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Underwater noise propagation modelling and estimate of impact zones for seismic operations in the Moray Firth

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APPROVALS

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EXECUTIVE SUMMARY

This report has been prepared by Kongsberg Maritime Ltd for the University of Aberdeen, Lighthouse Field Station and the Department of Energy & Climate Change. It provides the results of acoustic propagation modelling and the prediction of underwater noise from seismic survey operations proposed for the Moray Firth region during 2010 and / or 2011. The purpose of the study is to provide supporting data for the appropriate assessment and to provide an indication of monitoring locations for assessing the distribution and behavioural responses of cetaceans in the area.

An acoustic modelling study has been undertaken to predict the variation in noise level with range from seismic airgun array operations proposed for the Moray Firth region. The data have been compared with proposed injury and behavioural response criteria. Based on criteria proposed for peak levels of received noise and single shot M-Weighted Sound Exposure Levels (Southall *et al.* 2007) the study indicates that PTS auditory injury is likely to be limited to ranges within 130 m of the source, and hence at ranges well within the near field of the airgun array. This form of injury is therefore unlikely to occur.

Cumulative M-weighted Sound Exposure Level (SEL) has been used to assess the noise exposure for marine mammals exposed to multiple pressure pulses from the airgun array. The modelling has been conducted for a case where marine mammals remain static, and where the animals move away at a rate of 1 $m.s^{-1}$. For the static case, modelling of the noise exposure for marine mammals exposed to multiple pressure pulses as the airgun array moves along a ± 30 km survey line has indicated that the airgun array would have to pass very close to a marine mammal (ranges from 55 m for high frequency hearing marine mammals to 520 m for low frequency) for the cetacean auditory injury criteria to be exceeded. Hence, the data for the smaller cetaceans such as bottlenose dolphin and porpoise indicate that animals must be in very close proximity to the source for there to be any likelihood of PTS auditory injury.

Based on the single shot M-Weighted SEL criteria proposed by Southall *et al.* (2007), TTS onset in cetaceans may occur to a range of 150 m from the airgun array for high frequency hearing cetaceans (M_{hf}), 300 m for mid-frequency cetaceans (M_{mf}), 550 m for low frequency cetaceans (M_{lf}), and 1400 m for Pinnipeds (M_{pf}).

The predicted noise has also been compared with audiometric data for species of cetacean and seals. This form of analysis indicates that the mid-frequency components of the noise may remain above hearing threshold and may be audible to ranges beyond 20 km.

1. INTRODUCTION

This report has been prepared by Kongsberg Maritime Ltd for the University of Aberdeen, Lighthouse Field Station and the Department of Energy & Climate Change. This report provides the results of acoustic propagation modelling and the assessment of underwater noise from seismic survey operations proposed for the Moray Firth region during 2010 and / or 2011. This is a relatively shallow water region where acoustic propagation will be heavily influenced by both the sound speed profile and interaction with the seabed. The purpose of the study is to provide supporting data for the appropriate assessment and to provide an indication of monitoring locations for assessing the distribution and behavioural responses of cetaceans in the area.

The report summarises operational and site specific data for the region based on the modelling of underwater noise propagating through the middle of the survey region. Additional modelling has also been undertaken to investigate the underwater noise propagating into shallower water coastal regions inhabited by bottlenose dolphin and porpoise at Burghhead, Covesea Skerries and Lossiemouth, at Spey Bay and toward Cromarty and Nairn.

For illustrative purposes, data are presented from the source and to ranges at which the noise is attenuated to the levels of background sea noise in the region. When considering data and impact zones in the near field of the source, typically those that indicate impacts within a range of several hundred metres, it should be borne in mind that in this region noise levels vary inconsistently. Each airgun within the array produces underwater sound at peak levels of typically 220 to 230 dB re.1 μPa @ 1 m. The high level sound field required for seismic surveying is achieved by the superposition of the acoustic energy from multiple airgun emissions in a carefully controlled firing sequence. Hence, although far far-field measurements of airgun array noise indicate peak source levels from typically 240 to 265 dB re.1 μPa @ 1 m, actual sound levels close to the array are likely to be considerably lower and dominated by the noise from individual airguns.

The directionality of the airgun array acoustic source has been addressed by other studies (Hannay *et al.* (2009), MaGillivray (2007) for example). Hence, the modelling undertaken in this study assumes the airgun array is broadside of the receiver. Whilst it is appreciated that the airgun array is a directional source, and that endfire noise levels will be lower than broadside, this study has assumed a worst case condition. Airgun array noise characteristics are discussed more fully in Section 5.

The source level noise from the proposed airgun array has been estimated. Two propagation models have then been used to predict the frequency dependent variation in Transmission Loss. At low frequencies, the propagation modelling has been undertaken using the model RAM (Collins 1993). This uses the fully range dependent parabolic equation code for fluid seabeds. The frequency at which RAM becomes too cumbersome to use is dependent on the wavelength of the signal and the water depth in which the source is located. The Moray Firth region is a shallow water site with typical water depths of 40-50 m along propagation paths radiating from the survey regions. For these shallow water depths the changeover frequency occurs at 315 Hz, hence, at this and higher frequencies, the ray-trace model WADER® (OAD 2007) has been used. Like RAM, this is also a range-dependent model for fluid seabeds and the model is widely used in the defence industry.

Data are presented using a number of noise assessment metrics, with impact zones calculated based on proposed criteria from various studies. These are briefly reviewed in Section 3. The study does not make judgement as to the validity of the criteria, but applies the metrics to the predicted noise levels in order to determine the effect range.

2. DESCRIPTION OF UNDERWATER NOISE AND ASSESSMENT METRICS.

2.1 Introduction

Studies by Thomsen *et al.* (2006), Southall *et al.* (2007) for example, provide detailed reviews of the metrics used to measure and assess the impact of underwater noise in the marine environment. A detailed review has not therefore been provided here, although a brief overview is provided to assist the reader.

Sound may be defined as the periodic disturbance in pressure from some equilibrium value. The unit of pressure is given in Pascals (Pa) or Newton per square metre (N/m^2). By convention, however, sound levels are expressed in decibels (dB) relative to a fixed reference pressure commonly 1 μPa for measurements made underwater. This is because measurements typically cover a very wide range of pressure values

2.2 Peak Sound Level

For transient pressure pulses such as an explosion or a single discharge of an airgun, the peak sound level is the maximum absolute value of the instantaneous sound pressure recorded over a given time interval. Hence:

$$\text{Peak Level (zero-to-peak)} = 20 \times \log_{10} (P_{peak}/P_{ref}) \qquad \text{eqn. 2-1}$$

When the pulse has approximately equal positive and negative parts to the waveform, the peak-to-peak level is often quoted and this is equal to twice the peak level or 6 dB higher.

2.3 RMS Sound Pressure Level

The Root-Mean-Square (RMS) Sound Pressure Level is used to quantify noise of a continuous nature. Underwater sound sources of this type include shipping, sonar transmissions, drilling or cutting operations, or background sea noise. The RMS Sound Pressure level is the mean square pressure level measured over a given time interval (t), and hence represents a measure of the average sound pressure level over that time. It is expressed as:

$$\text{RMS Sound Pressure Level} = 20 \times \log_{10} (P_{RMS}/P_{ref}) \qquad \text{eqn. 2-2}$$

Where RMS Sound Pressure Levels are used to quantify the noise from transients, the time period over which the measurements are averaged must be quoted as the RMS value will vary with the averaging time period. Where the noise is continuous, as in the examples given above, the time period over which measurements are taken is not relevant as the measurement will give the same result regardless of the period over which the measurements are averaged.

2.4 Sound Exposure Level

The problems associated with the time period over which the Sound Pressure Levels are averaged, as highlighted above, can be overcome by describing a transient pressure wave in terms of the Sound Exposure Level (SEL). The Sound Exposure Level is the time integral of the square pressure over a time window long enough to include the entire pressure pulse. The Sound Exposure Level is therefore the sum of the acoustic energy over a measurement period, and effectively takes account of both the level of the sound, and the duration over which the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt$$ eqn. 2-3

where *P* is the acoustic pressure in Pascals, *T* is the duration of the sound in seconds and *t* is time. The Sound Exposure is a measure of the acoustic energy and therefore has units of Pascal squared seconds (Pa^2-s).

To express the Sound Exposure as a logarithmic decibel, it is compared with a reference acoustic energy level of 1 μPa^2.s. The Sound Exposure Level (SEL) is then defined by:

$$SEL = 10\log_{10}\int_0^T \frac{p^2(t)dt}{P_{ref}^{\;2}}$$ eqn. 2-4

Where a sound time period is less than a second the RMS Sound Pressure Level will be greater than the Sound Exposure Level. For signals of greater than 1 second, the Sound Exposure Level will be greater than the RMS Sound Pressure Level where:

SEL = SPL + 10 log10 T eqn. 2-5

2.5 Cumulative Sound Exposure Level

Where multiple transient pressure wave events occur, for example during pile driving or seismic operations, the total or cumulative Sound Exposure Level from multiple events can be calculated by summing the Sound Exposure Level from a number of individual events.

2.6 Source Level

The source level (SL) is the apparent strength of a sound source at a reference distance, usually 1 m, from the source. For example, a source may be quoted as having a source Sound Pressure Level of 100 dB re.1µPa @ 1 m. In practise the parameters of the source are rarely measured at such a close range, and the source level is inferred by back-propagating the noise from a number of far field measurements

2.7 Received Level

The Received level (RL) is the strength of the acoustic field at a given depth and range relative to the source. As the sound varies with range, it is important to state the range at which the measurement has been taken or the estimate has been made.

2.8 Transmission Loss

The transmission loss (TL) represents the loss in intensity or pressure of the acoustic field strength as the sound propagates from source to receptor. In general terms the transmission loss is given by:

TL = N log(r) + α r eqn. 2-6

where r is the range from the source, N is a factor for attenuation due to geometric spreading, and α (in $dB.km^{-1}$) is a factor for the absorption of sound in water. Hence, the received sound level at a range r from a source is given by:

$$RL = SL - TL \qquad \text{eqn. 2-7}$$

which can be written in the form :

$$RL = SL - N \log(r) - \alpha r \qquad \text{eqn. 2-8}$$

3. CRITERIA FOR ASSESSING IMPACTS UPON CETACEANS.

3.1 Introduction

This section of the report describes briefly the assessment criteria proposed by various investigators to assess the impact of underwater sound upon cetaceans. These criteria are then used to estimate impact zones about the sound source using the results from underwater sound propagation modelling.

It should be noted that currently these criteria have had little or no validation under open water conditions. Auditory injury data from controlled tests with a few captive animals have been used as the basis for developing the auditory injury, PTS and TTS guidance criteria. Observations of behavioural avoidance with concurrent acoustic measurements are sparse, and hence the behavioural avoidance criteria are speculative. No judgement is made here or throughout the subsequent calculations of mitigation zones regarding the merits or shortfalls of each approach. The data are presented solely as a guide to the proposed monitoring operations during the Moray Firth seismic operations.

3.2 NMFS (1995) guidelines.

US National Marine Fisheries Service (NMFS) and National Oceanographic and Atmospheric Administration (NOAA) agencies initially used RMS Sound Pressure Levels to determine underwater noise impact zones for marine mammals (NMFS, 1995). The US NMFS considered, as a guideline, that underwater Sound Pressure Levels (RMS) above 180 dB re 1 µPa, could cause TTS in cetaceans, and 190 dB re. 1 µPa in pinnipeds (NMFS, 1995). A lower (Level B) harassment criteria based on a received RMS Sound Pressure Level of 160 dB re.1µPa has also been used to establish behavioural avoidance zones. These metrics are conservative in terms of preventing auditory injury, but as they were developed for military sonar applications, are not directly applicable when considering impulsive sound, and do not consider either the peak level of noise, or it's frequency dependence in relation to the receptor species (Madsen, 2005). Southall *et al.* (2007) discusses these guidance criteria and considered that although the NMFS stated these criteria to be precautionary, there was no empirical evidence as to whether exposure to higher levels of pulsed sound would or would not cause auditory or other injuries.

3.3 NOAA (2006) guidelines

More recently, NOAA have also developed auditory injury exposure criteria based on the total energy exposure. A Sound Exposure Level of 195 dB re.1µPa^{2}s is considered as the onset of Temporary Threshold Shift (TTS) injury, with an exposure of 215 dB re.1µPa^{2}s specified by NOAA (2006) as the onset of Permanent Threshold Shift (PTS) auditory injury. These auditory injury criteria were based on noise exposure tests with captive marine mammals exposed to short duration (1 second), narrow band tones similar to sonar transmissions (Schlundt *et al*, 2000) and extrapolation of data from terrestrial mammals. The mean SEL required to produce an onset of TTS in these tests was found to be 195 dB re.1µPa^{2}s. This result was supported by the short-duration tone data of Finneran *et al*. (2000, 2003) and longer duration noise data from Nachtigall *et al*. (2003). Together, these data were considered to demonstrate that TTS in cetaceans is correlated with the received SEL and that the onset of TTS exposures fits with an equal-energy of 195 dB re.1µPa^{2}s. The criteria were therefore considered applicable to signals of varying duration.

Whilst this approach may not have been developed for assessing seismic airgun noise, the approach of calculating the cumulative SEL by summing the noise from successive transient pressure pulses has been used in a recent COWRIE study (SMRU 2007) for estimating auditory injury zones from pile driving operations.

3.4 Southall et al, 2007.

Southall and his co-workers produced a comprehensive review of the impacts of underwater noise on marine mammals and proposed criteria for preventing injury based on both peak sound levels and Sound Exposure Level (Southall *et al*. 2007). The Sound Exposure Level criteria can be applied either to a single transient pulse or the cumulative energy from multiple pulses.

To take account of the wide frequency dependence in the auditory response of marine species, M-Weighting frequency functions for low, mid and high frequency hearing cetaceans and for pinnipeds were proposed.

The Southall *et al.* (2007) study proposes a peak noise criterion of 230 dB re. 1 μPa for cetaceans (peak level), and 218 dB re. 1 μPa for pinnipeds, to prevent auditory injury (PTS onset); and a Sound Exposure Level of 198 dB re.1μPa^{2}s M-Weighted for cetaceans, and 186 dB re.1μPa^{2}s M-Weighted for pinnipeds. The lower (more conservative) of the criteria applies for any given application.

TTS onset is defined at a peak noise criterion of 224 dB re. 1 μPa for cetaceans, and 212 dB re. 1 μPa for pinnipeds; and a corresponding Sound Exposure Level of 183 dB re.1μPa^{2}s M-Weighted for cetaceans, and 171 dB re.1μPa^{2}s M-Weighted for pinnipeds. Again, the lower of the criteria applies.

3.5 HESS (1997) behavioural disturbance criteria

Behavioural disturbance from underwater sound sources is far more difficult to define and is dependent upon many factors related to the circumstances of the exposure (Southall *et al.* (2007). The Southall *et al.* study uses a 'behavioural response severity' scale as a measure of response.

The report by the High Energy Seismic Survey (HESS) Team (1997) prepared for the California State Lands Commission and the US Minerals Management Service concluded that behavioural disturbance to marine mammals would most likely occur at received Sound Pressure Levels above 140 dB re.1μPa (RMS), and quotes the studies of Richardson *et al.* (1995) in support of this. However, in stating this, the study recognised that there are a wide variety of responses by marine mammal groups when exposed to seismic sounds.

3.6 Comparison with hearing threshold

Behavioural response and auditory injury from underwater sound is often assessed by comparing the received sound level with the auditory threshold of marine mammals. Richardson *et al.* (1995), Erbe and Farmer (2000), Madsen *et al.* (2006), Thomsen *et al.* (2006), David (2006) for example, all use critical bands, normally octave or third octave band received levels of noise in comparison with the corresponding marine mammal hearing threshold in order to estimate the range of audibility and zones of influence from underwater sound sources.

The UK MOD and QinetiQ impact models (QinetiQ 2003) uses a level of 95 dB above hearing threshold as a criterion for assessing the onset of PTS, and 75 dB above hearing threshold for estimating the onset of TTS auditory injury; both with an additional factor taking into account the time duration over which the animal is exposed. These criteria are normally applied in the third octave band corresponding to either the peak sensitivity of the marine receptor, or the peak noise produced by the sound source in the case of sonar.

This form of analysis has been taken a stage further by Nedwell *et al.* (2005 and 2007) and Parvin *et al.* (2006), where the underwater noise is compared with receptor hearing threshold across the entire receptor auditory bandwidth in the same manner that the dB(A) is used to assess noise source in air for human subjects. The criteria used in these studies is behavioural based, where received sound levels of 90 dB above hearing threshold (comparable with 90 dB(A) in air) are considered to cause a strong behavioural avoidance, and levels of 75 dB above hearing threshold a mild behavioural response. Neither this criterion, nor that proposed by QinetiQ has been validated by experimental study. The approach that has been used in this study is to present the received levels of third octave band noise with hearing threshold and background sea noise levels, the comparison providing an indication of received signal to noise with range.

3.7 Summary of impact criteria

Exposure limit	Effect	Study
230 dB re 1 µPa (Peak)	PTS Auditory injury onset in cetaceans	(Southall *et al*, 2007)
218 dB re 1 µPa (Peak)	PTS Auditory injury onset in pinnipeds	(Southall *et al*, 2007)
224 dB re 1 µPa (Peak)	TTS onset in cetaceans	(Southall *et al*, 2007)
212 dB re 1 µPa (Peak)	TTS onset in pinnipeds	(Southall *et al*, 2007)
198 dB re.1µPa^{2}s SEL M-Weighted	PTS Auditory injury onset in cetaceans	(Southall *et al*, 2007)
186 dB re.1µPa^{2}s SEL M-Weighted	PTS Auditory injury onset in pinnipeds	(Southall *et al*, 2007)
183 dB re.1µPa^{2}s SEL M-Weighted	TTS onset in cetaceans	(Southall *et al*, 2007)
171 dB re.1µPa^{2}s SEL M-Weighted	TTS onset in pinnipeds	(Southall *et al*, 2007)
215 dB re.1µPa^{2}s SEL	PTS Auditory injury	(NOAA, 2006)
195 dB re.1µPa^{2}s SEL	TTS Auditory injury	(NOAA, 2006)
190 dB re 1 µPa (RMS)	Auditory injury criteria – pinnipeds	(NMFS, 1995)
180 dB re 1 µPa (RMS)	Auditory injury criteria – cetaceans	(NMFS, 1995)
160 dB re 1 µPa (RMS)	Behavioural disturbance, level B harassment	(NMFS, 1995)
140 dB re 1 µPa (RMS)	Low level disturbance	HESS (1997)

Table 3-1. Summary of marine mammal noise impact criteria.

4. BACKGROUND NOISE MORAY FIRTH

4.1 Introduction

An underwater noise remains audible to marine life until one of two conditions are met:

1. The noise falls so low that it is below the ambient noise level for that locality. It is then said to be masked by the background noise; or
2. The noise falls below the hearing threshold of a given marine creature.

During 2006 extensive measurements of background sea noise were undertaken in the Moray Firth (Senior *et al*, 2008). These data indicated a considerable variation in background sea noise at sites in the Outer Moray Firth compared with regions close to the coast, and within the inner Moray Firth near Cromarty and Nairn. Broadband RMS Sound Pressure Levels (1 Hz to 150 kHz) varied from 104 to 119 dB re 1μPa within the Inner Moray Firth and SAC. Corresponding levels measured in the outer Moray Firth are reported as being 20 dB higher due to the influence of heavy distant shipping that increased noise, particularly over the frequency range from 100 Hz to 500 Hz. The background noise was dominated by low frequencies below 1 kHz. Increased boat activity at a construction site in the middle of the Moray Firth increased the local background sea noise to maximum RMS Sound Pressure Levels of 138 dB re. 1μPa. Similar measurements at a distance of 800 m from an operating oil platform in the middle of the Moray Firth indicated levels of approximately 120 dB re 1μPa, with peaks in the noise spectrum at frequencies from 500 Hz to 2 kHz.

The data presented in Senior *et al.* (2008) have been analysed in the SEL and M-Weighted SEL formats to provide a comparison with the seismic noise data presented later in this report.

4.2 Data

Background sea noise data for the Moray Firth are presented as narrowband Power Spectral Density levels in dB re.1μPa^2.Hz^{-1} over the frequency range from 10 Hz to 100,000 Hz. From these narrowband data, third octave band levels of noise have been calculated in dB re. 1 μPa, and are presented for comparison. Figures 4-1 and 4-2 present data measured in the Outer and Inner Moray Firth regions respectively.

Table 4-1 presents the analysis of the noise data in terms of un-weighted SEL and M-weighted SEL noise analysis metrics. The data from the Outer Moray Firth region indicate considerably higher levels of low frequency noise. Noise at these frequencies is typical of that from shipping. It should be noted that the data for the Inner Moray Firth (RMS SPL, SEL and Mlf weighted SEL) appear to be dominated by the 50 Hz 1/3 octave band component, and hence the actual background sea noise in this region may be lower than indicated in Table 4-1. (Removing this 1/3 octave band gives an RMS SPL / SEL and Mlf Weighted SEL of 100 dB re.1μPa^{2}s).

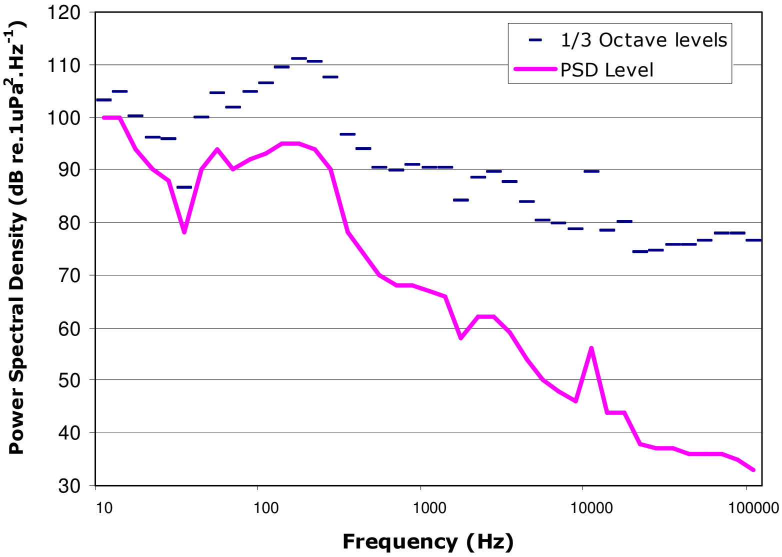


Figure 4-1. Background sea noise measured in the Outer Moray Firth from Senior et al. (2008) (Data are presented as Power Spectral Density and third octave band SPL's in dB re.1μPa).

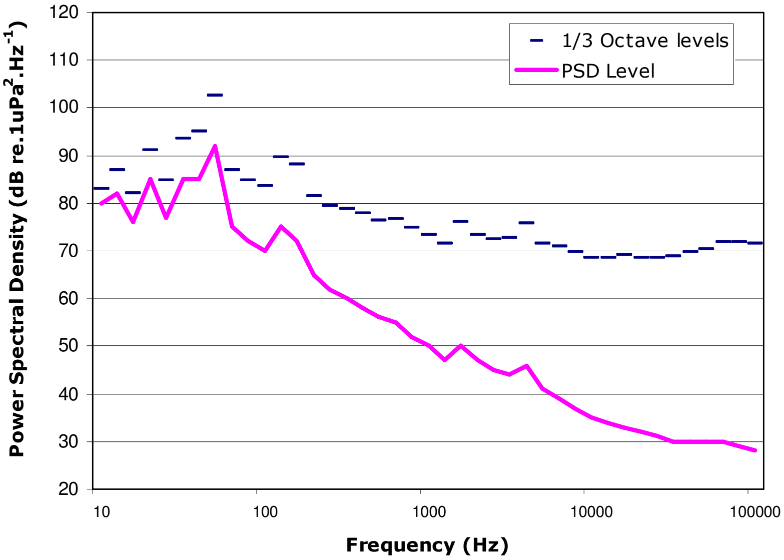


Figure 4-2. Background sea noise measured in the Inner Moray Firth from Senior et al. (2008). (Data are presented as Power Spectral Density and third octave band SPL's in dB re.1μPa).

Metric	**Outer Moray Firth**	**Inner Moray Firth**
RMS SPL / SEL	118	104
Mlf-Weighted SEL	117	104
Mmf-Weighted SEL	112	91
Mhf – Weighted SEL	110	89
Mpf – Weighted SEL	114	95

Table 4-1. Summary of background sea noise measurements undertaken in the Moray Firth region (Senior et al, 2006). Data are presented in RMS SPL, SEL and M-weighted SEL formats.

5. SOURCE LEVEL NOISE FROM SEISMIC AIRGUN ARRAYS.

5.1 Introduction

Seismic surveys are an essential part of an oil and gas exploration programme. During a survey, high intensity, low frequency sound emitted from a seismic array, is used to image the subsea rock formations so as to identify potential hydrocarbon traps and reservoirs. The reflections from the rock structures are recorded using hydrophones streamed behind the survey ship. The signals are then transmitted to the on-board processing equipment and analysed in order to reveal subsea structures.

The sound sources themselves are airguns. These are underwater pneumatic devices that expel a bubble of air under great pressure into the water. Once in the water, the pressure is released, the bubble collapses in on itself and may oscillate several times. The acoustic signal thus produced consists of a sequence of positive and negative pulses that are proportional to the rate of change of volume of the air bubbles.

A single airgun produces an acoustic signal that is non-directional and hence is unsuitable for penetrating the seabed. To achieve the right degree of directionality, it is necessary to form an array of several airguns, often 10 to 30 or more, and to stagger the times at which each airgun is discharged. In this way, a highly directional, very intense acoustic signal is produced and this has the potential to penetrate the subsea geology to a depth of several kilometres.

A single airgun generates source levels in the range 220-238 dB peak-peak re 1 μPa while an array of industry standard airguns produces 240-265 dB re 1 μPa (Richardson *et al.* 1995, Caldwell and Dragoset, 2000). Most of the energy produced by the array is in the sub-200 Hz frequency band with a broad peak around 20-120 Hz (Breitzke *et al.* 2008). However, it is also been noted that energy over a much higher frequency range is also generated, although very few data for this exists (Goold and Fish 1998, Madsen *et al.* 2006, Breitzke *et al.* 2008).

In the time domain, at short ranges, the acoustic signal is dominated by a sharp impulse or transient, representing the growth of the initial pulse as the bubble of air leaves the airgun. The impulse rises to a peak level over a time duration of approximately 1 ms. The signal decays over several bubble pulses during an extended period up to 0.1 sec. At longer range, the effect of geometrical dispersion and differential absorption with frequency of acoustic energy in the propagation path can have a marked effect on the pulse shape and duration (Ward *et al.* 1998). The result is that that the peak level is reduced, and the waveform duration may increase considerably. As an illustration of that, Ward *et al.* (1998b) showed that a Hanning weighted pulse of 0.2 sec duration and a source level of 220 dB re 1 μPa over a bandwidth of 90 – 110 Hz, had stretched to 0.4 sec duration after propagating 5 km through a lossy sediment, and to 1.5 sec duration at a range of 30 km.

Table 5-1 provides a summary of data for airguns and arrays widely used in seismic exploration (Richardson *et al.* 1995). The chamber pressure is the maximum pressure in the airgun prior to the release of the air; and the total volume represents the sum of the volumes of all the airguns in the array. The table shows that airgun arrays are generally towed at depths of 6 to 10 m. Peak to peak source pressures are given as bar at 1 m - this being the common unit of measurement in the seismic industry, and also as MPa at 1 m and dB re 1 μPa at 1 m – as these are more appropriate measures in acoustics.

Source	Chamber pressure (MPa)	Total volume (Litres)	Depth (m)	Source Pk-Pk pressure (bar @ 1 m)	Source Pk-Pk pressure (MPa @ 1 m)	Source Pk-Pk pressure (dB re. 1 uPa @ 1 m)
Airgun arrays						
GSC 7900	-	129.5	-	174	17.4	265
ARCO 4000	12.9	65.6	10	110	11.0	261
GECO 3100 + 1640	13.8	77.7	7.6	82.4	8.24	258
GSI 4000 pnu-con	13.8	66.8	6.1	80.0	8.00	258
GECO 3100	13.8	50.8	7.6	76.3	7.63	258
SSL 4440	13.8	72.8	8.5	73.4	7.34	257
GSI Jonsson 2000	13.8	32.8	6.1	55.0	5.50	255
GECO 1985 + 1640	13.8	59.4	7.6	49.4	4.94	254
Western 1050	31.0	17.2	6.1	42.0	4.20	252
GECO 1985	13.8	32.5	7.6	41.9	4.19	252
SSL 1460	13.8	23.9	7.6	25.3	2.53	248
Western 555	31.0	9.1	6.1	25.2	2.52	248
GECO 594 subarray	13.8	9.7	8.2	11.9	1.19	241
Single airguns						
Small airgun	13.8	0.16	9.1	1.2	0.12	222
Mid sized airgun	13.8	4.92	9.1	3.4	0.34	231
Large airgun	13.8	32.8	9.1	8.0	0.80	238

Table 5-1. Characteristics of some seismic sound sources used for offshore exploration (from Richardson et al. (1995), original data from Johnston and Cain (1981) except for the ARCO 4000 (Greene 1985), GSC 7900 (Parrott 1991) and single airguns (Lugg 1979).

5.2 Review of Airgun Array noise studies

The apparent source level from large dispersed sources such as airgun arrays is determined by undertaking a number of measurements in the far field and then back-propagating the data to the point of origin - typically a reference distance of one metre (see Section 2.6). The particular configuration of the airgun array and the discharge time of individual airguns can be varied to maximise the amplitude and quality of the outgoing acoustic signal in the vertical direction. In general, the loudness is related to the total volume of the airguns (See Table 5-1), although there are exceptions for unusual array configurations (MacGillivray and Chapman, 2005).

For measurements undertaken in the far field the signals from the individual airguns interfere constructively and the array is considered a point source (Caldwell & Dragoset, 2000). However, this approach may introduce inaccuracies as this apparent source level is often calculated by simple back-propagation using spherical spreading. In practice, the actual source Sound Pressure Level can be 20 dB lower than the apparent source level (Caldwell and Dragoset, 2000), as in the near field of the array the contributions to the noise from the individual airguns do not increase coherently. Hence, it should be noted that the actual source sound levels will be lower than those estimated by back-propagation estimates, and the estimated impact ranges at close range from the source are likely to be conservative.

When applying underwater noise impact criteria that vary with frequency, for example, when using the frequency M-weighting scales recommended by Southall *et al.* (2007) it is also important to consider the how the sound propagation varies with frequency. The available literature on airgun array spectra is generally disappointing. The data quoted is often ambiguous and incomplete; graphs are frequency mis-labelled and most frustratingly, few measurements have been made at high frequencies. The data provided for this study (MMS 2004) and as shown in Figure 5-1, indicates a peak pressure (zero to peak) of 37.5 bar–m (251 dB re.1 μPa @ 1 m) measured at a horizontal range of 9000 m. It is assumed that the actual measurement will have been considerably lower than this, but will then have been back-propagated to a source distance of 1 m. The apparent source frequency spectrum (Figure 5-2) indicates considerable acoustic energy over the frequency range from 10 Hz to 100 Hz, but then a very rapid decrease with frequency with little or no signal at frequencies above 250 Hz. The measurements in this case were only undertaken to a maximum frequency of 1000 Hz. Where measurements have been undertaken with greater sample rates, seismic airgun array noise has been shown to extend to considerably higher frequency (Goold and Fish 1998, Madsen *et al.* 2006, Breitzke *et al.* 2008, Goold and Coates (2006). Due to the variation of sound transmission loss with frequency and its dependence on water depth, sound speed profile, and seabed and sea-surface losses, etc., the frequency content of the sound will be very different in the far field compared with measurements taken close to the array.

At the outset of this study therefore the precise source frequency spectrum of the array is unknown, the spectral content may nevertheless be estimated by reviewing published data on other similar arrays, where available. More accurate impact modelling may be undertaken when the specific airgun array, and the array source spectrum are available.

5.3 Directionality

Directionality of a seismic array is controlled through the superposition of beam patterns from individual airguns. At low frequencies (<~80 Hz), the individual beam patterns indicate that sound propagates nearly uniformly in all directions (MacGillivray and Chapman (2005); Duncan *et al.* 2008). At higher frequencies, the output becomes increasingly directional. The overall effect is to produce an intense beam of high energy sound having considerable vertical and azimuthal dependence and being directed predominantly downwards for optimum penetration of the seabed. Measurements indicate that spectral levels may be as much as 6 dB down in the endfire direction compared with the vertical (Simpkin 2003). Similarly, broadside spectral levels can be down by at least the same amount compared with those in the vertical direction at frequencies up to 500 Hz and approaching 20 dB at frequencies up to 2 kHz (MacGillivray and Chapman (2005) and transcribed in Figure 5-3). It is recognised however, that substantial levels of high frequency sound are nevertheless emitted in the horizontal direction (Duncan *et al*. 2008) and these have the potential to propagate over considerable distances.

5.4 Estimation of Source Level Noise for the Moray Firth survey

Currently there is limited published data for seismic airgun array noise that covers the frequency range required to fully implement the M-weighting scale filters proposed by Southall *et al.* (2007) (i. e. from 10 Hz to 100 kHz and greater). This shortfall should be addressed by undertaking further high quality measurements at incremental ranges from seismic airgun sources. Opportunities to obtain this form of data should be undertaken during the proposed Moray Firth surveys.

To overcome this, the approach that has been undertaken in this study is to construct a composite frequency spectrum for an airgun array of 3090 cubic inches (50 Litres). The PSD levels at a number of key frequencies are given in Table 5-2. The low frequency data is based on data provided to this study from MacGillivray and Chapman (2005) and increased by 3 dB to account for the larger airgun array size. This gives spectral levels of source noise from 208 dB re.1µPa^2.Hz^{-1} at 10 Hz to 211 dB re.1µPa^2.Hz^{-1} at 20 Hz, extending to a frequency of 100 Hz. Figure 5.2 indicates a spectral peak at a frequency of 50 Hz. This data is in good agreement with the source noise spectrum used in the acoustic modelling study undertaken by MacGillivray and Chapman (2005) for airgun operations with a similar sized (3000 cubic inch) airgun array. In terms of calculating overall sound levels and M-Weighted SEL, it is these low frequencies components of the airgun array noise that dictate the noise calculations.

At higher frequencies the spectral levels in Figure 5.2 decrease rapidly, by 75 dB over the frequency range from 100 Hz to 240 Hz. The modelling predictions of MacGillivray and Chapman (2005) indicate more noise energy over this frequency range, with a decrease of 45 dB from the peak noise at 20 Hz, to a frequency of 1 KHz. The data from Duncan and McCauley (2000) indicate a similar decrease in level with frequency of 45 dB from a peak noise of 20 Hz to a frequency of 1 KHz. A more conservative (i. e. higher noise) roll-off estimate giving a noise spectrum level of 166 dB at 1 KHz and 145 dB re.1µPa^2.Hz^{-1} at 2 kHz has therefore been used. However, as with many of the datasets described earlier, the data of MacGillivray and Chapman (2005); and Duncan and McCauley (2000) do not extend to frequencies above 2 KHz.

The limited datasets that extend to frequencies above 2 kHz indicate a more gradual decrease with frequency than appears to occur at lower frequency. The data from Popper *et al.* (2005) concentrated on frequencies to 5 kHz when considering the impact of seismic airgun noise on fish. For a 730 cubic inch (12 Litre) airgun array underwater noise data measured at relatively short range (13 m and 17 m), broadside of the array indicates a decrease in spectral levels of noise approximately 5 dB over the frequency range from 2 kHz to 5 kHz. Goold and Fish (2005) indicate a similar decrease (6 dB) over this same frequency range with a further decrease of 25 dB over the frequency range from 5 KHz to 20 kHz in measurements undertaken at a range of 750 m broadside of 2120 cubic inches (34.8 Litres) airgun array. The data measured at a range of 8 km indicates a very much greater decrease in spectral levels of 30 dB over the frequency range from 5 kHz to 10 kHz, indicating the greater attenuation of the high frequency noise from the airgun array. To estimate the high frequency source noise spectrum this study has used a 5 dB roll off (decrease) in spectral levels of noise from 2 kHz to 5 kHz, with a more conservative 10 dB decrease from 5 to 10 kHz, and a further 20 dB decease over the decade of frequencies from 10 kHz to 100 kHz. This gives a source spectral level of 110 dB re 1 1µPa^2.Hz^{-1} at frequencies of 100 kHz, which is in keeping with the High frequency airgun measurements of Goold and Coates (2006).

Frequency (Hz)	Spectral level (dB re 1 1µPa^2.Hz^{-1})
10	208
20	211
50	212
100	211
200	190
500	180
1000	166
2000	145
5000	140

10000	130
20000	124
50000	116
100000	110

Table 5-2 Estimated spectral levels of underwater noise as a function of frequency for a3090 cubic inch airgun array operated at 6 m depth.

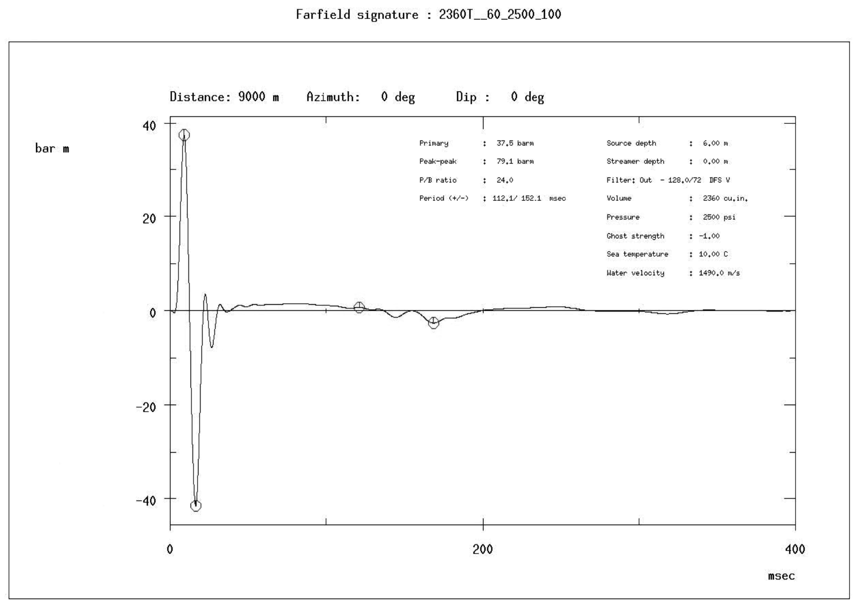


Figure 5-1. An underwater noise time history of a 2360 cubic inch (38.8 Litre) airgun array noise measured at a range of 9000 m and back-propagated to a source range of 1 m. (Acoustic pressure in bar @‘ 1 m)(MMS 2004)

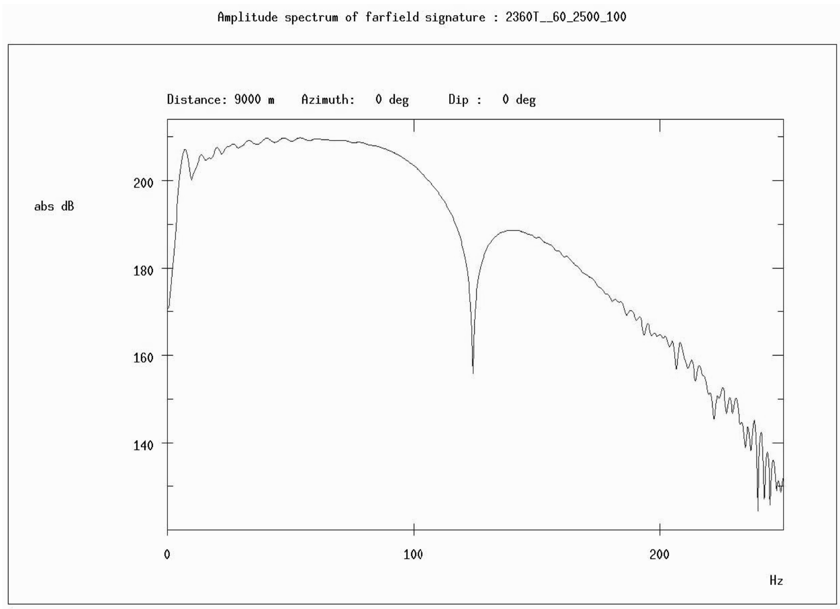


Figure 5-2. The peak noise spectrum (in dB re.1μPa^2.Hz) of a 2360 cubic inch (38.8 Litre) airgun array noise measured at a range of 9000 m and back-propagated to a source range of 1 m. (MMS 2004)

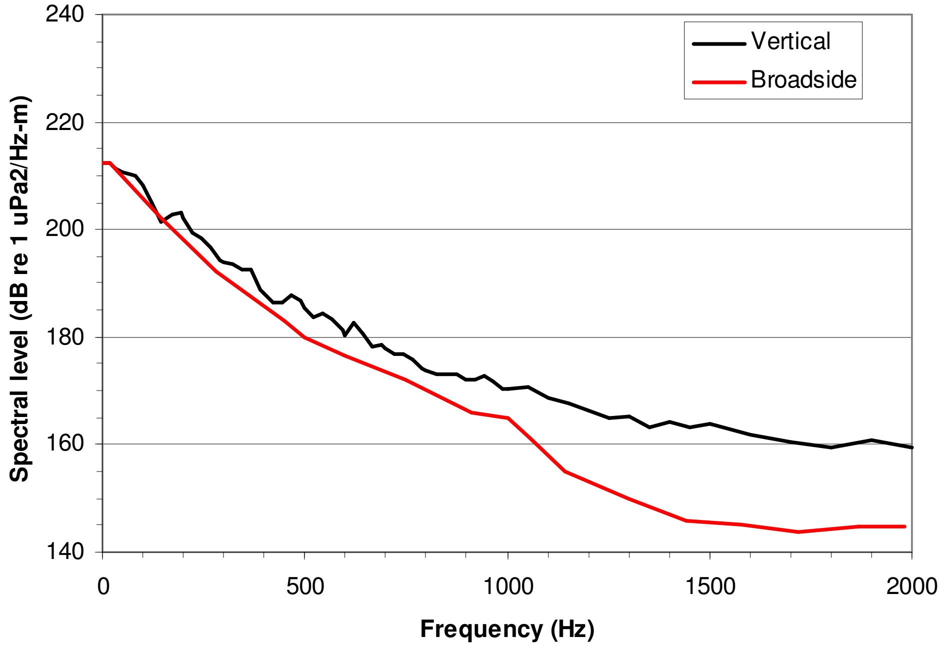


Figure 5.3 Frequency spectrum for 3000 cubic inch airgun (MacGillivray and Chapman 2005)

6. SOUND PROPAGATION MODELLING

6.1 Introduction

In order to assess the impact of seismic sound on marine life, it is necessary to model the propagation of underwater sound from the source to a point in the far field. For accuracy, the process invariably requires the use of sophisticated modelling techniques and site-specific data. This section discusses the acoustic models used and the geoacoustic and oceanographic data required as input parameters for the models.

6.2 Underwater acoustic propagation models

A very simple approach to modelling underwater propagation is to consider simple geometrical spreading laws given by

$$TL = N \log_{10}(r) \qquad \text{eqn. 6-1}$$

where TL is the propagation loss in dB, N is a constant: 20 for spherical spreading and 10 for cylindrical spreading; and r is the distance in metres from the source to the receptor.

When sound propagates uniformly in all directions, spherical spreading applies. When the propagation of sound is constrained by the water surface and the seabed, then cylindrical spreading is most applicable (see e.g. Urick 1983). Although computing the propagation loss in this way is very quick, the biggest drawback is that it fails entirely to take into account the influence of the environment on the propagation of sound and hence the propagation loss may be under- or over-estimated, often by a considerable amount. The solution to this is to make use of more sophisticated modelling techniques and these are described briefly below.

The calculation of propagated, underwater sound fields is based on the wave equation with appropriate boundary conditions (see e.g. Brekhovskikh and Lysanov 1991). The boundary conditions used and the modelling regime to be considered logically lead to one or other solution to the wave equation and this has given rise to a number of classes of models that employ similar techniques. The models are based on ray theory, normal mode, parabolic equation and full-field techniques (Buckingham 1992, Etter 2003). Each set of solutions are valid and computationally efficient over a limited frequency, depth and range regime. For instance, ray theory is most suited to short range and high frequency scenarios while normal mode and parabolic equation are applied to long range and low frequency models. Full-field models are applicable to many scenarios but are often computationally intensive and require a large level of user-experience to ensure that the mathematical iterative processes have reached convergence (Jensen *et al.* 2000).

In general the models operate at narrowband frequencies and do not therefore easily lend themselves to applications involving broadband sound sources and assessment metrics such as peak level and Sound Exposure Level. For the purposes of this study the sound transmission loss has been calculated at each third octave band centre frequency from 10 Hz to 125 kHz along propagation paths from the airgun array. Received levels of underwater sound have then been calculated by applying the frequency dependent transmission loss to the corresponding 1/3 octave band source levels.

To cover the broad range of frequencies emitted by a seismic airgun array, it is acceptable to use more than one type of model such that the whole frequency range of interest is covered. At low frequencies, the propagation modelling undertaken in the current study was carried out using the model RAM (Collins 1993). This uses the fully range dependent parabolic equation code for fluid seabeds and has been in wide use in modelling circles for many years. The frequency at which RAM becomes too cumbersome to use is dependent on the wavelength of the signal and the water depth in which the source is located. When the water depth reaches approximately 8λ where λ is the wavelength of sound and is equal to c_w/f where c_w is the sound speed in water and f is the frequency of the propagating signal; then it becomes more computationally efficient to use an alternative modelling technique. The Moray Firth region is a shallow water site with typical water depths of 40-50 m along propagation paths radiating from the survey regions. For these shallow water depths, the changeover frequency occurs at 315 Hz. At this and higher frequencies, the ray-trace model WADER® (OAD 2007) was used. Like RAM, this is also a range-dependent model for fluid sediment seabeds and the model is widely used in the defence industry.

Underwater acoustic modelling is a complex operation that has to take into account the oceanography as well as the geoacoustic nature of the site of interest. In each case, the computer models make use of a shallow water depth- and range-dependent layer overlying two lossy, fluid layers representing the seabed sediment and the underlying basement. This is shown schematically in Figure 6-1 below. It is noted that the classic 3-layer acoustic model as represented in RAM and WADER® (OAD 2007) assumes a basement that is semi-infinite in thickness. The data that is used to parameterise each layer is discussed below.

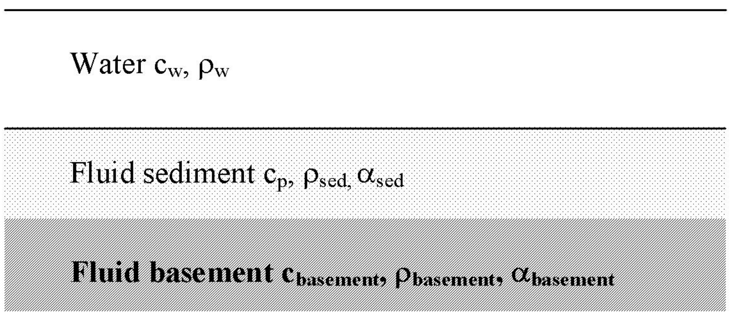


Figure 6-1. Schematic of acoustic model

6.3 Sound propagation transects

Water depth data was transcribed from the relevant Admiralty Chart for the Moray Firth (UKHO, 2000) and from this, bathymetric profiles were obtained for each of the modelling transects. The transect locations are indicated in Figure 6-2 and the bathymetric profiles along each transect are shown in Figures 6-3 to 6-6.

It will be seen that Transect T1 (Figure 6-3) is the only track that remains in deep water throughout its length with the water depth varying between 35 m and 53 m. Transects T2, T3 and T4 each start over the Beatrice Bank in a water depth of approximately 50 m, deeper water is attained before the seabed shelves as the transect approaches the coast.

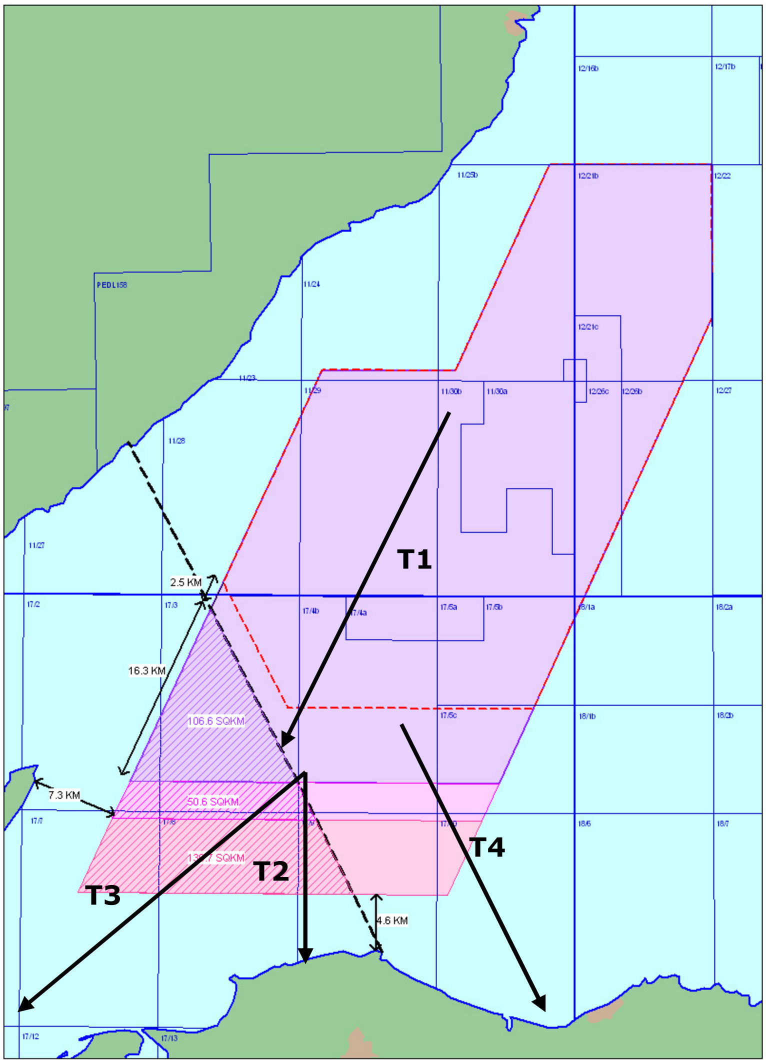


Figure 6-2. Transects selected for Moray Firth acoustic propagation modeling.

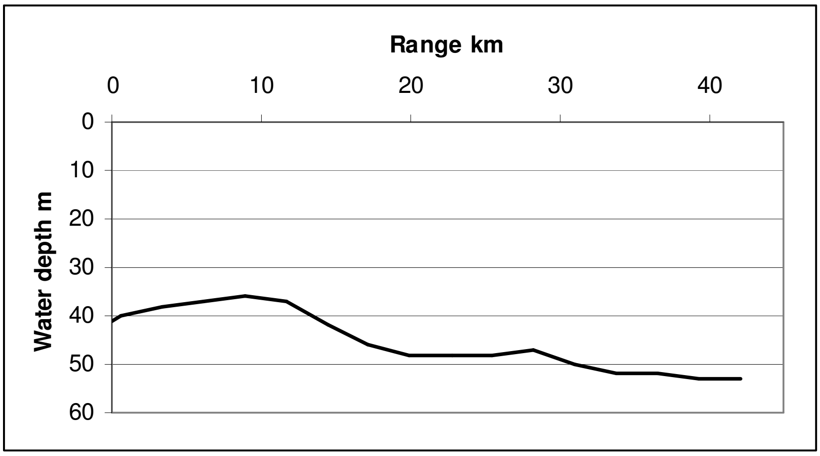


Figure 6-3. Depth profile for Moray Firth Transect T1

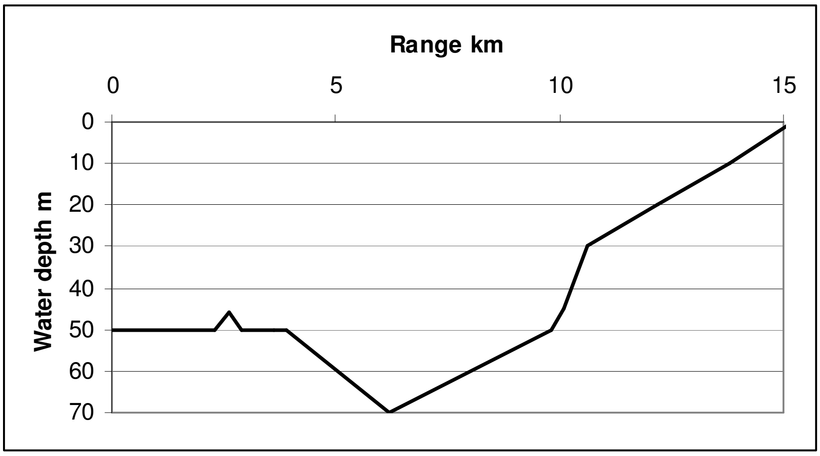


Figure 6-4. Depth profile for Moray Firth Transect T2

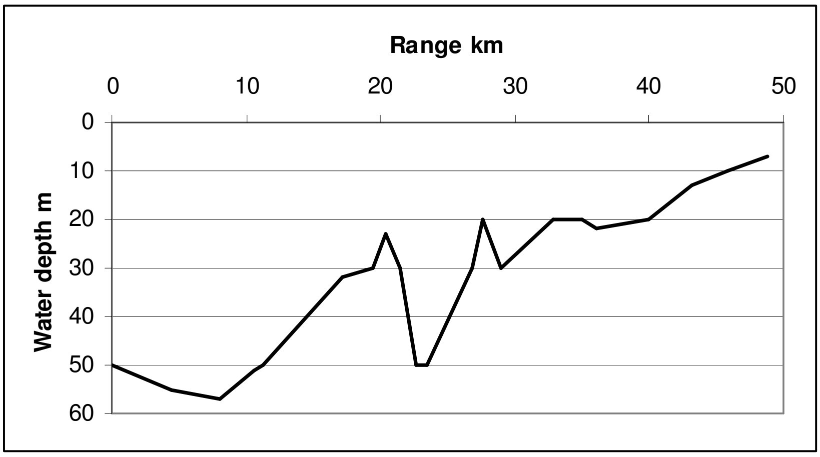


Figure 6-5. Depth profile for Moray Firth Transect T3

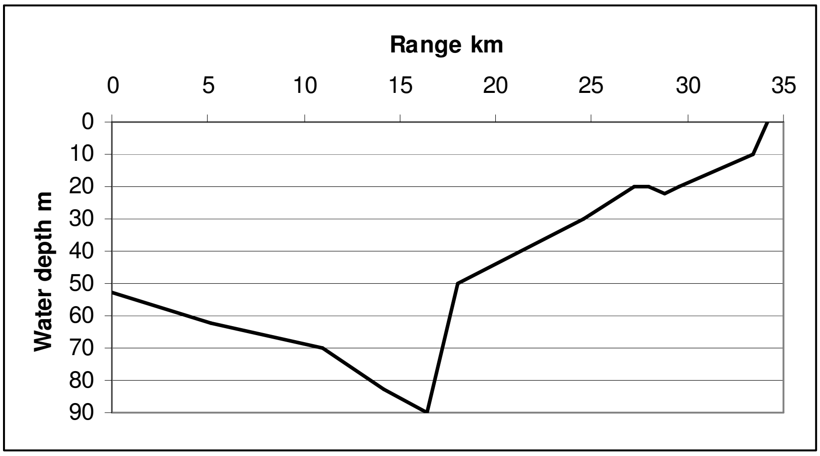


Figure 6-6. Depth profile for Moray Firth Transect T4

6.4 Oceanographic data

The oceanographic data was obtained through the World Ocean Atlas (WOA 2005). This consists of gridded monthly samples of temperature, salinity and depth and from which, sound speed profiles in the Moray Firth may be reconstructed.

It is known that in the temperate waters off the east coast of the UK, the seasons of winter and summer give rise to opposing sound speed profile conditions. Accordingly, representative profiles for winter and summer are used in the subsequent analysis and are shown in Figure 6-7. The figure shows that during the winter, the sound speed increases with increasing depth all the way to the seabed. This produces a profile that is upwardly refracting over the entire water column. For this condition, sound from the seismic array tends to be directed towards the sea surface where it is likely to propagate to relatively large ranges. By the summer, solar heating has generated a surface channel that extends to a depth of around 10 m and this overlies the seasonal thermocline which extends to the seabed. In summer therefore, the sound speed profile is generally downward refracting below 10 m. For this condition, sound tends to be directed into the lossy sediments and is unlikely to propagate to such long distances as might occur during the winter months.

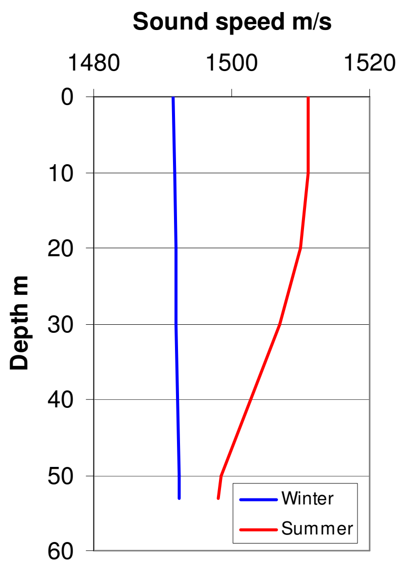


Figure 6-7. Sound speed profiles in the Moray Firth for summer and winter conditions

6.5 Geo-acoustic parameters

The relevant British Geological Society (BGS) chart for the area (BGS 1987) indicates that the seabed sediment in the Moray Firth is generally terrigenous sand overlying a sandstone basement. Hamilton (1963, 1970, 1972) provides advice on seabed sediment parameters and from this, the sound speed and attenuation data was obtained. The data is summarised in Table 6-1.

Layer	Compressional wave velocity Vp m/s	Density kg/m^3	Attenuation dB/m/kHz	Thickness m
Terrigenous sand	1647	2000	0.459	5
Sandstone basement	3913	2360	0.399	-∞

Table 6-1. Sediment parameters for acoustic models.

6.6 Sound source parameters

Sound emitted by a seismic source may be characterised by a pulse of finite duration and covering a wide range of frequencies. For this, a broadband, time-domain propagation model ideally should be used to represent the source and underwater acoustic environment. However, these tend to be difficult to use and have a considerable time overhead associated with them (Jensen *et al.*, 2000).

An alternative approach is to divide the source frequency bandwidth into 1/3 octave bands where each band has a given spectral level, centre frequency and bandwidth; and then to use a frequency-domain type program (such as the ones discussed in Section 6-2) for subsequent propagation modelling.

Seismic sources are generally deployed at shallow depths (see Table 5-1). For this analysis, the depth was taken to be 6 m.

Acoustic energy from the seismic array is generally directed towards the seabed. However, energy may also be transmitted in other directions. It is necessary to apply a beam pattern to the energy emitted by each frequency component. The lower frequencies tend to be omni-directional while the higher frequencies become increasingly directional.

The sea is modelled as a plane, smooth layer where this indicates a surface boundary that is not disturbed by wind or wave action. The reflection losses associated with this condition are minimal compared to those that arise when the surface is roughened (Etter 2003). Hence, overall sound levels at a given depth and range are higher than would otherwise occur if the surface was disturbed. Two sea states were modelled to give an indication of the variability likely to arise in propagation conditions: a flat sea surface referred to as a precautionary condition as this is likely to give rise to greater acoustic propagation; and a sea surface roughened by a surface wind speed which varies according to season and this is referred to as the typical condition, and is more likely to be experienced on any given day. In the Moray Firth, the average surface wind speed in the winter months is around 18 knots while during the summer months, the average speed falls to 11 knots.

The modelling input parameters for the seismic airgun array are summarised in Table 6-2.

Parameter	**Seismic array**
Frequency Hz	10, 12.5, 16, 20, 25, 31, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400, 500, 630, 800, 1k, 1.25k, 1.6k, 2k, 2.5k, 3.15k, 4k, 5k, 6.3k, 8k, 10k, 12.5k, 16k, 20k, 25k, 31.5k, 63k, 80, 100k
Source depth m	6
Beam pattern degrees	Variable in the range 0°/-80°

Table 6-2. Source parameters for acoustic model inputs

6.7 Discussion of model runs

A number of model runs were made using oceanographic data for the winter and summer seasons, using the seabed bathymetric profiles given in Figures 6-3 to 6-6, and using the source parameter information given in Table 6-1. The results are shown in Figures 6-8 to 6-12 inclusive.

Figure 6-8 shows the modelled propagation loss as a function of range over Transect T1 using the summer sound speed profile; the typical condition given by a sea surface roughened by the average surface wind speed; and a range of frequencies. The purpose of this is to assess the preferential propagation with frequency. It will be seen that the 125 Hz component falls by 120 dB over an approximate range of 17 km. As frequency increases, each component propagates with lower losses. The modelling indicates that the 500 Hz, 1 kHz and 2 kHz components each lose 100 dB over 35 km range. Thereafter, each higher frequency component records an increasingly greater loss at a given range. For example, the acoustic modelling indicates that the 64 kHz underwater sound component falls 120 dB over a range 2.5 km. Hence, the modelling indicates that in this very shallow water region, the low and high frequency components of the broadband airgun array noise are rapidly attenuated. By comparison, the mid-frequency components of the noise (500 Hz to 2 kHz) propagate with much lower losses.

This result is significant when it is realised that the bulk of the acoustic energy emitted by the seismic source is at frequencies below 100 Hz. The graph shows that this energy is unlikely to be transmitted over considerable distances.

Figure 6-9 shows the propagation loss modelled over Transect T2. Very similar trends to those on Transect T1 are in evidence. It is noted that this transect reaches the coast at 12 km. At this range, the data indicates a propagation loss of 80 dB and 100 dB for frequencies between 125 Hz and 8 kHz. Figure 6-9 also shows patterns of constructive and destructive interference particularly on the 125 Hz and 250 Hz components at a range up to 5 km. These indicate locations where there are regions of high intensity as well as relative shadow zones for these components.

Figure 6-10 indicates the propagation loss modelled over Transect T3. Optimum propagation conditions are met for the frequency components 500 Hz, 1 kHz and 2 kHz where, at a range of 30 km, the modelling predicts a transmission loss of approximately 120 dB.

Figure 6-11 indicates the propagation loss modelled over Transect T4. A feature of note in this is the sudden relative decrease in propagation loss of some 30 dB at a range of 17 km. This may be explained by referring to the bathymetric profile for this transect in Figure 6-6. The profile shows a gradual increase in water depth over the first 12 km followed by a greater increase in depth to 90 m over the next 4 km. Thereafter, the depth decreases suddenly by 40 m over the next 1 km or so. This upward slope redirects the seabed bouncing acoustic energy so that it constructively interferes with the energy that is propagating in mid water. It is this interference that gives rise to the change in propagation levels.

Figure 6-12 indicates the propagation loss modelled over Transect T1 for the 1 kHz frequency component using precautionary and typical conditions during the winter and summer seasons. It is seen that the winter profile produces lower propagation losses compared with the summer condition. The reason for this is that the acoustic energy is directed down into the seabed sediment during the summer months and the energy is dissipated. During the winter months, the energy is directed away from the seabed so longer range propagation is more likely to occur. It is noted that precautionary conditions bring about longer range propagation compared with typical conditions. The key cause in this instance is the roughness of the sea surface. This has the effect of scattering the acoustic energy that impinges on the sea surface and this is less likely to continue to propagate to any distance. At a range of 35 km, the difference in propagation loss between precautionary and typical conditions is around 12 dB during summer months to 15 dB during the winter months.

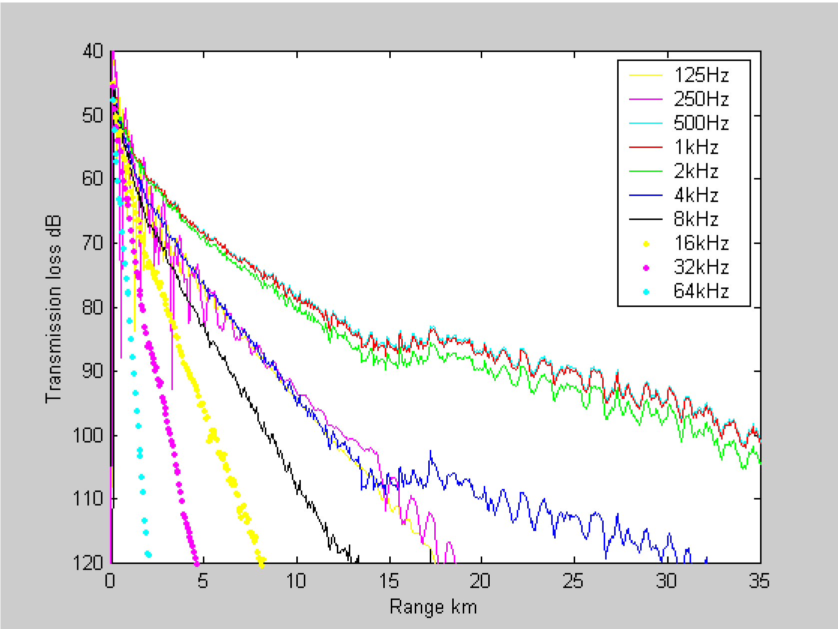


Figure 6-8. Predicted propagation loss in dB over Transect T1 using summer, typical conditions.

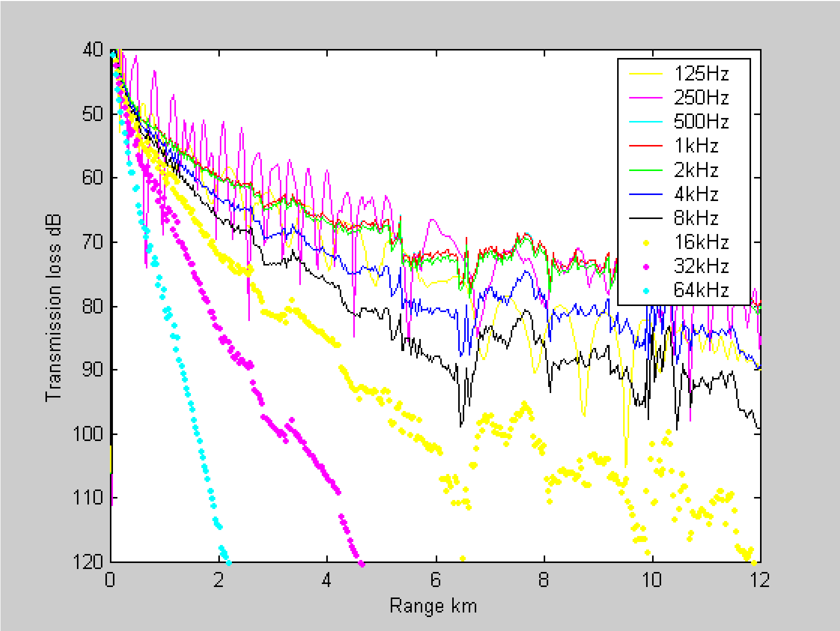


Figure 6-9. Predicted propagation loss in dB over Transect T2 using summer, typical conditions

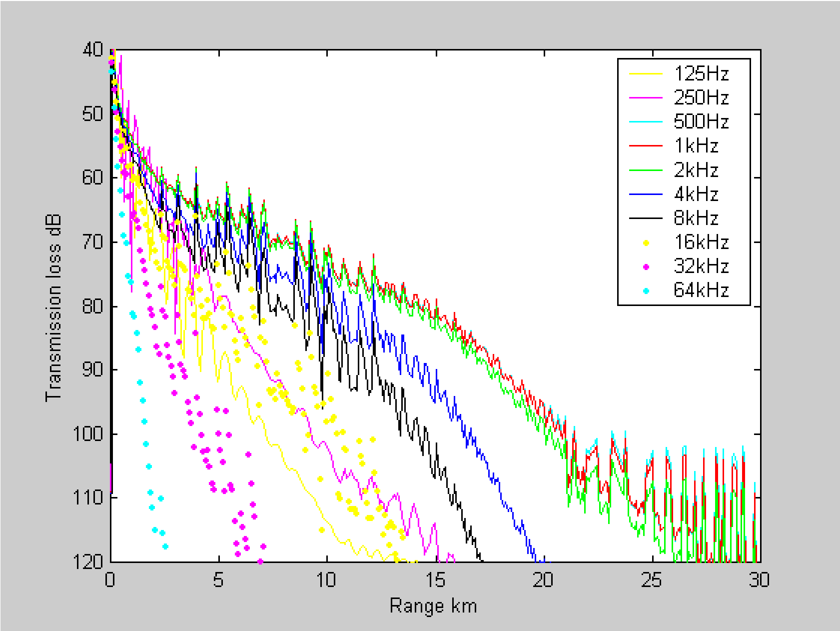


Figure 6-10. Predicted propagation loss in dB over Transect T3 using summer, typical conditions

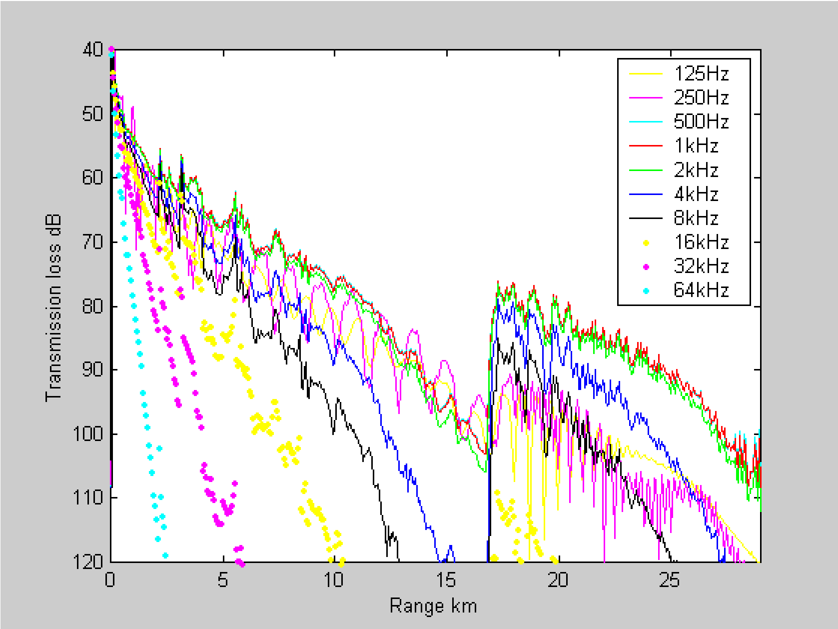


Figure 6-11. Predicted propagation loss in dB over Transect T4 using summer, typical conditions

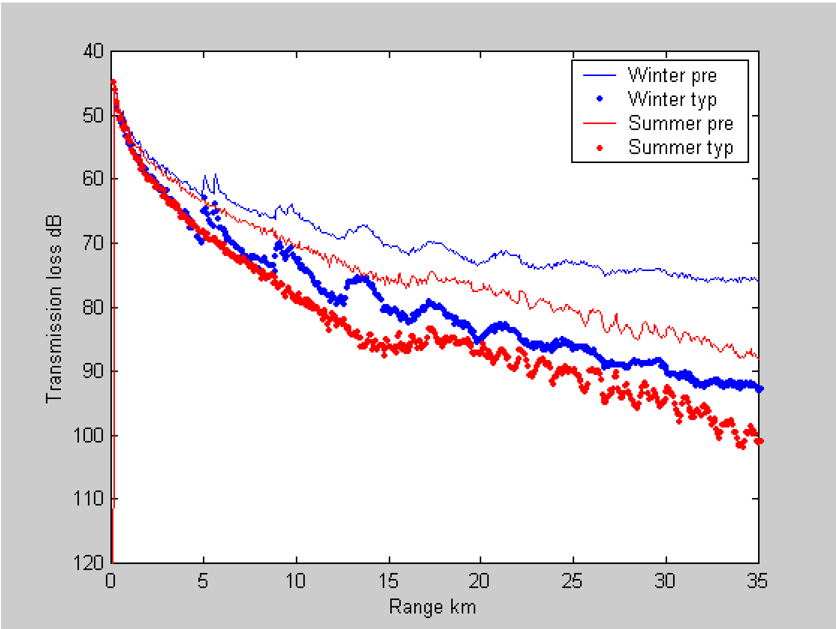


Figure 6-12. Predicted propagation loss in dB over Transect T1 comparing precautionary and typical conditions during winter and summer seasons

7. MODELLING RESULTS – UN-WEIGHTED NOISE

7.1 Introduction

This section of the report uses the acoustic modelling undertaken in Section 6 to predict the unweighted airgun array noise with range. Data are presented in terms of zero-to-peak level, un-weighted SEL and estimates are provided for RMS Sound Pressure Level with range for 1 second, 100 millisecond (msec) and 10 msec averaging times.

7.2 Un-weighted noise metrics

The un-weighted noise has also been calculated using the 1/3 octave band propagation modelling described in Section 6. This process involves calculating the 1/3 octave band levels of source noise from the spectral levels presented in Table 5-2, and then calculating the corresponding levels at range from the source by subtracting the propagation loss in each frequency band. The total sound energy at range from the source can be calculated by summing the energy in each frequency band. Hannay and Racca (2005) report that this technique has been validated against experimental data, and has proved accurate for estimating noise levels in the vicinity of seismic operations.

Using this method the modelling of underwater sound propagation in the deeper waters of the Moray Firth has indicated un-weighted geometric spreading loss factors (N) of either 17 or 18, and absorption losses from 1.1 to 2 dB.km^{-1} (Data presented in Figures 7-1 to 7-4). Where the sound enters very much shallower waters of less than 20 m depth near the coast, the modelling predicts a far more rapid attenuation of the sound.

To estimate the variation in zero to peak sound level with range, the propagation loss factors presented above have been applied to the zero to peak source level provided at the outset of this study (zero to peak level of 254 dB re.1μPa @ 1 m). At longer ranges from the source, particularly beyond 10 km, the effects of geometric dispersion and differential absorption of the high frequency components of the noise (see description in Section 5) mean that the peak noise is likely to be attenuated more rapidly. Hence, actual zero to peak noise levels at long range may be lower than those predicted here. The measurements of Senior *et al.* (2008) of the propagation of transient pressure waves in the same Moray Firth region, for example, indicate a slightly higher geometric attenuation factor of 20 (95% CI ± 1.2), but with a lower absorption loss factor of 0.4 dB.km^{-1} (95% CI ± 0.06).

Location	Water Depth	Geometric Loss (N)	Absorption Loss (α)	Reference
North Hoyle	11 to 26 m	17	1.1 dB.km^{-1}	Parvin *et al.*,2006
Kentish Flats	3 m	20	2.0 dB.km^{-1}	Parvin *et al.*,2006
Scroby Sands	4 to 43 m	20	3.0 dB.km^{-1}	Parvin *et al.*,2006
Barrow	10 to 30 m	18	0.3 dB.km^{-1}	Parvin *et al.*,2006
Burbo Bank	7 to 10 m	21 and 23	0.7 and 4.7 dB.km^{-1}	Parvin and Nedwell, 2006

Table 7-1. Summary of underwater sound transmission loss factors for peak to peak noise measured during pile driving operations for offshore wind farm construction.

Similar broadband propagation measurements of transient pressure waves in shallow UK waters during offshore wind farm construction have indicated peak noise level variation with geometric attenuation loss factors from 17 to 23, and absorption losses from 0.3 to 4.7 $dB.km^{-1}$ (See Table 7-1). Hence, due to strong interaction with the sea surface and seabed, propagation losses are high in shallow water regions compared with that in deeper waters. Section 7.5 discusses the variation in impact zones for geometric spreading loss factors (N) from 15 to 20.

7.3 RMS Sound Pressure Level duration

The use of RMS Sound Pressure Level to quantify the noise from a transient pressure pulse is more complex (Madsen *et al.* (2005), Thomsen *et al.* (2006)). As the RMS Sound Pressure Level is an average sound level over a given time period, the time period must be stated. The shorter the time period selected to contain the pulse, the higher will be the value of RMS Sound Pressure Level. The seismic industry uses the 90% RMS Sound Pressure Level, that is, the time window containing 90% of the pulse energy. RMS Sound Pressure Levels computed using this method are often referred to as 90% RMS Sound Pressure Levels. However, as the duration of the pulse increases with range the time averaging window will also increase with range. In the event that a long averaging time of 1 sec is used, the RMS Sound Pressure Level and SEL will be numerically equal.

To provide consistent and comparative results the approach that has been taken here is to calculate the RMS Sound Pressure Level using 1 second, 100 msec and 10 msec average RMS Sound Pressure Level values.

7.4 Results

The data in Figure 7-1 illustrates the zero to peak, and RMS Sound Pressure Level at mid-water (20 m) depth as it varies with range from the seismic source along Transect 1. Corresponding data for Transect 2, 3 and 4 are shown in Figures 7-2, 7-3 and 7-4 respectively. Within a few kilometres of the source the peak of the waveform would typically occur within 10 msec, with the subsequent bubble pulse waveform having a duration of the order of 100 ms. Hence, the Sound Pressure Level for these components of the pressure pulse are illustrated. At longer ranges, typically greater than 10 km, the individual components of the waveform are indistinct, and together with multiple reflections the overall waveform may last for a second or more. At these long ranges the 1 second average Sound Pressure Level is probably more appropriate.

Table 7-2 compares the predicted peak and RMS Sound Pressure Level data with underwater noise assessment criteria proposed by Southall *et al.* (2007), NMFS (1995) and NOAA (2006). Based on the peak noise criteria proposed by Southall *et al.* (2007) PTS auditory injury in cetaceans is only likely to occur within 25 m of the airgun array source, and in pinnipeds out to a range of 130 m. TTS auditory injury onset based on peak level noise extends to 58 m and 270 m respectively. These ranges are well within the near field of the airgun array and hence the actual levels are unlikely to be achieved.

If the more conservative criteria based on RMS Sound Pressure Levels are applied, then the modelling indicates an auditory injury zone for pinnipeds from 210 to 2400 m depending upon the RMS averaging time used, and a 180 dB re.1 μPa auditory injury zone for cetaceans that varies from 700 m to 5.6 km.

Figures 7-1 to 7-4 and Table 7-2 also indicate the predicted range for the airgun array pulses to have fallen to a level of 140 dB re.1 μPa (HESS, 1997). At long range, the pulse duration is likely to have extended in duration. The 1 second average data indicates that the sound will remain above a 140 dB re.1 μPa to a range of 19 km for propagation in the deeper waters of the Moray Firth (Transect 1). Where propagation occurs in shallower waters the transmission losses are higher and the 140 dB re.1 μPa, 1 second average Sound Pressure Level extends to ranges from 11.5 to 13 km.

Exposure limit	Effect	Range Transect 1	Range Transect 2	Range Transect 3	Range Transect 4
230 dB re 1 µPa (Peak)	PTS injury onset in cetaceans (Southall *et al*, 2007)	22 m	22 m	25 m	22 m
218 dB re 1 µPa (Peak)	PTS injury onset in pinnipeds (Southall *et al*, 2007)	100 m	100 m	130 m	100 m
224 dB re 1 µPa (Peak)	TTS injury onset in cetaceans (Southall *et al*, 2007)	45 m	45 m	58 m	45 m
212 dB re 1 µPa (Peak)	TTS injury onset in pinnipeds (Southall *et al*, 2007)	200 m	200 m	270 m	200 m
190 dB re 1 µPa (RMS) 10 ms 100 ms 1 sec	Auditory injury criteria – pinnipeds (NOAA, 2006)	2200 m 720 m 210 m	2200 m 720 m 210 m	2400 m 900 m 280 m	2000 m 700 m 220 m
180 dB re 1 µPa (RMS)) 10 ms 100 ms 1 sec	Auditory injury criteria – cetaceans (NOAA, 2006)	5600 m 2200 m 720 m	5600 m 2200 m 720 m	4700 m 2400 m 900 m	4600 m 2000 m 700 m
160 dB re 1 µPa (RMS)) 10 ms 100 ms 1 sec	Behavioural disturbance, level B harassment (US NMFS)	19 km 11.3 km 5.6 km	12 km 11 km 5.6 km	11.5 km 8 km 4.7 km	13.5 km 8.6 km 4.6 km
140 dB re 1 µPa (RMS)) 10 ms 100 ms 1 sec	Low level behavioural disturbance (HESS, 1997)	- 28 km 19 km	- 13.5 km 12 km	- 15.5 km 11.5 km	- 19 km 13.5 km

Table 7-2. Summary of effect ranges based on un-weighted noise assessment metrics for each Transect.

7.5 Variation with transmission loss

To provide an indication of the effect of propagation loss on the predicted impact zones, Table 7-3 compares the predicted impact ranges for PTS and TTS auditory injury based on peak level noise as proposed by Southall *et al.* (2007) for propagation conditions from 20 log r to 15 log r. The variability is a function of range, and hence for the longer ranges indicated in the table the impact zones can vary considerably (from 125 m to 630 m for pinniped TTS injury in the examples shown). Based on 17 log r propagation, the 160 dB re.1 µPa, 1 second average SPL would extend to a range of 17 km, and for 15 log r propagation, to a range of 63 km, in comparison with the 4.6 to 5.6 km ranges shown in

Table 7-2. It should be noted, however, that at these long ranges, propagation losses through absorption tend to dominate.

Exposure limit	Effect	20 log r	18 log r	17 log r	15 log r
230 dB re 1 µPa (Peak)	PTS injury onset in cetaceans (Southall *et al*, 2007)	16 m	22 m	26 m	40 m
218 dB re 1 µPa (Peak)	PTS injury onset in pinnipeds (Southall *et al*, 2007)	60 m	100 m	130 m	250 m
224 dB re 1 µPa (Peak)	TTS injury onset in cetaceans (Southall *et al*, 2007)	32 m	46 m	58 m	100 m
212 dB re 1 µPa (Peak)	TTS injury onset in pinnipeds (Southall *et al*, 2007)	125 m	220 m	300 m	630 m

Table 7-3. Variation of effect ranges and propagation conditions for peak un-weighted noise assessment metrics.

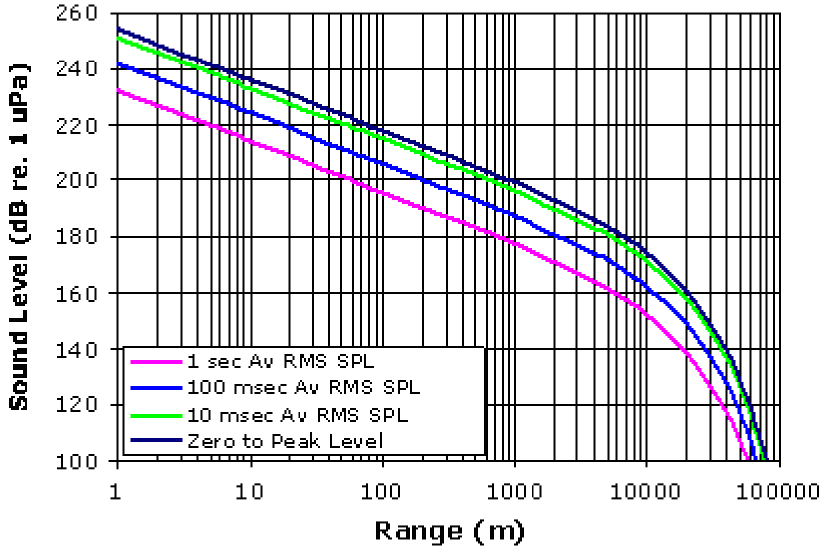


Figure 7-1. Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 3090 cubic inch seismic airgun array operations in the Moray Firth – Transect 1.

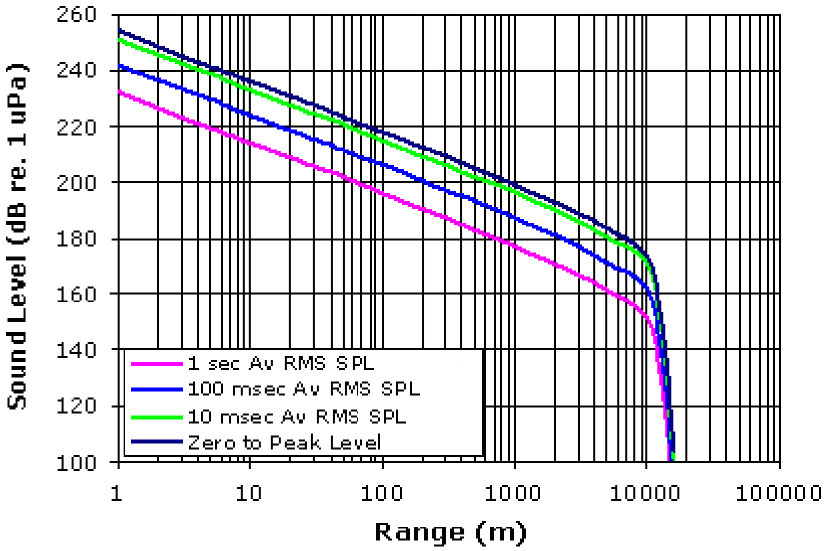


Figure 7-2. Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 3090 cubic inch seismic airgun array operations in the Moray Firth – Transect 2.

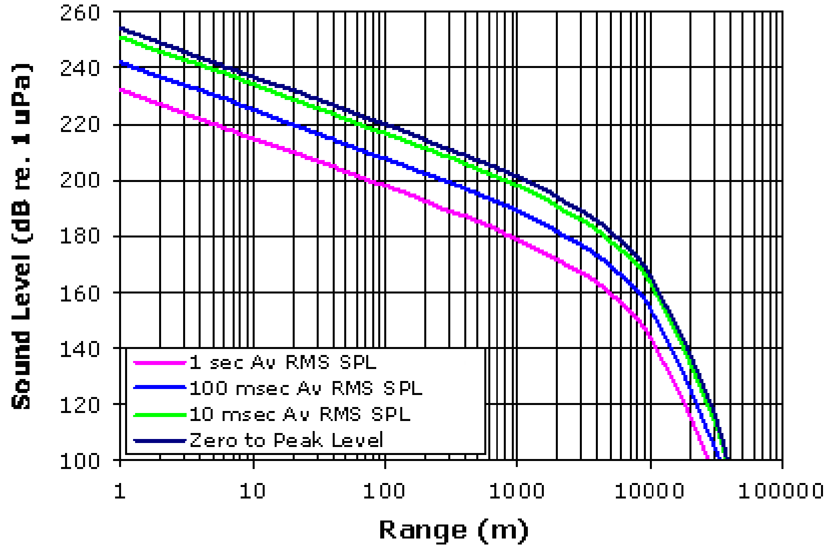


Figure 7-3. Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 3090 cubic inch seismic airgun array operations in the Moray Firth – Transect 3.

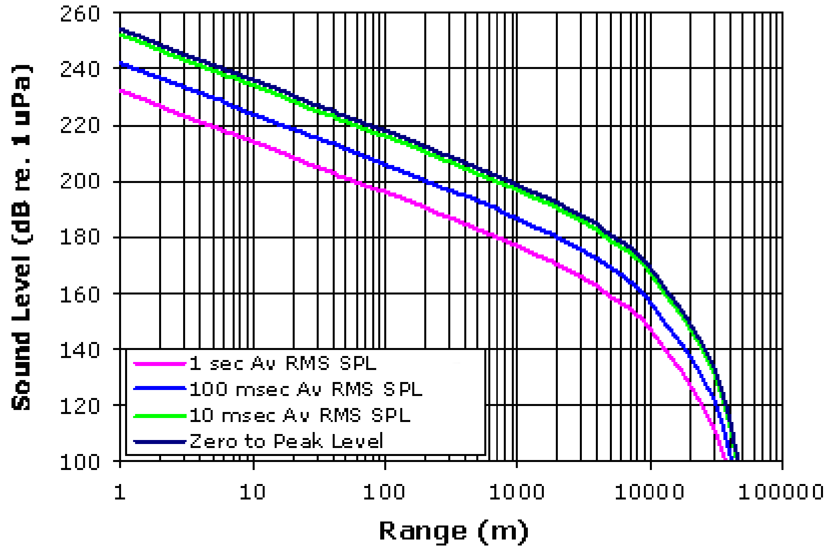


Figure 7-4. Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 3090 cubic inch seismic airgun array operations in the Moray Firth – Transect 4.

8. MODELLING RESULTS – M-WEIGHTED SEL

8.1 Introduction

This section of the report presents the predicted results for received sound levels at range from an airgun array to be used for seismic exploration in the Moray Firth. The data are presented in terms of un-weighted Sound Exposure Level, and using the M-Weighting filters for various marine mammal groups to determine M-Weighted SEL.

8.2 Analysis

The frequency dependent sound transmission loss modelling described in Section 6 was used to calculate received levels in 1/3 octave bands covering the frequency range from 10 Hz to 125 kHz. These levels were then used to calculate the un-weighted received Sound Exposure Level (SEL) of each seismic pulse, as it varies with range from the source. By applying the appropriate M-weighting filter as described by Miller *et al.* (2005) and Southall *et al.* (2007), the noise level was also calculated at each range in terms of:

- Mlf – weighted SEL for low frequency hearing cetaceans
- Mmf – weighted SEL for mid frequency hearing cetaceans
- Mhf – weighted SEL for high frequency hearing cetaceans
- Mpf – weighted SEL for pinnipeds

Using the approach used by Nedwell *et al.* (2007), Senior *et al.* (2008), and recommended from studies undertaken on behalf of the National Physical Laboratory (Robinson *et al*, 2009), a least-squares fit for each SEL metric has been applied to the acoustic propagation expression of the form;

$$RL = SL - N\log(r) - \alpha r \qquad \text{eqn. 8.1}$$

where RL (the received level) is the level at range r, SL is the Source Level noise, N is a factor for attenuation due to geometric spreading, and α is a factor for the absorption of sound in water and boundaries ($dB.km^{-1}$) (See Equation 3.

Figures 8-1 to 8-4 inclusive show the results of this modelling for un-weighted SEL, and for each of the M-weighted SEL metrics for the four acoustic propagation transects for typical summer conditions. Individual results for each impact criterion and along each transect are summarised in Tables 8-1 to 8-3 inclusive. For comparison, the auditory injury criteria proposed by Southall *et al.* (2007) are also shown.

8.3 Transect 4 variation

The modelling presented in Section 6 highlighted an inconsistent variation in the acoustic propagation as the sound reaches the very shallow water regions at a range of 17 km along Transect 4 (See Figure 6-11). Consequently, the calculated data has a poor fit to the propagation model over this region. For comparison, Figure 8-4 (Transect 4) presents the SEL data (pink data points) together with the fit (pink line) that was used in the subsequent modelling. It can be seen that an accurate fit is obtained over the modelled ranges from source to 16 km, but that the calculated SEL at a range of 20 km is approximately 10 dB higher than the data fit. As a result of this variation, the data point at 30 km is 10 dB lower than the fit. This study could have calculated more data points and dispensed with the fitted data over this region, but as the modelling indicates that the noise in this region is only marginally above background noise (approximately 10 dB) it does not influence the impact zones and may be considered to give rise to a low likelihood of behavioural disturbance to the species of interest to this study.

8.4 Results

The results in Figures 8-1 to 8-4 indicate that the single shot auditory injury range is within close proximity of the seismic array. The predicted single shot auditory injury ranges for mid and high frequency hearing cetaceans are within the near field of the acoustic emissions from the airgun array. The ranges vary from 15 m to 80 m for cetaceans and 140 m to 240 m for pinnipeds.

The modelling of underwater sound propagation in the Moray Firth, presented in terms of SEL and M-weighted SEL metrics, indicates geometric spreading loss factors (N) of either 18 or 19, and an absorption loss from 0.3 to 2.1 $dB.km^{-1}$. The specific values vary with each M-weighting metric depending upon the dominant frequency components. As would be expected, the data highlights that the un-weighted SEL has the highest level at each range, with each M-weighting metric removing a proportion of either the high or low frequency sound energy.

The data indicates that the highest received sound levels occur as sound propagates through relatively deep water (Transect 1). Transects 3 and 4 indicate the highest absorption due to propagation in shallower waters near Guillam Bank and off the coast of Cromarty (Transect 3) and where the sound enters shallower waters near the coast at Spey Bay (Transect 4). The data for Transect 2 indicates that the SEL remains above 150 dB re.1μPa^2s and above 140 dB re.1μPa^2s M-Weighted SEL over a range of 10 km, a point which is approximately 5 km off the coast at Covesea Skerries. Closer into shore, greater sound attenuation occurs and the SEL decreases rapidly.

The results in Table 8-2 indicate that TTS auditory injury is likely to occur in cetaceans at ranges of 100 m to 550 m and between 700 m and 1400 m for pinnipeds in each case, depending on transect.

For the auditory injury criteria propoased by NOAA (2006), the results in Table 8-3 show that PTS ranges are around 10 m while TTS arises between 110 m and 140 m.

Marine Mammal Species	criteria	Transect 1	Transect 2	Transect 3	Transect 4
Cetaceans (M_{lf}) Low Frequency	PTS Auditory injury 198 dB re 1 μPa^2.s	50 m	70 m	80 m	70 m
Cetaceans (M_{mf}) Mid Frequency	PTS Auditory injury 198 dB re 1 μPa^2.s	25 m	28 m	30 m	40 m
Cetaceans (M_{hf}) High Frequency	PTS Auditory injury 198 dB re 1 μPa^2.s	15 m	18 m	20 m	20 m
Pinnipeds (M_{pf})	PTS Auditory injury 186 dB re 1 μPa^2.s	150 m	190 m	240 m	140 m

Table 8-1. Single shot auditory injury range based upon PTS criterion proposed by Southall et al. (2007).

Marine Mammal Species	criteria	Transect 1	Transect 2	Transect 3	Transect 4
Cetaceans (M_{lf}) Low Frequency	TTS onset cetaceans 183 dB re 1 μPa^2.s	300 m	450 m	550 m	450 m
Cetaceans (M_{mf}) Mid Frequency	TTS onset cetaceans 183 dB re 1 μPa^2.s	140 m	190 m	250 m	300 m
Cetaceans (M_{hf}) High Frequency	TTS onset cetaceans 183 dB re 1 μPa^2.s	100 m	130 m	150 m	150 m
Pinnipeds (M_{pf})	TTS onset pinnipeds 171 dB re 1 μPa^2.s	800 m	1200 m	1400 m	700 m

Table 8-2. Single shot M-Weighted SEL TTS onset auditory injury range based upon criterion proposed by Southall et al. (2007).

criteria	Transect 1	Transect 2	Transect 3	Transect 4
PTS Auditory Injury 215 dB re 1 μPa^2.s	9 m	9 m	10 m	9 m
TTS Auditory injury 195 dB re 1 μPa^2.s	110 m	110 m	140 m	110 m

Table 8-3. Single shot PTS and TTS auditory injury range based upon the criterion proposed by NOAA (2006).

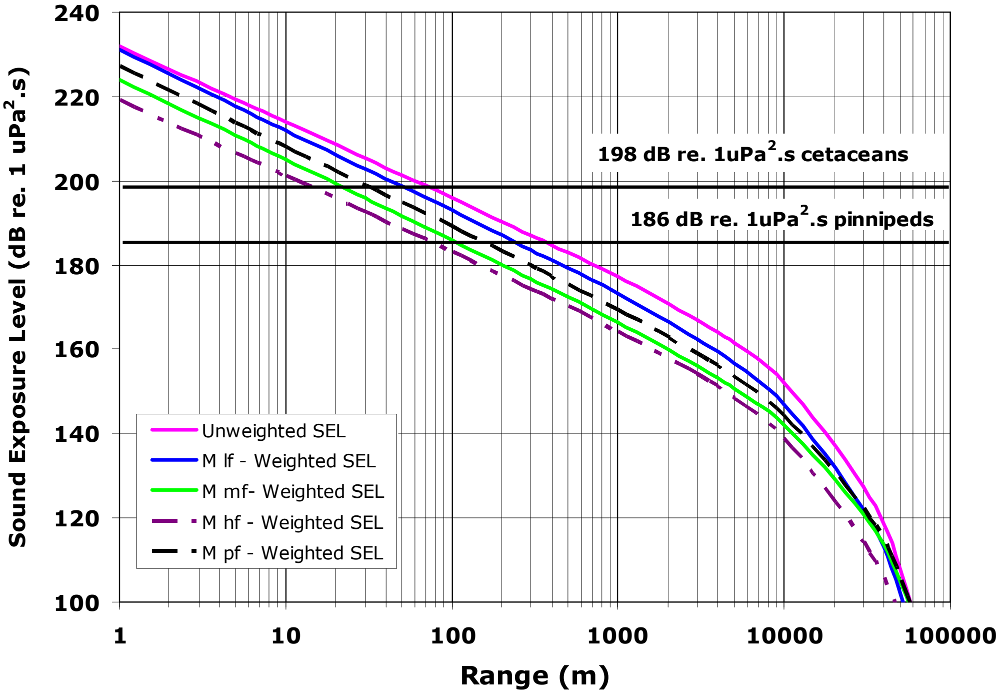


Figure 8-1. Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (Transect 1 – Summer).

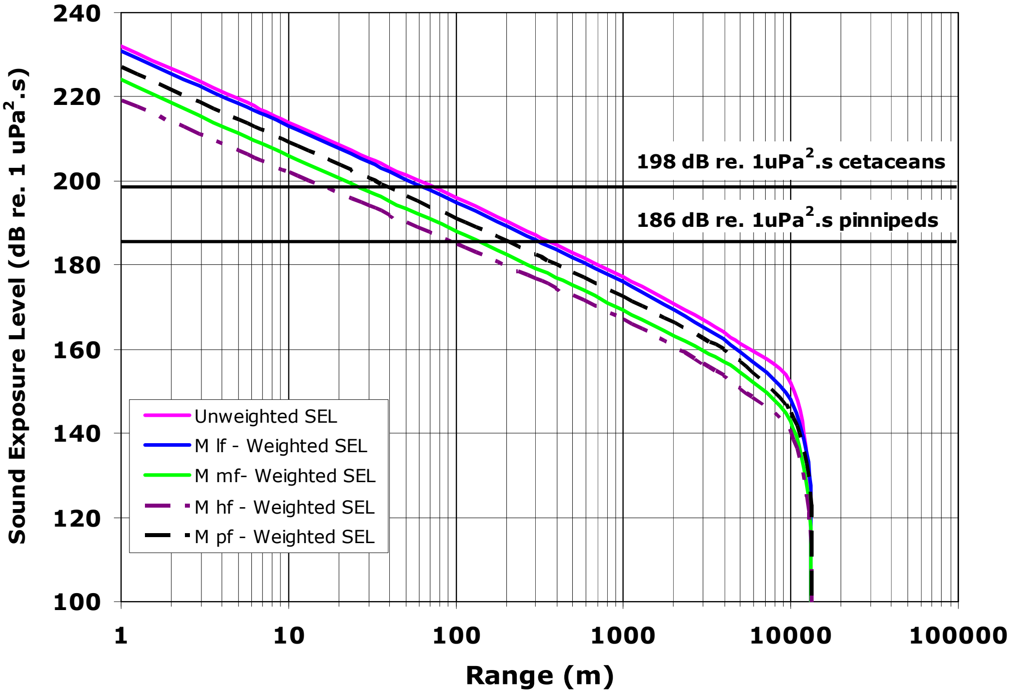


Figure 8-2. Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (Transect 2 – Summer).

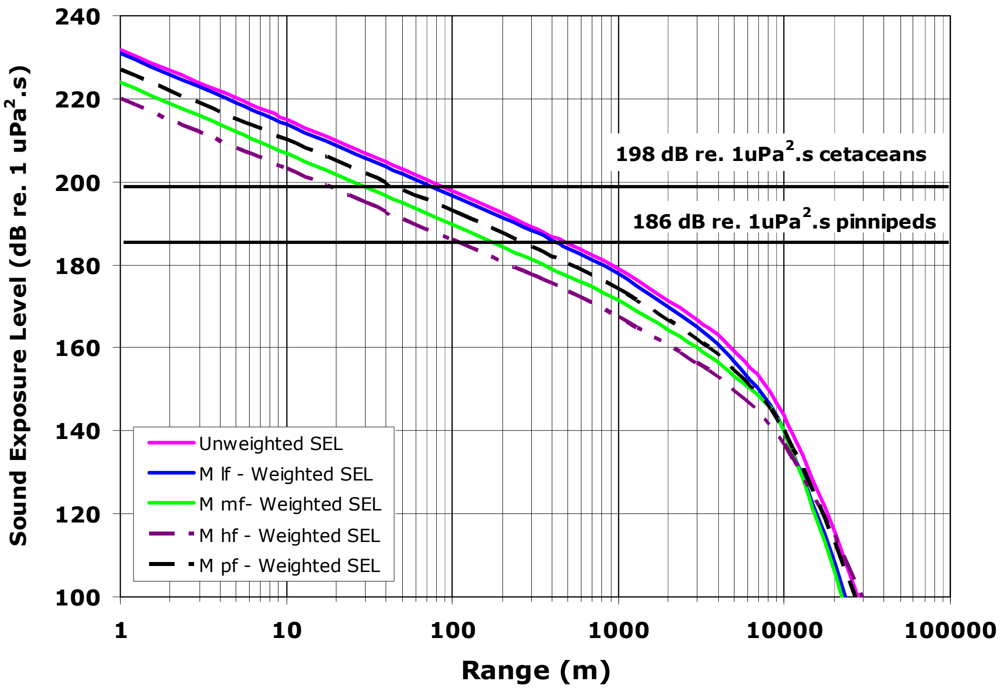


Figure 8-3. Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (Transect 3 – Summer).

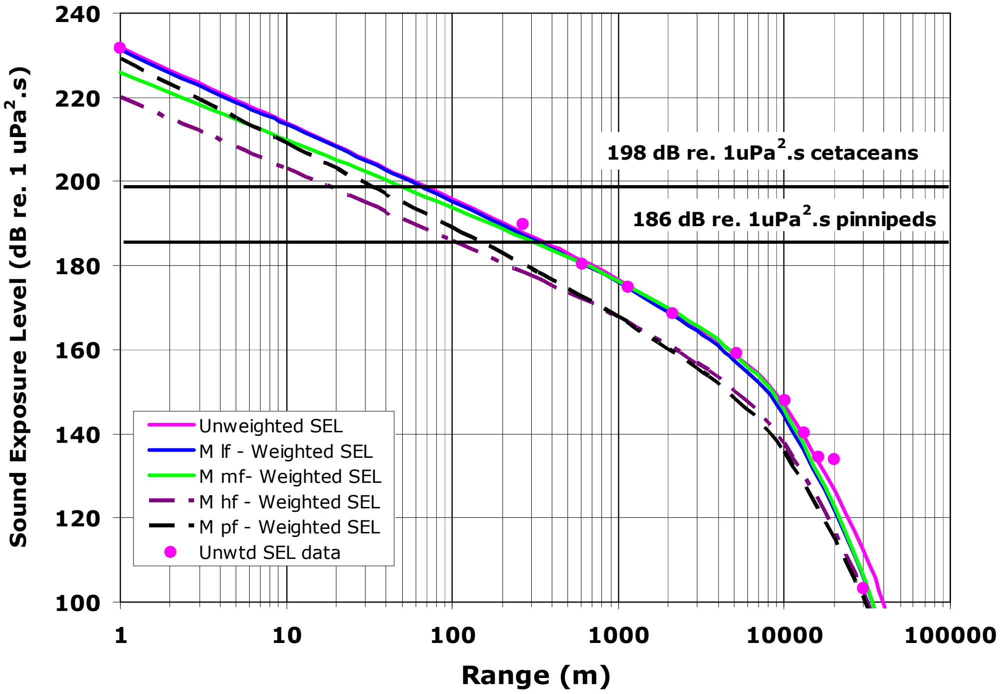


Figure 8-4. Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (Transect 4 – Summer).

9. MODELLING RESULTS – CUMULATIVE SEL

9.1 Introduction

This section of the report calculates cumulative SEL for a number of scenarios where marine mammals are either assumed to remain stationary, or move away from the seismic source at a defined swim rate. The cumulative noise level calculations are based on the levels with range presented in the previous section.

9.2 Moving animal and vessel

Cumulative M-weighted SEL has been calculated for 3090 cubic inch airgun array operations in the Moray Firth, with the survey vessel moving along a seismic survey line, firing every 18.75 m, and at a firing rate of once every 7 seconds. Data were calculated with the marine mammal broadside of the airgun array, and then moving away at a rate (escape speed) of 1 ms^{-1}, using a similar method to that of Hannay *et al* (2009) and SMRU (2007) on behalf of COWRIE. Hence, the model incorporates both a moving survey vessel and marine animal, and can be varied depending upon the airgun array firing sequence and local acoustic propagation conditions.

The data in Figure 9-1 illustrates the increase in cumulative M_{lf} – weighted SEL for a marine mammal at range of 250 m from the seismic airgun array. For this case, the data indicates that the animals will receive a cumulative SEL during successive airgun array firings that increases toward the 198 dB re 1 μPa^2.s auditory injury criterion proposed by Southall *et al.* (2007). Animals that are at a closer range would receive a cumulative M_{lf} – weighted SEL that increases above the 198 dB re 1 μPa^2.s, and hence the data indicates that auditory injury may occur. At greater ranges (Table 9-1 presents data for start ranges from 10 m to 4000 m), the data indicates that marine mammals are able to escape the source, with the total received cumulative M_{lf} – weighted SEL remaining below the auditory injury criteria. In this case, the critical range is 250 m. The modelling indicates that at this range marine mammals are just able to swim clear of the airgun array operations without incurring a cumulative SEL above 198 dB re 1 μPa^2.s.

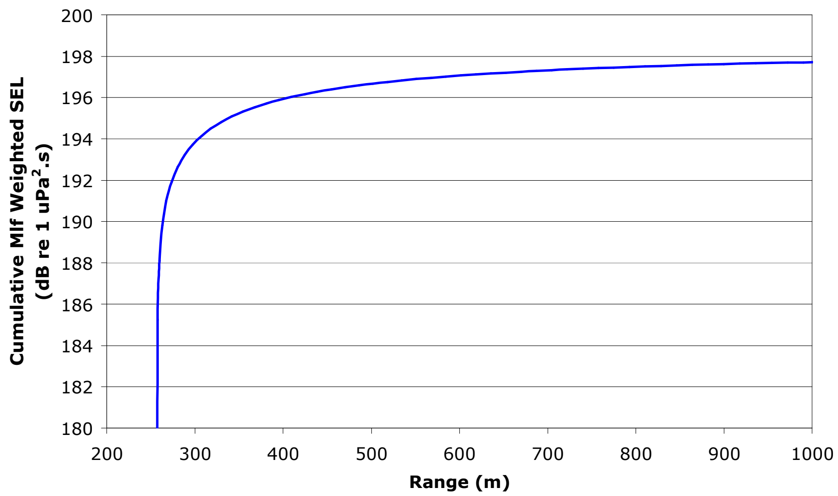


Figure 9-1. Predicted cumulative Mlf-weighted SEL for a marine mammal moving away at an escape speed of 1 ms^{-1} from 3090 cubic inch seismic airgun array operations in the Moray Firth. Data are presented for a marine mammal at a start range of 250 m.

Table 9-1 presents the results of cumulative M-weighted SEL calculations for the marine mammal groups proposed by Southall et al., (2007) based on the same survey operating parameters and marine mammal swim speed. The data highlights that if it is assumed that marine mammals will swim away from a high level noise source, then, based upon the criteria proposed by Southall et al. (2007), auditory injury is unlikely to occur unless the animal is in very close proximity to the source at the start of operations. The shaded boxes highlight the critical escape range indicated by the modelling in each case. These are also reproduced in Table 9-2 for comparison.

Start range (m)	**Mlf Wtd SEL** (dB re 1 μPa^2.s)	**Mmf-Wtd SEL** (dB re 1 μPa^2.s)	**Mhf –Wtd SEL** (dB re 1 μPa^2.s)	**Mpf – Wtd SEL** (dB re 1 μPa^2.s)
10	213	206	202	209
20	209	202	199	205
30	207	200	197	203
50	205	198	195	201
100	202	195	193	198
250	198	191	189	194
500	195	188	186	191
1000	191	185	183	187
2000	187	180	178	183
4000	181	175	173	177

Table 9-1.Summary of predicted cumulative M-weighted SEL for a marine mammal moving away at an escape speed of 1 ms^{-1} from 3090 cubic inch seismic airgun array operations in the Moray Firth. Data are presented for marine mammals at start ranges from 10 m to 4000 m – Transect 1.

Marine Mammal Species	Auditory injury criteria (Southall *et al.* (2007)	Start range from seismic survey line (m)
Cetaceans – Low Frequency	198 dB re 1 μPa^2.s (M_{lf})	250 m
Cetaceans – Mid Frequency	198 dB re 1 μPa^2.s (M_{mf})	50 m
Cetaceans – High Frequency	198 dB re 1 μPa^2.s (M_{hf})	23 m
Pinnipeds	186 dB re 1 μPa^2.s (M_{lf})	1100 m

Table 9-2. Summary of maximum range for auditory injury in species of marine mammal based upon cumulative M-Weighted SEL for animals moving away at a speed of 1 ms^{-1} from 3090 cubic inch seismic airgun array operations in the Moray Firth – Transect 1.

Table 9-3 presents the results of modelling for the same survey vessel / animal scenario, but using the PTS and TTS injury criteria proposed by NOAA (2006), and adopted in the recent study for COWRIE by SMRU (2007) for estimating auditory injury zones based upon cumulative SEL from successive pile strikes. This criteria does not use the M-weightings that were developed later by Southall *et al.* (2007), but are based on un-weighted SEL that caused auditory injury in captive marine mammals exposed to short duration (1 second), narrow band tones (Schlundt *et al*, 2000)

The PTS auditory range predicted is well within the near field of the source and hence indicates that this form of injury is unlikely to occur. The data predicts that an un-weighted cumulative SEL of greater than 195 dB re 1 μPa^2.s will occur for marine mammals within a range of 940 m.

Injury Criteria	Injury criteria	Start range from seismic survey line (m)
PTS from cumulative SEL (NOAA, 2006)	215 dB re 1 μPa^2.s (Unweighted)	11 m
TTS from cumulative SEL (NOAA, 2006)	195 dB re 1 μPa^2.s (Unweighted)	940 m

Table 9-3. Summary of maximum range for auditory injury in species of marine mammal based upon cumulative unweighted SEL for animals moving away at a speed of 1 ms^{-1} from 3090 cubic inch seismic airgun array operations in the Moray Firth.

9.3 Moving vessel, stationary population.

A second cumulative noise exposure scenario has also been modelled to investigate the build up of noise exposure upon resident marine mammal populations in the Moray Firth. In this scenario the build up of noise exposure using the cumulative SEL has been used to investigate the noise exposure in a particular region as the survey vessel and airgun array moves along a survey line, turns, and then starts to operate again as the vessel moves away along the next survey line. For the purposes of this analysis it has been assumed that the survey operations commence again immediately, with no opportunity for recovery by the animal from the noise exposure arising from the previous survey line. It is recognised that in practice the survey vessel will take a considerable time to turn and realign itself before firing operations re-commence.

For consistency, the cumulative M-weighted SEL has been calculated for 3090 cubic inch airgun array operations in the Moray Firth, with the survey vessel moving along a seismic survey line, firing every 18.75 m, and at a firing rate of once every 7 seconds.

9.3.1 Covesea Skerries region

Figure 9-2 presents the predicted single shot (top graph) and corresponding cumulative Mhf – weighted SEL (bottom graph) received underwater noise for a typical marine mammal population (bottlenose dolphin) located 4 km off of Covesea Skerries (see Figure 9-3), and remaining in this region whilst the airgun array operates along a survey line toward, and then away from the region.

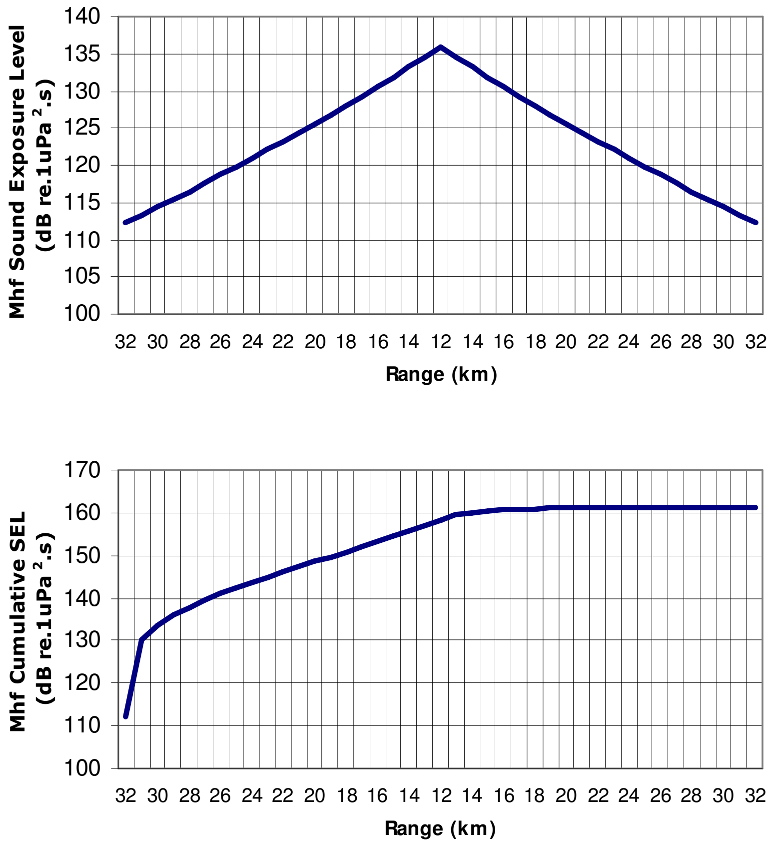


Figure 9-2. Predicted single shot and Cumulative Mhf-Weighted Sound Exposure Level for stationary bottlenose dolphin located 4 km off Covesea Skerries during seismic airgun array operations in the Moray Firth.

The Mhf weighted SEL has been calculated as the airgun array operates from a range of 32 km to the point at the southern perimeter of the proposed survey area, a position 12 km from the marine mammal population and 16 km from shore, and then returning along the next survey line (See Figure 6-2).

The single shot data (top graph) indicates that the Mhf Sound Exposure level varies from 112 dB re.1μPa^2.s with the airgun array operating at a range of 32 km, to a maximum of 136 dB re.1μPa^2.s at the closest operating range of 12 km on the southern perimeter of the survey region. The cumulative Mhf weighted data (bottom graph) presents the corresponding build up of received noise for marine mammals 4 km off of the coast at Covesea Skerries. This analysis indicates a cumulative Mhf weighted Sound Exposure Level of 161.4 dB re.1μPa^2.s. The build up of noise occurs during a total of over 2100 airgun array firings, over a 4 hour period (14900 seconds). The predicted un-weighted cumulative SEL was 174 dB re.1μPa^2.s. Based on the criteria proposed by Southall *et al.* (2007) the levels of single shot received noise are well below those likely to cause behavioural disturbance, and the cumulative noise energy is well below the levels that may cause auditory injury.

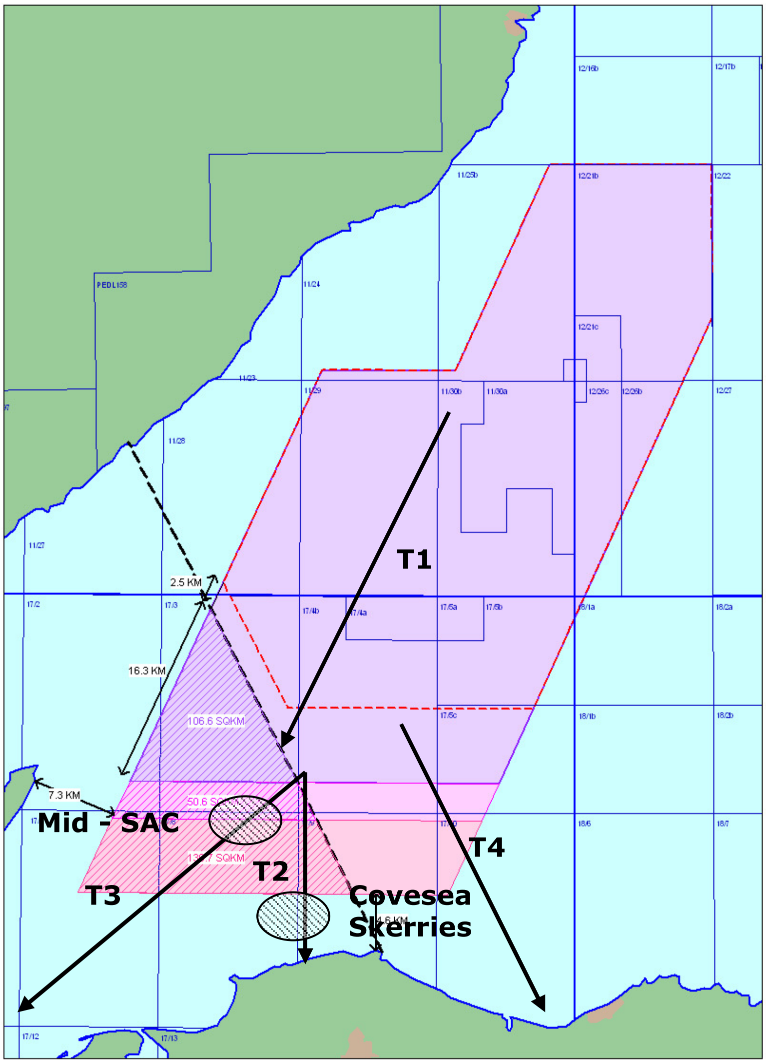
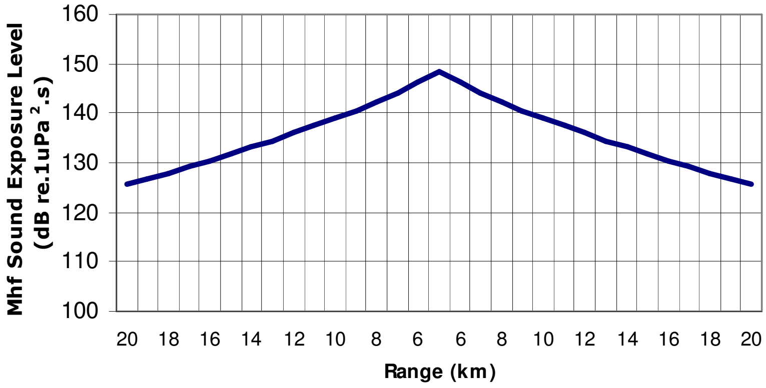


Figure 9-3. Moray Firth survey region with marine mammal populations indicated.

9.3.2 Middle of SAC.



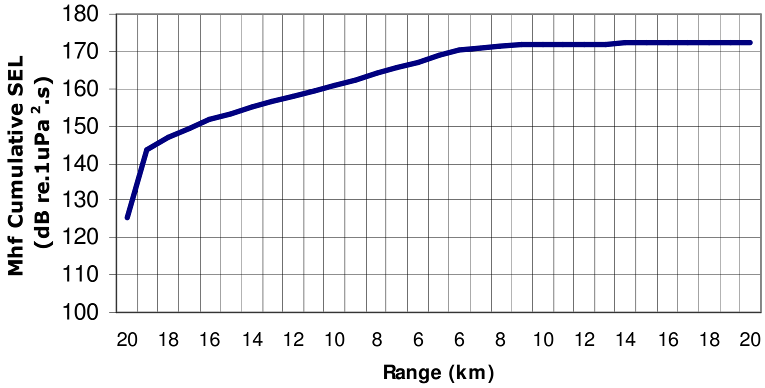


Figure 9-4. Predicted single shot and Cumulative Mhf-Weighted Sound Exposure Level for stationary high frequency hearing marine mammals located 5 km off of the south-west of the survey region in the middle of the SAC area, during seismic airgun array operations in the Moray Firth.

Figure 9-4 presents similar single shot and cumulative Mhf weighted SEL for marine mammals within the SAC area, at a distance of 5 km from the southern perimeter of the proposed survey area (See Figure 9-3). For this case the noise has been assessed as the survey vessel moves along a survey line initially at a distance of 20 km, closing to a distance of 5 km over a period of 1½ hours (5593 seconds), before turning and then moving away along a parallel survey line to a distance of 20 km.

For this case the modelling predicts single shot Mhf weighted SELs that vary from 126 dB re.1μPa^2.s with the survey vessel at a range of 20 km, to 148 dB re.1μPa^2.s at 5 km range. The corresponding cumulative Mhf weighted SEL for the 3 hour period reaches a level of 172 dB re.1μPa^2.

9.3.3 Survey area cumulative SEL

The closer that the survey vessel and airgun array come into to contact with marine mammal populations the higher the received sound exposure on the animals. To assess the cumulative SEL for marine mammal populations within the proposed Moray Firth survey area the noise energy has been modelled as the survey vessel moves along a survey line from a distance of 30 km, to the closest range adjacent to the population, and then moves away again to a distance of 30 km. Hence the noise has been modelled over 60 km (± 30 km) survey line, with a static marine mammal population at the mid-point (See Figure 9-5).

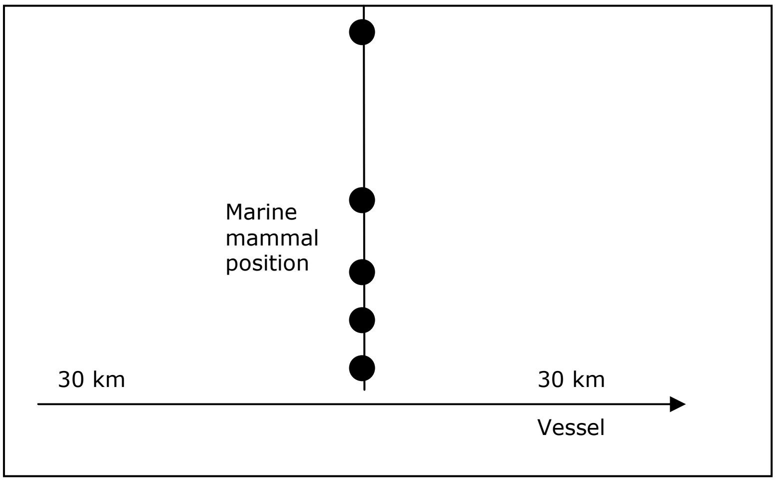


Figure 9-5. Illustration of marine mammal positions relative to survey line used for static cumulative SEL modelling

Figure 9-6 presents a summary of this data using the un-weighted and M-weighted cumulative SEL metrics. Where the survey line passes at the closest range of 10 km, the cumulative SEL and M-Weighted SEL remains below 180 dB re.1μPa^2.s. Where the survey line brings the vessel into closer contact with marine mammals the cumulative SELs are higher. Where the survey line brings the airgun array sound source to a range of 1000 m (at its closest passing point) the data (Figure 9-6) indicates a cumulative un-weighted SEL of 196 dB re.1μPa^2.s, and cumulative M-weighted SELs that vary from 186 re.1μPa^2.s for high frequency hearing cetaceans (Mhf) to 195 dB re.1μPa^2.s for marine animals that hear at low frequencies (Mlf).

Table 9-3 presents a summary of the range at which the auditory injury criteria proposed by Southall *et al.* (2007), and NOAA (2006) would be exceeded based upon a static marine mammal, with the survey vessel moving from and to a range of 30 km. The data highlights that the airgun array would have to pass very close to a marine mammal for the cetacean auditory injury criteria to be exceeded (ranges from 55 m to 520 m). These ranges agree well with the JNCC guidance (JNCC, 2004) for 500 m mitigation zones for seismic surveys. As Southall *et al.* (2007) propose a lower auditory injury criterion for pinnipeds, the modelling indicates that the vessel would have to pass within 2300 m for there to be a likelihood of auditory injury.

Cumulative SEL injury criteria are based on the total energy of the exposure. The individual airgun array pulses are at high pressure levels, but occur over a very short time period. Coupled with the low firing rate, once every 7 seconds, the seismic airgun noise has a low duty cycle and hence, compared for example with continuous wave sonar, has comparatively low total (cumulative) energy. However, each individual pressure pulse may be extremely loud and although it may not cause injury, it is likely to cause behavioural disturbance over considerably greater range.

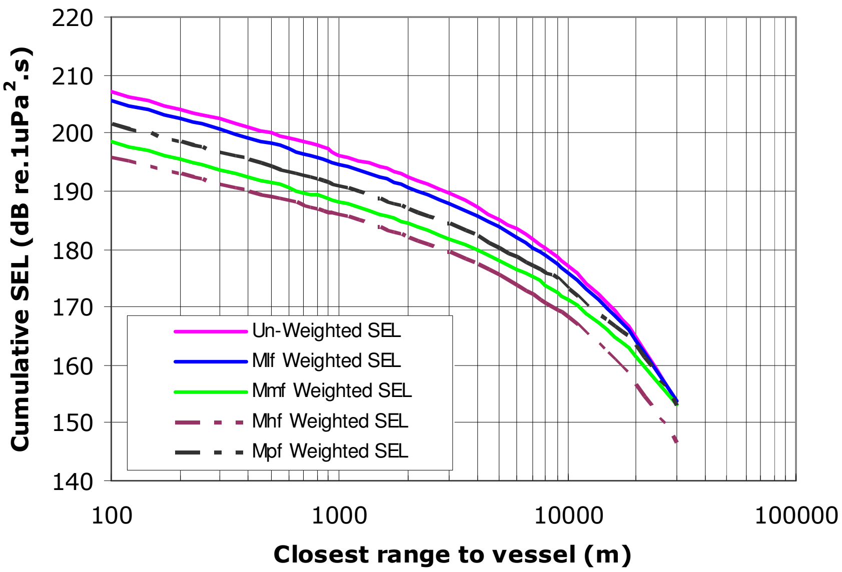


Figure 9-6. Summary of predicted cumulative Sound Exposure Level for stationary marine mammals during 3090 cubic inch airgun array in the Moray Firth operations along a ± 30 km survey line. (Data are compared in terms of the closest approach distance to the survey vessel.)

Marine Mammal Species	Auditory injury criteria (Southall *et al.* (2007)	Closest range to airgun array survey line (m)
Auditory injury Cetaceans – Low Frequency	198 dB re 1 μPa^2.s (M_{lf}) (Southall *et al.* (2007)	520 m
Auditory injury Cetaceans – Mid Frequency	198 dB re 1 μPa^2.s (M_{mf}) (Southall *et al.* (2007)	110 m
Auditory injury Cetaceans – High Frequency	198 dB re 1 μPa^2.s (M_{hf}) (Southall *et al.* (2007)	55 m
Auditory injury Pinnipeds	186 dB re 1 μPa^2.s (M_{lf}) (Southall *et al.* (2007)	2300 m
PTS from cumulative SEL	215 dB re 1 μPa^2.s SEL (NOAA, 2006)	22 m
TTS from cumulative SEL	195 dB re 1 μPa^2.s SEL (NOAA, 2006)	2000 m

Table 9-3. Summary of closest range to seismic survey line without exceeding proposed auditory injury criteria for cumulative SEL. (Data are based on predicted cumulative SEL for a stationary marine mammal, with airgun array operations along a ± 30 km survey line in the Moray Firth.

10. MODELLING RESULTS – HEARING THRESHOLD COMPARISON

10.1 Introduction

This section of the report compares the predicted received levels of seismic airgun array noise with published peer review hearing threshold data for species of marine mammal. The received levels of 1/3 octave band noise are compared with marine mammal hearing threshold and background sea noise to provide an indication of signal to noise with range. The data also illustrates the frequency components of the seismic array gun noise that contribute to the perceived loudness of the noise by marine mammals as it varies with range.

10.2 Hearing threshold data

Figure 10-1 presents cited audiogram data for species of marine mammal considered in this study. The audiogram data highlights that marine mammal species such as the bottlenose dolphin and the harbour porpoise are sensitive to a very broad bandwidth of sound. The audiogram data presented in Figure 10-1 indicates that they are responsive at frequencies from 100 Hz to 170 kHz. However, current auditory sensitivity data for these species does not extend to frequencies below 75 Hz for the bottlenose dolphin, or 250 Hz for the harbour porpoise. Hence, the approach that has been taken here is to use the hearing threshold data over the frequency ranges that are available, but when extrapolating to low frequency, to use the same approach as that of Southall *et al.* (2007) and Miller *et al.* (2005) and apply a consistent roll-off of sensitivity with range in accordance with the M-weighting factors applied to SEL data.

Figure 10-2 presents the underwater hearing threshold data for several species of seal. The data for the common (harbour) seal from Kastak and Schusterman (1998) indicates that seals have better low and mid-frequency hearing than the harbour porpoise and bottlenose dolphin, but that these species are not as sensitive to very high frequency underwater sound.

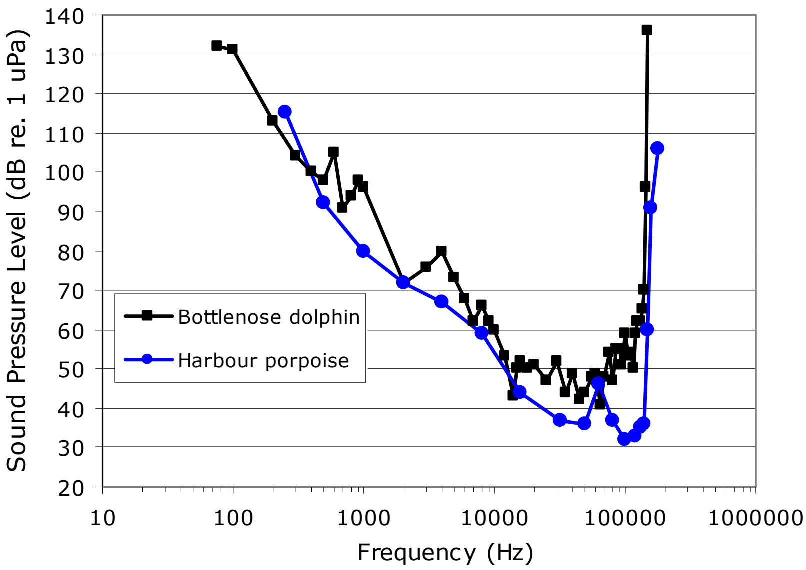


Figure 10-1. Audiogram data for the bottlenose dolphin(Johnson, 1967) and for the harbour porpoise(Kastelein et al, 2002).

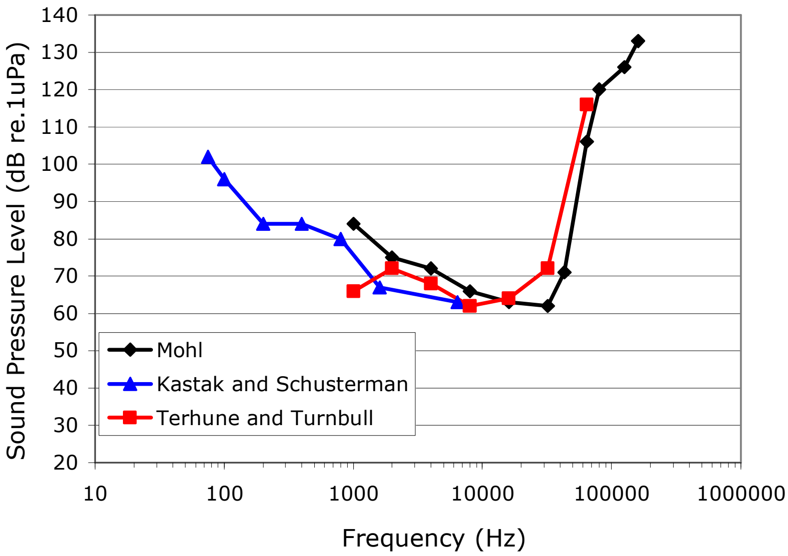


Figure 10-2. Audiogram data for the harbour seal from Møhl (1968), Kastak and Schusterman (1998) and Terhune and Turnbull (1995).

10.3 1/3 octave band noise comparison

Predicted 1/3 octave band noise levels with range can be compared directly with published marine mammal auditory thresholds. However, the problem when applying this to a pressure wave such a seismic airgun noise is that the audiogram data is typically obtained using continuous sound signals where the duration issue is removed by having a long duration signal, typically greater than 1 second. However, the discussion in Section 7 highlighted that, at ranges of approximately 10 km and greater, the seismic array noise is likely to be spread over a much longer time period, typically of 1 second or more.

Figures 10-3 to 10-5 illustrate the predicted 1/3 octave band levels of seismic airgun array noise as they vary with range from the source. Data at each range are presented for averaging times from 1 ms to 1 second. The levels have been calculated from the source levels of noise and propagation modelling presented in Section 6. Data are presented for the 1/3 octave band centred at 100 Hz (Figure 10-3), at 1 kHz (Figure 10-4) and at 20 kHz (Figure 10-5). These frequencies have been selected to coincide with the peak levels of noise from the airgun source, a typical mid-frequency where propagation losses are low, and the peak hearing sensitivity of small cetaceans, respectively. For comparison the hearing threshold of the bottlenose dolphin, harbour porpoise and for seals in each frequency band are also shown (the 100 Hz data for the harbour porpoise is an extrapolation based on Mhf – Weighting sensitivity roll off of Southall *et al.* (2007) and Miller *et al.* (2005)). Background sea noise levels for the corresponding 1/3 octave bands are also presented. These are based on the data for the Outer Moray Firth and Inner Moray Firth shown in Figures 4-1 and 4-2 respectively.

Assessing the noise in critical bands provides an indication of the level of the noise in comparison with audiometric levels. The data at 100 Hz and 20 kHz for example, highlight that marine mammals that hear predominantly high frequency noise are unlikely to perceive these sounds at ranges beyond 10 km. The high levels of propagation loss effectively remove the 100 Hz and 20 kHz noise to levels at or below hearing threshold (see Section 6 above). In comparison, the 1 kHz noise has much lower propagation losses and at ranges of 10 km and 20 km is still above hearing threshold, therefore is at a level that may be heard by various marine species. Species of seal in particular have good mid-frequency range hearing and so may hear these components of the airgun array noise at long range.

Comparison of the seismic noise with 1/3 octave band background sea noise levels suggests that the noise may remain above sea noise levels to ranges beyond 10 km at a frequency of 100 Hz and beyond 20 km at a frequency of 1 kHz. In contrast, the 20 kHz data suggests that the very high frequency components of the seismic noise will be masked by the background sea noise in both the Outer and Inner Moray Firth at ranges beyond 10 km.

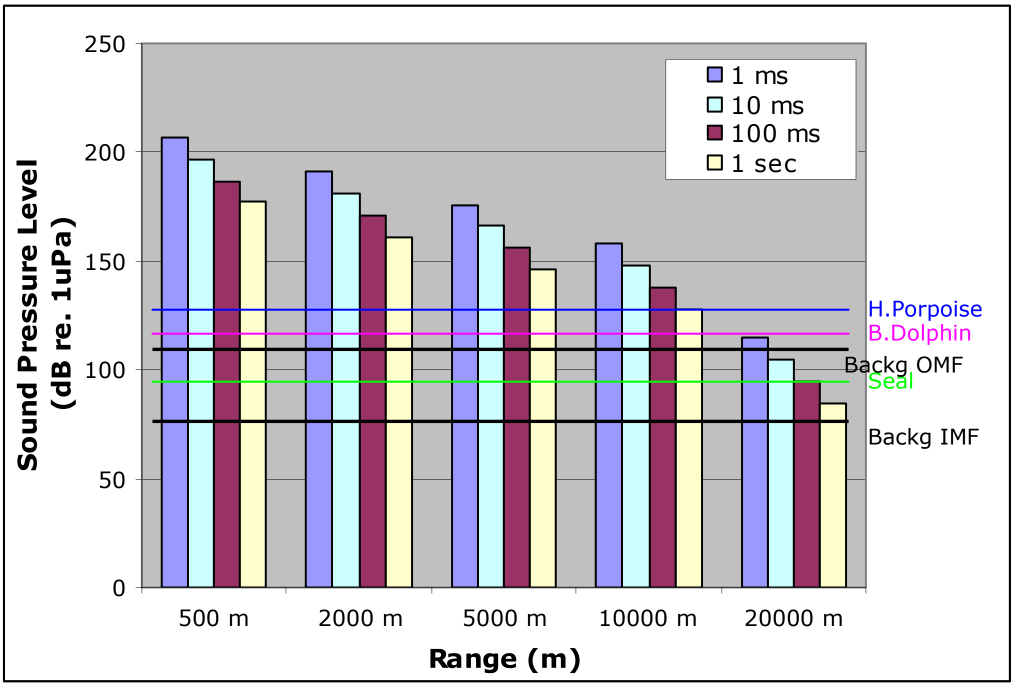


Figure 10-3. Comparison of 100 Hz 1/3 octave band noise with range from seismic array gun noise. Data are compared with marine mammal hearing thresholds and background sea noise data for the Outer (OMF) and Inner Moray Firth regions at 100 Hz (Transect 1 – summer).

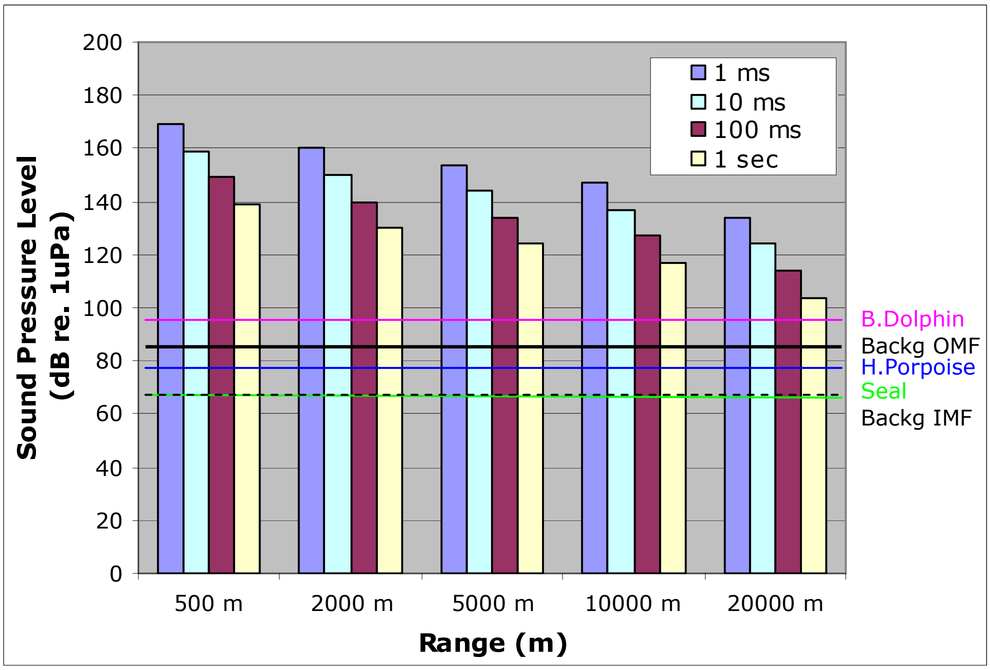


Figure 10-4. Comparison of 1 kHz 1/3 octave band noise with range from seismic array gun noise. Data are compared with marine mammal hearing thresholds and background sea noise data for the Outer (OMF) and Inner Moray Firth regions at 1 kHz (Transect 1 – summer).

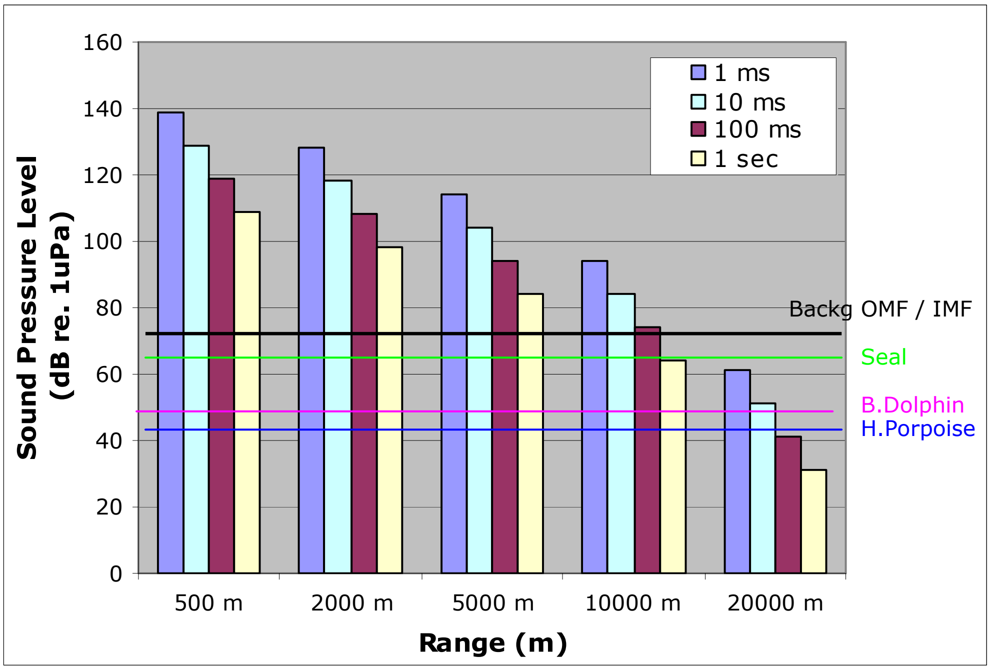


Figure 10-5. Comparison of 20 kHz 1/3 octave band noise with range from seismic array gun noise. Data are compared with marine mammal hearing thresholds and background sea noise data for the Outer (OMF) and Inner Moray Firth regions at 20 kHz (Transect 1 – summer).

11. SUMMARY AND CONCLUSIONS

An acoustic modelling study has been undertaken to predict the variation in noise level with range from an airgun array to be used in the Moray Firth. The RAM (Collins 1993) and WADER® (OAD 2007) acoustic propagation models have been used to estimate transmission loss at 1/3 octave band frequencies from 10 Hz to 100 kHz. These data have been compared with proposed injury and behavioural response criteria.

Based on a zero to peak source level noise from the airgun array of 254 dB re.1µPa @1 m, the modelling indicates that the single shot, peak noise, auditory injury criteria proposed by Southall *et al.* (2007) for cetaceans will be exceeded within a range of 25 m, and for pinnipeds to a range of 130 m. TTS onset ranges based upon peak level noise extend to 58 m and 270 m, respectively. These ranges are well within the near field of the airgun array and hence the actual levels are unlikely to be achieved.

The predicted single shot auditory injury ranges, based on the M-weighting criteria proposed by Southall *et al.* (2007), vary from 15 to 80 m for cetaceans, and 140 to 240 m for pinnipeds. These ranges are within the near field of the acoustic emissions from the airgun array and hence the actual sound levels are unlikely to be achieved.

Cumulative M-weighted SEL has been used to assess the noise exposure for marine mammals exposed to multiple pressure pulses from the airgun array. The cumulative noise modelling for animals that swim away from the sound source at a rate of 1 $m.s^{-1}$ indicates that auditory injury may occur for high frequency hearing cetaceans within a range of 23 m, low frequency hearing cetaceans within 260 m and pinnipeds within 1100 m Hence, based upon the criteria proposed by Southall *et al.* (2007), auditory injury is unlikely to occur unless the animal is in very close proximity to the source at the start of operations.

Cumulative SEL has been used to assess the noise exposure for marine mammals exposed to multiple pressure pulses from the airgun array. Modelling of the noise exposure for marine animals that move away from the airgun array at a rate of 1 $m.s^{-1}$ has indicated PTS auditory injury (215 dB re 1 $\mu Pa^2.s$) for animals within 11 m, and TTS auditory injury (195 dB re 1 $\mu Pa^2.s$) within a range of 940 m.

Cumulative M-weighted SEL has also been used to model the noise exposure for static marine mammals exposed to multiple pressure pulses as the airgun array moves along a ± 30 km survey line. The data highlights that the airgun array would have to pass very close to a marine mammal for the cetacean auditory injury criteria to be exceeded (ranges from 55 m for high frequency hearing marine mammals to 520 m for low frequency).

The Mhf weighted SEL has been calculated as the airgun array operates from a range of 32 km to the point at the southern perimeter of the proposed survey area, a position 12 km from the marine mammal population off Covesea Skerries and 16 km from shore. This analysis indicates a cumulative Mhf weighted Sound Exposure Level of 161.4 dB re.1$\mu Pa^2.s$.

Based on the M-Weighted SEL criteria proposed by Southall *et al.* (2007), the data indicates TTS onset in cetaceans may occur to a range of 150 m from the airgun array for high frequency hearing cetaceans (M_{hf}), 300 m for mid-frequency cetaceans (M_{mf}), 550 m for low frequency cetaceans (M_{lf}), and 1400 m for Pinnipeds (M_{pf}).

Comparison of the airgun array noise with audiometric data has indicated that marine mammals that hear predominantly at high frequencies are unlikely to hear the very low (typically 100 Hz) and very high (20 kHz) frequency components of the airgun array noise at ranges beyond 10 km. In comparison, acoustic modelling has indicated that the mid-frequency noise (typically 1 kHz) has much lower propagation losses and at ranges of 10 km and 20 km the noise may still be well above marine mammal hearing threshold.

Comparison of the airgun array noise with background sea noise levels suggests that the noise will remain above sea noise levels to ranges beyond 10 km at a frequency of 100 Hz and beyond 20 km at a frequency of 1 kHz. In contrast, the 20 kHz data suggests that the very high frequency components of the seismic noise will be masked by the background sea noise in both the Outer and Inner Moray Firth at ranges beyond 10 km.

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