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# Thistle Cluaran Deas Ear and Cluaran Ear-Thuath Geophysical Surveys Subsea Noise Assessment

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# 1 Introduction

Thistle Wind Partners (hereafter referred to as ‘TWP’) have been awarded two offshore wind (OWF) project sites located off the east coast of Scotland (i.e. Cluaran Ear-Thuath within the 200 km$^2$ NE2 plan option area and Cluaran Deas Ear within the 187 km$^2$ E3 plan option area) as part of the ScotWind seabed leasing round. Cluaran Ear-Thuath is located approximately 33 km off the east coast of Orkney and Cluaran Deas Ear approximately 47 km off the coast of Aberdeenshire.

Following TWP’s award of the two sites in the ScotWind leasing round in January 2022, geophysical surveys are due to commence in March 2023.

Noise from the geophysical survey equipment is readily transmitted underwater and there is potential for sound emissions from the survey to affect marine mammals and fish. As there is potential for EPS and basking shark to be disturbed by the proposed geophysical survey, this EPS and basking shark risk assessment and licence applications are required.

This report presents the results of a desktop study considering the potential effects of underwater sound on the marine environment from geophysical surveys associated with the proposed survey areas and cable routes. The proposed survey areas are shown in Figure 1.1 (Cluaran Deas Ear) and Figure 1.2 (Cluaran Ear-Thuath).

Noise is readily transmitted underwater and there is potential for sound emissions from the surveys to affect marine mammals. At long ranges the introduction of additional noise could potentially cause short-term behavioural changes, for example to the ability of cetaceans to communicate and to determine the presence of predators, food, underwater features and obstructions. At close ranges and with high noise source levels, permanent or temporary hearing damage may occur, while at very close range, gross physical trauma is possible. This report provides an overview of the potential effects due to underwater noise from the proposed survey on the surrounding marine environment. Noise from the proposed survey activities was modelled using a sound propagation model in order to determine the potential for injury and disturbance to marine mammals.

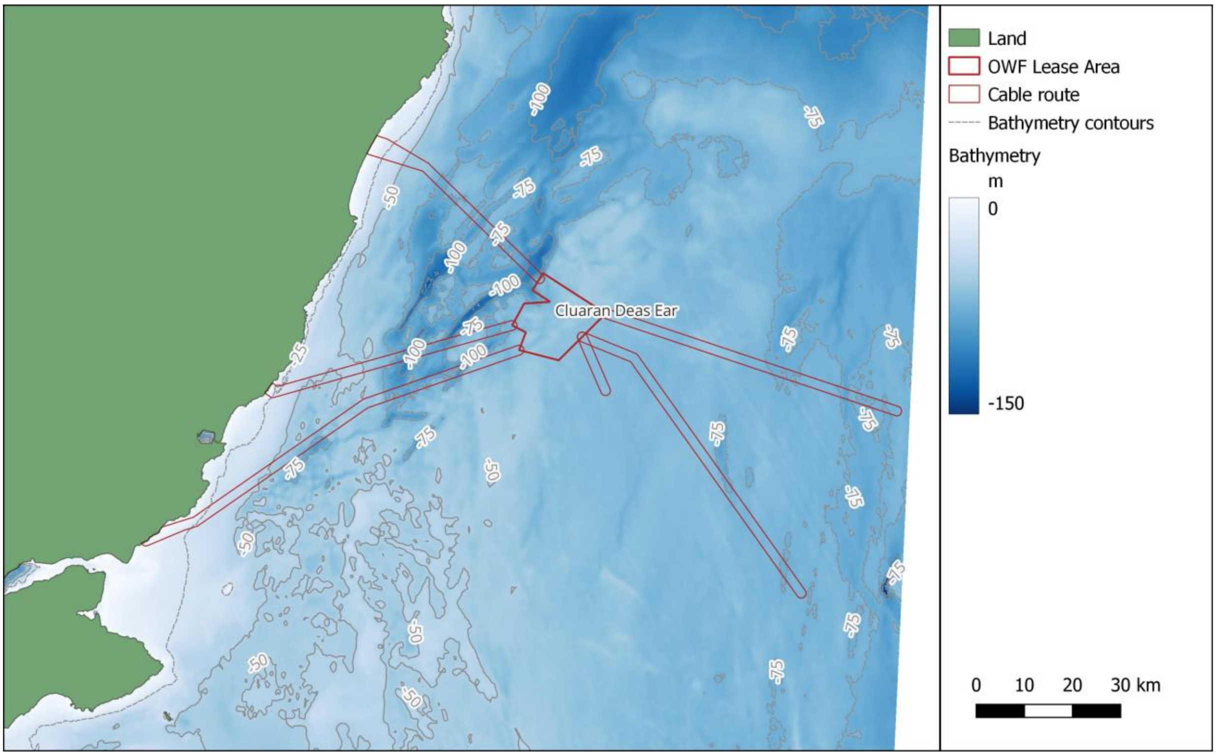

*Figure 1.1: Location of Cluaran Deas Ear OWF and cable routes*

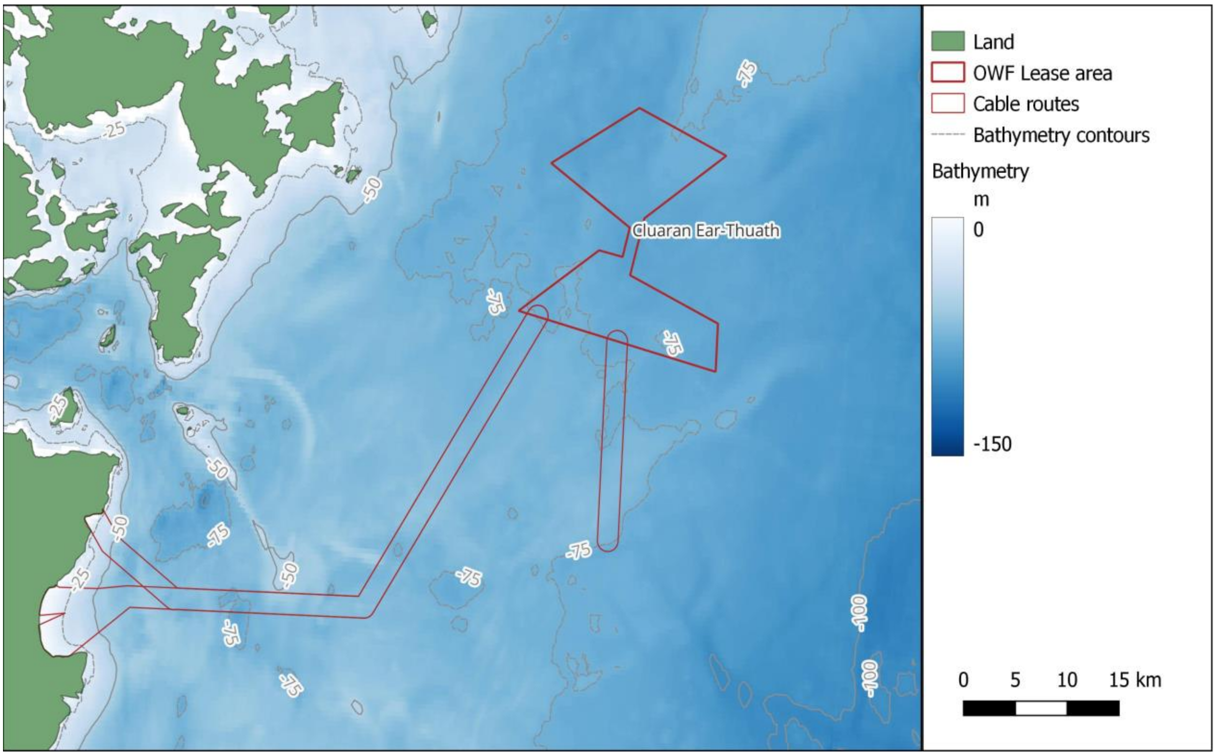

*Figure 1.2: Location of Cluaran Ear-Thuath OWF and cable routes*

# 2 Acoustic Concepts and Terminology

Sound travels through the water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure) and rarefactions (negative pressure). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The decibel (dB) scale is used to conveniently communicate the large range of acoustic pressures encountered, with a known pressure amplitude chosen as a reference value (i.e., 0 dB). In the case of underwater sound, the reference value ($P_{ref}$) is taken as 1 μPa, whereas the airborne sound is usually referenced to a pressure of 20 μPa. To convert from a sound pressure level referenced to 20 μPa to one referenced to 1 μPa, a factor of 20 log (20/1) i.e., 26 dB has to be added to the former quantity. Thus 60 dB re 20 μPa is the same as 86 dB re 1 μPa, although differences in sound speeds and different densities mean that the decibel level difference in sound intensity is much more than the 26 dB when converting pressure from air to water. All underwater sound pressure levels in this report are quantified in dB re 1 μPa.

There are several descriptors used to characterise a sound wave. The difference between the lowest pressure variation (rarefaction) and the highest-pressure variation (compression) is called the peak to peak (or pk-pk) sound pressure level. The difference between the highest variation (either positive or negative) and the mean pressure is called the peak pressure level. Lastly, the root mean square (rms) sound pressure level is used as a description of the average amplitude of the variations in pressure over a specific time window. Decibel values reported should always be quoted along with the $P_{ref}$ value employed during calculations. For example, the measured $SPL_{rms}$ value of a sound may be reported as 100 dB re 1 μPa. These descriptions are shown graphically in Figure 2.1.

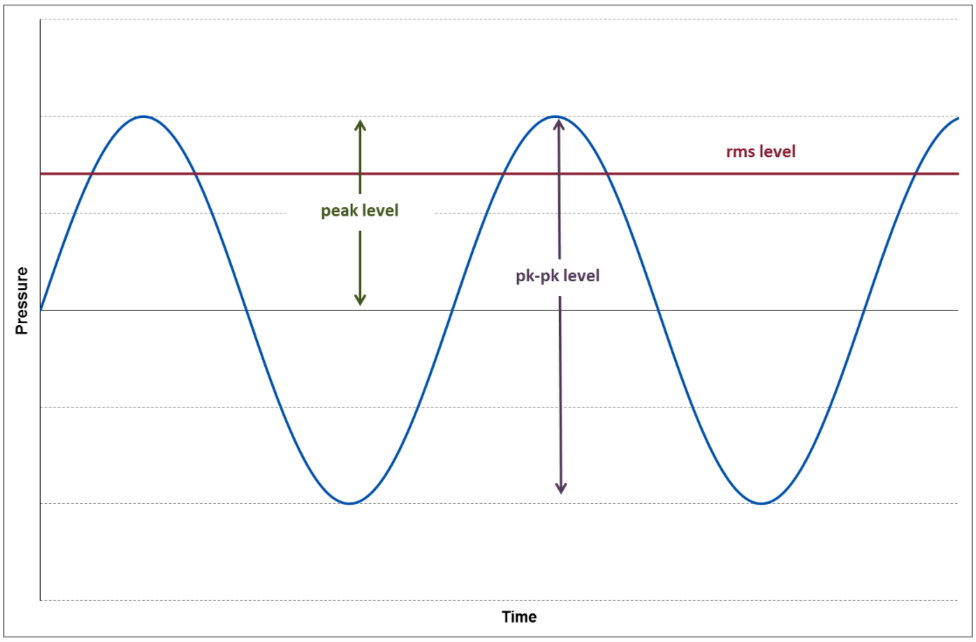

*Figure 2.1: Graphical representation of acoustic wave descriptors*

The rms sound pressure level (SPL) is defined as follows:

$$SPL_{rms} = 10log_{10}\left(\frac{1}{T}\int_{0}^{T}\left(\frac{p^2}{p_{ref}^2}\right)dt\right)$$

The magnitude of the rms sound pressure level for an impulsive sound (such as that from a seismic source array) will depend upon the integration time, T, used for the calculation (Madsen 2005). It has become customary to utilise the T90 time period for calculating and reporting rms sound pressure levels. This is the interval over which the cumulative energy curve rises from 5% to 95% of the total energy and therefore contains 90% of the sound energy.

Another useful measure of sound used in underwater acoustics is the Sound Exposure Level, or SEL. This descriptor is used as a measure of the total sound energy of an event or a number of events (e.g., over the course of a day) and is normalised to one second. This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis[1]. The SEL is defined as follows:

$$SEL = 10log_{10}\left(\int_0^T \left(\frac{p^2(t)}{p_{ref}^2 t_{ref}}\right) dt\right)$$

The frequency, or pitch, of the sound is the rate at which the acoustic oscillations occur in the medium (air/water) and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dBA. However, the hearing faculty of marine mammals is not the same as humans, with marine mammals hearing over a wider range of frequencies and with a different sensitivity. It is therefore important to understand how an animal's hearing varies over its entire frequency range to assess the effects of anthropogenic sound on marine mammals. Consequently, use can be made of frequency weighting scales (m-weighting) to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 2.2. (It is worth noting that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown).

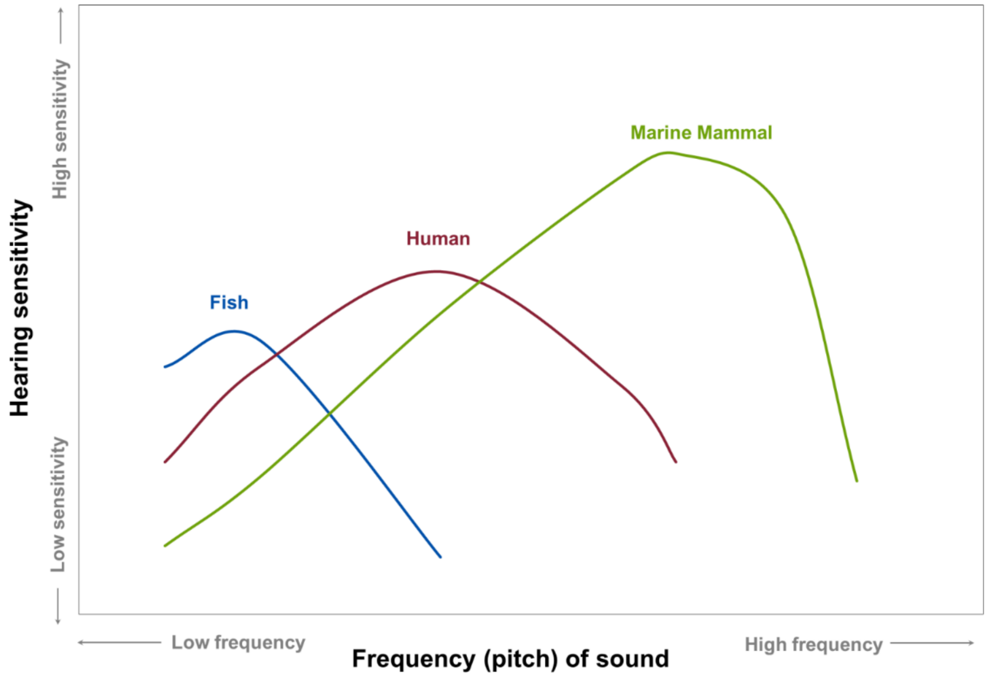

*Figure 2.2: Comparison between hearing thresholds of different animals*

Other relevant acoustic terminology and their definitions used in the report are detailed below.

**<u>1/3rd octave bands</u>**

The broadband acoustic power (i.e., containing all the possible frequencies) emitted by a sound source, measured/modelled at a location within the survey region is generally split into and reported in a series of frequency bands. In marine acoustics, the spectrum is generally reported in standard 1/3rd octave band frequencies, where an octave represents a doubling in sound frequency.

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*[1] Historically, use was primarily made of rms and peak sound pressure level metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events to be considered.*

## Source level (SL)

The source level is the sound pressure level of an equivalent and infinitesimally small version of the source (known as *point source*) at a hypothetical distance of 1 m from it. The source level may be combined with the transmission loss (TL) associated with the environment to obtain the received level (RL) in the *far field* of the source. The far field distance is chosen so that the behaviour of the distributed source can be approximated to that of a point source.

## Transmission loss (TL)

TL at a frequency of interest is defined as the loss of acoustic energy as the signal propagates from a hypothetical (point) source location to the chosen receiver location. The TL is dependent on water depth, source depth, receiver depth, frequency, geology, and environmental conditions. The TL values are generally evaluated using an acoustic propagation model (various numerical methods exist) accounting for the above dependencies.

## Received level (RL)

The RL is the sound level of the acoustic signal recorded (or modelled) at a given location, that corresponds to the acoustic pressure/energy generated by a known active sound source. This considers the acoustic output of a source and is modified by propagation effects. This RL value is strongly dependant on the source, environmental properties, geological properties and measurement location/depth. The RL is reported in dB either in rms or peak-to-peak SPL, and SEL metrics, within the relevant third-octave band frequencies. The RL is related to the SL as

$$RL = SL - TL$$

where TL is the transmission loss of the acoustic energy within the survey region.

The directional dependence of the source signature and the variation of TL with azimuthal direction $\alpha$ (which is strongly dependent on bathymetry) are generally combined and interpolated to report a 2-D plot of the RL around the chosen source point up to a chosen distance.

# 3 Acoustic Assessment Criteria

## 3.1 Marine Mammals

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Richardson *et al*. (1995) defined four zones of noise influence which vary with distance from the source and level. These are:

- **The zone of audibility:** this is the area within which the animal can detect the sound. Audibility itself does not implicitly mean that the sound will have an effect on the marine mammal.
- **The zone of masking:** this is defined as the area within which noise can interfere with detection of other sounds such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how marine mammals detect sound in relation to masking levels (for example, humans can hear tones well below the numeric value of the overall noise level).
- **The zone of responsiveness:** this is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction.
- **The zone of injury / hearing loss:** this is the area where the sound level is high enough to cause tissue damage in the ear. This can be classified as either temporary threshold shift (TTS) or permanent threshold shift (PTS). At even closer ranges, and for very high intensity sound sources (e.g., underwater explosions), physical trauma or even death are possible.

For this study, it is the zones of injury and disturbance (i.e., responsiveness) that are of concern (there is insufficient scientific evidence to properly evaluate masking). To determine the potential spatial range of injury and disturbance, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

Sound propagation models can be constructed to allow the received noise level at different distances from the source to be calculated. To determine the consequence of these received levels on any marine mammals which might experience such noise emissions, it is necessary to relate the levels to known or estimated impact thresholds. The injury criteria proposed by Southall *et al* (2019). are based on a combination of linear (i.e., un-weighted) peak pressure levels and mammal hearing weighted sound exposure levels (SEL). The hearing weighting function is designed to represent the bandwidth for each hearing group within which acoustic exposures can have auditory effects. The categories include:

- **low-frequency (LF) cetaceans** (i.e., marine mammal species such as baleen whales);
- **high-frequency (HF) cetaceans** (i.e., marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales);
- **very high-frequency (VHF) cetaceans** (i.e., marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 kHz);
- **phocid pinnipeds (PCW)** (i.e., true seals; hearing in air is considered separately in the group PCA); and
- **other marine carnivores (OCW)** (including otariid pinnipeds (e.g., sea lions and fur seals), sea otters and polar bears; in-air hearing considered separately in the group OCA).

These weightings have therefore been used in this study and are shown in Figure 3.1.

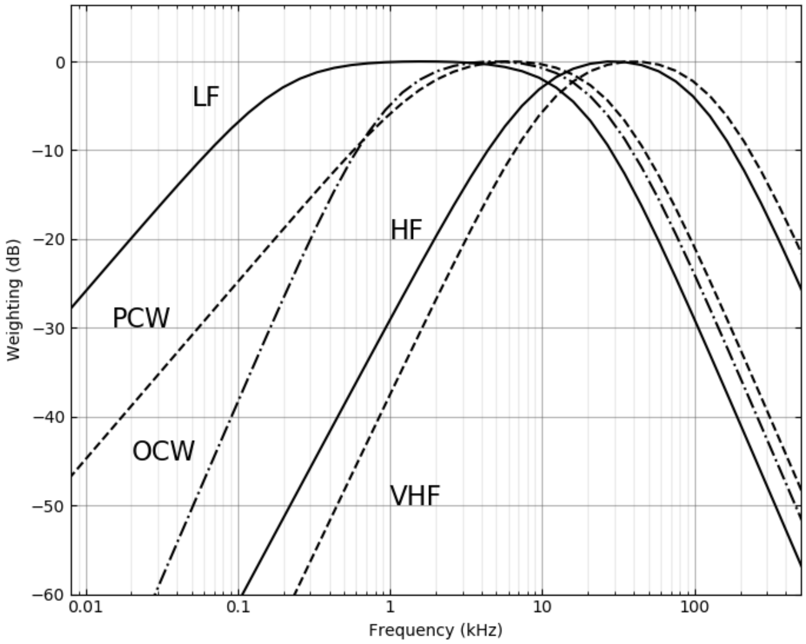

*Figure 3.1: Hearing weighting functions for pinnipeds and cetaceans (Southall et al., 2019)*

Injury criteria are proposed in Southall *et al* (2019) are for two different types of sound as follows:

- **Impulsive sounds** which are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). This category includes sound sources such as seismic surveys, impact piling and underwater explosions; and
- **Non-impulsive sounds** which can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998). This category includes sound sources such as continuous running machinery, sonar and vessels.

The relevant criteria proposed by Southall *et al*. (2019) are as summarised in Table 3.1.

*Table 3.1: Summary of PTS onset acoustic thresholds (Southall et al. 2019)*

| Hearing Group | Parameter | Impulsive | Non-impulsive |
|---|---|---|---|
| Low-frequency (LF) cetaceans | Peak, unweighted | 219 | - |
| | SEL, LF weighted | 183 | 199 |
| High-frequency (HF) cetaceans | Peak, unweighted | 230 | - |
| | SEL, MF weighted | 185 | 198 |
| Very High-frequency (VHF) cetaceans | Peak, unweighted | 202 | - |
| | SEL, HF weighted | 155 | 173 |
| Phocid Carnivores in Water (PCW) | Peak, unweighted | 218 | - |
| | SEL, PW weighted | 185 | 201 |
| Other Marine Carnivores in Water (OCW) | Peak, unweighted | 232 | - |
| | SEL, OW weighted | 203 | 219 |

These updated marine mammal injury criteria were published in March 2019 (Southall *et al.*, 2019). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document NMFS (2018) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in Table 3.2.

For avoidance of doubt, the naming convention used in this report is based upon those set out in Southall *et al* (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall *et al*. (2019).

***Table 3.2: Comparison of hearing group names between NMFS 2018 and Southall 2019***

| NMFS (2018) hearing group name | Southall *et al*. (2019) hearing group name |
|---|---|
| Low frequency cetaceans (LF) | Low-frequency cetaceans (LF) |
| Mid frequency cetaceans (MF) | High-frequency cetaceans (HF) |
| High frequency cetaceans (HF) | Very high-frequency cetaceans (VHF) |
| Phocid pinnipeds in water (PW) | Phocid carnivores in water (PCW) |

Beyond the area in which injury may occur, the effect on marine mammal behaviour is the most important measure of impact. Significant (i.e., non-trivial) disturbance may occur when there is a risk of animals incurring sustained or chronic disruption of behaviour or when animals are displaced from an area, with subsequent redistribution being significantly different from that occurring due to natural variation.

Therefore, this assessment adopts a conservative approach and uses the US National Marine Fisheries Service (NMFS, 2005a) Level B harassment thresholds for impulsive and non-impulsive sounds. Level B Harassment is defined as having the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild. This description of non-trivial disturbance has therefore been used as the basis for onset of behavioural change in this assessment.

The (NMFS 2005) guidance sets the marine mammal level B harassment threshold for continuous noise at 120 dB re 1 μPa (rms). This value sits approximately mid-way between the range of values identified in Southall *et al*. (2007) for continuous sound but is lower than the value at which the majority of mammals responded at a response score of 6 (i.e. once the received rms sound pressure level is greater than 140 dB re 1 μPa). Taking into account the paucity and high level variation of data relating to onset of behavioural effects due to continuous sound, it is recommended that any ranges predicted using this number are viewed as probabilistic and possibly over-precautionary.

The High Energy Seismic Survey workshop on the effects of seismic sound on marine mammals (HESS 1997) concluded that **mild** behavioural disturbance to impulsive sound would most likely occur at sound levels greater than 140 dB re 1 μPa (rms). This workshop drew on several studies but recognised that there was some degree of variability in reactions between different studies and mammal groups. This value is similar to the lowest threshold for disturbance of low-frequency cetaceans noted in Southall *et al*. (2007). It is, however, considered unlikely that a threshold for the onset of mild disturbance effects could be defined as significant disturbance. Consequently, this study utilises the NMFS (2005) marine mammal level B harassment threshold of 160 dB re 1 μPa (rms) as a proxy for significant disturbance due to impulsive sound.

## 3.2 Basking Shark

The thresholds for effects on fish species are based on the sound exposure guidelines for fish proposed by the ANSI-Accredited Standards Committee S3/SC 1, Animal Bioacoustics Working Group (Popper *et al.*, 2014). The guidelines represent the Working Group's consensus efforts to establish broadly applicable guidelines for fish and sea turtles, with specific criteria relating to mortality and potential mortal injury, recoverable injury and TTS. The Working Group defines the criteria for injury and TTS as follows:

- mortality and mortal injury – immediate or delayed death
- recoverable injury – injuries, including hair cell damage, minor internal or external hematoma, etc. None of these injuries is likely to result in mortality
- TTS – short or long-term changes in hearing sensitivity that may or may not reduce fitness (defined as any persistent change in hearing of 6 dB or greater).

There are no accepted peer reviewed criteria for assessing injury or disturbance to sharks due to sound. According to Casper and Mann (2006), sharks are sensitive to particle motion and not sound pressure with a hearing range of approximately 10 to 800 Hz, with the highest hearing sensitivity at the lower end of this range. The most relevant criteria for injury and disturbance are therefore considered to be those for fish without swim bladders contained in the Sound Exposure Guidelines for Fishes and Sea Turtles (Popper et al., 2014), as set out in Table 3.3.

*Table 3.3: Summary of Fish Injury Exposure Criteria for Seismic Airguns (Popper et al. 2014)*

| Type of animal | Parameter | Mortality and potential mortal injury | Impairment | |
|---|---|---|---|---|
| | | | Recoverable injury | TTS |
| Fish: no swim bladder (particle motion detection) | SEL, dB re 1 µPa$^2$s | - | - | 186 |
| | Peak, dB re 1 µPa | 213 | 213 | - |

The most recent criteria for disturbance to group 1 fish are shown Table 3.4. The risk of behavioural effects is categorised in relative terms as “high”, “moderate” or “low” at three distances from the source: “near” (i.e. in the tens of metres), “intermediate” (i.e. in the hundreds of metres) or “far” (i.e. in the thousands of metres).

*Table 3.4: Criteria adopted for onset of behavioural effects in fish (Popper et al., 2014)*

| Type of animal | Relative risk of behavioural effects |
|---|---|
| Fish: no swim bladder (particle motion detection) | (Near) High<br>(Intermediate) Moderate<br>(Far) Low |

# 4 Assessment Methodology

## 4.1 Source Levels

Underwater noise sources are usually quantified in dB re 1 µPa, as if measured at a hypothetical distance of 1 m from the source (the Source Level). In practice, it is not usually possible to measure at 1 m from a source, but this metric allows comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source this imagined point at 1 m from the acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from this imagined acoustic centre point. Therefore, the stated sound pressure level at 1 m does not actually occur for large sources. In the acoustic near-field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the SL.

The survey proposes to use a range of sonar based equipment. This equipment will use a transmitter that emits an acoustic signal directly toward the sea bed (or alongside, at an angle to the seabed, in the case of side scan and MBES techniques). The equipment likely to be used can typically work at a range of signal frequencies, depending on the distance to the bottom and the required resolution. The signal is highly directional and acts as a beam, with the energy narrowly concentrated within a few degrees of the direction in which it is aimed. The signal is emitted in pulses, the length of which can be varied as per the survey requirements.

It is currently not known the exact sonar/ impulsive based survey equipment that will be used for proposed survey. For the purposes of this assessment a range of equipment examples have been provided for each survey equipment type. Sound source data of the examples identified have been presented based on the manufacturers specification. The characteristics for each example sonar based survey device modelled in this assessment are summarised in Table 4.1 and impulsive device parameters are summarised in Table 4.2. The pulse rate has been used to calculate the SEL, which is normalised to one second, from the rms sound pressure level. Directivity corrections were calculated based on the transducer dimensions and ping frequency and taken from manufacturer's datasheets. It is important to note that directivity will vary significantly with frequency, but that these directivity values have been used in line with the modelling assumptions stated above.

*Table 4.1: Sonar based survey equipment parameters used in assessment*

| Survey type | Frequency, kHz | Source level, dB re 1 µPa re 1 m (rms) | Pulse rate, $s^{-1}$ | Pulse width, ms | Beam width |
|---|---|---|---|---|---|
| Multibeam Echo Sounder (MBES) | 170-450 | 191- | Up to 60 | 15µs-1ms | 0.45° X0.9° at 450 kHz |
| Side Scan Sonar (SSS) | 300 & 600 | 213 & 214 | 15 (Seiche assumption) | 10 ms / 5 ms | Horizontal Beam Width: 0.26°<br>Vertical Beam Width: 50° |
| Parametric Sub Bottom Profiler (SBP) | 85-115 | 248 | Up to 40 | 0.07 – 2 | 2.5° |
| USBL | 20 - 30 | 190 | Not provided by manufacturer – assumed constant operation | Not provided by manufacturer – assumed constant operation | 80° |

*Table 4.2: Impulsive survey equipment parameters used in assessment*

| Source | Equipment | Source level, dB re 1 µPa re 1 m (0-pk) | Source SEL, dB re 1 µPa$^2$s re 1 m |
|---|---|---|---|
| Sparker<br>(Multi Channel Seismic) | Sparker GSO 360 | 223 | 182 |

## 4.2 Propagation Modelling

Increasing the distance from the sound source usually results in the level of sound becoming lower, due primarily to the spreading of the sound energy with distance, analogous to the way in which the ripples in a pond spread after a stone has been thrown in, in combination with attenuation due to absorption of sound energy by molecules in the water. This latter mechanism is more important for higher frequency sound than for lower frequencies.

The way that the sound spreads (geometrical divergence) will depend upon several factors such as water column depth, pressure, temperature gradients, salinity as well as water surface and bottom (i.e. seabed) conditions. Thus, even for a given locality, there are temporal variations to the way that sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source) or a cylindrical pattern (much further from the source), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases.

In acoustically shallow waters[2] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton 2002; Etter 2013; Urick 1983; Kinsler *et al*. 1999). Whereas in deeper waters the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound may be reflected from either or both boundaries (potentially more than once).

At the sea surface, the majority of sound is reflected back in to the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. Scattering of sound at the surface of the sea can be an important factor with respect to the propagation of sound. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound wave energy will be reflected back into the sea. For rough seas, however, much of the sound energy is scattered (e.g. Eckart 1953; Fortuin 1970; Marsh, Schulkin, and Kneale 1961; Urick and Hoover 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or fish. Scattering my also result from the presence of suspended solids in the water such as particulates and marine life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex.

Because surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the source sound and in acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the sea state/wind speed, water depth, frequency of the sound, temperature gradient, angle of incidence and range from source. It should be noted that variations in propagation due to scattering will vary temporally within an area primarily due to different sea-states / wind speeds at different times. However, over shorter ranges (e.g. several hundred meters or less) the sound will experience fewer reflections and so the effect of scattering should not be significant.

When sound waves encounter the bottom, the amount of sound reflected will depend on the geoacoustic properties of the bottom (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the angle of incidence and frequency of the sound (Mackenzie, 1960; McKinney and

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[2] *Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and bottom (Etter 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the sound speed gradient, water depth, frequency of the sound and distance between the source and receiver.*

Anderson, 1964; Cole, 1965; Hamilton, 1970; Urick, 1983; Lurton, 2002; Etter, 2013). Thus, bottoms comprising primarily mud or other acoustically soft sediment will reflect less sound than acoustically harder bottoms such as rock or sand. This effect will also depend on the profile of the bottom (e.g. the depth of the sediment layer and how the geoacoustic properties vary with depth below the sea floor). The effect is less pronounced at low frequencies (a few kHz and below). A scattering effect (similar to that which occurs at the surface) also occurs at the bottom (McKinney and Anderson, 1964; Kuo, 1992; Essen, 1994; Greaves and Stephen, 2003), particularly on rough substrates (e.g. pebbles).

Another phenomenon is the waveguide effect, which means that shallow water columns do not allow the propagation of low frequency sound (Urick, 1983; Etter, 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties. Any sound below this frequency will not propagate far due to energy losses through multiple reflections.

Another important factor is the sound speed gradient. Changes in temperature and pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for high frequency sound. Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel but, for example, a 25 m thick layer would not act as a duct for frequencies below 1.5 kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

Sound energy is also absorbed due to interactions at the molecular level converting the acoustic energy into heat. This is another frequency dependent effect with higher frequencies experiencing much higher losses than lower frequencies.

There are several methods available for modelling the propagation of sound between a source and receiver ranging from very simple models which simply assume spreading according to a 10 log (r) or 20 log (r) relationship (as discussed above) to full acoustic models (e.g. ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available which lie somewhere in between these two extremes in terms of complexity.

In choosing which propagation model to employ, it is important to ensure that it is fit for purpose and produces results with a suitable degree of accuracy for the application in question, taking into account the context (as detailed in Monitoring Guidance for Underwater Noise in European Seas Part III, NPL Guidance and Farcas *et al*., 2016). Thus, in some situations (e.g. low risk due to underwater noise, range dependent bathymetry is not an issue, non-impulsive sound) a simple (N log R) model will be sufficient, particularly where other uncertainties outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. very high source levels, impulsive sound, complex source and propagation path characteristics, highly sensitive receivers and low uncertainties in assessment criteria) warrant a more complex modelling methodology.

The first step in choosing a propagation model is therefore to examine these various factors, such as set out below:

- balancing of errors / uncertainties;
- range dependant bathymetry;
- frequency dependence; and
- source characteristics.

For impulsive sound, such as that produced by a seismic survey source, the sound propagation is rather more complex than can be modelled using a simple N log (R) relationship. For example, as discussed previously, the rms sound pressure level of an impulsive sound wave will depend upon the integration window used. An additional phenomenon occurs where the seismic waveform elongates with distance from the source due to a combination of dispersion and multiple reflections. This temporal “smearing” can significantly affect the peak pressure level and reduces the rms amplitude with distance (because the rms window is longer). Another important factor affecting the received sound pressure level from geophysical surveys is the source directivity characteristics. Sound sources are designed so that the majority of acoustic energy is directed downwards towards the ocean bottom. Therefore, the amount of energy emitted horizontally will be significantly less than directed downwards. This is a frequency dependent effect and is more pronounced at higher frequencies than at lower frequencies.

Sound propagation modelling for this assessment was therefore based on an established, peer reviewed, range dependent sound propagation model which utilises the semi-empirical model developed by Rogers (1981). The model provides a robust balance between complexity and technical rigour over a wide range of frequencies, has been validated by numerous field studies and has been benchmarked against a range of other models. The following inputs are required for the model:

- third-octave band source sound level data;
- range (distance from source to receiver);
- water column depth (input as bathymetry data grid);
- sediment type;
- sediment and water sound speed profiles and densities;
- sediment attenuation coefficient; and
- source directivity characteristics.

The propagation loss is calculated using the formula:

$$TL = 15log_{10}R + 5\log_{10}(H\beta) + \frac{\beta R\theta_L^2}{4H} - 7.18 + \alpha_w R$$

Where $R$ is the range, $H$ the water depth, $\beta$ the bottom loss, $\theta_L$the limiting angle and $\alpha_w$ the absorption coefficient of sea water ($\alpha_w$ is a frequency dependant term which is calculated based on Ainslie and McColm, 1998).

The limiting angle, $\theta_L$ is the larger of $\theta_g$ and $\theta_c$ where $\theta_g$ is the maximum grazing angle for a skip distance and $\theta_c$ is the effective plane wave angle corresponding to the lowest propagating mode.

$$\theta_g = \sqrt{\frac{2Hg}{c_w}} \qquad \theta_c = \frac{c_w}{2fH}$$

where $g$ is the sound speed gradient in water and $f$ is the frequency.

The bottom loss $\beta$ is approximated as:

$$\beta \approx \frac{0.477(\rho_s/\rho_w)(c_w/c_s)K_s}{[1-(c_w/c_s)^2]^{3/2}}$$

where $\rho_s$ is the density of sediment, $\rho_w$ the density of water, $c_s$ the sound speed in the sediment, $c_w$ the sound speed in water and $K_s$ is the sediment attenuation coefficient.

The propagation model also takes into account the depth dependent cut-off frequency for propagation of sound (i.e. the frequency below which sound does not propagate):

$$f_{cut-off} = \frac{c_w}{4h\sqrt{1-\frac{c_w^2}{c_s^2}}}$$

where $c_s$ and $c_w$ are the sound propagation speeds in the substrate and water.

The propagation and sound exposure calculations were conducted over a range of water column depths within each survey area in order to determine the range for injury and disturbance. It should be noted that the effect of directivity has a strong bearing on the calculated zones for injury and disturbance because a marine mammal could be directly underneath an array for greater distances in deep water compared to shallow water.

It should be borne in mind that noise levels (and associated range of effects) will vary depending on actual conditions at the time (day-to-day and season-to-season) and that the model predicts a typical worst case scenario. Taking into account factors such as animal behaviour and habituation, any injury and disturbance ranges should be viewed as indicative and probabilistic ranges to assist in understanding potential impacts on marine life rather than lines either side of which an impact definitely will or will not occur. (This is a similar approach to that adopted for airborne noise where a typical worst case is taken, though it is known that day to day levels may vary to those calculated by 5 - 10 dB depending on wind direction etc.).

## 4.3 Exposure Calculations

As well as calculating the un-weighted rms and peak sound pressure levels at various distances from the source, it is also necessary to calculate the SEL for a mammal using the relevant hearing weightings described above taking into account the number of pulses to which it is exposed. For operation of the source array, the SEL sound data for a single pulse was utilised, along with the maximum number of "pulses" expected to be received by marine mammals in order to calculate cumulative exposure.

Exposure modelling was based on the assumption of a mammal swimming at a constant speed in a perpendicular direction away from a moving vessel (see Figure 4.1).

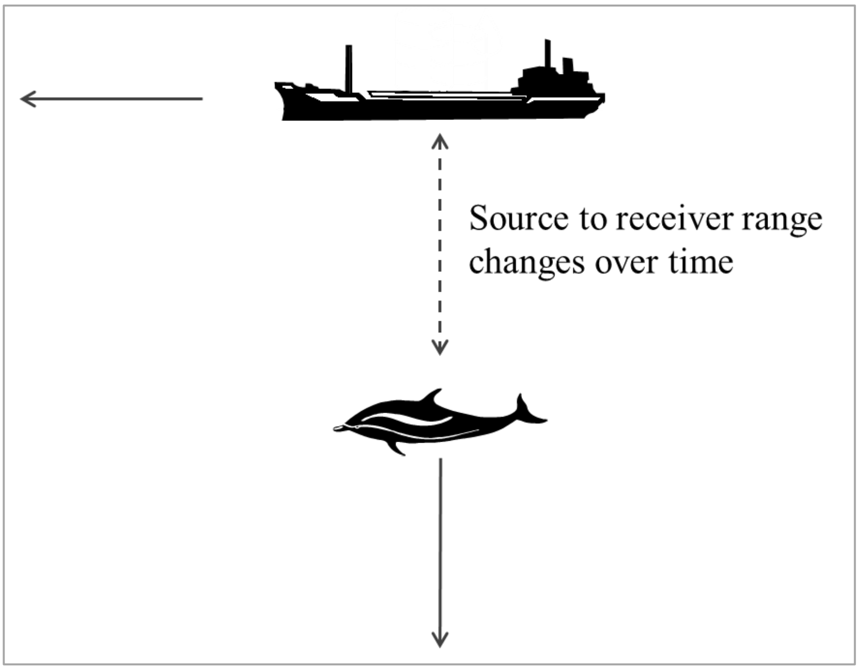

*Figure 4.1 Sound exposure modelling*

The above case was modelled for a range of start distances (initial or closest passing distance between the animal and vessel) in order to calculate cumulative exposure for a range of scenarios. In each case, the pulses to which the mammal is exposed in closest proximity to the vessel dominate the sound exposure. This is due to the logarithmic nature of sound energy summation.

In order to carry out the swimming mammal calculation, it has been assumed that a mammal will swim away from the noise source at an average speed of 1.5 ms$^{-1}$. The calculation considers each pulse to be established separately resulting in a series of discrete SEL values of decreasing magnitude (see Figure 4.2).

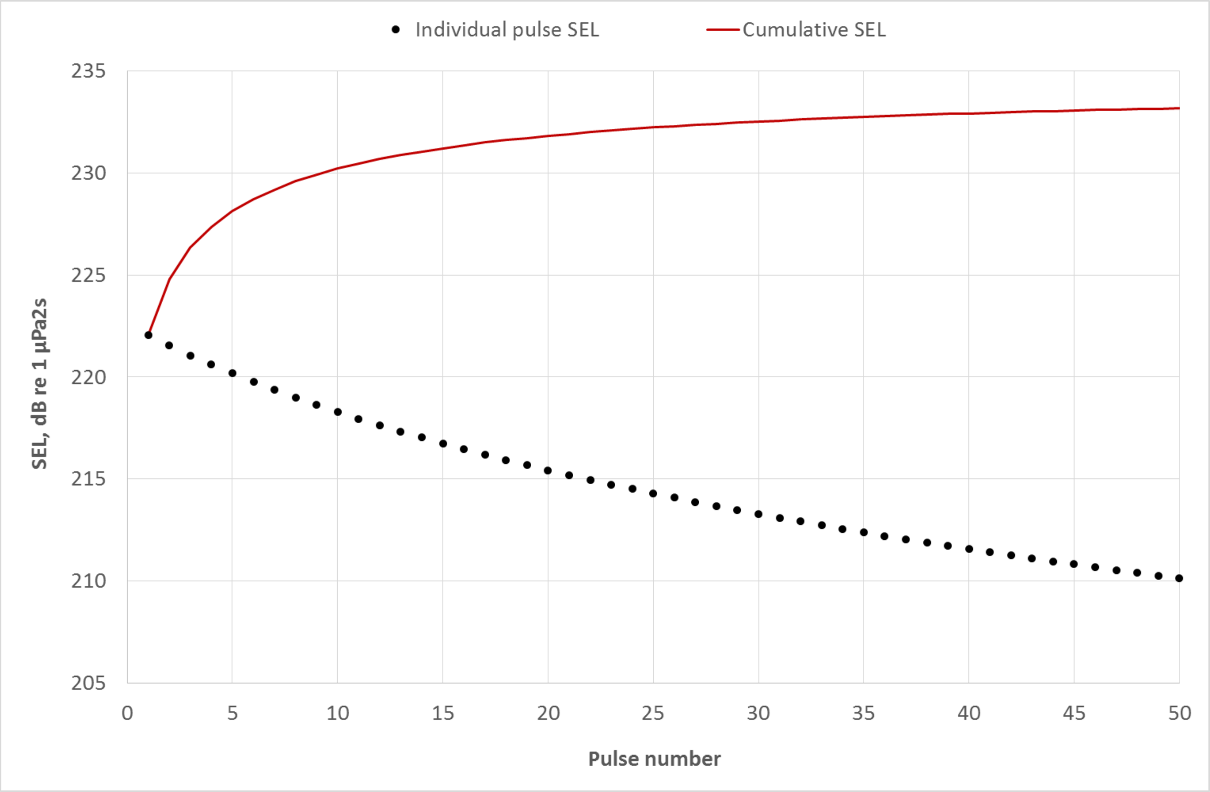

*Figure 4.2 Discrete "pulse" SEL and cumulative SEL*

As a mammal swims away from the source, the noise will become progressively quieter; the cumulative SEL is worked out by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for a marine mammal in order for it to be exposed to sufficient sound energy to result in the onset of potential injury. It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a fairly constant relative speed. The real world situation is more complex and the animal is likely to move in a more complex manner. Swim speeds of marine mammals have been shown to be up to 5 ms$^{-1}$ (e.g. cruising minke whale 3.25 ms-1 (Cooper *et al*., 2008) and harbour porpoise up to 4.3 ms$^{-1}$ (Otani *et al*., 2000)). The more conservative swim speed of 1.5 ms$^{-1}$ used in this assessment allows some headroom to account for the potential that the marine mammal might not swim directly away from the source, could change direction or does not maintain a fast swim speed over a prolonged period.

# 5 Results and Conclusions

## 5.1 Sonar Based Surveys

Based on the results of the noise modelling the radii of effect for injury and disturbance to marine mammals are presented in Table 5.1 to Table 5.4. It should be noted that the some of the injury ranges are limited to the approximate water depth in each area. Sonar based systems have very strong directivity which effectively means that there is only potential for injury when a marine mammal is directly underneath (or within the "beam" of) the sound source. Once the animal moves outside of the main beam then there is no potential for injury. The same is true in many cases for TTS where an animal is only exposed to enough energy to cause TTS when inside the direct beam of the sonar. For this reason, many of the TTS and PTS ranges are similar (i.e. limited by the depth of the water). The injury ranges presented in the table are based on the average radius of injury within the area but these my vary by typically a few meters between different water depths. Likewise, it should be noted that injury ranges in shallower waters (e.g. nearest the coast for the cable routes) will typically be smaller than those presented in the tables.

*Table 5.1: Marine mammal noise modelling results for MBES*

| Survey Area | Injury range, m | | | | |
|---|---|---|---|---|---|
| | LF | HF | VHF | PCW | Disturbance |
| Cluaran Deas Ear | | | | | |
| Nearshore section of cable routes | N/E | 37 | 40 | 5 | 573 |
| Cable routes (west) | N/E | 66 | 76 | 5 | 490 |
| Cable routes (east) | N/E | 60 | 68 | 5 | 460 |
| OWF area | N/E | 75 | 89 | 5 | 455 |
| Cluaran Ear-Thuath | | | | | |
| Nearshore section of cable routes | N/E | 37 | 40 | 5 | 573 |
| Cable routes | N/E | 57 | 64 | 5 | 485 |
| OWF area | N/E | 66 | 77 | 5 | 410 |

*Table 5.2: Marine mammal noise modelling results for SSS*

| Survey Area | Injury range, m | | | | |
|---|---|---|---|---|---|
| | LF | HF | VHF | PCW | Disturbance |
| **Cluaran Deas Ear** | | | | | |
| Nearshore section of cable routes | N/E | 31 | 38 | N/E | 255 |
| Cable routes (west) | N/E | 44 | 75 | N/E | 262 |
| Cable routes (east) | N/E | 43 | 67 | N/E | 253 |
| OWF area | N/E | 47 | 88 | N/E | 278 |
| **Cluaran Ear-Thuath** | | | | | |
| Nearshore section of cable routes | N/E | 31 | 38 | N/E | 255 |
| Cable routes | N/E | 42 | 63 | N/E | 248 |
| OWF area | N/E | 45 | 75 | N/E | 265 |

*Table 5.3: Marine mammal noise modelling results for SBP*

| Survey Area | Injury range, m | | | | |
|---|---|---|---|---|---|
| | LF | HF | VHF | PCW | Disturbance |
| **Cluaran Deas Ear** | | | | | |
| Nearshore section of cable routes | 38 | 46 | 268 | 38 | 1,385 |
| Cable routes (west) | 75 | 80 | 310 | 75 | 1,358 |
| Cable routes (east) | 67 | 71 | 295 | 67 | 1,357 |
| OWF area | 88 | 92 | 342 | 88 | 1,348 |
| **Cluaran Ear-Thuath** | | | | | |
| Nearshore section of cable routes | 38 | 46 | 268 | 38 | 1,385 |
| Cable routes | 63 | 67 | 283 | 63 | 1,363 |
| OWF area | 75 | 78 | 320 | 76 | 1,345 |

*Table 5.4: Marine mammal noise modelling results for USBL*

| Survey Area | Injury range, m | | | | |
|---|---|---|---|---|---|
| | LF | HF | VHF | PCW | Disturbance |
| **Cluaran Deas Ear** | | | | | |
| Nearshore section of cable routes | N/E | N/E | 45 | N/E | 1,690 |
| Cable routes (west) | N/E | N/E | 60 | N/E | 1,657 |
| Cable routes (east) | N/E | N/E | 57 | N/E | 1,622 |
| OWF area | N/E | N/E | 65 | N/E | 1,643 |
| **Cluaran Ear-Thuath** | | | | | |
| Nearshore section of cable routes | N/E | N/E | 45 | N/E | 1,690 |
| Cable routes | N/E | N/E | 56 | N/E | 1,638 |
| OWF area | N/E | N/E | 60 | N/E | 1,590 |

There are no numerical thresholds for injury to basking shark due to high frequency sonar and therefore no results are presented for this species.

## 5.2 Impulsive Source Surveys

Based on the results of the noise modelling the radii of effect for injury and disturbance to marine mammals due to impulsive sound sources are presented in Table 5.5.

*Table 5.5: Marine mammal noise modelling results for impulsive sound source surveys (Sparker)*

| Survey Area | Injury range, m | | | | | |
|---|---|---|---|---|---|---|
| | LF | HF | VHF | PW | Disturbance (mild) | Disturbance (strong) |
| **Cluaran Deas Ear** | | | | | | |
| Nearshore section of cable routes | N/E | N/E | 22 | N/E | 657 | 98 |
| Cable routes (west) | N/E | N/E | 17 | N/E | 569 | 83 |
| Cable routes (east) | N/E | N/E | 18 | N/E | 579 | 85 |
| OWF area | N/E | N/E | 17 | N/E | 547 | 80 |
| **Cluaran Ear-Thuath** | | | | | | |
| Nearshore section of cable routes | N/E | N/E | 22 | N/E | 657 | 98 |
| Cable routes | N/E | N/E | 18 | N/E | 587 | 86 |
| OWF area | N/E | N/E | 17 | N/E | 562 | 83 |

The results for basking shark are provided in Table 5.6. The injury ranges do not differ between survey areas because the sound levels are in very close proximity to the source and so are not affected by the bathymetry or sediment.

*Table 5.6: Basking shark noise modelling results for impulsive sound source surveys (Sparker)*

| Class: | Injury range, m |
|---|---|
| Mortality | 5 m |
| Impairment | 5 m |

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