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### **2D seismic survey in the Moray Firth: Review of noise impact studies and re-assessment of acoustic impacts**

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## APPROVALS

### Report 250103/2.0

### 2D seismic survey in the Moray Firth: Review of noise impact studies and re-assessment of acoustic impacts

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## EXECUTIVE SUMMARY

This report has been prepared by Kongsberg Maritime Ltd for Genesis Oil and Gas Consultants Ltd and the Department of Energy & Climate Change. It provides reviews of noise impact assessments produced by both BMT Cordah Ltd and Subacoustech Environment Ltd in advance of a seismic survey that is expected to take place late in 2010.

It was found that the underwater noise propagation studies undertaken by BMT Cordah Ltd were rudimentary in scope and depth whereby the modelling made use of simple geometrical spreading laws that failed to take into account the effects of oceanography and bathymetry on the attenuation of sound. The Subacoustech report relied on a technique for propagating noise that has not, as far as can be ascertained, been reported in the open literature previously and for which, only a brief description of the methodology was provided. The noise impact studies contained in both reports centred around the  $dB_{ht}$  model (Nedwell *et al.* 2007) but failed to make reference to several key papers on other impact models (e.g. Southall *et al.* 2007) that, it is felt, should also have been discussed.

Subsequently, a more robust study was undertaken drawing on proven computer models for underwater acoustic propagation as well as the latest information on acoustic impact studies. The acoustic modelling study was undertaken to predict the variation in noise level with azimuth and range from seismic airgun array operations in 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 the study indicates that PTS auditory injury is likely to be limited to ranges within 6 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.

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 45 m from the airgun array for high frequency hearing cetaceans ( $M_{hf}$ ), 55 m for mid-frequency cetaceans ( $M_{mf}$ ), 100 m for low frequency cetaceans ( $M_{lf}$ ), and 75 m for pinnipeds ( $M_{pf}$ ). Using the impact criterion proposed by Lucke *et al.* (2009), TTS in harbour porpoises may occur up to 150 m from the source.

Aversive behavioural reactions may be seen in harbour porpoises at ranges of 4.5 – 10 km from the source. For pinnipeds and the other cetacean species, Level B harassment (NMFS 1997) is likely to occur right up to the coastline on some transects and at ranges up to 14 km for those transects that remain in open seas. Similarly low level behaviour (HESS 1997) could be observed on the coastline on some transects and at ranges up to 60 km on others.

For animals that remain beyond 500 m from array at the commencement of seismic firing, neither PTS nor TTS is likely to occur.

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 the hearing threshold and may be audible to ranges beyond 20 km.



## 1. INTRODUCTION

This report has been prepared by Kongsberg Maritime Ltd for Genesis Oil and Gas Consultants Ltd and the Department of Energy & Climate Change. The report provides reviews of underwater noise assessments undertaken by BMT Cordah Ltd on behalf of Rudall Blanchard Associates for Caithness Oil Ltd; and by Subacoustech Environment Ltd on behalf of Metoc plc for PA Resources UK Ltd. The BMT report was originally produced as part of an Environmental Impact Assessment (EIA) prior to a seismic survey in Moray Firth in 2008. In the event, the survey was delayed and following a change in scope, a new report was subsequently produced by Subacoustech.

This report provides an expert review of the two noise assessment studies carried out previously. This is followed by an assessment of the impact of underwater sound on marine life found in the Moray Firth using rigorous and accepted methodologies and procedures.

Following on from the review, the report summarises operational and site specific data required for the modelling of underwater noise propagating through the seismic survey region. Modelling has been undertaken using computer programs to investigate the underwater noise propagating along four transects radiating from the centre of the survey area. The transects run approximately north-west and south-west to the Cromarty coast in water of decreasing depths; and north-east and south-east into the deeper waters in the centre of the Firth.

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 210 to 220 dB re.1  $\mu$ Pa @ 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  $\mu$ Pa @ 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 (see 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 6.

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 Bellhop has been used. Like RAM, this is also a range-dependent model for fluid seabeds and the model is increasingly used in underwater noise assessment studies.



The EIAs produced for PA Resources UL Ltd and Caithness Oil Ltd both identified a number of species of marine mammals that are local to the area. These are the white-beaked dolphin, harbour porpoise, bottlenose dolphin, long-finned pilot whale and minke whale; while pinnipeds species are grey seal and harbour seal. Data are presented using a number of noise assessment metrics for generic species of marine animal, with impact zones calculated based on proposed criteria from various studies.



## **2. REVIEW OF NOISE IMPACT STUDIES IN MORAY FIRTH 2D SEISMIC SURVEY EIA**

### **2.1 Introduction**

Environmental Impact Assessments (EIAs) have been produced by Metoc plc for PA Resources UK Ltd and by RPS Energy Ltd for Caithness Oil Ltd as a necessary condition to gaining consent for a 2D seismic survey to be carried out in the Moray Firth in September to November 2010.

The PA Resources EIA contains a noise assessment carried out by Subacoustech Environmental Ltd (Nedwell *et al.* 2010a). The RPS EIA contains underwater noise assessments carried out by BMT Cordah Ltd (BMT 2008) and Subacoustech Environmental Ltd (Nedwell *et al.* 2010b). The BMT report was produced in 2008 prior to a survey which, in the event, was delayed then subsequently underwent a change in scope. For this reason, an additional noise assessment was then provided by Subacoustech in March 2010. It is noted that the two Subacoustech reports are practically identical: the one appended to the PA Resources EIA being a Draft version of the one provided with the RPS EIA.

The objective of the current tasking is to provide a review of the noise studies contained in the EIA reports.

### **2.2 Detailed review of BMT noise report**

The report commences with a high level description of the survey area and its relation to the Moray Firth Special Area of Conservation off the north-east coast of Scotland. The time of the year for the survey is also noted.

Section 2 concentrates on the seismic operations and this includes a description of the acoustic characteristics of the seismic source. The source array consists of G Gun types but the report fails to provide any reference or explanation for this particular type of equipment.

The report goes on to note that although seismic surveys are commonly thought to involve low frequencies (<200 Hz); for modelling purposes, the upper frequency is taken at 100 kHz. While this is largely correct, it is considered that the upper limit should really be extended to 125 kHz as this revised figure is more likely to cover the high echo-location frequencies emitted by the smaller odontocetes as well as the uppermost frequencies at which a number of odontocetes have had their hearing tested (Richardson *et al.* 1995).

Section 3 provides a detailed description of the Existing Environment in the vicinity of the seismic survey site. This gives a comprehensive account of the species of fish, cetacean, pinniped and bird that are extant to or else transit through the site of interest. It covers spawning or breeding periods, observation data including locations of nesting and haul-out sites and abundance data including the species Conservation Status where appropriate. The Existing Environment discusses nationally and internationally protected sites; giving details on the particular feature that has led to their protected status. Section 3 concludes with brief descriptions of socio-economic activities *viz.* shipping and fishing, that may be impacted by the presence of the seismic survey.

Section 4 discusses the methodology by which the impact of an activity may be assessed. In terms of acoustic emissions, there commences a discussion of disturbance or harassment as defined by European and UK law. This leads on to a high-level review of





the international literature on injurious and behavioural impacts on marine fauna when exposed to underwater sound. It is known that this is a huge subject area with many papers published annually world-wide. However, it was noted that the latest reference in Section 4 was dated no later than 1998 (this being a compilation of even earlier reports). As a result, it is considered that a considerable number of relevant, later papers may have been overlooked.

The BMT noise modelling study itself is presented as an appendix to the main report. It starts off by breaking down the modelling process into two stages: estimation of noise levels due to the sound source in the study area; and estimation of potential impacts of marine animals at various distances from the sound source.

The Source Level Transmission Loss model (attributed to Nedwell and Howell 2004) has been around for many years (see e.g. Urick 1983 for the references contained therein). It is actually a mathematical statement of how sound level at a given location might be determined given the Source Level and the transmission loss between source and receptor.

Transmission loss is defined as the sum of geometrical spreading losses and attenuation losses. It is considered that this gives a very simplistic representation of the spread of noise underwater and this may be considered adequate if that is all that is required. However, it also fails completely to take into account any other contributing mechanisms. In the short range, i.e. at ranges from the source of less than the water depth (~50 m), the loss is based on spherical spreading; while at longer ranges, it is based on cylindrical spreading. Transmission Loss Coefficients range from 20 for spherical spreading and 10 for cylindrical spreading (Urick 1983). The Model Input Data given in Table 1 of the report gives a Transmission Loss Coefficient of 22 – which is neither spherical or cylindrical, and also fails to give provide any evidence to support this value. The report goes on to state that sound intensity can be attenuated due to sea surface and seabed interactions and that it is a complex process. This idea is supported by the references quoted (Jensen *et al.* 1994 and Richardson *et al.* 1995) both of which provide guidance on the selection of suitable models for underwater propagation. Indeed, one of them (Jensen *et al.* 1994) is considered to be the authoritative guide to underwater propagation modelling. If a noise study relies on such a simplistic model after stating that the modelling of underwater propagation is a complex process, then it is reasonable to expect that the errors inherent in such a technique, should be estimated at least qualitatively. It is noted that this has not taken place in the report. The outcome of the modelling undertaken by BMT indicates that sound propagates uniformly in all directions. Any standard reference on underwater acoustic propagation will indicate that in the presence of changing bathymetry, this clearly is not the case.

A number of acoustic impacts on marine species are given and these include physiological, audiological and behavioural impacts including masking of communication signals. In order to assess the scale of the impacts, use has been made of the dB<sub>ht</sub> model. While there is some merit in this approach, the dB<sub>ht</sub> should be considered as just one of a number of metrics against which to quantify potential acoustic impacts. A comprehensive report published some six months before the BMT report was issued, provides a number of additional injury and behaviour criteria for pinnipeds and cetaceans and this should have been included in the assessment.

### **2.3 Detailed review of Subacoustech noise report**

Subacoustech Ltd undertook a desk study of the underwater noise propagation and potential impacts likely to arise due to the forthcoming seismic survey in the Moray Firth.

The report provides an overview of the seismic survey area in relation to the Moray Firth Special Area of Conservation and also the wider Moray Firth. The location of local grey



seal breeding colonies are noted and this provides justification for carrying out acoustic propagation and impact studies at the chosen locations on the edge of the proposed survey area.

The assessment of underwater noise centres around the lethality and physical impacts; and behavioural effects. The lethality and physical injury impacts draw on the definitive work by Yelverton *et al.* (1975), and other work reported by Richardson *et al.* (1995). The impacts themselves are based on unweighted metrics that is, threshold levels that are not dependent in any way on the audiology of a target species. Hence lethality is expected to occur at peak-to-peak levels in excess of 240 dB re 1  $\mu$ Pa and physical injury arises above 220 dB re 1  $\mu$ Pa peak-to-peak. It is noted that this latter threshold appears somewhat precautionary when compared with the physical injury impact criterion of 230 dB re 1  $\mu$ Pa proposed by Southall *et al.* (2007). Behavioural effects are evaluated using the dB<sub>ht</sub> method introduced by Nedwell *et al.* (2007). The use of the technique is supported by BERR, however, in an ever-evolving knowledge field, it is felt that this is not the only technique which ought to be considered in work of this nature (see for example Southall *et al.* 2007). A number of behavioural impacts are given. These vary in severity from 75 dB<sub>ht</sub> which corresponds to a level of "significant avoidance" where approximately 85% of individuals show signs of modified behaviour in the presence of the noise through to 130 dB<sub>ht</sub> which corresponds to the onset of traumatic hearing damage in an individual following g exposure to a single event.

The acoustic propagation model used in connection with this study and developed in-house by Subacoustech, is known as INSPIRE (Impulse Noise Sound Propagation and Impact Range Estimator). The report states that this is based on underwater noise data from previous seismic airgun operations and other transient noise sources that is used to calculate absorption and depth-dependent transmission losses used in conjunction with bathymetric data for the current site of interest. From these data sets, ranges for given impacts are estimated along a number of transects radiating from the site location. It is noted that, as far as can be ascertained, the model has not been reported in the open literature so the precise methodology remains unknown. This contrasts sharply with other underwater propagation models (Buckingham 1992, Jensen *et al.* 1997, Etter 2005) that have undergone rigorous benchmarking and extensive peer-review.

Section 5 of the Subacoustech report provides a discussion of the un-weighted results from the propagation modelling. It is noted that there was no breakdown of results at ranges closer to the source than 500 m and only spot ranges at four sound pressure level values. It is felt that individual graphs showing the variation in SPL over range would have been much more instructive. In addition, extrapolating the results back to the point of origin would have indicated the expected source level for the seismic array. This information is not presented in the report so it is unclear precisely what the source level was as used in subsequent calculations. The way the data was presented therefore makes comparison with other propagation loss model somewhat difficult especially given the unknown methodology contained in INSPIRE and as discussed briefly above.

It is thought that the 500 m distance refers obliquely to the radius of the zone monitored by JNCC-approved observers during seismic surveys (JNCC 2004). A reference to that effect would have been helpful.

The report discussed peak-to-peak sound levels and sound exposure levels in relation to acoustic impacts. It was stated that "...there is no well accepted criterion for effect based on the use of the (sound exposure level)." It is considered that the work by Southall *et al.* (2007) should have been mentioned here, at least in passing.

Behavioural impact ranges for three target species are based on the dB<sub>ht</sub>-weighted results and these are given for both modelling locations. Likely behavioural avoidance impacts are given at a distance of 500 m from each location. These range from 94 dB<sub>ht</sub>



to 107 dB<sub>ht</sub>. While these impact metrics fit within the impact continuum discussed earlier in the report, the significance of the behaviour likely to arise amongst the animals exposed to such sound levels is not discussed at all.

## 2.4 Concluding remarks

The noise modelling study conducted by BMT Cordah Ltd was considered to be generally elementary in scope and depth. The propagation modelling was based on a very simple representation of the underwater sound field in that it failed entirely to take in account the complex nature of the undersea environment and its effect on the distribution and attenuation of acoustic energy. The acoustic impact model was based entirely on the dB<sub>ht</sub> approach and overlooked a key report that had been published in the international literature prior to the publication date of the BMT study.

The Subacoustech report was based on the use of their own proprietary underwater acoustic propagation model which has not been benchmarked and peer-reviewed in the open literature. As with the BMT report, this work draws use of the dB<sub>ht</sub> but makes no mention of the work by Southall *et al.* (2007).

Neither report shows the un-weighted sound pressure levels with respect to range. The BMT report indicates that sound propagation is uniform in all directions over the modelled transects while the Subacoustech work shows that this is not the case.

In conclusion, whilst neither report was sufficiently rigorous to estimate accurately the sizes of the potential impact zones, both modelling approaches and impact assessment criteria used have been applied in previous noise impact assessments and were deemed probably acceptable given the previous scopes of work. However, in view of the sensitivity of the inner Moray Firth area, Kongsberg was asked to undertake a more detailed study to support the regulator's assessment of the proposals.

The remainder of the current tasking relates to the reporting of underwater noise propagation modelling using proven modelling techniques which in turn leads to an assessment of the likely impacts from the proposed seismic survey operations, on protected species local to the Moray Firth area.



### **3. DESCRIPTION OF UNDERWATER NOISE AND ASSESSMENT METRICS.**

#### **3.1 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<sup>2</sup>). 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.

#### **3.2 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:

$$\text{Peak Level (zero-to-peak)} = 20 \times \log_{10} (P_{\text{peak}}/P_{\text{ref}}) \quad \text{eqn. 3-1}$$

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.

#### **3.3 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:

$$\text{RMS Sound Pressure Level} = 20 \times \log_{10} (P_{\text{RMS}}/P_{\text{ref}}) \quad \text{eqn. 3-2}$$

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.

#### **3.4 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:

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

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 ( $\text{Pa}^2\text{-s}$ ).

To express the Sound Exposure as a logarithmic decibel, it is compared with a reference acoustic energy level of  $1 \mu\text{Pa}^2\text{-s}$ . The Sound Exposure Level (SEL) is then defined by:

$$SEL = 10 \log_{10} \frac{\int_0^T p^2(t) dt}{P_{ref}^2} \quad \text{eqn. 3-4}$$

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:

$$SEL = SPL + 10 \log_{10} T \quad \text{eqn. 3-5}$$

### 3.5 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.

### 3.6 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.  $1\mu\text{Pa}$  @ 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

### 3.7 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.

### 3.8 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:

$$TL = N \log(r) + \alpha r \quad \text{eqn. 3-6}$$



where  $r$  is the range from the source,  $N$  is a factor for attenuation due to geometric spreading, and  $\alpha$  (in  $\text{dB.km}^{-1}$ ) 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:

$$RL = SL - TL \quad \text{eqn. 3-7}$$

which can be written in the form :

$$RL = SL - N \log(r) - \alpha r \quad \text{eqn. 3-8}$$



## 4. CRITERIA FOR ASSESSING IMPACTS UPON CETACEANS.

### 4.1 Introduction

This section of the report describes briefly the assessment criteria proposed by various investigators to assess the impact of underwater sound upon species of interest to the Moray Firth. 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.

### 4.2 Species of interest to Moray Firth

The Moray Firth 2D seismic survey EIA (RPS Energy 2010) identified a number of species of cetacean and pinniped of interest to the Moray Firth. Cetacean species of note to this study include: harbour porpoise, bottlenose dolphin, minke whale, long-finned pilot whale and white-beaked dolphin. Common or harbour and grey seals are the only pinniped species native to the Moray Firth.

For the purpose of the impact analysis subsequently undertaken in this report, the cetacean species are divided into generic groups based on the hearing frequency range (Southall *et al.* 2007, Harland 2008). Harbour porpoise and white-beaked dolphin are classified as high-frequency hearing mammals  $M_{hf}$ ; bottlenose dolphins are classified as medium-frequency hearing mammals  $M_{mf}$ ; and minke whales are classified as low-frequency hearing mammals  $M_{lf}$ .

### 4.3 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  $\mu$ Pa, could cause TTS in cetaceans, and 190 dB re. 1  $\mu$ Pa in pinnipeds (NMFS, 1995). A lower (Level B) harassment criteria based on a received RMS Sound Pressure Level of 160 dB re.1 $\mu$ Pa 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 its 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.

### 4.4 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.1 $\mu$ Pa<sup>2</sup>s is considered as the



onset of Temporary Threshold Shift (TTS) injury, with an exposure of 215 dB re.1 $\mu$ Pa<sup>2</sup>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.1 $\mu$ Pa<sup>2</sup>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.1 $\mu$ Pa<sup>2</sup>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 (Gordon *et al.* 2007) for estimating auditory injury zones from pile driving operations.

#### **4.5 Southall *et al.* 2007 report**

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  $\mu$ Pa for cetaceans (peak level), and 218 dB re. 1  $\mu$ Pa for pinnipeds, to prevent auditory injury (PTS onset); and a Sound Exposure Level of 198 dB re.1 $\mu$ Pa<sup>2</sup>s M-Weighted for cetaceans, and 186 dB re.1 $\mu$ Pa<sup>2</sup>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  $\mu$ Pa for cetaceans, and 212 dB re. 1  $\mu$ Pa for pinnipeds; and a corresponding Sound Exposure Level of 183 dB re.1 $\mu$ Pa<sup>2</sup>s M-Weighted for cetaceans, and 171 dB re.1 $\mu$ Pa<sup>2</sup>s M-Weighted for pinnipeds. Again, the lower of the criteria applies.

#### **4.6 Lucke *et al.* 2009 report**

In a series of controlled experiments, Lucke *et al.* (2009) exposed a harbour porpoise to seismic airgun sounds. It was found that TTS was exceeded at a received level of 199.7 dB re. 1  $\mu$ Pa pk-pk (193.7 dB re. 1  $\mu$ Pa peak) and an SEL of 164.3 dB re. 1  $\mu$ Pa<sup>2</sup>.s. Aversive behavioural reactions were consistently recorded above 174 dB re. 1  $\mu$ Pa pk-pk (168 dB re. 1  $\mu$ Pa peak) and an SEL of 145 dB re. 1  $\mu$ Pa<sup>2</sup>.s. It is noted that this work represents the only available data on TTS in harbour porpoises and that the levels proposed by Lucke *et al.* are 24 dB lower than those put forward by Southall *et al.* (2007) for other high-frequency hearing mammals.





#### 4.7 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.1 $\mu$ Pa (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.

#### 4.8 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.* (2006b), 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 QinetiQ impact model (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. The QinetiQ impact model was developed specifically to assess the impact of sonars deployed during naval activities. It is considered that the impact model, being based therefore on energy which is substantially contained within a relatively narrow range of frequencies, is not really suited to apply to the much wider range of frequencies emitted during seismic surveys.

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. This dB<sub>ht</sub> 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 invoke 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. The dB<sub>ht</sub> method may be used to determine impact ranges for fish, cetacean and pinnipeds.



#### 4.9 Summary of impact criteria

Exposure limit	Effect	Study
230 dB re 1 $\mu$ Pa (Peak)	PTS Auditory injury onset in cetaceans	(Southall <i>et al.</i> 2007)
218 dB re 1 $\mu$ Pa (Peak)	PTS Auditory injury onset in pinnipeds	(Southall <i>et al.</i> 2007)
224 dB re 1 $\mu$ Pa (Peak)	TTS onset in cetaceans	(Southall <i>et al.</i> 2007)
212 dB re 1 $\mu$ Pa (Peak)	TTS onset in pinnipeds	(Southall <i>et al.</i> 2007)
200 dB re 1 $\mu$ Pa (Peak)	TTS onset in harbour porpoises	(Lucke <i>et al.</i> 2009)
174 dB re 1 $\mu$ Pa (Peak)	Aversive behavioural reaction in harbour porpoises	(Lucke <i>et al.</i> 2009)
198 dB re.1 $\mu$ Pa <sup>2</sup> s SEL M-Weighted	PTS Auditory injury onset in cetaceans	(Southall <i>et al.</i> 2007)
186 dB re.1 $\mu$ Pa <sup>2</sup> s SEL M-Weighted	PTS Auditory injury onset in pinnipeds	(Southall <i>et al.</i> 2007)
183 dB re.1 $\mu$ Pa <sup>2</sup> s SEL M-Weighted	TTS onset in cetaceans	(Southall <i>et al.</i> 2007)
171 dB re.1 $\mu$ Pa <sup>2</sup> s SEL M-Weighted	TTS onset in pinnipeds	(Southall <i>et al.</i> 2007)
215 dB re.1 $\mu$ Pa <sup>2</sup> s SEL	PTS Auditory injury	(NOAA, 2006)
195 dB re.1 $\mu$ Pa <sup>2</sup> s SEL	TTS Auditory injury	(NOAA, 2006)
164 dB re.1 $\mu$ Pa <sup>2</sup> s SEL	TTS onset in harbour porpoises	(Lucke <i>et al.</i> 2007)
145 dB re.1 $\mu$ Pa <sup>2</sup> s SEL	Aversive behavioural reaction in harbour porpoises	(Lucke <i>et al.</i> 2007)
190 dB re 1 $\mu$ Pa (RMS)	Auditory injury criteria – pinnipeds	(NMFS, 1995)
180 dB re 1 $\mu$ Pa (RMS)	Auditory injury criteria – cetaceans	(NMFS, 1995)
160 dB re 1 $\mu$ Pa (RMS)	Behavioural disturbance, level B harassment	(NMFS, 1995)
140 dB re 1 $\mu$ Pa (RMS)	Low level disturbance	HESS (1997)
90 dB <sub>ht</sub> above species specific hearing threshold	Strong behavioural reaction	Nedwell <i>et al.</i> (2005)
75 dB <sub>ht</sub> above species specific hearing threshold	Mild behavioural reaction	Nedwell <i>et al.</i> (2005)

Table 4.1: Summary of underwater noise impact criteria for fish, cetacean and pinniped.



## 5. BACKGROUND NOISE MORAY FIRTH

### 5.1 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 1 $\mu$ Pa 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. 1 $\mu$ Pa. 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 1 $\mu$ Pa, 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.

### 5.2 Data

Background sea noise data for the Moray Firth are presented as narrowband Power Spectral Density levels in dB re.1 $\mu$ Pa<sup>2</sup>.Hz<sup>-1</sup> 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  $\mu$ Pa, and are presented for comparison. Figures 5.1 and 5.2 present data measured in the Outer and Inner Moray Firth regions respectively.

Table 5.1 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 5.1. (Removing this 1/3 octave band gives an RMS SPL / SEL and Mlf Weighted SEL of 100 dB re.1 $\mu$ Pa<sup>2</sup>s).

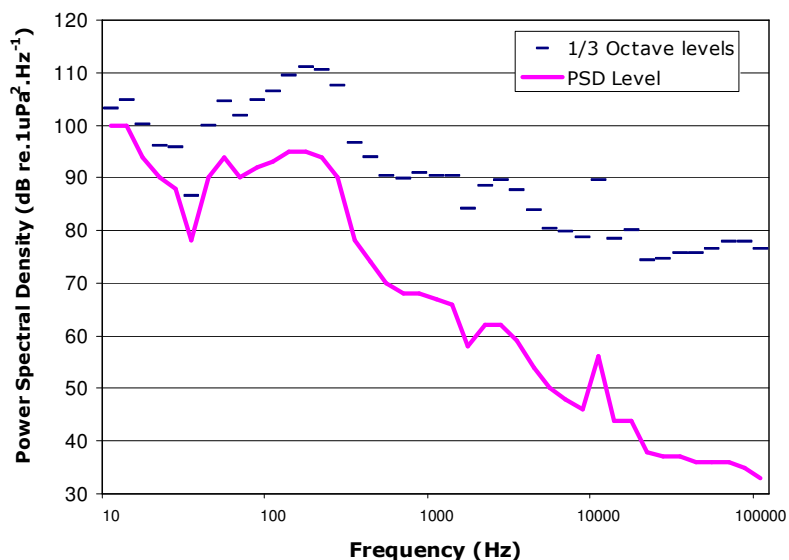


Figure 5.1: Background sea noise measured in the Outer Moray Firth from Senior et al. (2008) (Data are presented as Power Spectral Density and third octave band SPL's in dB re.1µPa).

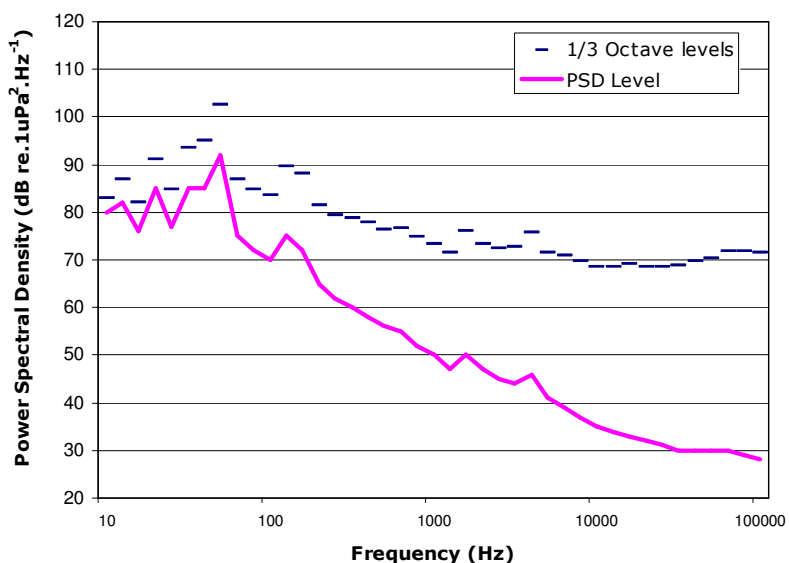


Figure 5.2: Background sea noise measured in the Inner Moray Firth from Senior et al. (2008). (Data are presented as Power Spectral Density and third octave band SPL's in dB re.1µPa).

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 5.1: 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.



## 6. SOURCE LEVEL NOISE FROM SEISMIC AIRGUN ARRAYS.

### 6.1 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  $\mu$ Pa while an array of industry standard airguns produces 240-265 dB re 1  $\mu$ Pa (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 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  $\mu$ Pa 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.

Very little specific information is provided regarding the operating characteristics of the seismic array to be used in the proposed Moray Firth survey. It is understood that the array consists of 2 G-guns, having a total volume of 470 cubic inch (7.7 litres) and deployed at a depth of 6 m (DECC 2010). Neither the overall source level nor the frequency spectrum characteristics were given. In order to determine suitable values for these parameters, the published literature was accessed for details of similar sized airguns and the results are discussed below.



## 6.2 Seismic array source level

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 3.6). 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 6.1), although there are exceptions for unusual array configurations (MacGillivray and Chapman, 2005; MacGillivray 2009).

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.

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)
<b>Airgun arrays</b>						
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
<b>Single airguns</b>						
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 6.1: 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).

Table 6.1 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  $\mu$ Pa at 1 m - as these are more appropriate measures in acoustics.



It is known that the Moray Firth seismic array has a capacity of 470 cubic inches (7.9 litres). From the data presented in Table 6.1, it may be assumed that this array has a peak to peak source level of 243 dB re 1  $\mu$ Pa.

### 6.3 Seismic array spectral levels

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 important to consider 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. Few studies provide data to frequencies beyond around 150 Hz (Goold and Fish 1998, Madsen *et al.* 2006, Goold and Coates 2006), and only one, (Breitzke *et al.* 2008) has provided spectral data at frequencies high enough to be of value to this study and this is illustrated below in Figure 6.1. This shows 1/3 octave band levels over the frequency range 1 Hz to 80 kHz for an 8.5 litre capacity G gun (slightly larger than the one to be used in the forthcoming Moray Firth survey) measured at a range of 550 m from the source. It will be seen that most of the energy falls in the frequency range 50 Hz to 500 Hz with a band level of 153 dB at 100 Hz.

From the information given in Figure 6.1, it is necessary to back-propagate the data in order to provide source spectral data. Breitzke *et al.* provides back-calculated parameters of 237 dB re 1  $\mu$ Pa peak-to-peak and a sound exposure level of 207 dB re 1  $\mu$ Pa. In addition, the spectral data levels indicate a roll-off in frequency of approximately 35 dB/decade over the range 80 kHz to 125 kHz. From this information, source spectral levels may be estimated and these are given in Table 6.2 below.

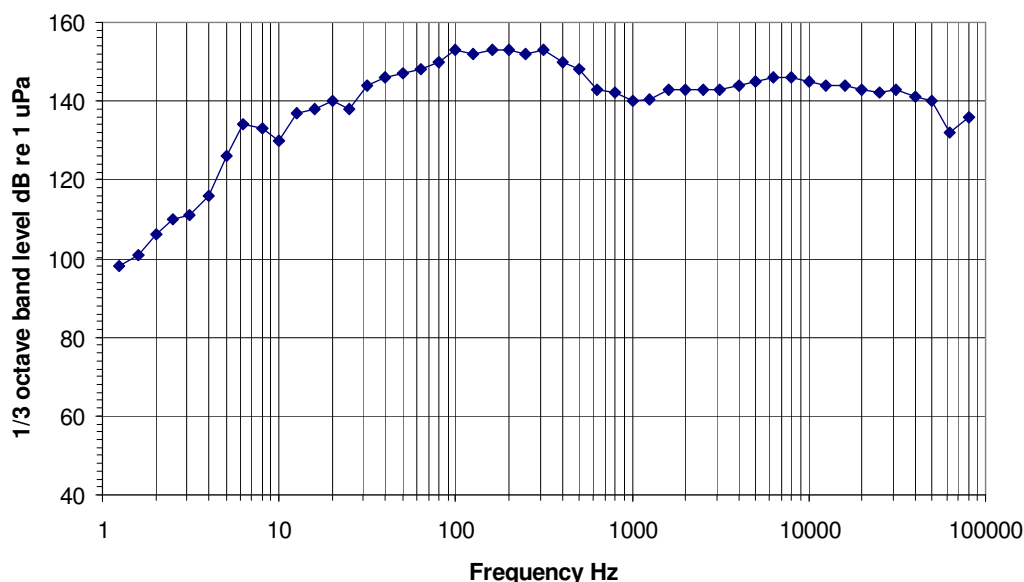


Figure 6.1: Frequency spectrum in 1/3 octave bands for 8.5 litre G gun measured at a range of 550 m (Breitzke *et al.* 2008)



Frequency (Hz)	Spectral pk-pk level (dB re $1\mu\text{Pa}^2\cdot\text{Hz}^{-1}$ @ 1 m)	Spectral SEL level (dB re $1\mu\text{Pa}^2\cdot\text{s}$ @ 1 m)
10	190	160
20	200	170
50	199	169
100	200	170
200	194	164
500	184	154
1000	172	142
2000	169	139
5000	164	134
10000	156	126
20000	148	118
50000	134	104
100000	121	91
125000	116	86

Table 6.2: Estimated source spectral levels of underwater noise as a function of frequency for a 470 cubic inch airgun array operated at 6 m depth.

#### 6.4 Directionality

Directionality of a seismic array is controlled through the superposition of beam patterns from individual airguns. At low frequencies ( $<\sim 80$  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). 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.





## 7. SOUND PROPAGATION MODELLING

### 7.1 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.

### 7.2 Underwater acoustic propagation models

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

$$TL = N \log_{10}(r) \qquad \text{eqn. 7.1}$$

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 both the environment and of signal frequency 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 narrow-band 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 the current study the sound transmission loss has been calculated at each third octave band centre frequency from 10 Hz to 125 kHz along four propagation paths radiating 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  $8\lambda$  where  $\lambda$  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 computationally more 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 Bellhop was used. Like RAM, this is also a range-dependent model for fluid sediment seabeds and the model is widely used in underwater noise modelling.

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 7.1 below. It is noted that the classic 3-layer acoustic model as represented in RAM and Bellhop assumes a basement that is semi-infinite in thickness. The data that is used to parameterise each layer is discussed below.

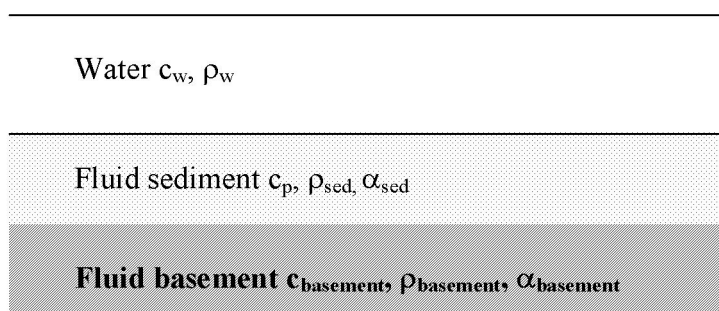


Figure 7.1: Schematic of acoustic model

### 7.3 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 7.2 and the bathymetric profiles along each transect are shown in Figures 7.3 to 7.6.

The nominal centre of the survey area is located at  $58^\circ\text{N } 003^\circ30'\text{W}$  and in a water depth of 40 m. The north-west bearing transect (Figure 7.3) heads towards the coast in water whose depth decreases gradually to zero over a distance of just under 12 km. By contrast, both the north-east and south-east transects (Figure 7.4 and 7.5 respectively) remain in relatively deep water throughout their length. The north-east transect decreases to 30 m at a range of 10 km, falling to nearly 70 m at 52 km then recovering to 55 m at 60 km range while the south-east transect remains between 48 m and 62 m depth over 30 km before reducing to 22 m fairly rapidly over the next 5 km. The water depth for the south-west transect (Figure 7.6) reduces gradually to zero (with a small increase around 13 km) as it makes landfall some 23 km distant.

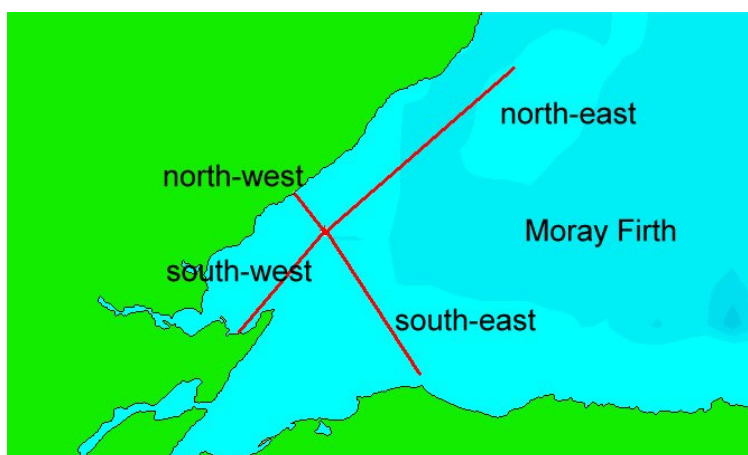


Figure 7.2: Transects selected for Moray Firth acoustic propagation modeling

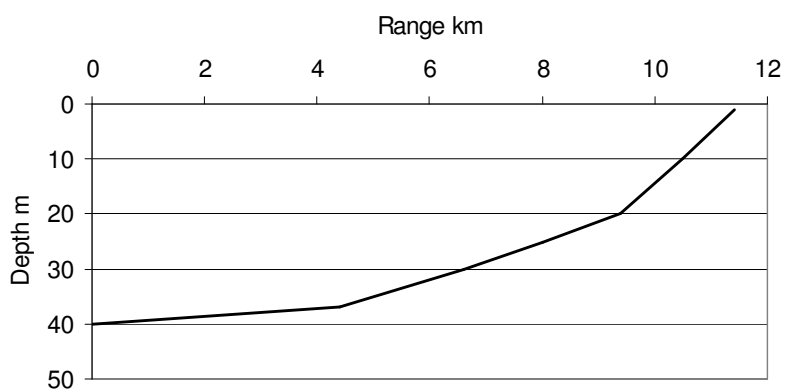


Figure 7.3: Depth profile for Moray Firth Transect north-west

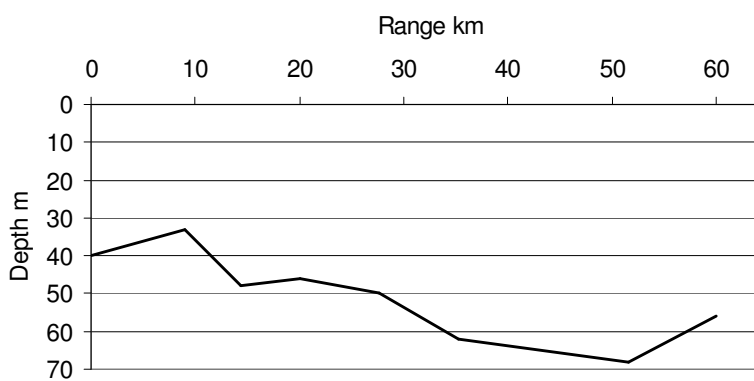


Figure 7.4: Depth profile for Moray Firth Transect north-east

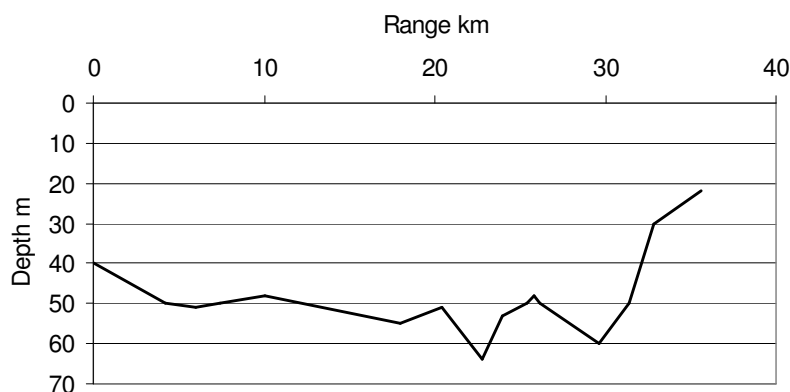


Figure 7.5: Depth profile for Moray Firth Transect south-east

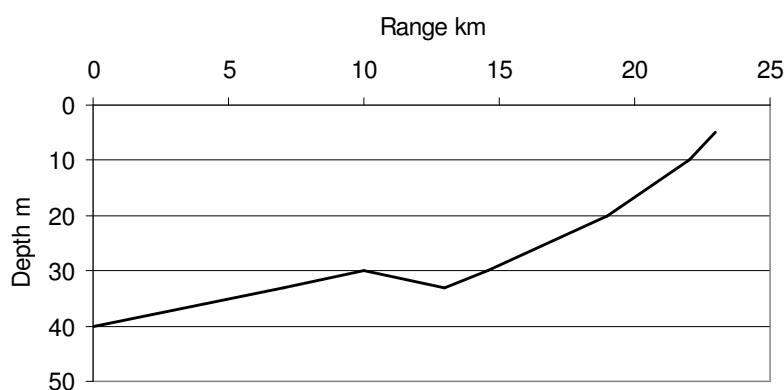


Figure 7.6: Depth profile for Moray Firth Transect south-west

#### 7.4 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.

The seismic survey is expected to proceed within the period September to November 2010. From an oceanographic perspective, over this period of time the sound speed profile in the relatively shallow waters of the UK undergoes a transition from summer conditions to late autumn conditions. The variation in sound speed with respect to depth shows that summer profiles tend to be marked by a surface duct around 10-20 m deep followed by a seasonal thermocline which gives rise to a downwardly refracting profile. As the surface waters cool down and become well-mixed due to the autumnal storms, the surface duct is lost and the profile tends to become increasingly upwardly refracting. Longer distance propagation is more likely to occur in an upwardly refracting profile hence, in order to limit the number of acoustic runs necessary, the most precautionary condition from a propagation perspective will be modelled and this will be for the month of November.

The sound speed profile covering the Moray Firth for the month of November is shown in Figure 7.7. It will be seen that the sound speed increases uniformly with increasing water depth. This gives a profile that is upwardly refracting to a depth of 50 m with the



remnants of the seasonal thermocline persisting below 50 m and down to the seabed. For this profile, there is a tendency for underwater sound to be generally directed towards the sea surface. Given such conditions, underwater sound is likely to propagate to longer distances than if it was directed towards the seabed.

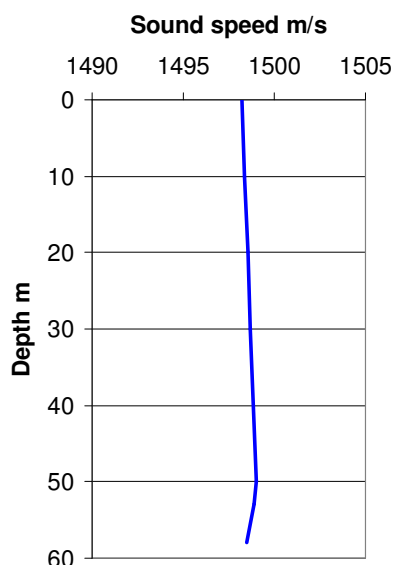


Figure 7.7: Sound speed profiles in the Moray Firth for the month of November

## 7.5 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 7.1.

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

Table 7.1: Sediment parameters for acoustic models

## 7.6 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 6.1). 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 and this is referred to as the precautionary condition.

The modelling input parameters for the seismic airgun array are summarised in Table 7.2.

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, 80k, 100k, 125k
Source depth m	6
Beam pattern degrees	Variable in the range 0°-80°

Table 7.2: Source parameters for acoustic model inputs

## 7.7 Discussion of model runs

A number of model runs were made using oceanographic data for the month of November, using the seabed bathymetric profiles given in Figures 7.3 to 7.6, and using the source parameter information given in Table 7.1. The results are shown in Figures 7.8 to 7.12 inclusive.

Figure 7.8 shows the modelled propagation loss as a function of range over the north-west transect using 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 75 dB over an approximate range of 9 km. As frequency increases, each component propagates with lower losses. The optimum frequency is 1 kHz where, for this component, the losses due to propagation are minimal – only 65 dB lost over 9 km. 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 3 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 7.9 shows the propagation loss modelled over the north-east transect. Very similar trends to those on the north-west transect are evident. It is noted that this transect remains in deep water at a range of 60 km. At this range, the data indicates a propagation loss of 80 dB and 115 dB for frequencies between 500 Hz and 8 kHz. Figure



7-9 also shows patterns of constructive and destructive interference particularly on the 250 Hz component at a range up to around 8 km. These indicate locations where there are regions of high intensity as well as relative shadow zones for these components.

Figure 7.10 indicates the propagation loss modelled over the south-east transect. Optimum propagation conditions are met for the frequency components 500 Hz, 1 kHz and 2 kHz where, at a range of 35 km, the modelling predicts a transmission loss of approximately 75 dB.

Figure 7.11 indicates the propagation loss modelled over the south-west transect. The water depth along this transect gradually reaches zero as the transect reaches the coast just over 18 km distant. The behaviour of each frequency component with respect to range is therefore very similar to those along the north-west transect.

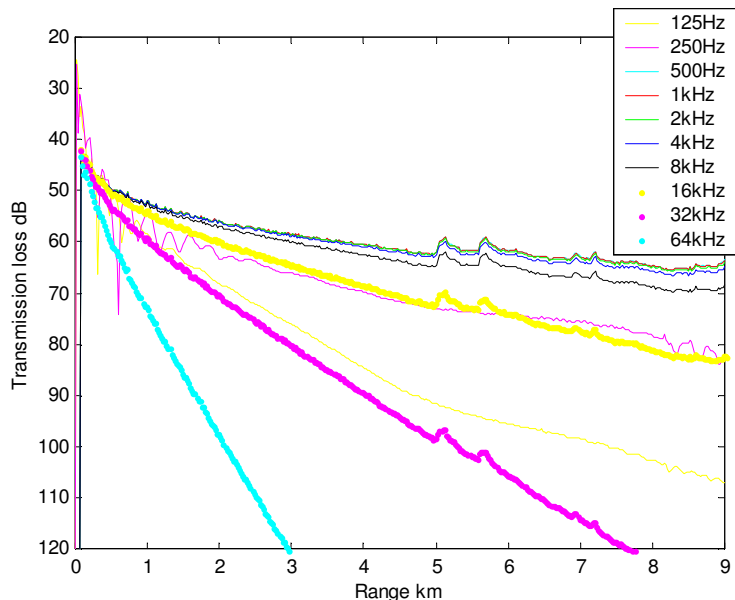


Figure 7.8: Predicted propagation loss in dB over north-west transect

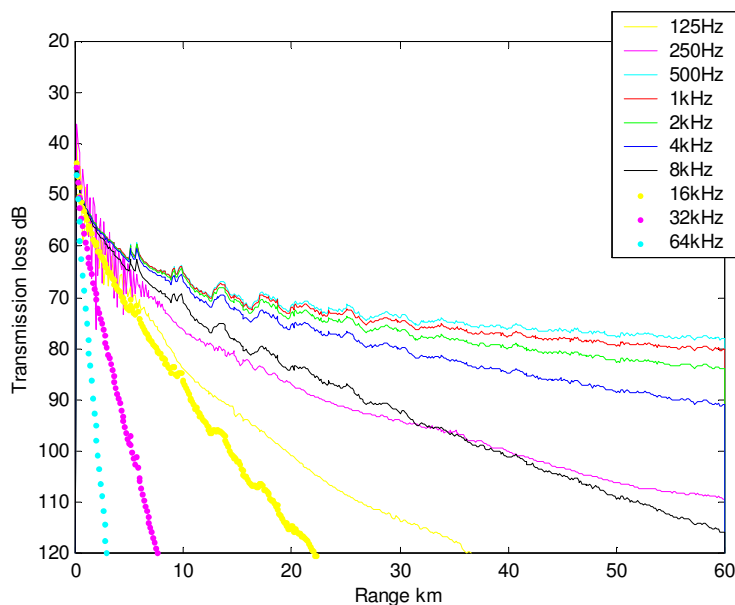




Figure 7.9: Predicted propagation loss in dB over north-east transect

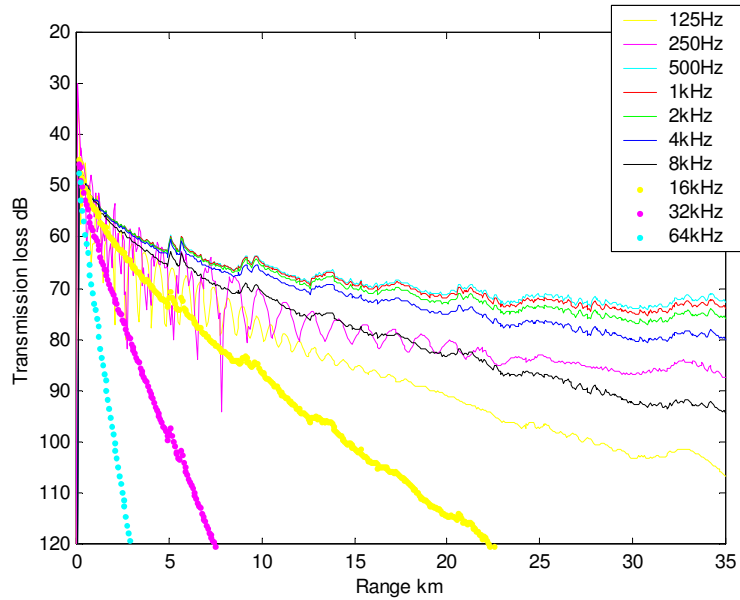


Figure 7.10: Predicted propagation loss in dB over south-east transect

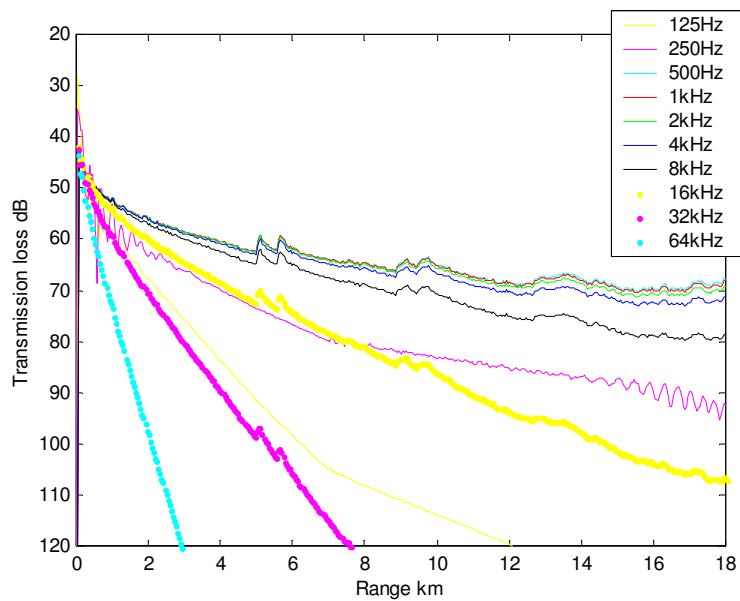


Figure 7.11: Predicted propagation loss in dB over south-west transect





## 8. MODELLING RESULTS – UN-WEIGHTED NOISE

### 8.1 Introduction

This section of the report uses the acoustic modelling undertaken in Section 7 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.

### 8.2 Un-weighted noise metrics

The un-weighted noise has also been calculated using the 1/3 octave band propagation modelling described in Section 7. This process involves calculating the 1/3 octave band levels of source noise from the spectral levels presented in Table 6.2, 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<sup>-1</sup> (Data presented in Figures 8.1 to 8.4). 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 234 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<sup>-1</sup> (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 <sup>-1</sup>	Parvin <i>et al.</i> ,2006
Kentish Flats	3 m	20	2.0 dB.km <sup>-1</sup>	Parvin <i>et al.</i> ,2006
Scroby Sands	4 to 43 m	20	3.0 dB.km <sup>-1</sup>	Parvin <i>et al.</i> ,2006
Barrow	10 to 30 m	18	0.3 dB.km <sup>-1</sup>	Parvin <i>et al.</i> ,2006
Burbo Bank	7 to 10 m	21 and 23	0.7 and 4.7 dB.km <sup>-1</sup>	Parvin and Nedwell, 2006

Table 8.1: 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<sup>-1</sup> (See Table 8.1). 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 8.5 discusses the variation in impact zones for geometric spreading loss factors (N) from 15 to 20.

### 8.3 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.

### 8.4 Results

The data in Figure 8.1 illustrates the zero to peak, and RMS Sound Pressure Level at 20 m depth as it varies with range from the seismic source along the north-west transect. Corresponding data for the north-east, south-east and south-west transects are shown in Figures 8.2, 8.3 and 8.4 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 8.2 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 2 m of the airgun array source, and in pinnipeds within a range of 6 m. TTS auditory injury onset based on peak level noise extends to 3 m and 18 m respectively. Also included are the ranges for the Lucke *et al.* (2009) TTS onset impact criterion for harbour porpoises. These are seen to vary between 100 m and 150 m depending on transect. All ranges quoted 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 20 to 140 m depending upon the RMS averaging time used, and a 180 dB re.1  $\mu$ Pa auditory injury zone for cetaceans that varies from 64 m to 440 m.

Figures 8.1 to 8.4 and Table 8.2 also indicate the predicted range for the airgun array pulses to have fallen to a level of 140 dB re.1  $\mu$ Pa (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 140 dB re.1  $\mu$ Pa as it reaches the coast having propagated along the relatively shallow waters on the north-west and south-west transects respectively. Along the deeper waters of the north-east and south-east transects, the



sound level remains above the 140 dB re.1  $\mu$ Pa threshold at ranges of 60 km and 35 km respectively. By contrast, the aversive behavioural reaction impact criterion for harbour porpoises (Lucke *et al.* 2009) is likely to occur right up to the coast line on the north-west transect and between 4.5 km to 5 km on the remaining transects.

Exposure limit	Effect	Range Transect NW	Range Transect NE	Range Transect SE	Range Transect SW
230 dB re 1 $\mu$ Pa (Peak)	PTS injury onset in cetaceans (Southall <i>et al.</i> 2007)	2 m	2 m	2 m	2 m
218 dB re 1 $\mu$ Pa (Peak)	PTS injury onset in pinnipeds (Southall <i>et al.</i> 2007)	6 m	6 m	6 m	6 m
224 dB re 1 $\mu$ Pa (Peak)	TTS injury onset in cetaceans (Southall <i>et al.</i> 2007)	3 m	3 m	3 m	3 m
212 dB re 1 $\mu$ Pa (Peak)	TTS injury onset in pinnipeds (Southall <i>et al.</i> 2007)	13 m	18 m	15 m	14 m
199.7 dB re 1 $\mu$ Pa (Peak-Peak)	TTS injury onset in harbour porpoises (Lucke <i>et al.</i> 2009)	100 m	150 m	130 m	120 m
190 dB re 1 $\mu$ Pa (RMS) 10 ms 100 ms 1 sec	Auditory injury criteria – pinnipeds (NOAA, 2006)	80 m 62 m 20 m	140 m 105 m 30 m	105 m 80 m 24 m	98 m 75 m 22 m
180 dB re 1 $\mu$ Pa (RMS) 10 ms 100 ms 1 sec	Auditory injury criteria – cetaceans (NOAA, 2006)	280 m 200 m 64 m	440 m 340 m 105 m	350 m 270 m 81 m	370 m 270 m 75 m
174 dB re 1 $\mu$ Pa (Peak-Peak)	Aversive behavioural reaction in harbour porpoises (Lucke <i>et al.</i> 2009)	10 km+	4.5 km	5.0 km	4.5 km
160 dB re 1 $\mu$ Pa (RMS) 10 ms 100 ms 1 sec	Behavioural disturbance, level B harassment (US NMFS)	10 km+ 10 km+ 0.9 km	5.7 km 4.3 km 1.2 km	13 km 5 km 0.87 km	14 km 4.5 km 0.9 km
140 dB re 1 $\mu$ Pa (RMS) 10 ms 100 ms 1 sec	Low level behavioural disturbance (HESS, 1997)	10 km+ 10 km+ 10 km+	60 km+ 60 km+ 60 km	35 km+ 35 km+ 35 km+	20 km+ 20 km+ 20 km+

Table 8.2: Summary of effect ranges based on un-weighted noise assessment metrics for each transect.



## 8.5 Variation with transmission loss

To provide an indication of the effect of propagation loss on the predicted impact zones, Table 8.3 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 13 m to 29 m for pinniped TTS injury in the examples shown). Based on 17 log r propagation, the 160 dB re.1  $\mu$ Pa, 1 second average SPL would extend to a range of 23 km, and for 15 log r propagation, to a range of 86 km, in comparison with the 0.9 to 1.2 km ranges shown in Table 8.2. 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 $\mu$ Pa (Peak)	PTS injury onset in cetaceans (Southall <i>et al.</i> 2007)	2 m	2 m	2 m	2 m
218 dB re 1 $\mu$ Pa (Peak)	PTS injury onset in pinnipeds (Southall <i>et al.</i> 2007)	6 m	8 m	9 m	12 m
224 dB re 1 $\mu$ Pa (Peak)	TTS injury onset in cetaceans (Southall <i>et al.</i> 2007)	3 m	4 m	5 m	5 m
212 dB re 1 $\mu$ Pa (Peak)	TTS injury onset in pinnipeds (Southall <i>et al.</i> 2007)	13 m	17 m	20 m	29 m

Table 8.3: Variation of effect ranges and propagation conditions for peak un-weighted noise assessment metrics

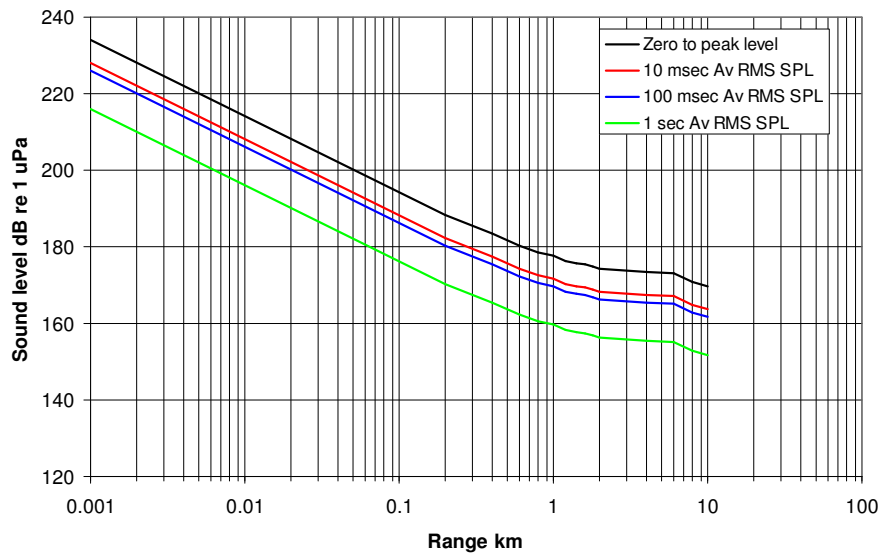


Figure 8.1: Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 470 cubic inch seismic airgun array operations in the Moray Firth – north-west transect

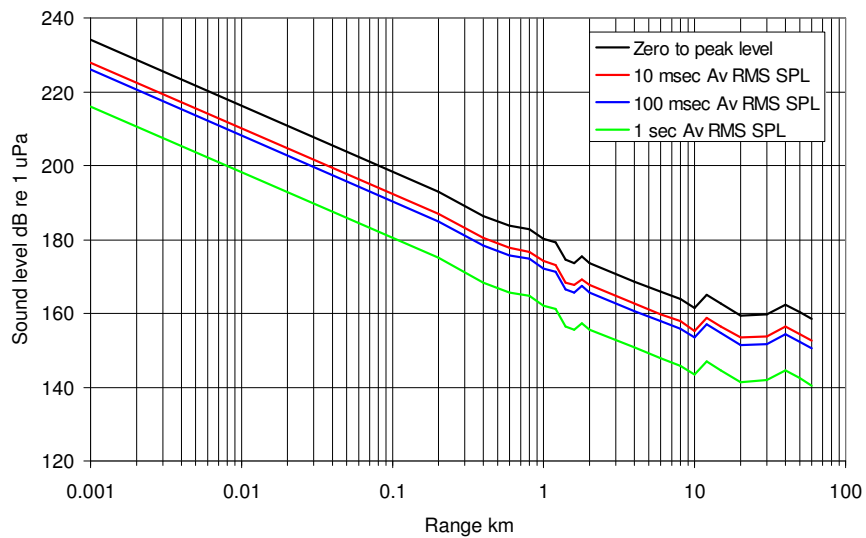


Figure 8.2: Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 470 cubic inch seismic airgun array operations in the Moray Firth – north-east transect

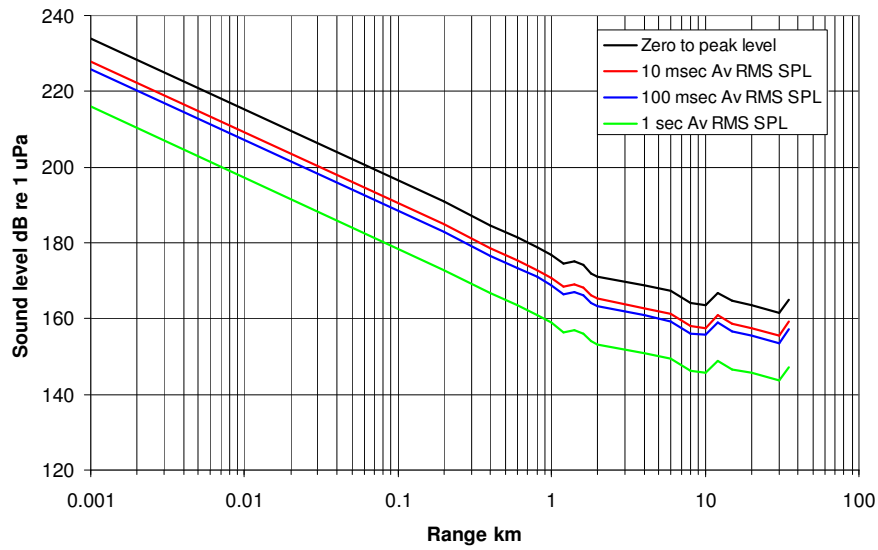


Figure 8.3: Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 470 cubic inch seismic airgun array operations in the Moray Firth – south-east transect

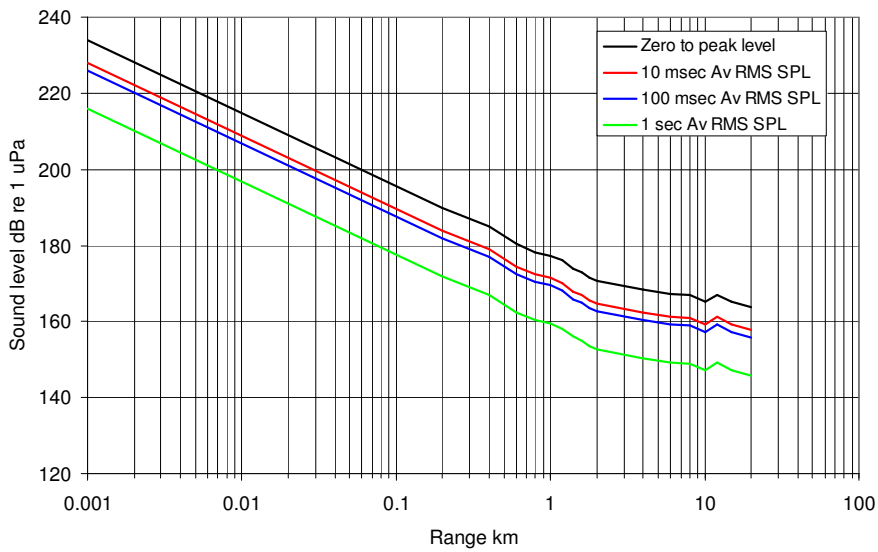


Figure 8.4: Predicted peak and RMS Sound Pressure Levels of underwater noise broadside of 470 cubic inch seismic airgun array operations in the Moray Firth – south-west transect



## 9. MODELLING RESULTS – M-WEIGHTED SEL

### 9.1 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.

### 9.2 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;

$$RL = SL - N \log(r) - \alpha r \quad \text{eqn. 9.1}$$

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  $\alpha$  is a factor for the absorption of sound in water and boundaries ( $\text{dB.km}^{-1}$ ) (See Equation 3.8).

Figures 9.1 to 9.4 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 November conditions. Individual results for each impact criterion and along each transect are summarised in Tables 9.1 to 9.3 inclusive. For comparison, the auditory injury criteria proposed by Southall *et al.* (2007) are also shown.

### 9.3 Results

The results in Figures 9.1 to 9.4 indicate that the single shot auditory injury range is within close proximity of the seismic array. In fact, the predicted single shot auditory injury ranges for low, mid and high frequency hearing cetaceans are within the near field of the acoustic emissions from the airgun array being no more than 3 m. Similarly for pinnipeds, the range along each transect is 11 m or less.

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 ( $N$ ) around 18 to 19, and an absorption loss from 0.3 to 2.1  $\text{dB.km}^{-1}$ . 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 (north-east and south-east transects). The north-west and south-west transects indicate the highest absorption due to propagation in shallower waters close in to the Cromarty shore at Helmsdale (north-west transect) and just west of Tarbat Ness (south-west transect). The data for the south-west transect indicates that the SEL falls to 140 dB re.1 $\mu$ Pa<sup>2</sup>s M-Weighted SEL at a range of 5 km just off the coast at Helmsdale.

The results in Table 9.2 indicate that TTS auditory injury is likely to occur in cetaceans at ranges of 9 m to 100 m and around 10 m for pinnipeds in each case depending on transect.

For the auditory injury criteria proposed by NOAA (2006), the results in Table 9.3 show that PTS ranges are all less than 1 m while TTS occurs less than 5 m.

<b>Marine Mammal Species</b>	<b>Criteria</b>	<b>Transect NW</b>	<b>Transect NE</b>	<b>Transect SE</b>	<b>Transect SW</b>
Cetaceans (M <sub>lf</sub> ) Low Frequency	PTS Auditory injury 198 dB re 1 $\mu$ Pa <sup>2</sup> .s	3 m	3 m	3 m	3 m
Cetaceans (M <sub>mf</sub> ) Mid Frequency	PTS Auditory injury 198 dB re 1 $\mu$ Pa <sup>2</sup> .s	2 m	2 m	2 m	2 m
Cetaceans (M <sub>hf</sub> ) High Frequency	PTS Auditory injury 198 dB re 1 $\mu$ Pa <sup>2</sup> .s	2 m	2 m	2 m	2 m
Pinnipeds (M <sub>pf</sub> )	PTS Auditory injury 186 dB re 1 $\mu$ Pa <sup>2</sup> .s	9 m	11 m	10 m	9 m

*Table 9.1: Single shot auditory injury range based upon PTS criterion proposed by Southall et al. (2007)*

<b>Marine Mammal Species</b>	<b>Criteria</b>	<b>Transect NW</b>	<b>Transect NE</b>	<b>Transect SE</b>	<b>Transect SW</b>
Cetaceans (M <sub>lf</sub> ) Low Frequency	TTS onset cetaceans 183 dB re 1 $\mu$ Pa <sup>2</sup> .s	16 m	100 m	19 m	18 m
Cetaceans (M <sub>mf</sub> ) Mid Frequency	TTS onset cetaceans 183 dB re 1 $\mu$ Pa <sup>2</sup> .s	10 m	55 m	12 m	11 m
Cetaceans (M <sub>hf</sub> ) High Frequency	TTS onset cetaceans 183 dB re 1 $\mu$ Pa <sup>2</sup> .s	9 m	45 m	10 m	9 m
Pinnipeds (M <sub>pf</sub> )	TTS onset pinnipeds 171 dB re 1 $\mu$ Pa <sup>2</sup> .s	45 m	75 m	60 m	52 m

*Table 9.2: Single shot M-Weighted SEL TTS onset auditory injury range based upon criterion proposed by Southall et al. (2007)*





Criteria	Transect NW	Transect NE	Transect SE	Transect SW
PTS Auditory Injury 215 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$	<1 m	<1 m	<1 m	<1 m
TTS Auditory injury 195 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$	4 m	5 m	4 m	4 m

Table 9.3: Single shot PTS and TTS auditory injury range based upon the criterion proposed by NOAA (2006)

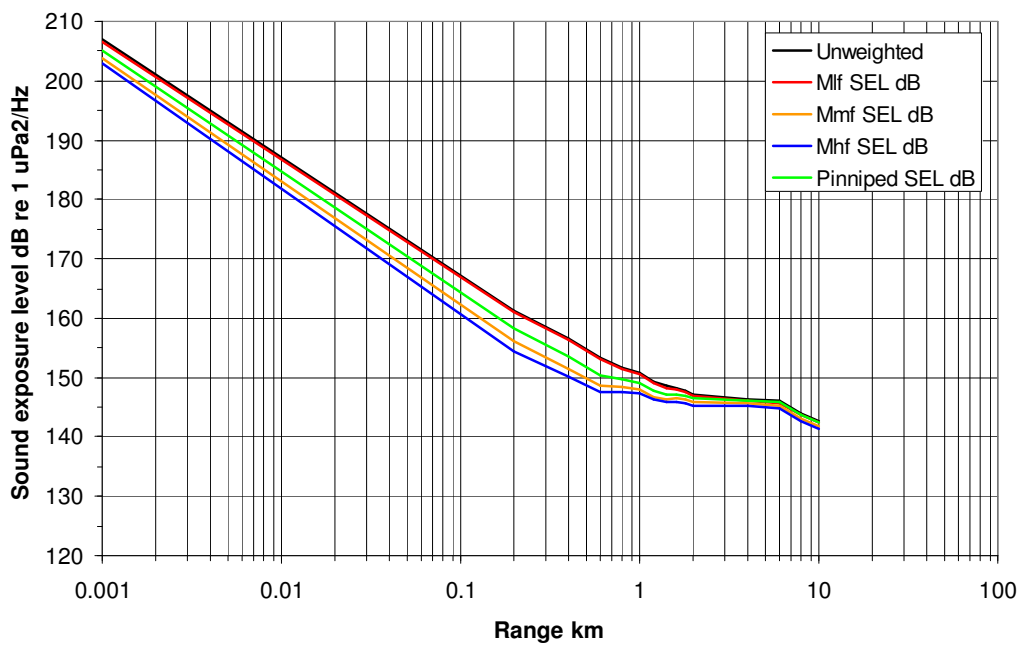


Figure 9.1: Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (north-west transect)

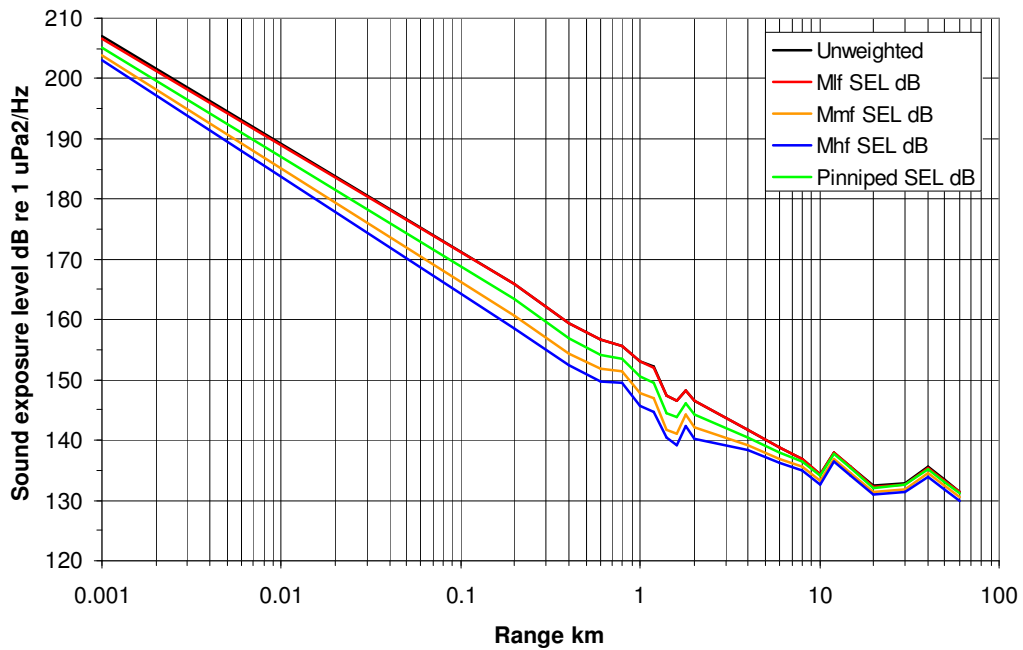


Figure 9.2: Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (north-east transect)

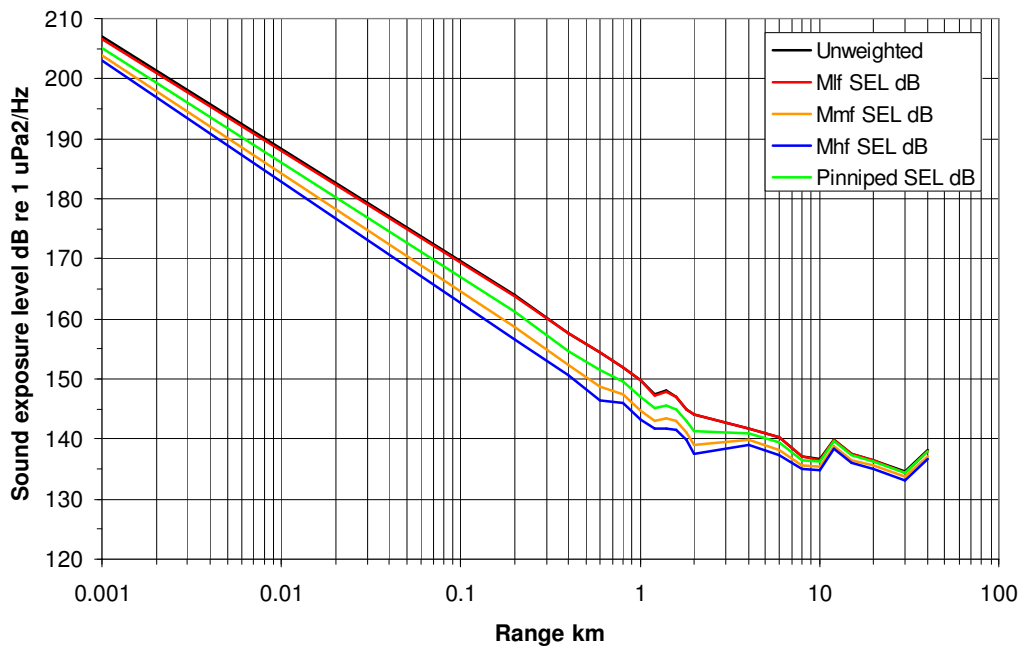


Figure 9.3: Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (south-east transect)

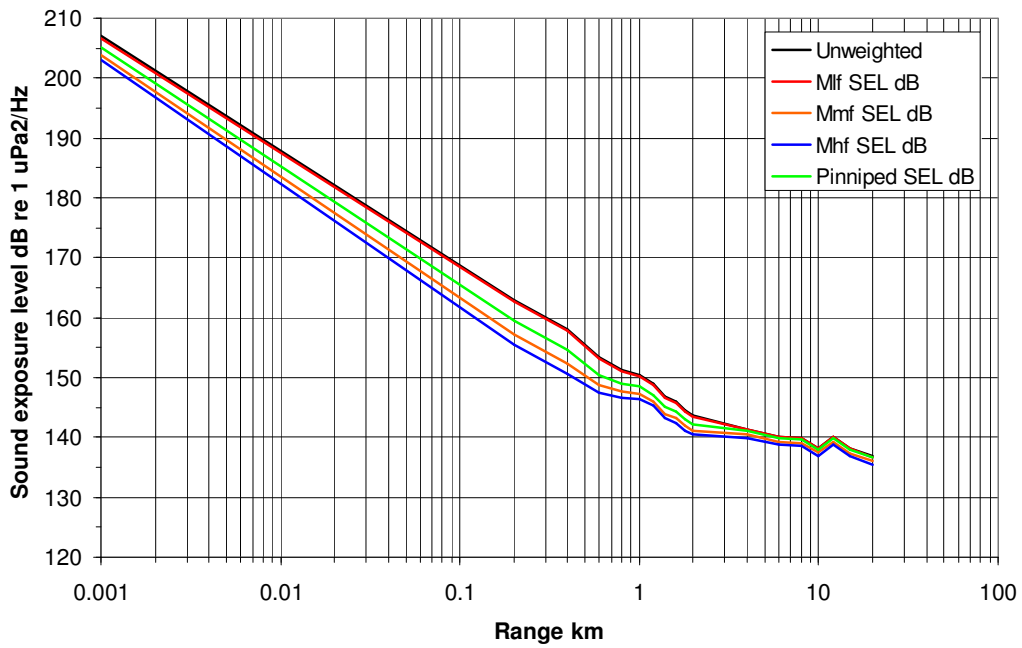


Figure 9.4: Predicted variation in SEL and M-weighted SEL with range from seismic operations in the Moray Firth (south-west transect)



## 10. MODELLING RESULTS – CUMULATIVE SEL

### 10.1 Introduction

This section of the report calculates cumulative SEL for a number of scenarios where marine mammals are assumed either to remain stationary or else 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.

### 10.2 Stationary animal and moving vessel

Cumulative M-weighted SEL has been calculated for 470 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 remaining at a fixed location in the sea at an initial distance of 500 m from the source vessel, using a similar method to that of Hannay *et al* (2009) and SMRU (2007) on behalf of COWRIE. The significance of the 500 m initial distance is that it corresponds to the JNCC guidance for the monitoring distance from seismic vessels at the commencement of a survey (JNCC 2004). Hence, the model incorporates both a moving survey vessel and a stationary marine animal, and can be varied depending upon the airgun array firing sequence and local acoustic propagation conditions.

The data in Figure 10.1 illustrates the instantaneous and cumulative  $M_{mf}$  – weighted SEL for a marine mammal at an initial range of 500 m from the seismic airgun array for a period of 30 minutes from the commencement of firing. For this case, the data indicates that the animals will receive a cumulative SEL during successive airgun array firings that remains below the 198 dB re 1  $\mu\text{Pa}^2\cdot\text{s}$  auditory injury criterion for cetaceans as proposed by Southall *et al.* (2007).

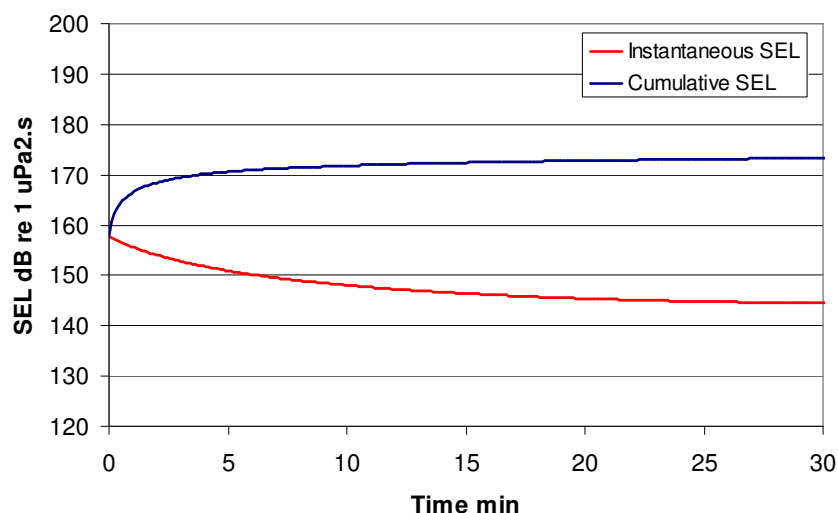


Figure 10.1. Predicted cumulative  $M_{mf}$ -weighted SEL for a stationary marine mammal at an initial start range of 500 m from 470 cubic inch seismic airgun array operations in the Moray Firth

Animals that are at a closer range would receive a cumulative  $M_{mf}$  – weighted SEL that approaches the 198 dB re 1  $\mu\text{Pa}^2\cdot\text{s}$  level, and hence the data would indicate that auditory injury to cetaceans may occur. Figure 9-2 shows the results for an animal that remains stationary at an initial distance of 3 m. It will be seen that the 198 dB re 1  $\mu\text{Pa}^2\cdot\text{s}$  threshold is reached immediately and the cumulative SEL remains at this level over the remaining 30 minute period.

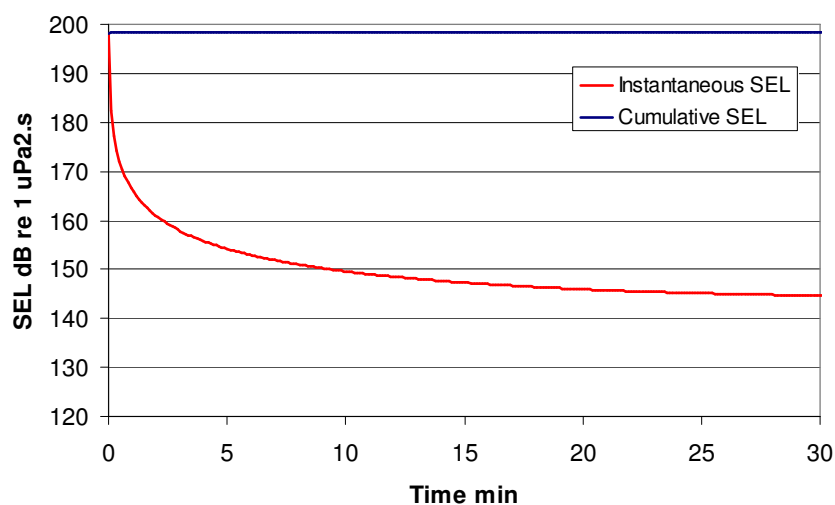


Figure 10.2. Predicted cumulative Mmf-weighted SEL for a stationary marine mammal at an initial start range of 3 m from 470 cubic inch seismic airgun array operations in the Moray Firth

Table 10.1 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. The data highlights that if it is assumed that marine mammals remain stationary while the seismic vessel moves away at a constant speed while firing, then, based upon the criteria proposed by Southall *et al.* (2007), auditory injury (either permanent or temporary) 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. Also included are the escape ranges for the harbour porpoise calculated using the Lucke *et al.* (2009) impact criterion for TTS. In this case, due to the apparent enhanced audiological sensitivity of the harbour porpoise compared with other cetaceans, it is likely that TTS would arise even when the initial start range is as great as 5 km.

Start range (m)	Mlf - SEL (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	Mmf - SEL (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	Mhf - SEL (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	Mpf - SEL (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )	Harbour porpoise (dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ )
2	201	201	200	201	201
5	194	193	191	193	194
10	189	188	185	187	189
20	185	183	180	183	185
50	181	178	173	177	181
100	178	175	169	174	178
200	176	173	166	171	176
500	173	170	162	168	173
1000	171	168	159	166	171
2000	170	167	157	165	170
5000	170	167	157	165	170

Table 10.1: Summary of predicted cumulative M-weighted SEL for a stationary marine mammal adjacent to 470 cubic inch seismic airgun array operations in the Moray Firth. Cells dark shaded indicate commencement of PTS; cells light shaded indicate commencement of TTS. Data are presented for marine mammals at start ranges from 2 m to 5000 m – south-west transect



### 10.3 Moving vessel, moving animal

A further cumulative noise exposure scenario has 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 as the survey vessel and airgun array moves along a survey line while a cetacean moves in the opposite direction from an initial separation of 500 m. The animal swims away at a speed of 1 m/s while the vessel proceeds in the opposite direction at a speed of 7 m/s firing every 18.75 m, and at a firing rate of once every 7 seconds.. From the results shown in Figure 10.3 it will be seen that the 198 dB re  $1 \mu\text{Pa}^2\cdot\text{s}$  auditory injury criterion is not reached and further, neither is the 183 dB re  $1 \mu\text{Pa}^2\cdot\text{s}$  level for the onset of TTS.

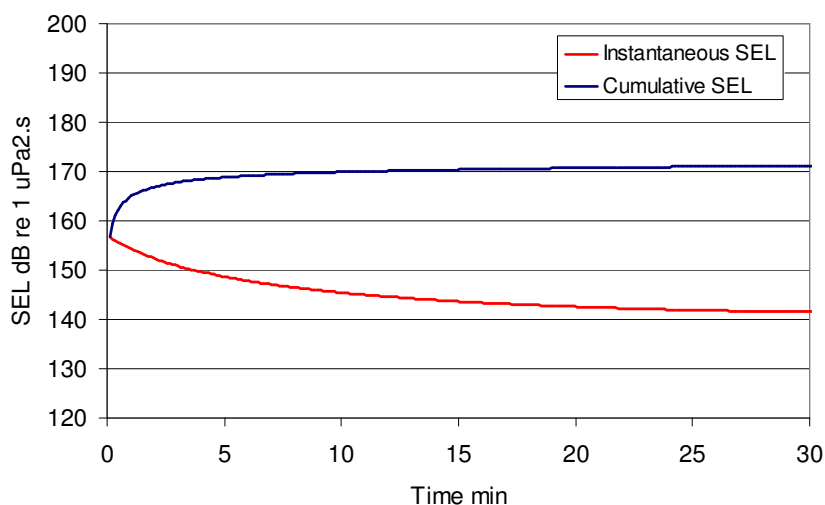


Figure 10.3. Predicted cumulative Mmf-weighted SEL for a marine mammal at an initial start range of 500 m from 470 cubic inch seismic airgun array operations in the Moray Firth with animal moving in one direction and vessel moving in the opposite



## 11. MODELLING RESULTS – HEARING THRESHOLD COMPARISON

### 11.1 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.

### 11.2 Hearing threshold data

Figure 11.1 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 11.2 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.

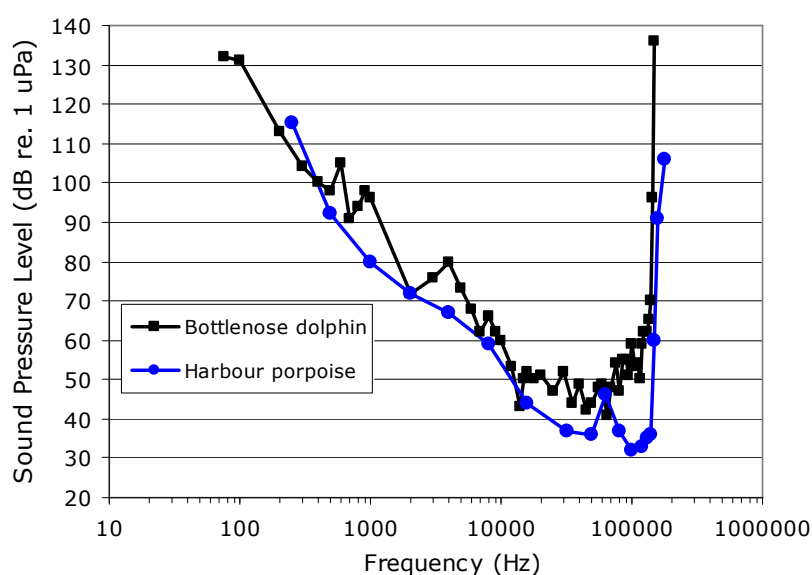


Figure 11.1: Audiogram data for the bottlenose dolphin (Johnson, 1967) and for the harbour porpoise (Kastelein *et al.* 2002).

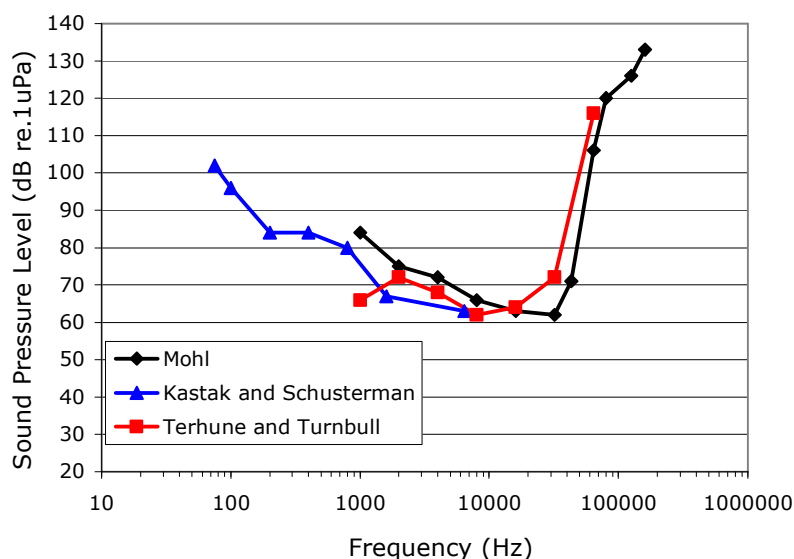


Figure 11.2: Audiogram data for the harbour seal from Møhl (1968), Kastak and Schusterman (1998) and Terhune and Turnbull (1995)

### 11.3 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 as 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 11.3 to 11.5 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 11.3), at 1 kHz (Figure 11.4) and at 20 kHz (Figure 11.5). 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 5.1 and 5.2 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 7 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.

It is noted that where the impact thresholds indicated in Table 8.2 fall beyond the ranges at which the background noise levels mask the noise generated during the seismic surveys, the impact is not likely to be observed. For instance, on the north-east transect, low level behavioural disturbance (HESS 1997) is expected to occur at ranges around 60 km, however, the seismic sound is likely to fall below background noise levels at 20 km or thereabouts and hence will not give rise to an impact.

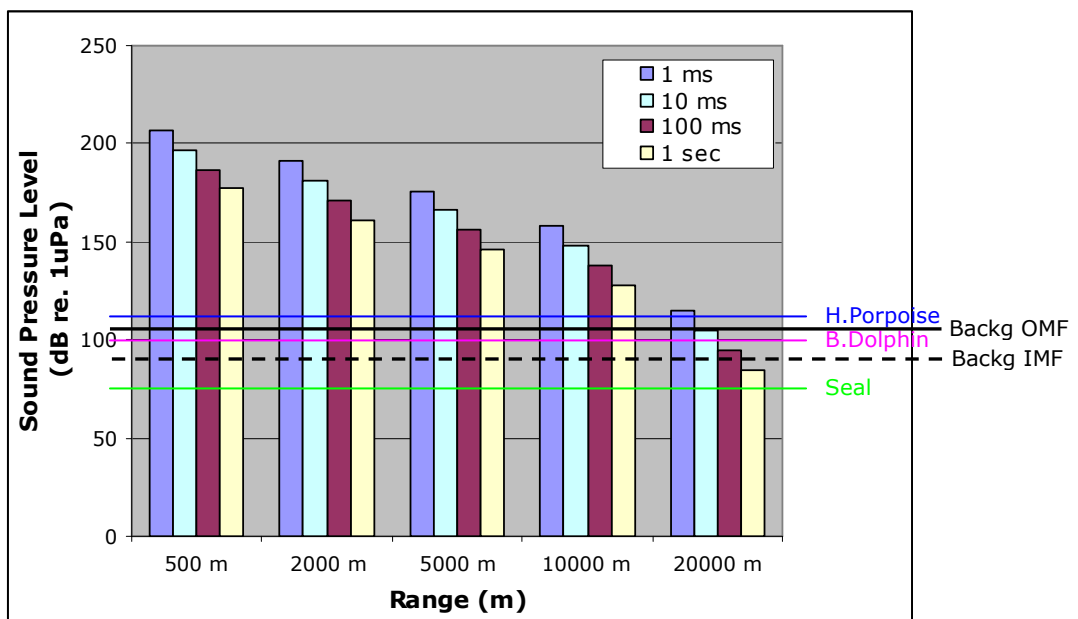


Figure 11.3: Comparison of 100 Hz 1/3 octave band noise with range from seismic array gun noise. Data are compared with marine mammal hearing thresholds and background sea noise data for the Outer (OMF) and Inner Moray Firth regions at 100 Hz over the north-west transect

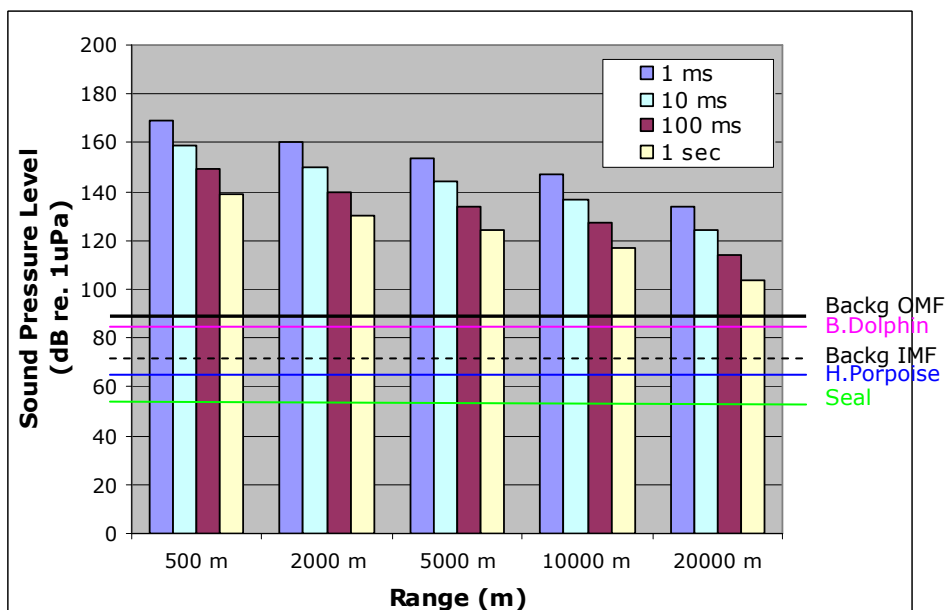




Figure 11.4: Comparison of 1 kHz 1/3 octave band noise with range from seismic array gun noise. Data are compared with marine mammal hearing thresholds and background sea noise data for the Outer (OMF) and Inner Moray Firth regions at 1 kHz over the north-west transect

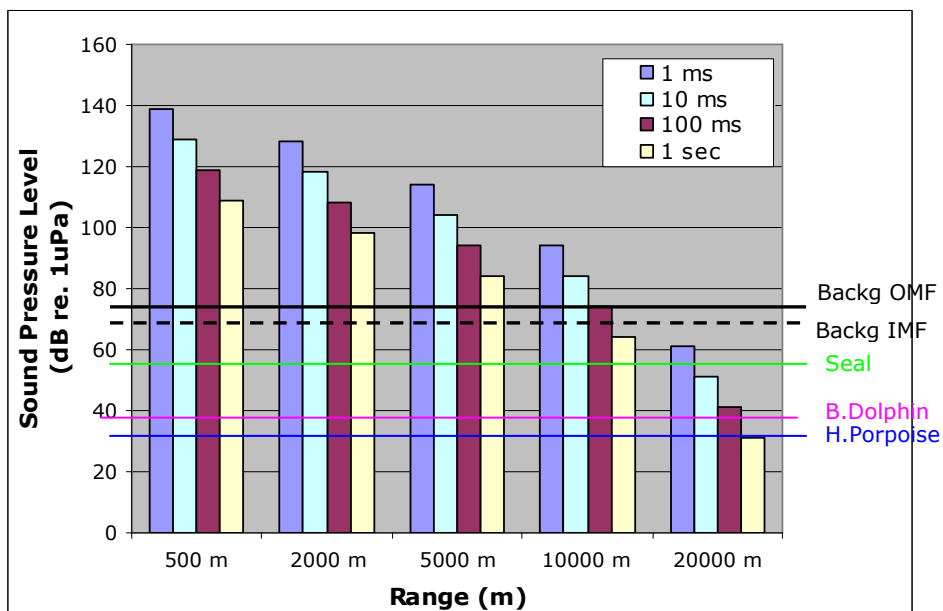


Figure 11.5: Comparison of 20 kHz 1/3 octave band noise with range from seismic array gun noise. Data are compared with marine mammal hearing thresholds and background sea noise data for the Outer (OMF) and Inner Moray Firth regions at 20 kHz over the north-west transect



## 12. SUMMARY AND CONCLUSIONS

Both the BMT and Subacoustech underwater noise reports have been reviewed. The BMT report was considered to have grossly simplified the acoustic propagation modelling while the Subacoustech report relied on a technique that has not, as far as can be ascertained, been reported in the open literature previously.

As a follow-up to the studies carried out by BMT and Subacoustech, 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 Bellhop 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.

The propagation modelling has shown that there is an azimuthal dependency with range. Sound is likely to travel further over the deeper waters on the north-east and south-east transects while the shelving nature of the seabed more rapidly attenuates the sound on the north-west and south-west transects.

Based on a zero to peak source level noise from the airgun array of 243 dB re.1 $\mu$ Pa @1 m, the modelling indicates that the single shot, peak noise, PTS auditory injury criteria proposed by Southall *et al.* (2007) for cetaceans will be met at a range of 2 m; and for pinnipeds to a range of 6 m. TTS onset ranges based upon peak level noise extend to 3 m and 18 m for cetaceans and pinnipeds respectively. By contrast, using the TTS impact criterion for harbour porpoises as proposed by Lucke *et al.* (2009), the ranges are likely to extend to 150 m. All these ranges are well within the near field of the airgun array and hence the actual levels are unlikely to be achieved.

The auditory injury criterion for cetaceans (NOAA 2006) is met between 64 m and 440 m depending on transect and pulse spreading while that for pinnipeds is met between 20 m and 140 m.

Both Level B harassment (NMFS 1997) and low level behaviour (HESS 1997) are likely to occur right up to the coastline along some transects and up to 14 km and 60 km respectively when the transects remain in the open seas. Aversive behavioural reactions (Lucke *et al.* 2009) are generally likely to be observed out to 5 km.

The predicted single shot PTS auditory injury ranges, based on the M-weighting criteria proposed by Southall *et al.* (2007), are no more than 3 m for cetaceans, and around 10 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.

Based on the M-Weighted SEL criteria proposed by Southall *et al.* (2007), the data indicates TTS onset in cetaceans may occur up to a range of 45 m from the airgun array for high frequency hearing cetaceans ( $M_{hf}$ ), 55 m for mid-frequency cetaceans ( $M_{mf}$ ), 100 m for low frequency cetaceans ( $M_{lf}$ ), and 75 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.

Cumulative SEL has been used to assess the noise exposure for marine mammals exposed to multiple pressure pulses from a moving airgun array. When cetaceans and



pinnipeds are as close as 10 m from the array at the commencement of firing, then both PTS and TTS are likely to arise. For the same scenario, TTS may occur in harbour porpoises out to 5 km. From an initial separation of 500 m, when the animals move away in the opposite direction to the source vessel, neither PTS nor TTS are likely to arise.

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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