moray offshore renewables ltd

Environmental Statement

Technical Appendix 7.3 C - MORL SAFESIMM noise impact assessment for seals and cetaceans

Telford, Stevenson, MacColl Wind Farms and associated Transmission Infrastructure Environmental Statement

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Contents

1. Introduction

The assessment approach combines three key pieces of quantitative information to estimate the number of animals likely to be affected by each type of impact:

1) The predicted spatial pattern and extent of underwater noise produced by piling activities;
2) The spatial pattern of abundance of marine mammals across the area of potential impact; and
3) The way in which animals are predicted to move in response to sound.

This report presents the results of these modelling exercises for both species of seal (harbour seal and grey seal) and for bottlenose dolphins, harbour porpoises, and minke whales for a series of construction scenarios at MORL.

2. Methodology

The SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna) algorithm is a software tool for estimating the potential effects of anthropogenic noise on marine fauna. SAFESIMM can also be used to compare the effectiveness of different strategies for mitigating the effects of anthropogenic sound by determining the risk associated with these strategies under a range of scenarios. For example, a proposed sound producing activity can be analysed with SAFESIMM to determine the likely effects of changes in operational parameters (such as the activity location and time of year, or the source level, frequency and duty cycle of the sound production) on the risk to marine mammals (please see Appendix at the end of this report for details of the algorithm).

2.1 Physical effects

The main physical effect on marine mammals that is likely to occur as a result of turbine construction is Permanent Threshold Shift (PTS). This involves a permanent impairment in hearing sensitivity at a particular frequency caused by exposure to excessive sound levels. There have been no direct experiments on marine mammals to determine what sound levels may cause PTS. Rather, these levels have been estimated by determining what sound levels are required to cause a temporary threshold shift (TTS) and then estimating what additional sound exposure would be required to cause PTS by inference from the results of experiments with small mammals.

Southall *et al*. (2007) used this approach to derive interim recommendations of the sound levels that could cause PTS in different groups of marine mammals. They also developed a series of weighting functions (M-weightings) that could be used to take account of the hearing sensitivities of four different marine mammal groups (low frequency cetaceans, mid-frequency cetaceans, high frequency cetaceans and pinnipeds). The authors recommend the following values for the onset of PTS based on M-weighted Sound Exposure Levels (SELs) for both pulsed (such as those produced during pile driving) and non-pulsed sounds (such as vessel noise or that produced during cable laying):

Cetaceans = Pulsed (198dB), Non-pulsed (215dB)

Pinnipeds = Pulsed (186dB), Non-pulsed (203dB)

However, exposure to SELs at or above these levels does not mean that an animal is certain to experience TTS or PTS, because the onset of threshold shift is a probabilistic phenomenon. The data from Finneran *et al.* (2005) that were used by Southall *et al*. (2007) to develop the TTS values for mid-frequency cetaceans indicate that ~18-19% of exposures to an SEL of 195 dB re 1 μ$Pa^2.s^{-1}$ resulted in measurable TTS. SAFESIMM therefore uses a series of dose-response relationships derived from Finneran *et al.*'s (2005) work to determine the likely effect of sound exposure on the different marine mammal groups. These dose-response relationships are shown in Figure 1: Dose-response curves used within SAFESIMM to relate the probability of Temporary Threshold Shift (black curves) and Permanent Threshold Shift (red curves) to M-weighted Sound Exposure Level (SEL) for cetaceans and pinnipeds exposed to pulsed and non-pulsed sounds. In these relationships, the probability that an animal which is exposed to an SEL equivalent to the threshold values recommended by Southall *et al.* (2007) will experience PTS or TTS is set at 0.18, and that probability increases as the SEL increases

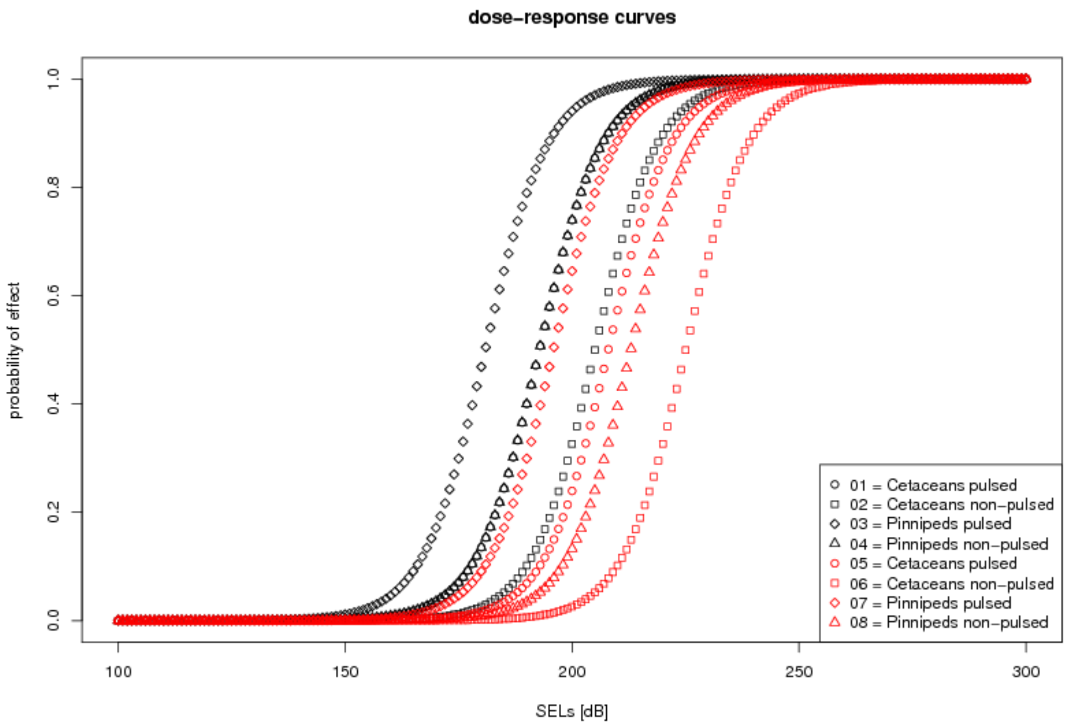

Figure 1: Dose-response curves used within SAFESIMM to relate the probability of Temporary Threshold Shift (black curves) and Permanent Threshold Shift (red curves) to M-weighted Sound Exposure Level (SEL) for cetaceans and pinnipeds exposed to pulsed and non-pulsed sounds.

SAFESIMM provides estimates of the number of individuals of each species of marine mammal that may experience PTS and TTS from a particular sound field by simulating the three dimensional movements of thousands of simulated animals through this field, based on known characteristics of the diving and swimming behaviour of each species, and recording the cumulative SEL of each simulated individual. The species-specific PTS and TTS dose-response curves are then used to convert each individual's SEL into a probability that it will experience PTS or TTS. The initial locations of these simulated animals are chosen at random, although the density of simulated animals in any grid cell is proportional to the expected density provided by the animal density data. The actual number of animals predicted to experience PTS and TTS at individual locations is then calculated by scaling these simulated values using estimates of the expected densities of all marine mammal species at each location.

The density data for grey seals and harbour seals used in the simulations were provided by the Sea Mammal Research Unit at a resolution of 5 x 5 km and the University of Aberdeen at a resolution of 4 x 4 km. This grid was converted into a 0.083 degree grid for incorporation into SAFESIMM.

2.2 Behavioural effects

SAFESIMM has the capability to simulate behavioural responses of marine mammals to sound exposure. Incorporating behavioural responses where animals move away or towards the sound source provides also is likely to have an important bearing on the number of individuals predicted to experience physical injury. Unless otherwise specified, animals are predicted to follow a correlated random walk. However, they can be simulated to move towards or away from the sound source, both horizontally and/or vertically, if the received level of sound is above a given threshold. For the purposes of this assessment, an individual's movement in response to sound was determined probabilistically using a dose-response curve based on the seal assessment framework (Thompson *et al*., 2011; Figure 2) which predicts the proportional change in the occurrence of harbour porpoises with distance from a piling event and is based on data from changes in the detection rates during piling at the Horns Rev 2 wind farm from Brandt et al (2011). In the absence of empirical data other species, this curve has been adopted in this assessment. It should be highlighted that the Seal Assessment Framework uses dB_{ht} as a metric to predict behavioural response; however, to simplify the incorporation of a behavioural response in SAFESIMM, an M-Weighted SEL dose response curve based on Thompson *et al*'s (2011) work was used.

At each time step, the probability that each simulated individual will respond to the instantaneous M-weighted SEL experienced at its location is determined by this dose-response curve (Figure 2). The response simulated for both pinniped species is a movement away from the sound source in a directed manner (i.e. a flight response). The response simulated for other species is a movement directly away from the sound source manner (i.e. a flight response). The speed at which grey seals and harbour seals move was determined from unpublished telemetry data collected by SMRU. This gave a minimum speed of 0.01 $m.s^{-1}$ for both species and maximum speeds of 2.6 $m.s^{-1}$ for grey seals and 2.3 $m.s^{-1}$ for harbour seals. The minimum and maximum values of 0.01 $m.s^{-1}$ and 5.6 $m.s^{-1}$ for bottlenose dolphins were obtained from an extensive literature search.

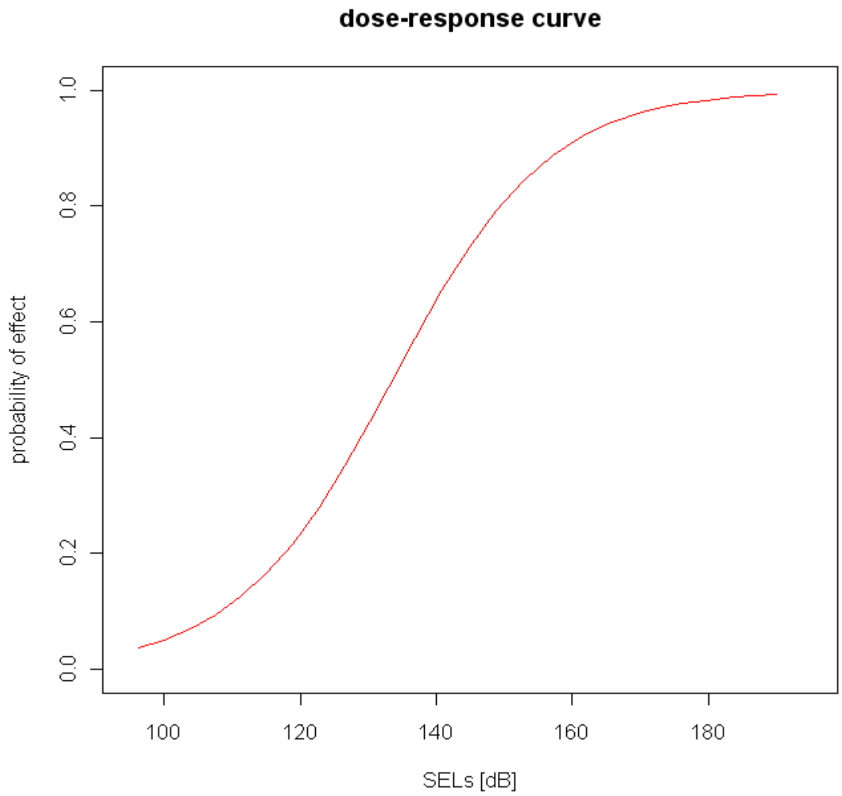

Figure 2. Dose-response curve used within SAFESIMM to relate the probability of behavioural displacement to M-weighted Sound Exposure Level (SEL) used for cetaceans and pinnipeds exposed to pile driving noise.

2.3 Parameters modelled

Subacoustech provided SMRU Ltd with the outputs of sound propagation models for each pile driving scenario in the format of a calculated SEL for a single hammer blow (of 0.5 sec duration) for each blow energy used during the piling event on 96 transects radiating from the source location (3.75° apart). The predicted SEL was provided at steps of 100 m along each transect. SAFESIMM then carried out a simulation of animal exposure over the whole piling duration using parameters for duration and strike rate provided by MORL. Where ramp ups were included in the engineering scenarios, Subacoustech provided a separate sound field for each different blow force – SAFESIMM cycled through these in accordance with the duration of each step in the ramp up. The details of the engineering scenarios can be found in Table 1.

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Table 1. Summary of scenarios assessed

Construction scenario	Description
1	Two piling vessels on MacColl; 2.5m pin piles at locations 1 and 2;
2	Two piling vessels on Stevenson 2.5m pin piles at locations 4 and 6;
3	Two piling vessels on Telford; 2.5m pin piles at locations 3a and 5a;
4	One piling vessel to build out all three schemes; 2.5m pin pile at location 1;
5	Two piling vessels to build out all three schemes; 2.5m pin piles at locations 1 and 5;
6	Six piling vessels to build out all three schemes; 2.5m pin piles at locations 1, 2, 3, 4, 5 & 6;
7	OFTO route; location 2 for 3m pin pile;
8	BOWL A&B
9	BOWL A and MORL 1 (2.5m pin pile);
10	BOWL A;
11	One piling vessel on MacColl; 2.5m pin piles at locations 1a;
12	One piling vessel on Stevenson; 2.5m pin piles at location 4;
13	One piling vessel on Telford; 2.5m pin piles at location 3a;

3. Results

Results of the SAFESIMM modelling for each of the scenarios are shown in Table 2 for seals and Table 3 for cetaceans.

Table 2: The number of harbour seals and grey seals predicted to experience physical injury (PTS) as a result of each of the construction scenarios.

scenario	Description	Harbour seal: 186	Harbour seal: 198	Grey seal: 186	Grey seal: 198
1	Two piling vessels on MacColl; 2.5m pin piles at locations 1 and 2;	179.5	41.1	268.7	58.8
2	Two piling vessels on Stevenson 2.5 m pin piles at locations 4 and 6;	171.5	40.2	242.9	51.7
3	Two piling vessels on Telford; 2.5 m pin piles at locations 3a and 5a;	174.5	41.9	262.9	54.4
4	One piling vessel to build out all three schemes; 2.5 m pin pile at location 1;	120.9	25.5	169.9	35.3
5	Two piling vessels to build out all three schemes; 2.5 m pin piles at locations 1 and 5;	197.5	46.6	301.3	65.3
6	Six piling vessels to build out all three schemes; 2.5 m pin piles at locations 1, 2, 3, 4, 5 & 6;	305.4	88.8	477.6	119.4
7	OFTO route; location 2 for 3 m pin pile;	125.4	26.9	203.4	41.9
8	BOWL A&B	237.2	59.9	347.5	78.0
9	BOWL A and MORL 1 (2.5 m pin pile);	168.6	38.6	236.5	49.8
10	BOWL A;	210.1	50.8	300.0	66.9
11	One piling vessel on MacColl; 2.5 m pin piles at locations 1a;	118.9	25.2	175.0	35.4
12	One piling vessel on Stevenson; 2.5 m pin piles at location 4;	121.4	26.2	167.0	33.8
13	One piling vessel on Telford; 2.5 m pin piles at location 3a;	121.8	26.6	182.9	37.4

Table 3: The number of bottlenose dolphins, harbour porpoises, and minke whales predicted to experience physical injury (PTS) as a result of each of the construction scenarios.

Scenario	Description	Bottlenose dolphin 198	Harbour porpoise 179	Harbour porpoise 198	Minke whale 198
1	Two piling vessels on MacColl; 2.5 m pin piles at locations 1 and 2	0.08	1176.2	10.0	8.9
2	Two piling vessels on Stevenson 2.5 m pin piles at locations 4 and 6	0.06	1036.6	8.9	9.6
3	Two piling vessels on Telford; 2.5 m pin piles at locations 3a and 5a	0.06	1052.5	9.0	9.2
4	One piling vessel to build out all three schemes; 2.5 m pin pile at location 1	0.06	801.8	6.4	12.3
5	Two piling vessels to build out all three schemes; 2.5 m pin piles at locations 1 and 5	0.07	1177.8	10.2	10.7
6	Six piling vessels to build out all three schemes; 2.5 m pin piles at locations 1, 2, 3, 4, 5 & 6	0.12	1792.2	21.9	9.9
7	OFTO route; location 2 for 3m pin pile	0.05	825.8	6.2	28.1
8	BOWL A&B	0.11	1311.9	12.9	24.7
9	BOWL A and MORL 1a (2.5 m pin pile)	0.07	984.9	8.2	35.4
10	BOWL A	0.10	1249.5	11.5	24.2
11	One piling vessel on MacColl; 2.5 m pin piles at locations 1a	0.05	816.3	6.2	14.8
12	One piling vessel on Stevenson; 2.5 m pin piles at location 4	0.04	773.5	6.1	13.2
13	One piling vessel on Telford; 2.5 m pin piles at location 3a	0.04	781.2	5.9	14.6

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5. Appendix

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Environmental Risk Management Capability: Advice on Minimising the Impact of Both Sonar and Seismic Offshore Operations on Marine Mammals

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Abstract

There is growing concern about the effect of noise pollution from Offshore Operations on whales, dolphins, porpoises and other marine fauna both in the scientific and political communities. The general public, media and key decision makers are becoming more aware of the potential impact of such operations and this is increasing the pressure on organisations to manage their acoustic impact on the marine environment.

The Environmental Risk Management Capability (ERMC - a software package developed by BAE Systems in collaboration with the Sea Mammal Research Unit (SMRU) and the Centre for Research into Ecological and Environmental Modelling (CREEM) at the University of St Andrews) is the first system to provide a quantitative, robust and repeatable risk assessment method of the potential impact of sonar on both human divers and marine fauna. To assist in the effective management of this impact, ERMC can provide the user with recommendations of potential mitigation measures, and more importantly supports a basis from which the user can continue to use active sonar whilst

complying with their operating policies and legislative obligations to protect the environment.

This paper will discuss how ERMC can be employed to provide a risk assessment for both sonar and seismic offshore operations which introduce sound into the marine environment. It will also discuss whether such an approach would provide a more flexible and reliable outcome to methods commonly in use today.

Introduction

In the increasingly complex world that we live in, our dependency on oil and gas is increasing – recent events both nationally and internationally have demonstrated that without regular access to these natural resources, the ability to carry out our daily activities is severely limited. Although significant work is being undertaken to investigate alternative sources of energy (wind farms, nuclear power etc) it is still expected that this dependency will be dominant for several decades. From a UK perspective, it is important that we are able to continue to explore for and produce our own oil and gas to minimise our reliance on other countries.

The industrial process of finding and producing oil and gas has an unavoidable impact on the marine environment. Seismic surveys (and high resolution site surveys) are used by the industry to locate and evaluate oil and gas deposits. The sound produced by these surveys has the potential to adversely affect marine mammals and other marine organisms that are sensitive to noise. Although the available data on the effects of noise on marine mammals varies greatly in both quantity and quality, most regulators adopt a precautionary approach by implementing a system of mitigation and management activities based on the most up-to-date information available. In the context of seismic surveys, mitigation activities are aimed at reducing or removing adverse effects for individual surveys, whereas risk management is designed to reduce or remove additive and cumulative[1] effects.

In the UKCS, an Operator may not carry out geological surveys, or drill for the purpose of obtaining geological information without prior consent granted from the Regulator. For some activities, it will be necessary to submit an environmental assessment to demonstrate that the potential impact on the environment has been fully understood and appropriate mitigation and management activities have been undertaken. Any consent provided for seismic surveys will require that the activity be conducted in accordance with the latest Joint Nature Conservation Committee (JNCC) guidelines for "The Protection of Marine European Protected Species from injury and disturbance" (JNCC, 2009). This guideline provides Operators, Regulators and advisors with information on the legislative guidance to be considered if an offence of disturbing, injuring or killing a marine European Protected Species has occurred or is likely to occur.

[1] We define additive effects as those effects that can arise from multiple surveys being conducted in a single year whereas cumulative effects are effects that can occur over multiple years.

The JNCC Guidelines recognise that in many cases, the information to undertake a risk assessment for the disturbance and injury / killing offences may be less than ideal. However, advanced risk assessment systems such as ERMC, which account for the uncertainty in scientific knowledge and data availability and quality, can be used to assess the potential impacts and help to identify appropriate mitigation strategies to adopt to meet the JNCC Guidelines.

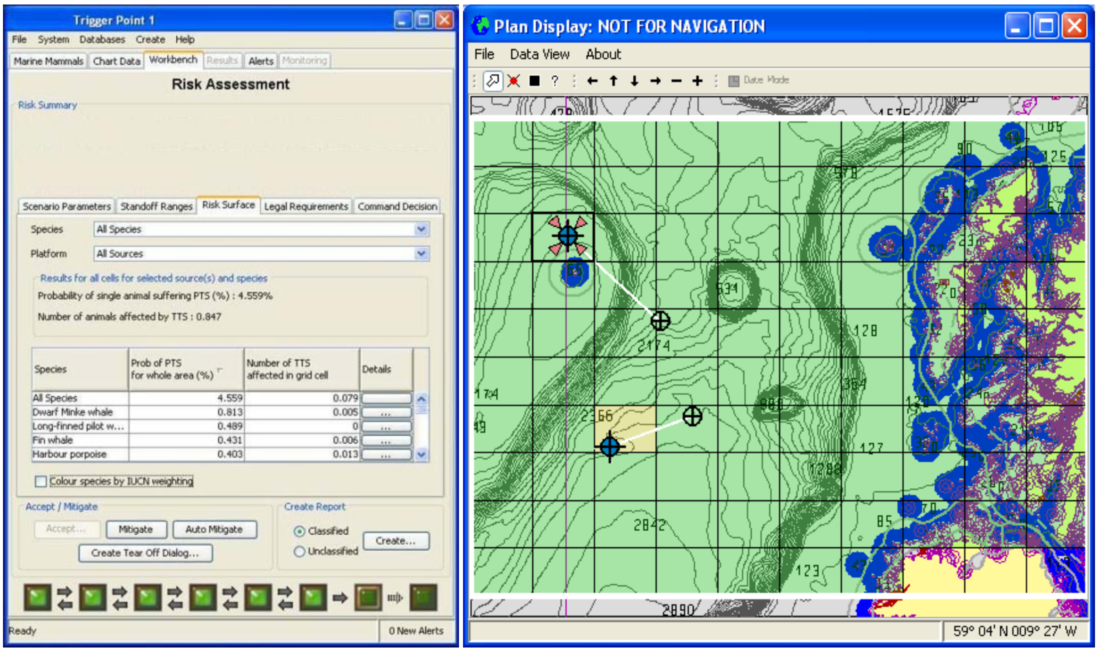

Figure 1 - ERMC provides an automated solution for assessing the potential impact of underwater anthropogenic noise on marine fauna, allowing environmental risks to be assessed, mitigated and reported.

Quantifying the effects of sonar on marine fauna

ERMC provides a flexible approach to the management of risk and generation of the required Environmental Impact Assessment (EIA) during sonar operations. The system is underpinned by a combination of global scientific research and data, statistical modelling and open-systems design and implementation.

ERMC provides five key elements to support a risk assessment:

- Risk Assessment Methodology - developed by SMRU and CREEM, which provides a fully quantitative EIA process. The algorithms, called SAFESIMM (Statistical Algorithms For Estimating the Sonar Influence on Marine Megafauna), provide a quantitative evaluation of the risks to marine mammals posed by sonar, whilst accounting for uncertainties in our knowledge of both marine mammal densities and the likely biological consequences of exposure to sound.

- Risk Mitigation – through which alternative scenario options are assessed to allow trades between desired operational performance and risk to be managed.
- Approval and Auditing Process – makes decision making and responsibility clear, and records the risk assessment inputs and outputs on which they were based.
- Cumulative Sound Exposure – caters for extended durations by accumulating exposure over longer periods of noise emitting activities. This process ensures the cumulative effects of exposure to multiple sequential elements of a scenario are considered.
- Data – is at the core of the ERMC system and the adaptability and maintenance of it is fundamental to the quality of the output as discussed below.

The predictive power of the algorithms and models in the ERMC system ultimately depend on the quality, quantity, variability and breadth of the data that is available. The following categories of data are stored within the system and can be accessed and updated as required:

- Acoustic device parameters;
- Environmental descriptors – water depth, sediment characteristics, sound speed profiles;
- Marine Species - maps for species' density; and species (or group) specific information on behaviour (e.g. dive patterns) and sensitivity to sound (audiograms);
- Areas and Limits – coastlines, marine protected areas, fishing areas, legal boundaries, etc.

The majority of the above datasets are loaded from an extension to the IHO's S-57 Electronic Chart Transfer Format called Additional Military Layers (AML). One example of such an extension is the dataset that maps species densities to world locations provided as part of the United Kingdom Hydrographic Office's Integrated Water Column product. The data has been derived from the Relative Environmental Suitability models of Kaschner (2006), and calibrated by the University of St Andrews using published survey data for each species. The data is global, stored at half degree resolution and gives both a density estimate and an uncertainty measure for 115 marine mammal species. Due to the availability of information, 46 marine mammal species (including all species occurring in UK waters) have additional estimates for the seasons of the year. Figure 2 shows the global predicted mean densities for Bottlenose Dolphin (Tursiops truncatus).

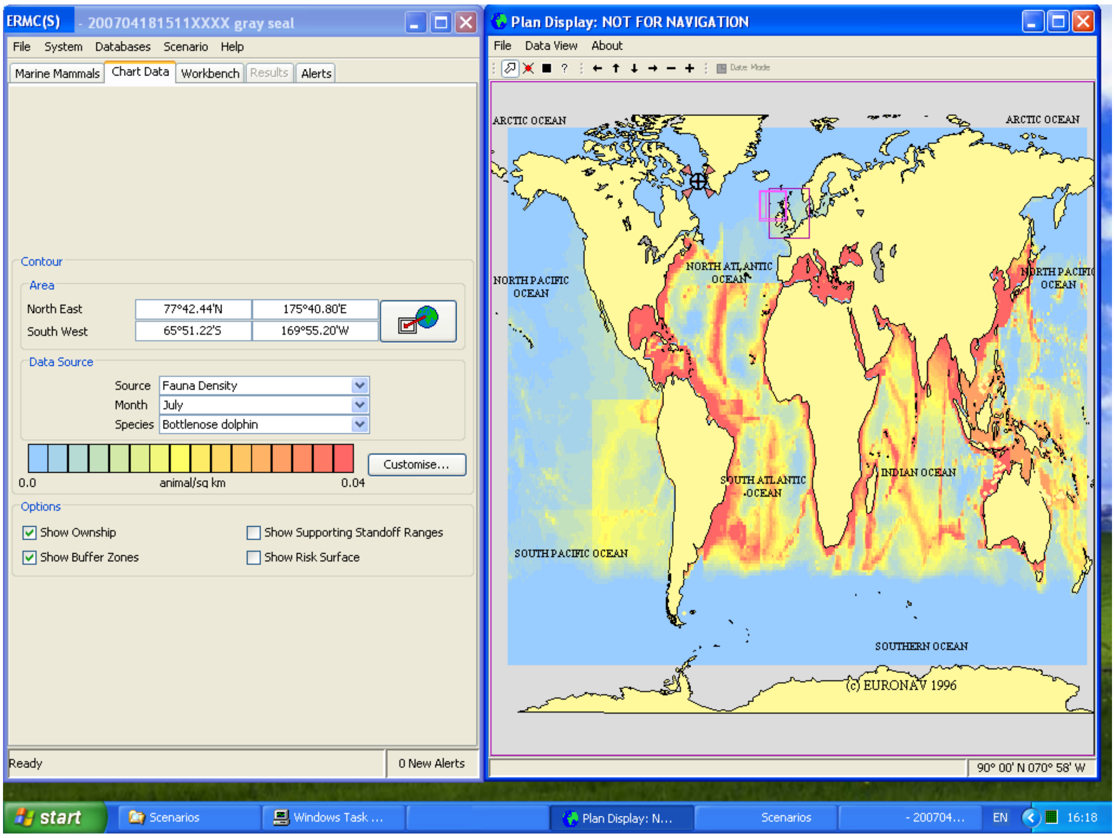

Figure 2 – Global density map for Bottlenose Dolphin (Tursiops truncates), based on the relative environmental suitability model of Kaschner (2006) and calibrated by the University of St Andrews against survey data.

To calculate the potential risk to marine fauna of noise, the component within ERMC called SAFESIMM has been developed. The SAFESIMM component (as depicted in Figure 3) comprises a sound propagation model, a simulation model and databases of marine mammal data. Output from the sound propagation model is combined with probabilistic information on the location of marine mammals through time to give sound exposure histories for individual simulated animals. These sound exposure histories are used to determine the probability for each individual of it suffering a Permanent Threshold Shift (PTS) or Temporary Threshold Shift (TTS) in hearing or modification of its natural behaviours (such as feeding habits or maternal characteristics). SAFESIMM uses a dose-response curve based on the results of Finneran et al (2005) to link the probability of experiencing TTS to Sound Exposure Level (SEL) accumulated over the period of a survey. Due to the lack of data on dose-response parameters for PTS, SAFESIMM assumes that the dose-response curve for PTS has the same shape as for TTS with an offset by +20dB; following the approach adopted by Heathershaw (2001) and Chief of Naval Operations (2006). These dose-response curves predict the probability that an individual will experience TTS or PTS as a result of a particular SEL. Uncertainty in these biological consequences is captured by sampling from a Binomial distribution with this probability, to determine whether or not an individual does actually experience either of these threshold shifts.

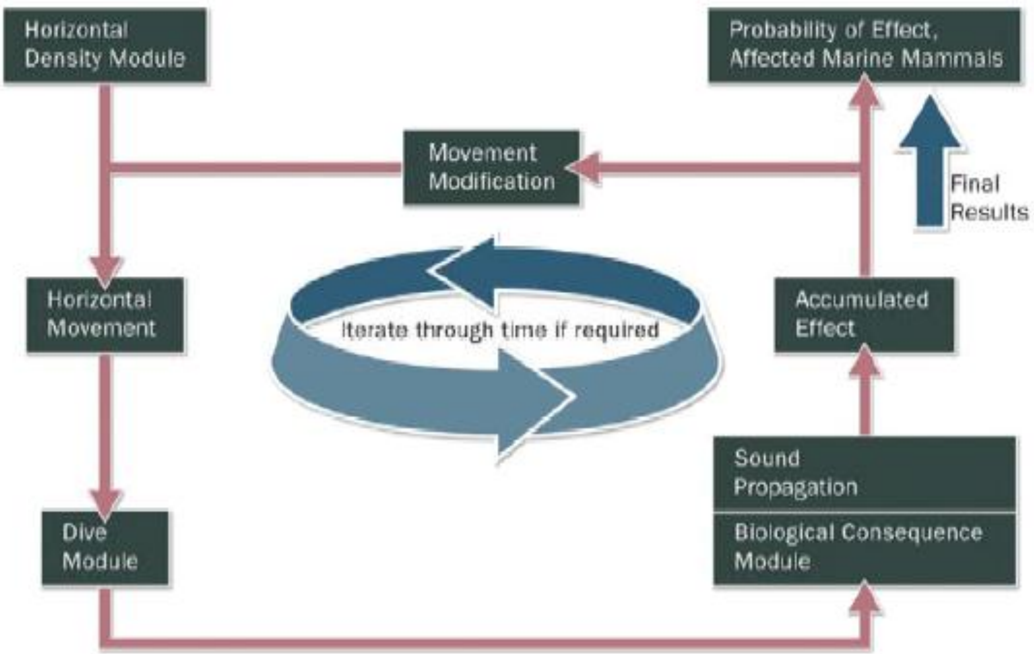

Figure 3 –Broad overview of the ERMC risk assessment framework

SEL is calculated relative to the hearing sensitivity of each species determined from an audiogram following the approach suggested by Heathershaw (2001). The following decision framework is used to assign an audiogram to each species:

- if species-specific information is available then it is used;
- if no species-specific information is available but information from a similar species (i.e. within the same guild and thus sharing similar ecological, behavioural, physiological or taxonomic characteristics) is available then the related species' information is used;
- if no guild-specific information is available, a generic function (e.g. the Global EIA audiogram in Heathershaw (2001)) is used (see Figure 4).

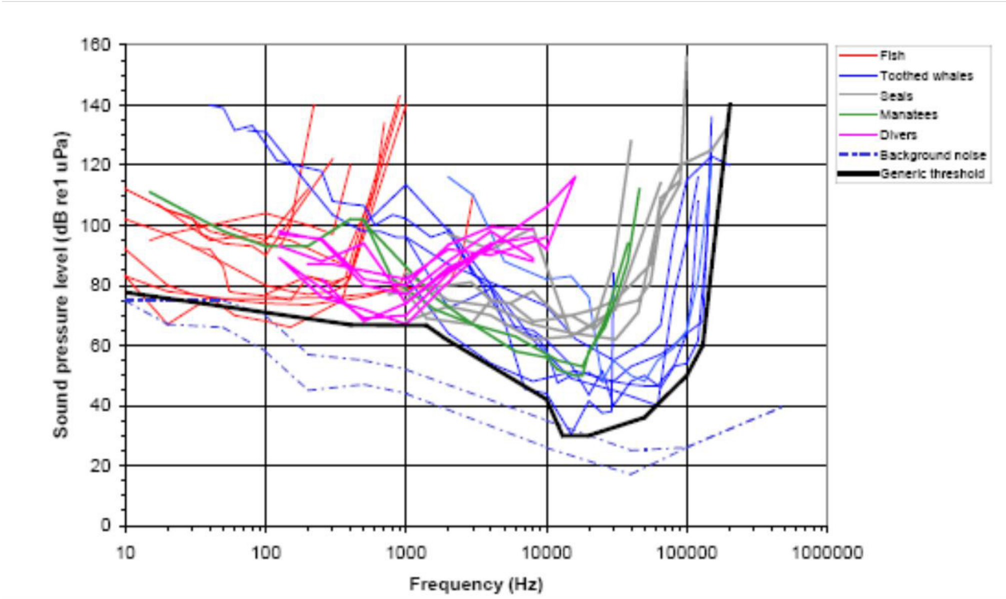

Figure 4 –Generic audiogram in Heathershaw (2001) is used in ERMC if no species or guild specific audiogram information is available

Information on the predicted density and behaviour of marine mammals from the ERMC databases is used by SAFESIMM to give repeated realisations of marine mammal locations and movements during a sonar scenario. Simulated movement includes representative diving behaviour and horizontal travel. The information necessary to carry out such movements is held in a comprehensive database of marine mammal diving behaviour, mostly derived from tagging surveys. This is used, together with information on local bathymeytry, to model the duration and depth of individual dives.

To take into account the effect that noise will have on species movement characteristics, both horizontal and vertical movements can be modified when a simulated animal experiences an SEL above their hearing threshold if there is scientific evidence that a species or guild's movement is affected by exposure to sound, such as with beaked whales.

To model the stochastic nature of real life, SAFESIMM samples from the statistical distribution of density values for each grid cell during every simulation run, rather than using mean values. This allows it to take account of the uncertainty associated with these density estimates. This uncertainty is not currently displayed within the system due to the confusion that could arise from displaying confidence intervals to the user, particularly around thresholds, however there is scope for this to be included with an intuitive visualisation to enable better understanding of the risk assessment output.

The simulation results can be used to estimate a variety of risk metrics derived from the statistical distribution of SELs that could be expected at a particular geographic location which can then be visualised through the systems' Human Computer Interface. The current system configuration displays the probability that any marine mammal will suffer PTS during a scenario and the expected number of animals that might suffer TTS.

Quantifying the Effects of Seismic Surveys on Marine Fauna

Marine seismic vessels typically tow arrays of air guns and streamers containing hydrophones a few meters below the surface of the water. The air guns are activated periodically, such as every 25 m (about 10 seconds), and the resulting sound wave travels into the seabed, is reflected back by the rock layers to a hydrophone and then relayed to the recording vessel.

A typical air gun is a relatively simple mechanical device that stores compressed air in a reservoir and releases it rapidly through small ports when a firing command is received. The ports are opened and closed by either an external movable piece called a sleeve or an internal movable piece called a shuttle. When an air gun fires, part of the energy contained in the escaping air is converted to sound, thereby generating a seismic signal that travels into the earth's subsurface. The pressure signature of an individual airgun consists of a sharp rise and then a fall in pressure, followed by several positive and negative excursions caused by oscillation of the resulting air bubble. The sizes, arrangement, and firing times of the individual airguns in an array are designed and synchronized to suppress the pressure oscillations subsequent to the first cycle. The resulting downward-directed pulse has duration of 10–20 ms, with only one strong positive and one strong negative peak pressure (Hatton, 2007). A typical airgun array will have a volume of 4000 cu.in (about 65 litres) and be made up of around 30 guns of various sizes.

Most energy emitted from airguns is at relatively low frequencies. For example, typical high-energy airgun arrays emit most energy at 10–120 Hz, however, the pulses contain significant energy up to 500–1000 Hz and some energy at higher frequencies (Hatton, 2007). Studies in the Gulf of Mexico have shown that the horizontally propagating sound can contain significant energy above the frequencies that airgun arrays are designed to emit (Tyack, 2006). Energy at frequencies up to 150 kHz was found in tests of single 60-in3 and 250-in3 airguns (Goold and Coates, 2006). However the predominant energy is at low frequencies.

Several important factors need to be considered in the extension of the ERMC system when assessing the effects of seismic surveys on marine fauna:

- Airgun arrays are designed to transmit strong sounds downward through the seafloor, and the amount of sound transmitted in near-horizontal directions is considerably reduced;
- Airgun arrays produce intermittent sounds, involving emission of a strong sound pulse for a small fraction of a second followed by several seconds of near silence;
- An airgun array is a distributed source, not a point source. The nominal source level is an estimate of the sound that would be measured from a theoretical point source emitting the same total energy as the airgun array. That figure is useful in calculating the expected received levels in the far field, i.e., at moderate and long distances, but not in the near field. As the airgun array is not a single point source there is no particular location within the near field where the received level is as high as the nominal source level;

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- Seismic airgun surveys can last for many weeks. Currently ERMC calculates the probability of injury on the basis of each individual marine mammal's accumulated SEL and assumes that the effect of sound accumulated over any given period is identical to the effect of the same sound accumulated over a short period (i.e. less than 24 hours). This is almost certainly unrealistic for longer (>1 week) periods because an individual animal's hearing will recover from TTS between exposure events.

The factors discussed above together with literature such as Hatton (2007) on air-gun modelling suggest that an approach where the sound field is partitioned into "zones" whose boundaries are defined by varying propagation characteristics (Figure 5) would be most appropriate. For each of these zones, a different modelling technique will be required; the modelling and propagation zones are as follows:

- Zone 1 – within the downward facing near-field of the array, where the sources can be heard individually as the receiver is close enough such that the time gap between the source signals arriving is less than the pulse length of the source. Spherical spreading can be assumed with potential to produce a complex interference pattern;
- Zone 2 – within the downward facing far-field of the array where the signals combine to create a single pulse.

Spherical spreading can be assumed as the bottom has not been reached;

- Zone 3 – close to the array but outside the downward pointing beam, where the sources can be heard individually as they are at separate ranges, but the impact of the channel and bottom is such that spherical spreading can be assumed and the propagation is frequency independent;
- Zone 4 – further from the array but outside the downward pointing beam, where the airgun pulses are affected by multi-path, sediment, absorption, etc., hence propagation is complex; the pulse shape is changed by the frequency dependence and multi-path.

Based on the recommendations in Southall (2007) and the JNCC Guidelines (2009) it is essential that the ERMC system is able to model the peak pressure and SEL in Zones 1 to 4. The modelling procedure for seismic airguns can be summarised as follows:

- Zone 1 – within this region each gun is heard separately, hence the peak pressure can be assumed as the peak pressure from the largest gun or largest cluster of guns and falls off proportionally to (1/range) from the gun. The SEL can be created by summing up the SEL from the individual guns/clusters, falling off proportionally to (1/range2) from the gun;
- Zone 2 – within this region the signals are combined into a single pulse, hence the peak pressure is that of the combined array working synchronously with a fall-off proportional to (1/range) from the nominal centre of the gun array. The SEL can also be created from the combined array with a fall-off proportional to (1/range2);
- Zone 3 – within this region each gun is heard separately, hence the peak pressure and SEL can be calculated as for Zone 1;

- Zone 4 – within this region the airgun pulses are affected by multi-path, sediment, absorption, etc. and therefore a different technique needs to be employed. For this area, it is necessary to model the frequency dependent propagation, apply to the pulse spectrum close to the array and re-build the pulse to determine its peak at other ranges/depths. A similar technique is used to determine the SEL. Typically this modelling technique is undertaken in octave bands of frequency (or sometimes one third octaves depending upon the resolution of the underlying data available).

From the literature (Hatton, 2007), there are several models of air-gun arrays that can be used to simulate close range pulses, nominally based on original work by Ziolkowski (1970). Available results indicate that these types of model are suitable for generating all the data required in Zones 1, 2 and 3.

For Zone 4, air-gun models can generate a suitable nominal close range pulse shape, spectrum levels and SEL. The propagation can be modelled using a number of possible alternative solutions, some of which are defined below:

- SPUR - an extended version of RAM to include the signal integration which has been used for the modeling of air- gun arrays
- RAM – a Parametric Equation (PE) model which can be used with a frequency summing extension in a similar way to SPUR.
- PROSIM – a wideband normal mode model produced by NURC at La Spezia.
- Kraken or Supersnap – normal mode models that can be used with a suitable frequency sum component.

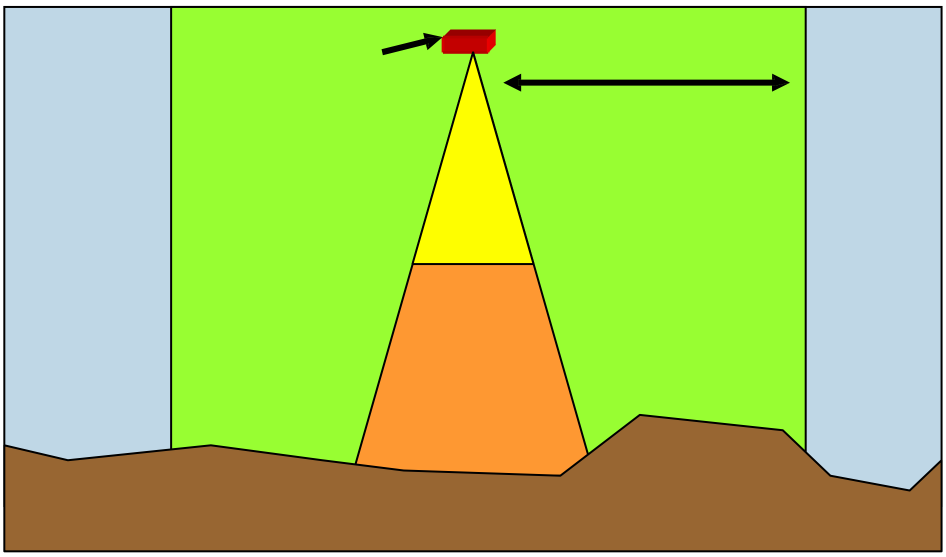

Figure 5 : Schematic diagram of modelling zones for an air-gun array. Zones 1 & 2 contain the main downward propagation beam. Within zones 1, 2 & 3 spherical spreading can be assumed. Absorption and bottom effects are also low so propagation is frequency independent.

From this analysis, it appears that the inclusion of an appropriate air-gun model and propagation model will be required to model the effects of seismic air-guns within the ERMC system.

Conclusion

As we become increasingly dependent on natural resources and the exploration activities that are required to meet and sustain our needs there will be a growing responsibility on Operators and Survey companies to actively manage and mitigate the environmental impacts that such operations will have on the surrounding environment. Organisations will be put under more and more pressure by political and public bodies and will be required to take a much more proactive approach to risk management and to push forward research into the possible impacts and mitigation techniques.

Moving forwards, a solution is required that stands up to legislative scrutiny, yet is adaptable enough to incorporate future research, better data and more capable technologies. The ERMC system provides such a solution through its flexible open architecture and the close partnership between BAE Systems Integrated System Technologies Ltd and St Andrews University. The system has proven results in the mitigation and management of sonar operations and has potential for application within the seismic survey industry as has been highlighted within this paper.

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