Hz are quite good.

Over long horizontal distances, the form of pressure pulse changes compared to the original transmitted pulse. This is due to the boundary effects and the various paths that a sound pulse will travel between the source and receiver. The overall effects of this are to spread out the impulse in time resulting in additional attenuation of the sound. This suggests that a simple, zero absorption model would present a worst case for pressures levels as far as horizontal propagation is concerned.

2.9 A spectral display of Transmission Loss

Figures 2.5 b and 2.6 b show an alternative way of presenting the pressure/time signatures of Figures 2.5 a and 2.5 a respectively. These displays present the waveforms as power spectra where the amplitude information at different frequencies is presented against an axis of frequency. The transformation is made with a reversible mathematical method called the Fourier Transform. These spectral displays are useful for examining the frequency content of a pulse particularly in relationship to other acoustic and environmental phenomena that are also frequency sensitive.

Figure 2.15 taken from Reference 1 gives the equivalent spectral relationships for the transmission loss curves shown in Figure 2.14b. These presents the spectral data in 1/3 octave pass bands and plotted at ranges from 100m to 50 km. If this transmission loss information is combined with the spectra generated by a seismic source, then a modified spectrum, given in terms of the SEL attribute will result.



- 1) The Source Pressure Levels of the array and an array of separate arrays that make up seismic source.
- 2) The directionality patterns of the source.
- 3) The near/far field characteristics of an array
- 4) A frequency dependent Transmission Loss equation
- 5) A consistent and useful method for evaluating acoustic impulses in terms that reflect the amplitude and duration of the seismic pulse. The Sound Exposure Level, SEL, has been proposed as a metric

In previous chapters we have discussed:

2.9 Summary of the seismic processes required for long range pressure field estimation.

The advantage of the spectral display is that different life forms in the ocean may well be susceptible to acoustic energy in different frequency bands and these techniques enable remote Sound Pressure Levels to be estimated at any range over a variety of frequency bands.

The points given at the right hand side of Figure 2.16 and titled "Overall" are effectively the sum or integral with respect the 1/3 octave spectral bands. These measurements are equivalent to the SEL values calculated solely using an equivalent SEL value for the source combined with an overall transmission loss curve for Track S1 shown in Figure 2.15.

This is given in Figure 2.16 for selected horizontal distances along the Track S1 south of Sable Island.

Figure 2.16 Transmission Loss Spectra combined with source spectrum for Track S1

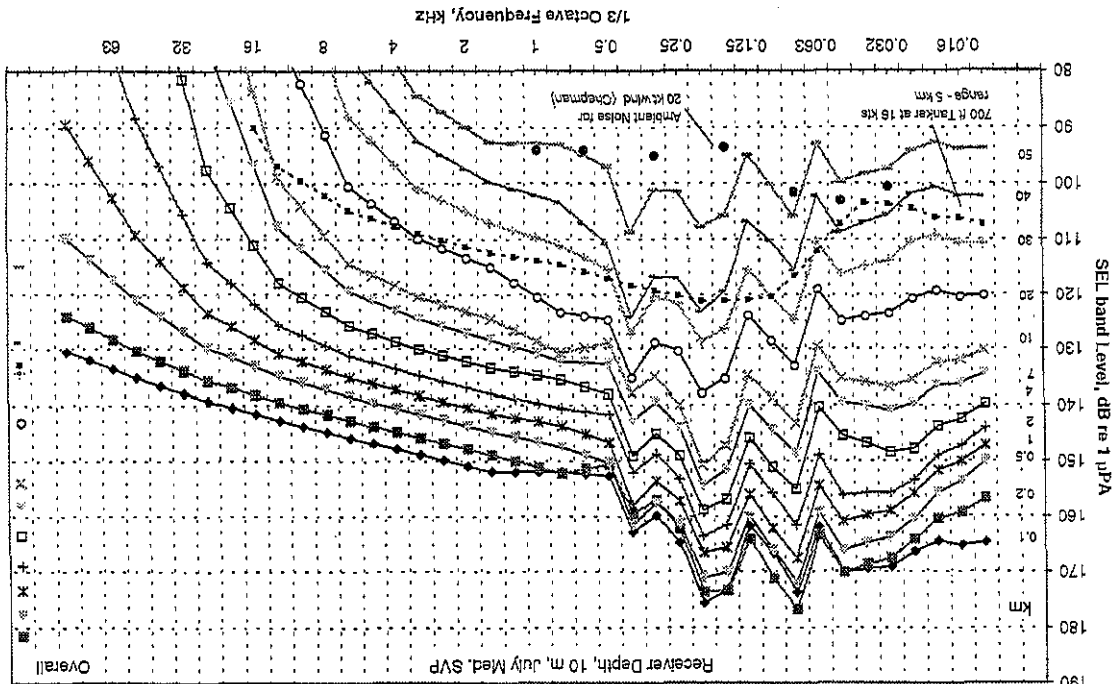


Figure 17. Sable Bank Track S1 Seismic Array, Sound Exposure Level Spectra

Figure 2.15 Sable Island Bank Track S1 Transmission Loss Spectra

that could be useful for investigating the effects of high level pulses on marine mammals and fish species.

All of these factors must be known to a certain degree of accuracy if any forecasting and study of environmental effects of seismic exploration are to be made. Possible sources of information are for:-

- Item 1) The Source signature for a single airgun is generally available from the airgun manufacture's specification which will have been derived by direct measurement in the far field and referred to a standard distance say 1 m. For an array of airguns, this information would be most likely available from the seismic contractor and would be obtained by direct measurement in the far field and in deep water.
- Item 2) The directivity characteristics of an array again should be available from the seismic contractors. As far as long range horizontal propagation is concerned, the low angle of incidence directivity information is of paramount importance.
- Item 3) The Near/Far field, on-axis information may be available from contractors but can be estimated to a certain degree of accuracy if the spatial arrangement of the array is known and the far-field array signatures of each individual gun type is known.
- Item 4) A frequency dependent Transmission Loss equation or graph for the area of interest obtained either by direct measurement or by a suitable robust mathematical model involving physical data describing the boundaries, in particular the sea floor.
- Item 5) A method of comparing the physical attributes of underwater anthropogenic² sounds with natural sources of sound and the effects of these sources on underwater life forms.

3.0 A review of Seismic operating techniques

Seismic exploration generally follows the following path from exploration to final production.

- 1) Exploration geophysical surveys on a regional basis designed to provide an overall geological framework in the area of interest. These surveys use large air gun arrays to address the deep geological structure and normally configured in a 2D basis or as a very broad grid. Time duration for these surveys would be weeks to months.
- 2) Areas of interest resulting from 1) could then be surveyed in more detail with the more expensive 3D format to better describe potential hydrocarbon target zones. Duration of these surveys could be weeks and be limited to a localized target area.
- 3) Prior to drilling, detailed 2D site surveys would be conducted on a tight grid basis covering the proposed drill site to delineate possible hazards to drilling that might occur in the first km or so of the seabed. A much smaller air gun array or other suitable source would be used in this program. These surveys generally last several days for each prospective well site. For several prospects in the same general location, the survey period may last weeks rather than days.
- 4) Following successful drilling, engineering work would take place that may involve shallow sediment studies and route surveys for pipelines etc. These would involve low energy seismic profiling systems and possibly sidescan sonar systems for seafloor characterization for a period of several weeks depending on location and distance offshore.

² Anthropogenic sources of sound or noise are sound sources that are produced by human activity.

For surveys identified in items 1) and 2) large airgun arrays with o-p SPL's in the range 230 - 260 dB//1 μ Pa@1m could be involved while the site surveys, Item 3) would use smaller arrays with o-p SPL's in the range 220 - 236 dB//1 μ Pa@1m. It must also be mentioned that in the near-field region of an array, i.e. a volume approximately contained by a cube with sides equal in length to the maximum dimension of the array, the o-p pressure is unlikely to exceed the 230 dB level representing an individual airgun peak SPL.

For route surveys the SPL's (o-p) of the boomer or chirp sonar type sources with short duration 100 - 200 μ s pulses that would not exceed 220 dB//1Pa@1m. These sources have SEL's approximately 177 dB//1Pa@1m and do not pose a threat to any lifeform in the at distances greater than 5-1-m.

4.0 Natural and Anthropogenic sound levels in the sea

Chapter 2 of this review deals exclusively with the generation, transmission and absorption of manmade impulsive sound in the sea and Chapter 3 briefly mentions the survey procedures and source levels for various survey activities. However, there are many other sources of sound that are ever present derived both from living creatures and naturally occurring environmentally generated sources. Appendix 1 lists many of these sources together with typical seismic and sonar sources.

These are presented for individual cases as SPL's relative to 1 μ Pa @ 1m as discussed above. Much work has been done in measuring natural sound in the ocean as it forms a lower limit to which reception of transmitted sound can be detected. This is important for all human and non-human activities including any place where the marine environment supports communication. This is also the case with geophysical exploration.

Indeed, with geophysical exploration, much effort is spent in developing detecting systems that operate in a low noise environment, as it is against a background noise threshold that small echoes from deeper geologic structure are detected. Figure 4.1 shows background sea noise in 1/3 octave bands.

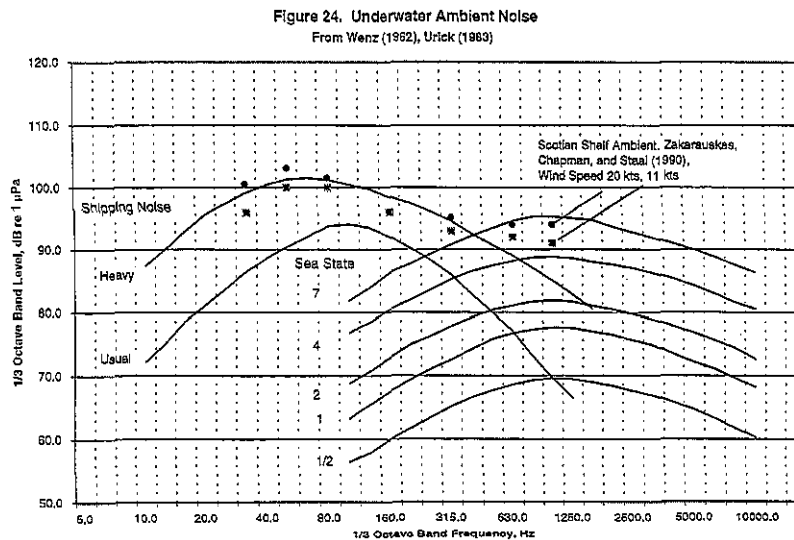


Figure 4.1 Shipping and sea state noise curves for open ocean conditions.

Figure 4.1 is taken from Reference 1) which also comments:-

The curves for wind-related ambient noise shown in Figure 24 are reasonable averages, although relatively large departures from these curves can be experienced depending on

site location and other factors, such as bottom topography and proximity to island or land features.

Distant shipping

The presence of a relatively constant low frequency component in ambient noise within the 10-200 Hz band has been observed for many years and has been related to distant ship traffic as summarized by Wenz and Urick. Low frequency energy radiated primarily by cavitating propellers and by engine excitation of the ship hull is propagated efficiently in the deep ocean to distances of 100 n.mi. (182 km) or more. Higher frequencies do not propagate well to these distances due to acoustic absorption. Also, high frequency sounds radiated by relatively nearby vessels will frequently be masked by local wind-related noise. Thus, distant shipping contributes little or no noise at high frequency. Distant ship-generated low frequency noise incurs more attenuation when it propagates across continental shelf regions and into shallow near-shore areas than occurs in the deep ocean.

Figure 24 provides two curves which approximate the upper bounds of distant ship traffic noise. The upper curve represents noise at sites exposed to heavily used shipping lanes. The lower curve represents moderate or distant shipping noise as measured in shallow water. As shown, highest observed ambient noise levels for these two categories, on a third-octave basis, are 102 dB and 94 dB, respectively, in the 60-100 Hz frequency range. In shallow water, the received noise from distant ship traffic can be as much as 10 dB below the lower curve given in Figure 24, depending on site location on the continental shelf. In fact, some near-shore areas can be effectively shielded from this low frequency component of shipping noise due to sound propagation loss effects.

Note that the shipping noise curves shown in Figure 24 show typical received levels attributable to distant shipping. Considerably higher levels can be received when a ship is present within a few miles. The data for the Scotian Shelf area are shown to have higher levels than the expected sea state 2 - 4 range for the wind speeds shown. This indicates that shipping noise heavily influences the ambient noise levels in this area. The relatively low transmission loss in this area is also a factor since it permits noise to propagate further from the source zone.

Surf Noise

Very few data have been published relating specifically to local noise due to surf in near-shore areas along mainland and island coasts. Wilson et al. (1985) presented underwater noise levels for wind-driven surf along the exposed Monterey Bay coast, as measured at a variety of distances from the surf zone. Wind conditions varied from 25-35 kt. Noise levels varied from 110-120 dB in the 100-1000 Hz band at a distance of 656 ft (200 m) from the surf zone, down to levels of 96-103 dB in the same band 4.6 n.mi (8.5 km) from the surf zone. Assuming that these data are also representative of levels near shorelines in the Sabie Island area, surf noise in the 100-500 Hz band some 200 m from shore will be 15-30 dB above that due to wind-related noise in the open ocean under similar wind speed conditions.

Thus, in the absence of acoustic noise generated by seismic exploration activity, all life in the sea will be subject to a background noise from environmental and biological sources. The effect of introducing impulsive seismic energy into this environment is to subject the various life forms to a different noise regime, comprising of the background noise and repetitive, high amplitude pulses of short duration. The methodology for understanding the effects of this added "noise" is briefly dealt with in the next chapter.

5.0 Impacts of Seismic “noise” on fish and marine mammals.

Reference 6 summarizes the impacts of acoustic technology as:

Environmental Impacts

In assessing the potential for environmental impacts of acoustic technology, we try to address two major themes:

Injury

The questions that need to be addressed are:

- Can the equipment physically kill or injure an animal and if so at what range?
- Can the equipment damage an animals hearing and if so over what range?

This area is difficult because there is little research on injuries to wild animals and most literature relates to humans and to the use of explosives, which are rarely used for scientific purposes.

Disturbance

The major questions to be answered are:

- Does the use of the equipment affect animal behaviour and over what area?
- Does the behavioural disturbance constitute a threat to populations by changing behaviour at critical times and in critical areas?
- Will a survey affect large numbers of animals, a small important group of animals or will the area be free of most species during the survey?
- Will a survey affect prey species in a way that will increase or decrease their availability to predators?
- What proportion of an area used by the animals is affected by the survey?

These are important questions yet are difficult to answer for a particular region because relevant information may not be available. However, in recent years some steps have been taken to address the pertinent issues.

Figure 5.1, taken from Reference 1 is a cartoon of a Transmission Loss curve showing hypothetical SPL's that are considered important reference points for various physical and physiological effects of seismic energy on marine life.

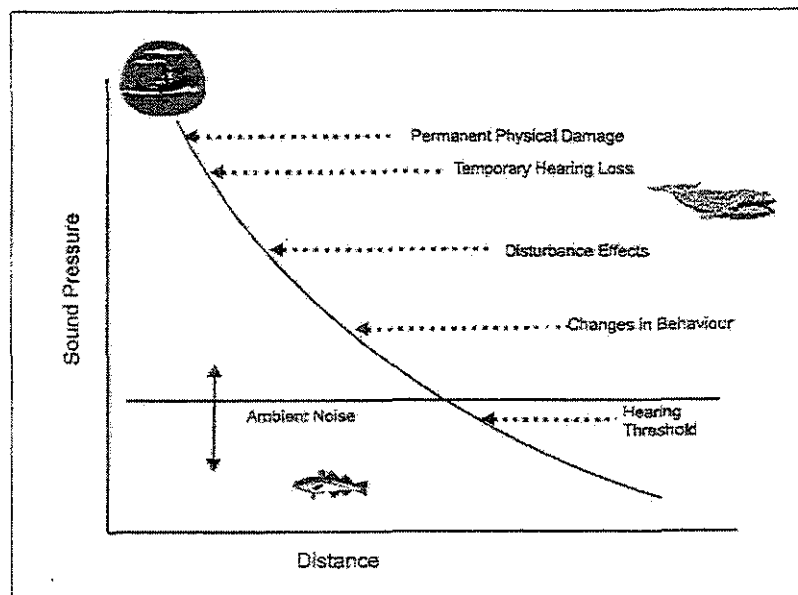


Figure 4. Zones of potential influence of sound.

Figure 5.1 Zones of potential influence from an anthropogenic sound source on marine life.

Here the ambient noise is assumed to be constant over the whole path and the SPL takes the characteristic Transmission Loss form decreasing with distance from source. The hearing threshold is shown to be below the ambient noise and all physiological effects identified occur well above the ambient noise level.

The lowest categorized effect of seismic “noise” involves changes in behavior of fish and mammals involve a recognition response but not necessarily avoidance or changes in behavior or feeding patterns.

The next category is disturbance that is sometimes evident from changes in behavior patterns of the marine animal in question. Disturbance effects can also include slight changes in respiration rate of mammals and the onset of avoidance procedures.

Temporary hearing loss is the first category that involves physical damage followed by the highest category that involves permanent physical damage.

These categories are discussed in detail in all of the cited literature for many forms of marine life and for different regions of the world. Also mentioned in several references is the fact that different animals have different audio responses and some may be more sensitive to certain frequency bands than others.

At the higher Sound Pressure Levels, size can have a dominant effect since all fish and mammals have swim bladders or pockets of air within their boundaries that can resonate if excited at certain frequencies. The larger the volume the lower the resonant frequency. In some species, habituation to anthropogenic affects occurs over a period of time.

These broad categories have lead to two threshold levels being defined for assessing physical damage in particular to hearing loss sustained by marine mammals.

These are temporary hearing loss identified as Temporary Threshold Shift (TTS) and more permanent hearing Loss identified as Permanent Threshold Shift (PTS). TTS is reversible over time but exposure to higher intensity sounds or prolonged exposure to lower intensity sounds would result in PTS, which is non-reversible.

In a review of effects of seismic noise on fish as presented in Reference 1, Turmpenny and Nedwell (1994) summarize the effects of noise on fish in general as follows:

Effect	Pressure Level dB//1μPa (o-p)
Transient Stunning	192
Internal Injuries	220
Egg/larval damage	220
Fish Mortality	230 - 240

Table 5.1 Damage criteria for fish

Fish mortality could be expected in the near field region of a large array (<25m) and transient stunning inside a 50 - 100m range could be expected.

Reference 3) presents comprehensive data on certain cetaceans off Nova Scotia, however, no summary information is presented.

For marine mammals Reference 8) mentions that SPL's o_p of 180 dB // 1μPa has become the *de facto* danger threshold level by biologists, however, this is not supported by hard scientific data.

Using for comparison the overall spectral level shown for the Sable Track 1 experiment shown in Figure 2.16 (water depths 40-50m for first 27 km) for an array with characteristics similar to that shown in Figures 2.6a and b, the SEL o_p is found to be 181 dB // 1μPa at a range of 100m when

measured at 10m depth in 40m of water. This is reasonably consistent if we use the directionality spectra (Figure 2.9b) and the near/far field curves. The expected SPL_{o-p} for the same geometry and worst case direction (in line with ship's track) would give $255 - 40 - 30 = 185$ dB // 1 μ Pa at 100m. At 200m and 10m measurement depth, this would reduce to <175 dB // 1 μ Pa.

At greater ranges, SPL's would drop corresponding to the transmission loss curves for the locality.

The effect of high-pressure pulses on benthic life forms inhabiting the seafloor and living in the sediments directly beneath a survey track would vary inversely with water depth but due to geometric considerations, the area of exposure would increase with water depth. In this case the near-far field on-axis approach and the directivity information of the source could be used to estimate these levels and areas of influence.

Using a water depth of say 50m, and a source SPL_{o-p} of 255 dB // 1 μ Pa @1m, the pressure incident on the seafloor immediately beneath the array would be 221 dB // 1 μ Pa. This would reduce by 6 dB within 40m from the survey line based on average directional information. Since the shooting interval at 10 seconds rate is normally about every 20m then each patch of the seafloor beneath the array would be subject to about 4 shots at this pressure level as a survey vessel passed over.

6.0 Details of Air gun array provided by on the Geophysical Services International survey ship, GSI Admiral

Reference 1 gives typical SPL's for an air gun array in both vertical and horizontal directions. This information has been adapted to match of SPL of the airgun proposed by GSI using a 2 x 6 airgun array on the GSI Admiral. The data are presented in Table 6.1. This source also has a peak spectrum level, on axis of 214.1 dB// 1 μ Pa/ \sqrt{Hz} @1m. See Figures 6.1, 6.2. (11)

	dB //1 μ Pa à 1m vertical	dB //1 μ Pa @1m at -10 degree from horizontal *
Peak-Peak	257.5	239
Zéro to Peak SPL.	251.5	233
rms	240.8	222
SEL (20ms)	224.0	205

Table 6.1 : Comparison of Sound pressure levels for vertical and horizontal directions computed for the air gun array proposed for use in the Gulf of St. Lawrence (GSI Admiral , *Estimates only).

	dB //1 μ Pa @1m at -10 degree from horizontal*	dB //1 μ Pa @100m horiz. (-30 dB)	dB //1 μ Pa @1km horiz. (-45dB)	dB //1 μ Pa @10km horiz. (-65dB)
Peak-Peak	239			
Zéro to Peak	233	203	188	168
rms	222	192	177	157
SEL (20ms)	205	175	160	140

Table 6.2 : Estimates of Sound pressure levels for the air gun array proposed for use in the Gulf of St. Lawrence (GSI Admiral) extended in horizontal direction.

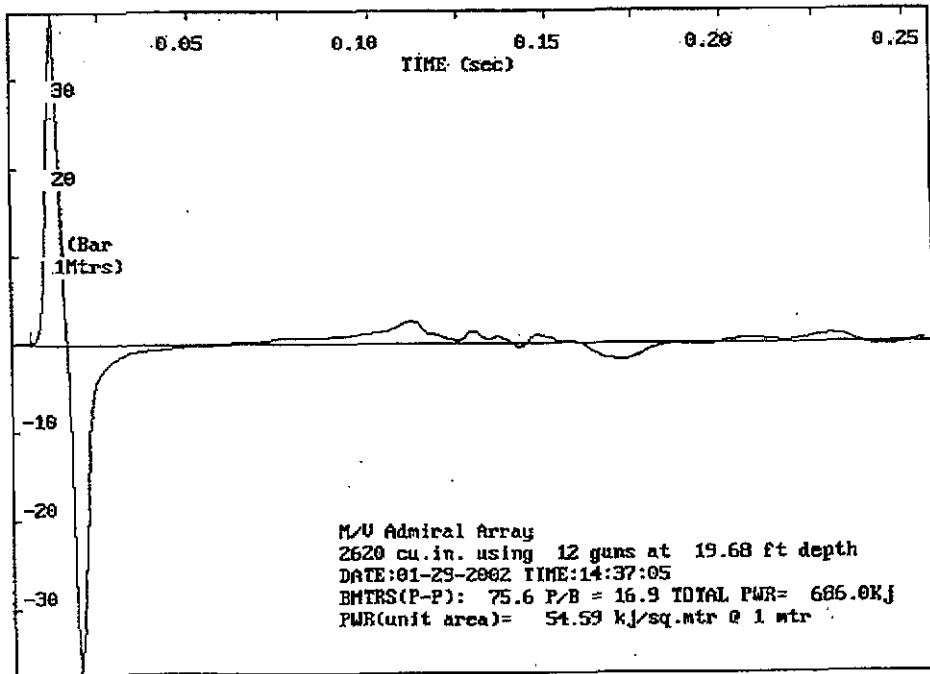


Figure 6.1 Far field pressure signature from the GSI Admiral 2626 cu. in. air gun array

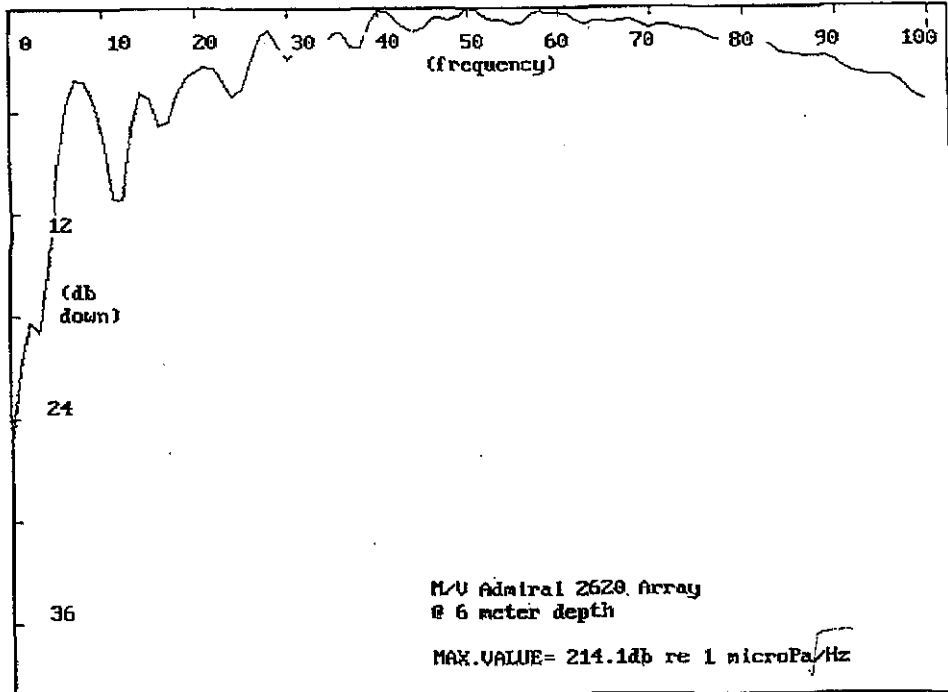


Figure 6.2 Power spectrum of Pressure signature shown in Figure 6.1

Combining Tables 5.1, 6.1 and 6.2 indicate that fish kill is likely in the near field regions of an airgun array <20m distant and transient stunning of fish may occur up from 100 - 400m distant. Behavioral changes such as startle response may occur up to 10 km distant. The danger threshold of 180 dB //1uPa_{r.p.} mentioned in Ref. 8 would be reached between 2 and 4 km from the array. These figures are computed and based on worst case scenarios of array directivity and of the restricted water depth in the Gulf of St. Lawrence region. More accurate predictions for distance pressure contours could be computed with additional knowledge of water depth and the seafloor sediment regime for any particular survey area.

7.0 Review of cited literature

Chapters 1 through 4 have concentrated on the acoustic aspects of seismic exploration with a primary goal of providing researchers and managers in the field with a basic knowledge underwater acoustics. Included in these chapters are sections on the generation and transmission of seismic energy, survey specific information, underwater noise and criteria used to assess damage to marine life.

The quoted references in the Bibliography contain many useful discussions and comments on the effects of seismic activity on natural wildlife in the oceans. Most of those references, which themselves cite the results of many other environmental studies and research activities worldwide, seem to be consistent in their format.

References 4) and 8) certainly strongly supported the seismic industry side and contain much useful and practical data.

References 1), 3) and 7) are studies relating to specifically offshore Nova Scotia and Reference 2) concerns icebound Antarctic operations.

Reference 6) is particularly complete based primarily on North Sea seismic activities that in the last 30 years have been extensive.

Reference 9) is particularly useful for the Gulf of St. Lawrence as far as the distribution of animal life is concerned.

Reference 10) covers the screening procedures that are activated when a proposal is received by CNSOPB for seismic surveys in Nova Scotian waters.

A useful set of guidelines taken from the executive summary of reference 3) concerning a sensitive area called The Gully, off Sable Island, Nova Scotia is given below.

Monitoring and Mitigation of Noise-producing Anthropogenic Activities

There are a number of guidelines for monitoring and mitigating the potential effects of seismic exploration, petroleum production and other operations where acoustic energy is released:

- Where possible, limit the types and levels of sounds emitted, the duration of the operations, and the season or location of the operations to minimize overlap with sensitive areas and or species (e.g., northern bottlenose and sperm whales in the Gully).
- Where possible, avoid acoustic overlap from concurrent operations near the Gully such that the possible synergistic effects of multiple operations are reduced or eliminated .
- Where possible, operators should employ appropriately qualified and experienced personnel to act as marine mammal observers at the noise source, both to document reactions, and to start or suspend operations where there is a risk of injury or strong

reaction by the species of interest.

- Where possible, implement measures to mitigate the potential noise effects of stationary facilities, including (1) improved equipment design, (2) seasonal and hourly timing of noisy operations to minimize overlap with important marine mammal activities, (3) alternate routing and positioning to avoid sensitive areas (e.g., the Gully), and (4) improved visual monitoring of marine mammals.

Key Research Recommendations

Much research remains to be done on issues that have direct relation to (1) how the sound energy from anthropogenic activities is perceived by marine mammals (particularly large odontocetes), (2) what measures might be taken to reduce or eliminate the effects (if any) of the anthropogenic noise, and (3) what methods might be best-suited to detect marine mammals within the estimated field of effects, and monitor their reactions to the sounds:

- Improve methods to detect marine mammals near anthropogenic sound sources.
- Obtain comprehensive measurements and conduct experiments to determine if more effective night vision and passive acoustic detection and location technologies offer the possibility of improved marine mammal detection and monitoring.
- Obtain comprehensive measurements and conduct experiments to determine behavioral, physical (masking, TTS, PTS), and physiological responses by marine mammals to anthropogenic sounds.
- Obtain comprehensive measurements to determine whether there has been habituation by northern bottlenose or sperm whales to anthropogenic sounds in or near the Gully.
- Obtain comprehensive measurements to determine what, if any, is the biological significance of these responses at individual and population levels. The last point must address such issues using judicious comparative studies of marine mammals in both control (i.e., relatively undisturbed) and experimental areas, and over long periods, when possible.
- Studies of the long-term and/or cumulative effects of anthropogenic operations should be undertaken.
- Obtain comprehensive measurements and conduct experiments to determine the hearing sensitivity of northern bottlenose and sperm whales across their entire hearing range (a difficult and very expensive exercise)
- Determine whether “ramp-up” (“soft start”) is effective in inducing marine mammals of various types close to an airgun array (or any other strong sound source) to move away before the full array begins to operate.
- Alternate mitigation measures, such as reducing acoustic output through improved equipment design and sound source isolation, or bubble screens, should be assessed.
- Obtain controlled recordings of the *anthropogenic* sounds. These should not be restricted to those with the greatest source levels or that are most likely to propagate great distances—marine mammals’ responses to sounds may be influenced as much by the source’s duty cycle, location, movement and frequency as by its total energy.

8.0 Conclusions

In the immediate vicinity of impulsive seismic sources used for seismic exploration at sea, pressure pulses can be generated that can permanently damage and possibly kill fish and marine mammals. However, in many sensitive areas world-wide that have been extensively surveyed over long periods of time there has been relatively few case of fish/animal damage having been reported even though local jurisdictions have enforced increased monitoring in recent years and instigated environmentally based observation programs on board survey vessels. This suggests that at least for fish and marine mammals that can take avoiding actions, avoiding action is taken if at all possible. However, in most cases, the long-term effects of continuous exposure to seismic activities to wildlife in the water column and on the benthic community inhabiting the seafloor sediments are not well established but are the subject of much ongoing research activity worldwide. Examples of this research can be seen in the cited references. Recent yet still unreported experiments in the Nova Scotian part of the Gulf of St. Lawrence where crustacea were deliberately exposed to an air gun array at close range, did not produce any kills.

In Nova Scotia where offshore exploration activities have been underway for 30 years, there are guidelines and screening procedures in place to control and monitor exploration activity (10). These guidelines and operating procedures are applied on a case-by-case basis where certain mitigation procedures would be applied in environmentally sensitive areas.

These mitigation procedures include: -

- 1) Denial of access to an area ,
- 2) Changes to the proposed program to fit in with animal migration patterns,
- 3) Changes to the proposed program to fit in with fish nursery areas and breeding seasons,
- 4) Reduction in source levels in certain areas,
- 5) Denial of access to very shallow water areas (cutting survey lines short),
- 6) Use of "soft start" procedures,
- 7) Changes in the survey program to minimise time spent in a certain area,
- 8) Interruption of a survey program if mammal activity is sighted within a certain radius.

The regulations may also demand that the survey vessel/client provide a trained observer to oversee operations and to record environmentally related events.

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1) First Page – of Table of Contents.

“Environmental Assessment of Seismic Exploration on the Scotian Shelf”.

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2) Executive Summary

“Impacts of marine acoustic Technology on the Antarctic Environment.”

Executive Summary

Equipment using sound waves to investigate the seabed and the water column are essential to the understanding of the Antarctic marine environment. At the same time, there is active research into the effects of such technology on marine animals, particularly cetaceans. The potential risks posed by equipment are a combination of source level, frequency and local effects that define the likelihood of interacting with animals. Many acoustic instruments are of sufficiently low power and high frequency as to pose a minor risk to the environment. The equipment with the highest risk potential are airgun arrays and low frequency, high power transducers with wide beam angles.

Cetaceans have been observed avoiding powerful, low frequency sound sources and there is now a documented case of injury to whales from multiple, mid frequency (2.6 - 8.2 kHz) military echo sounders. At the same time, some whale populations co-exist with commercial seismic exploration surveys. In the case of other animals, there is some evidence for short-term displacement of some seals and fish by seismic surveys but there is little literature available.

The working group felt that the evidence available did not justify a ban on seismic surveys or scientific echo sounders in Antarctic waters, however, surveys should be examined, on a case by case basis and mitigation strategies should be used to reduce the risk to Antarctic wildlife from high power, low frequency sources. Acoustic releases and similar low power, occasional source were not considered a threat to wildlife. Mitigation strategies should be investigated to evaluate their effectiveness and there should be a regular review of mitigation strategies and the progress of research in the field to ensure that new research findings will be available to the Antarctic community. Research into the hearing and reaction to noise of Antarctic animals should be encouraged as should research into sound propagation conditions around Antarctica. Records of the locations, timing, duration, frequency, and nature of hydroacoustic and other activities should be maintained to permit retrospective assessment of the likely causes of any future observed changes in the distributions, abundance, or productivity of the potentially affected species and populations

Some mitigation strategies in use are:

1. Use of the minimum source level to achieve the result
2. Use of “soft starts” whereby power is increased gradually over periods of 20 minutes or more.
3. Care should be taken with line lay outs to avoid restricting animals’ ability to avoid the source.
4. Equipment should be shut down if cetaceans are observed within a distance of the vessel defined by the source power, directionality and propagation characteristics.
5. Surveys should be planned to minimize repeated surveying of areas in consecutive years with high-risk equipment.
6. Care should be exercised to minimize impacts in known sensitive areas and times.

Further research is needed to assess whether these measures work and to better monitor the proximity of wildlife to a vessel. The Antarctic community and permitting agencies will need to monitor research progress to ensure practices are up to date.

3) First page of **Table of Contents of:**

“Assessment of Noise Issues Relevant to Key Cetacean Species (Northern Bottlenose and Sperm whales in the Sable Gully area of Interest.”

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6) Proceedings of the "Seismic and Marine Mammal workshop.

<http://smub.st-and.ac.uk/index.htm>

Proceedings of the Seismic and Marine Mammals Workshop
London, 23-25 June 1998
Edited by: Mark L. Tasker and Caroline Weir

Introduction

This conference brought together scientists from the biological and seismic communities along with other interest groups to review the state of knowledge of the effects of seismic exploration activity on marine mammals.

It is hoped that the contents of these proceedings will serve to improve the understanding of the scientific issues. In particular, a theme of the workshop was for inter-disciplinary understanding.

There remains much research to be done and many difficulties in devising well designed scientific studies to improve our knowledge.

Content Organisation

The full text is not available in HTML because some sections are very large. Therefore, each section consists of a hyperlink to download the full text in MS Word, pkzipped MS Word, or PDF format. A hyperlink is also provided for those who wish to download the entire proceedings (pkzipped in MS Word or PDF Format) - please be conscious of the bandwidth you are using.

Author: Gary Hampson, Texaco Ltd

7) Abstracts from:-

“Background Noise Levels in the area of the Gully, Laurentian Cannel and Sable Bank”,

Abstract

The Sable Gully is a submarine canyon at the edge of the continental shelf, east of Sable Island. This region is a potential Maritime Protected Area (MPA) under the Oceans Act. New data sets in the area of Sable Bank, Sable Gully and Laurentian Channel were analyzed to characterize the current ambient noise field in these areas. It was found that the new data sets fit reasonably well with previously published levels for Sable Bank. The directionality of the noise field showed a small increase in the noise levels in the north or northeast direction. This directionality agrees with a previous analysis of several sites on the Scotian Shelf and Grand Banks area.

Résumé

Le passage de l'île de Sable est un canyon sous-marin qui se trouve au bord de la plate-forme continentale, à l'est de l'île de Sable. Cette région peut devenir une zone de protection marine (ZPM) aux termes de la *Loi sur les océans*. Des séries de données obtenues de la région du banc de l'île de Sable, du passage de l'île de Sable et du chenal Laurentien ont été analysées en vue de caractériser le champ sonore ambiant actuel de ces régions. On a trouvé que les nouvelles séries de données correspondent raisonnablement bien avec les niveaux de bruit déjà publiés pour le banc de l'île de Sable. La directionnalité du champ sonore a indiqué une légère augmentation des niveaux du bruit dans la direction nord ou nord-est. Cette directionnalité correspond à la précédente analyse de plusieurs sites se trouvant sur le plateau Scotian et dans la région des Grands bancs.

Appendix 1

Natural and Anthropogenic sources of Underwater Sound

Notes: All source levels (SPL) are in dB re 1 μ Pa at 1 m.

Some Natural Sources of Underwater Sound

Sound	Broadband Levels
Lightning Strike on Water Surface	~260 dB (ref #6)
Seafloor Volcanic Eruption	~255 dB (ref #7)
Sperm Whale Clicks	163 - 223 dB (ref #8)
Fin Whale Moans	155 - 186 dB (ref #9)
Humpback Whale Song	144 - 174 dB (ref #10)
Humpback Whale Fluke and Flipper Slap	183 - 192 dB (ref #11)
Bowhead Whale Tonal Moans and Song	128 - 189 dB (ref #12)
Blue Whale Moans	155 - 188 dB (ref #13)
Southern Right Whale Passive Call	172 - 187 dB (ref #14)
Gray Whale Moans	142 - 185 dB (ref #15)
Snapping Shrimp	183 - 189 dB peak-to-peak (ref #16)
Beluga Whale Echolocation Click	206-225 dB peak-to-peak (ref #17)
Spinner Dolphin Pulse Bursts	108-115 dB (ref #18)
Bottlenose Dolphin Whistles	125-173 dB (ref #1)
White-beaked Dolphin Echolocation Clicks	194-219 dB peak-to-peak (ref #19)

Anthropogenic sources of Underwater Sound

Vessels Underway	
Sound	Broadband Levels
Tug and Barge (18 km/hour)	171 dB (ref #1)
Supply Ship (<i>Kigoriak</i>)	181 dB (ref #1)
Large Tanker	186 dB (ref #1)
Icebreaking	193 dB (ref #1)

Ocean Acoustics Studies	
Sound	Broadband Levels
Heard Island Feasibility Test (HIFT) (Center frequency 57 Hz)	206 dB for a single projector, with up to 5 projectors operating simultaneously in a vertical array 221 dB overall (ref #5)
Acoustic Thermometry of Ocean Climate (ATOC) (Center frequency 75 Hz)	195 dB (ref #1)

Sound Sources (Impulsive)		
Seismic Survey		Notes: All source levels are in dB re 1 μPa at 1 m.
Large Air gun array (32 guns)	Peak	259 dB (Broadband) (ref #1)
<u>Airgun array proposed for Gulf of St. Lawrence</u>	<u>Peak SPL</u> <u>Spectral Peak</u>	<u>250 dB//1μPa@1m</u> <u>214.1 dB// 1μPa/ \sqrtHz@1m.</u>
Explosions		
0.5 kg (1.1 lb) TNT	Peak	267 dB (Broadband) (ref #1)
2 kg (4.4 lb) TNT	Peak	271 dB (Broadband) (ref #1)
20 kg (44 lb) TNT	Peak	279 dB (Broadband) (ref #1)
4,536 kg (10,000 lb) TNT	Peak	>294 dB (Broadband) (ref #2)

Military Sonars	
AN/SQS-53C (U. S. Navy tactical mid-frequency sonar, center frequencies 2.6 and 3.3 kHz)	235 dB (ref #4)
AN/SQS-56 (U. S. Navy tactical mid-frequency sonar, center frequencies 6.8 to 8.2 kHz)	223 dB (ref #4)
SURTASS-LFA (100-500 Hz)	215 dB for a single projector, with up to 18 projectors operating simultaneously in a vertical array (ref #3)

Notes: All source levels are in dB re 1 μ Pa at 1 m.

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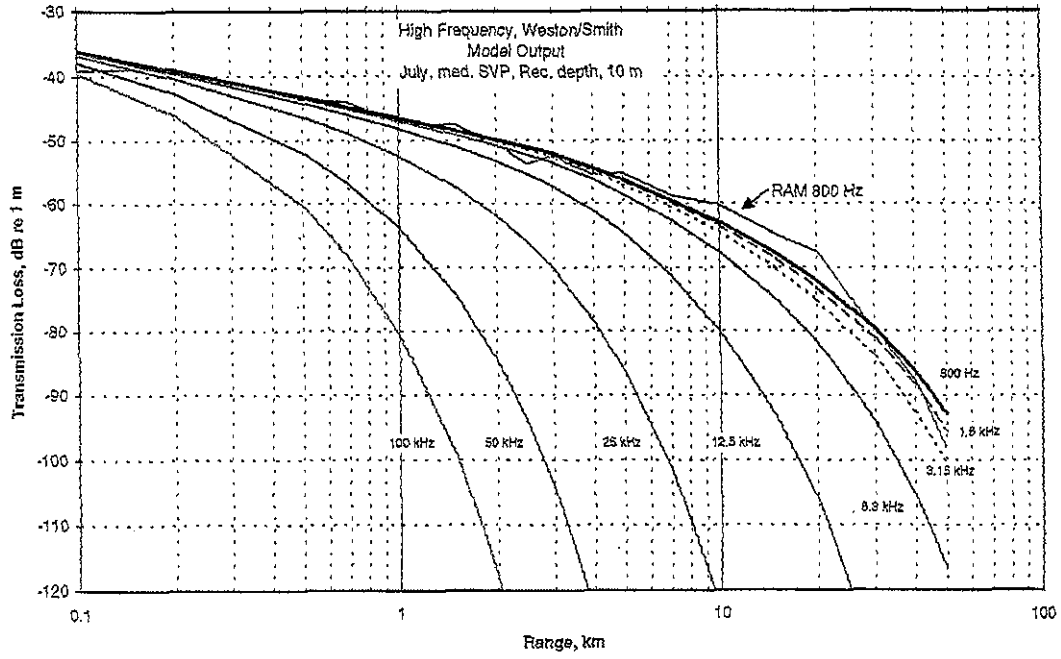
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