Estimating Sound Pressure Levels that correspond to maximum legal disturbance of seals and turtles

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ABSTRACT

Loud underwater sounds can disturb the behaviour of aquatic animals, and potentially affect their populations and hence biodiversity. A method is described for determining the Sound Pressure Levels (SPL) of multi-pulse signals to which seals and turtles may be exposed without contravening the Australian Commonwealth Environment Protection and Biodiversity Conservation (EPBC) Act 1999. For seals, it is deduced from reported behaviour in response to incident SPL that the corresponding legal wideband SPL has a range of values with a median of 195 dB re 1 μPa. The corresponding "Noise Sensation Ratio" (NSR) in the frequency band of seals' best hearing (10-20 kHz) is between 40 and 50 dB. For the turtle, it is deduced from reported behaviour in response to an airgun that the corresponding legal wideband SPL is 166 dB re 1 μPa. For this wideband SPL, the NSR in the frequency band of turtles' best hearing (100-200 Hz) is either 30 or 50 dB, depending on species. Thus for a given disturbance response, the NSRs for the groups are similar, whereas the wideband SPLs differ by around 30 dB. Although these NSRs appear large, they are comparable with NSRs encountered by humans during conversational speech in the frequency band of humans' best hearing (3.5-4 kHz). Since there is a large difference in wideband SPLs but only a small difference between the NSRs, noise exposure criteria should be based on NSR rather than wideband SPL.

INTRODUCTION

For virtually all aquatic animals in Australian waters, the prevailing protective legislation is the Australian Commonwealth Environment Protection and Biodiversity Conservation (EPBC) Act 1999. This Act is administered by the Commonwealth Department of Sustainability, Environment, Water, Population and Communities (SEWPAC). Of the eight matters of national environmental significance to which the EPBC Act applies (SEWPAC, 2013a), those which relate to underwater noise appear to be (a) nationally threatened species (SEWPAC, 2013b) and ecological communities, and (b) migratory species. The Act aims to balance the protection of crucial environmental and cultural values with society's economic and social needs by creating a legal framework and decision-making process based on the guiding principles of ecologically sustainable development. It aims to provide for the protection of the environment (especially matters of national environmental significance), and conserve Australia's biodiversity. Many aquatic animal groups have been classified and given a conservation status under the EPBC Act.

An underwater signal with a high Sound Pressure Level (SPL), such as that from a seismic airgun or from offshore pile-driving, can disturb the behaviour of aquatic animals. For the initial study of noise effects to be described in this paper, the seal and turtle groups have been selected. The particular species within each group that will be examined (since data are available in the literature), along with their EPBC status, are listed in Table 1.

The maximum SPL that may occur without causing such behaviour disturbance as would reduce Australia's aquatic biodiversity differs markedly from one animal group to another. The aim of the present paper is to make a contribution toward developing a standard method for estimating such maximum SPLs for use in Environmental Impact Statements (EIS). At present there is no standard agreed method for use in EIS to do with effects of underwater noise on aquatic animals.

Table 1. EPBC Act conservation statuses of the seal and turtle groups, and the particular species to be examined.

Key to status: E - endangered; V - vulnerable.

Animal group	EPBC Status	Species
Seal	V	Harbour Seal Ringed Seal
Turtle	E and V	Green Turtle Loggerhead Turtle

BEHAVIOUR DISTURBANCE

Findings on noise exposure criteria for marine mammals have been summarised by Southall et al (2007). This summary distinguished between two basic sound types: (1) multi-pulse and (2) non-pulse (continuous) signals, on the basis that pulses generally have a different potential to cause physical effects, particularly on hearing. The present paper is confined to multi-pulse signals, a common source of which is the seismic airgun.

In producing recommendations on noise exposure criteria for disturbance of (as distinct from injury to) cetaceans and pinnipeds, an ordinal ranking of behavioural response severity, with Disturbance "response scores" from 0 to 9, was developed (Southall et al, 2007:449):

> The intent of this scaling was to delineate those behaviours that are relatively minor and/or brief (scores 0-3); those with higher potential to affect

> foraging, reproduction, or survival (scores 4-6); and those considered likely to affect these vital rates (scores 7-9).

Although this ranking scheme was developed in the context of marine mammals, it appears to be sufficiently general that it may also be applied to other aquatic animals. Examples of disturbed behaviour include avoidance of the sound source, separation of females from dependent offspring, and cessation of reproductive behaviour. A Disturbance response score (DRS) of 0 corresponds to "no observable response" while 9 corresponds to "outright panic, flight, stampede,… or stranding events".

It has been argued (Beale, 2007) that short term avoidance behaviour does not necessarily lead to a negative impact on the animal in the longer term. Avoidance behaviour is indicative of a long term problem only if it alters the fitness of an individual through changing foraging rates or reproductive output. The approach taken here is to regard as illegal those impacts that have a potential to reduce either the life expectancy of an individual animal, or the number of its offspring. Southall's DRS of 6 corresponds to several behaviours that include (Southall et al 2007:450):

> minor or moderate avoidance of sound source, brief or minor separation of females and dependent offspring, aggressive behaviour related to noise exposure ... , extended cessation or modification of vocal behaviour, visible startle response, brief cessation of reproductive behaviour.

It will therefore be assumed that a legal SPL is one that causes a Southall DRS of 6. If there is a distribution of such values, then the median or mode of that distribution will be regarded as the acceptable value.

According to Southall et al, the appropriate acoustic parameter for describing behaviour disturbance by mammals is "RMS" SPL (like many authors, Southall described the symbol 'SPL' as denoting RMS pressure, although it actually denotes mean square pressure).

For a given SPL incident on an animal, the method adopted here for estimating the consequent degree of disturbance is to compare that SPL spectrum with the animal's audiogram, in accordance with the following statement (Bradley & Stern, 2008:50):

> The most meaningful comparative metric for evaluating the respective loudness of a sound to a marine mammal is the extent to which it is known or estimated to exceed their hearing sensitivity in the same medium (called noise sensation level).

Although this ratio was described as a "level", it will be described in the present paper as a Noise Sensation Ratio (NSR). An alternative method would be to compare the incident SPL with ambient noise; but this would be inappropriate for animals whose audiograms are higher than ambient noise (such animals never hear ambient noise).

For each of three types of mammal: Low-frequency (LF) cetacean, mid-frequency (MF) cetacean, and pinniped, Southall presented distributions of wideband SPL that had been observed to give rise to the various DRSs. The results for a DRS of 6, which have a tolerance of ± 5 dB, are listed here in Table 2. In each case, the mode of the distribution was the same as its median.

Also listed in Table 2 are results for SPL (McCauley et al, 2000) that disturbed two turtles to a degree that is considered to be approximately equivalent to a Southall DRS of 6. It is evident that across these four groups there is a large variation in the wideband SPL that gives rise to a given DRS. A natural issue to address is whether there exists an acoustical parameter that exhibits a much smaller variation.

Table 2. Wideband SPLs (dB re 1 μPa) that give rise to a Southall Disturbance Response Score of 6.

Animal group	Minimum	Maximum	Median	Source
LF cetacean	115	175	125	Southall Table 7
MF cetacean	125	175	175	Southall Table 9
Pinniped	165	195	195	Southall Table 11
Turtle	166	166	166	McCauley

SENSITIVITY OF HEARING TO FREQUENCY

It has been noted that underwater hearing by marine mammals shares some of the features of human hearing in air, albeit with significant differences (Richardson et al, 1995). Four spectra of human "equal loudness" SPL are shown in Figure 1 (Poeppel, 2009): the lowest curve shows the SPL that is just audible (the human hearing threshold), and the highest shows the SPL that will cause pain to a human listener. The frequency of best hearing is around 3.5 to 4 kHz. It can be seen that:

loudness would be similar to NSR at frequencies near the frequency of best hearing (from an octave below to an octave above, say); and

frequency-dependences of the curves of equal loudness are similar to that of the threshold curve at low loudness, but become flatter at higher loudness.

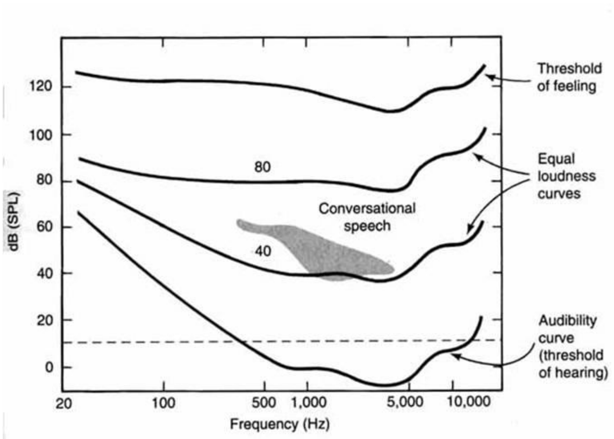

Figure 1. "Equal loudness" spectra of SPL for humans (Poeppel, 2009). Ordinate is airborne SPL in dB re 20 μPa (add 26 dB to convert to dB re 1 μPa). Numerals on two curves denote the loudness in phons.

Thus, as frequency is varied away from the frequency of best hearing, the loudness would decrease below NSR. It will be assumed here that a similar result would apply to aquatic animals.

Audiograms

Audiograms for Harbour Seals and a Ringed Seal are shown in Figure 2. The curve for Harbour Seals is an average of the four curves compiled by Nedwell et al (2004). The Ringed Seal curve (Terhune and Ronald, 1975a) starts at a frequency of 1 kHz and from its shape it is unclear how it would behave if extrapolated to lower frequencies. Since the Harbour Seal audiogram steadily increases as frequency is lowered from 1 kHz to 100 Hz, it will be assumed that the Ringed Seal audiogram would also increase if extrapolated to frequencies below 1 kHz.

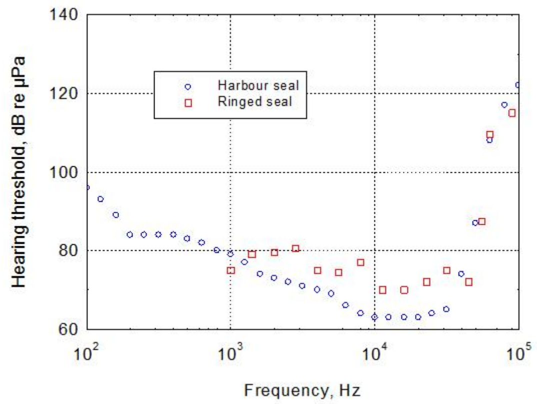

Figure 2. Audiograms of Harbour Seals (Nedwell et al, 2004) and a Ringed Seal (Terhune and Ronald, 1975a).

Audiograms of a Green Turtle (Tech Environmental, 2006) and a Loggerhead Turtle (Martin et al, 2012) are shown in Figure 3. It can be seen that the hearing bandwidth for turtles is relatively narrow (from 50 Hz to 1000 Hz) and that maximum sensitivity is in the band between 100 and 200 Hz.

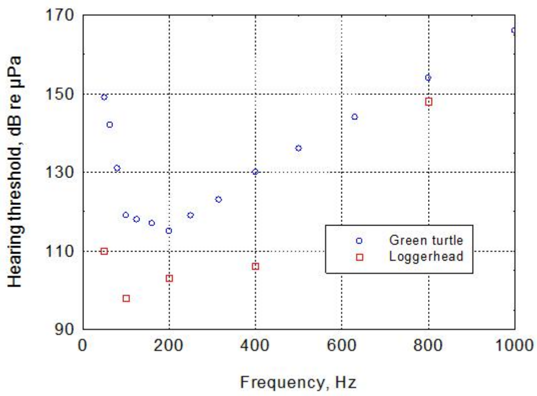

Figure 3. Audiograms of the Green Turtle (Tech Environmental, 2006) and the Loggerhead Turtle (Martin et al, 2012).

Critical Ratios

Since audiograms are measured with steady single-frequency tones, whereas it will be required to predict animal response to a wide-band signal, it is necessary to characterise (Richardson et al, 1995:31):

> the audibility of a pure tone in the presence of background noise. ... The critical ratio is the ratio of the level of a barely audible tone to the spectrum level of background noise at similar frequencies

By convention, Critical Ratio (CR) is expressed in decibels. Since it has the dimension of frequency, it should be expressed as dB re 1 Hz. Later in this paper the bandwidth in Hz that corresponds to the decibel measure will be referred to as the "Critical Ratio Bandwidth" (CRBW) in Hz: CR = 10 log (CRBW). CRBW is different from "Critical Band", which is another parameter in the field of hearing spectral sensitivity.

Results for the Critical Ratio of a Ringed Seal (Terhune and Ronald, 1975b) are shown by the blue points in Figure 4. These measurements were performed at frequencies of 4, 8, 16 and 32 kHz.

Critical Ratios of a turtle have not yet been systematically measured (Martin et al, 2012). The hearing thresholds of a loggerhead turtle measured by Martin at frequencies of 50, 100, 200, 400 and 800 Hz were shown in Figure 3. The background noise spectrum was also measured, and the ratios of the tonal threshold SPL to the background noise spectral density were 8 dB re 1 Hz at 50 Hz, and 11 dB re 1 Hz at 100 Hz. These ratios increased rapidly as frequency was further increased, as may be inferred from Figure 3 (the background noise decreased monotonically as frequency increased). The ratios at 50 and 100 Hz are shown (by the red points) in Figure 4. They may be regarded as estimates of the Critical Ratios if the background noise was high enough to have raised the hearing threshold, which Martin considered to be a "strong possibility". What may be concluded confidently is that the true Critical Ratios at 50 and 100 Hz may not exceed the values shown in Figure 4, since if the true Critical Ratio at either frequency were higher, then the tone at a lower SNR would have been inaudible.

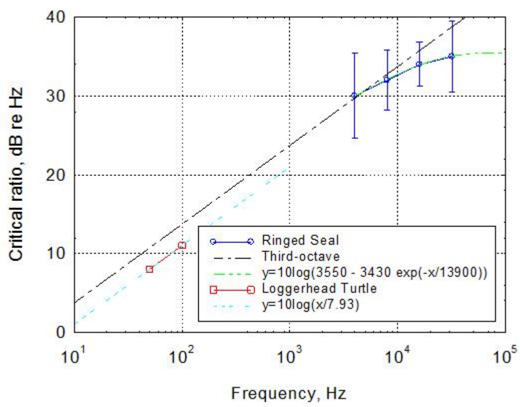

Figure 4. Results for Critical Ratio for hearing by the Ringed Seal (Terhune and Ronald, 1975b), and estimates for the Loggerhead Turtle based on the Signal to Noise ratios that prevailed during the low-frequency measurements by Martin et al (2012).

It has been observed (Richardson et al, 1995) that critical ratio bandwidths are often roughly one-third octave wide. The width of the third-octave band is also shown in Figure 4, and is evidently a useful approximation.

Compilations of spectra of Critical Ratios for a number of pinniped species (Au & Hastings, 2008) indicate that it is generally 15 ± 5 dB re 1 Hz for frequencies less than 1 kHz, increases to 30 ± 5 dB re 1 Hz as frequency increases to around 30 kHz, and is almost invariably less than the third-octave band. From Figure 4 it can be seen that these findings are consistent with using the Turtle (turquoise) curve for frequencies below 1 kHz, the Ringed Seal (green) curve for frequencies above 4 kHz, and an interpolation between these two curves for frequencies between 1 and 4 kHz.

SPECTRUM OF AN AIRGUN PULSE

In order to produce a spectrum of the acoustic pulse from a single airgun shot, the following results for the pressure (p) of the primary pulse waveform as reported by Cochrane (2007) have been used. The primary pulse is modelled by a linear increase over a time U from zero to the peak pressure P, which is followed by exponential decay with a time constant to be denoted by W:

$$p(r = 1, t) = P \frac{t}{U}, \quad 0 \le t \le U$$

$$p(r = 1, t) = P \exp\left[\frac{-t+U}{W}\right], \quad t > U \qquad (1)$$

where p(r=1,t) denotes the pressure waveform at a range of 1 m. The peak pressure P (Bar-m) is expressed as:

$$P = 0.708\, \mathrm{V}^{1/3} (\mathrm{Q}/2000)^{0.75}\, \mathrm{N}^{0.75} \qquad (2)$$

where V is the volume of a single gun in cubic inches, Q the gun pressure in pounds per square inch, and N the number of identical guns in the array (which can be 1). These quantities are expressed here in imperial units as reported by Cochrane (2007), in order to facilitate the process of consulting that report should the reader wish to do so. The rise time U and decay time constant W (in seconds) are expressed as:

$$\mathrm{U} = 2.43 \times 10^{-6}\, \mathrm{V}^{1/3}\, \mathrm{P}^{1/2}\, \mathrm{N}^{0.75} \qquad (3)$$

$$\mathrm{W} = 5.46 \times 10^{-4}\, \mathrm{V}^{1/3} \qquad (4)$$

The contribution of the bubble-pulses subsequent to the primary pulse to SPL will be small, and for the present study is neglected.

LEGAL SOUND PRESSURE LEVELS FOR THE ANIMAL GROUPS

Seals

For pinnipeds exposed to multiple pulses, Southall's Table 11 has a total count of 96 individuals or groups, of which 49 exhibited a DRS of 6, while the remainder exhibited a DRS of 0. By cross-referencing between Southall's Tables 10 and 11, it can be seen that the seals that scored 6 were almost entirely Ringed Seals. The disturbances and airgun SPL data were reported by Harris et al (2001), who had deployed an array of 11 airguns each with a volume of 1966 cc (120 cubic inches). Since it will be expedient later to describe a sound pulse in terms of its Sound Exposure Level (SEL), we note that in general the relation between SEL and SPL (in decibels) may be written as

$$\mathrm{SEL} = \mathrm{SPL} + 10 \log \mathrm{T} \qquad (5)$$

where T (seconds) is the duration of the pulse, and SPL is the mean-square pressure over that duration. In the present paper, SEL will refer to the energy of a single shot, since the cumulative SEL of a number of shots is not pertinent to disturbance (as distinct from injury). For the airgun used by Harris et al (2001), the relation between SEL and SPL was reported as:

$$\mathrm{SEL(Harris)} = \mathrm{SPL} - 15, \qquad (6)$$

which indicates that the pulse duration was approximately 30 msec. The results reported by Harris et al (2001) include their horizontal SPL Source Level (at 1 m), and SPL at ranges of 31, 240, 960 and 3600 m. The two longest ranges will be omitted from the following analysis since they lie well beyond the maximum range of interest to the present study. The SPLs at 1, 31 and 240 m have been converted to SEL using Equation (6), and the results are shown in Figure 5. It can be seen from Figure 5 that SEL equalled 180 dB re 1 μPa^2.s at a range of approximately 90 m (From Equation (6) an SPL of 195 dB re μPa corresponds to an SEL of 180 dB re 1 μPa^2.s).

Fitting a curve of the form

$$\mathrm{SEL(r)} = \mathrm{A} - \mathrm{B} \log(\mathrm{r}) \qquad (7)$$

yields A = 207 (which coincides with the stated SEL Source Level) and B = 13.6. Since B = 20 for spherical spreading, the finding that the coefficient B is significantly less than 20 indicates that steep reflections from layers in the seabed made a significant contribution to SEL. These reflections will over-ride the Lloyd Mirror surface interference that would otherwise be evident, especially at low frequencies. Since there is insufficient information available on the seabed for computing Propagation Loss (PL) with a mathematical model, it is necessary to assume that PL is independent of frequency. It follows that the spectrum of the waveform will be independent of range. In view of the short ranges involved, the error in this assumption is expected to be no more than a few decibels.

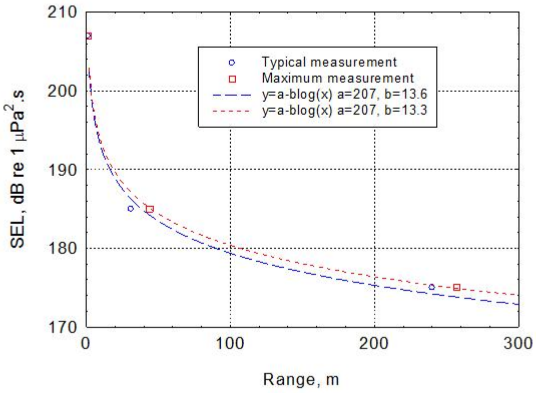

Figure 5. Measured results and a fitted curve for Sound Exposure Level (SEL) from the airgun used by Harris et al (2001).

According to the data summarised by Southall for the relation between DRS and SPL for pinnipeds (their Table 11), there is a 90 to 95% chance that an SPL that causes a DRS of 6 will lie in the interval from 190 – 200 dB re 1 μPa. This interval will be characterised here by its mid-point of 195 dB re 1 μPa. Notwithstanding that this conclusion is a robust interpretation of Southall's Table 11, it is open to question on the following grounds (Anonymous, 2013):

> A behavioural disturbance criterion of SPL 195 dB re 1 μPa seems very high. From (Table 3 in) Southall (2007), the hearing damage criterion (Temporary Threshold Shift) for pinnipeds in water is SEL 186 dB re 1 μPa^2.s. From the author's paper, an SPL 195 dB re μPa typically equates to an SEL 180-185 dB re 1 μPa^2.s for airgun noise. So TTS would occur after exposure to 2 to 4 airgun shots (say 40 seconds) using the proposed behavioural disturbance criterion. This criterion therefore seems unrealistic.

While acknowledging the logic of this argument, the present paper, which is concerned only with disturbance, will proceed on the assumption that a straightforward interpretation of Southall's Table 11 is valid.

The airgun array used by Harris had the following properties: V = 1966 cc (120 cubic inches), Q = 13.8 MPa (2000 pounds per square inch), and N = 11. With these values, Equation (2) yields P = 21 Bar-m. Although the actual peak pressure was measured to be 3.2 Bar-m, this value is not used here, since the analysis does not require it. When the Cochrane value for P is used, the value for SEL at 1 m computed by integrating $p^2(r=1, t)$ over time is 222 dB re 1 μPa^2.s (15 dB higher than the observed value).

If q(f) is the Fourier Transform of p(t) then by Parceval's theorem the energy spectral density of SEL, the integral of $p^2(t)$ over all time, is $|q(f)|^2$. SEL spectral density will be denoted by SEL SD. The spectrum of the Cochrane waveform at 1 m will be normalised to the data by reducing it by 222 – 180 = 42 dB. The resulting spectrum of SEL SD is shown in Figure 6. There is some uncertainty in this spectrum at the lower frequencies due to the possibility of some destructive interference but, in the absence of a geoacoustic model for the seabed, it is impossible to define this spectrum any more precisely. The surface reflection has therefore been neglected.

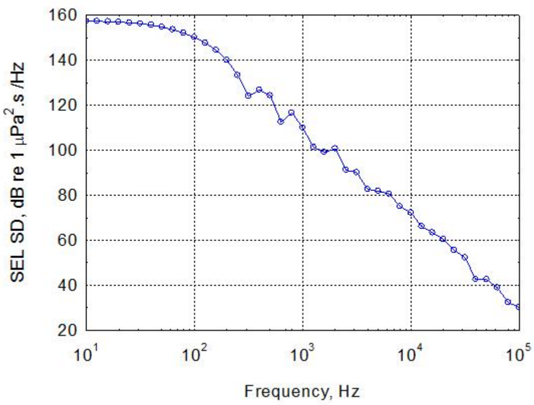

Figure 6. Estimated Sound Exposure Level spectral density of the airgun used by Harris et al (2001) at the range where SEL = 180 dB re 1 μPa^2.s. Surface interference effects are neglected.

A spectrum of the estimated SPL per critical ratio bandwidth (CRBW) of the Ringed Seal due to noise radiated from the airgun operated by Harris et al (2001) is shown in Figure 7. We recall that the Ringed Seal CRBW is set equal to a third octave for frequencies below 4 kHz, and to the function associated with the green curve in Figure 4 for frequencies above 4 kHz. Each point on this curve was obtained by adding 10 log (CRBW /T) to the SEL SD in Figure 6: +10 log CRBW to convert from spectral density to band level, and -10 log T to convert from SEL to SPL. It is evident that for this wideband SPL, the Noise Sensation Ratio (NSR) decreases steadily as frequency increases, from around 80 dB at 100 Hz, to zero at around 50 kHz. In the frequency band of seals' best hearing (10-20 kHz) NSR is approximately 50 and 40 dB for the Harbour and Ringed Seals respectively.

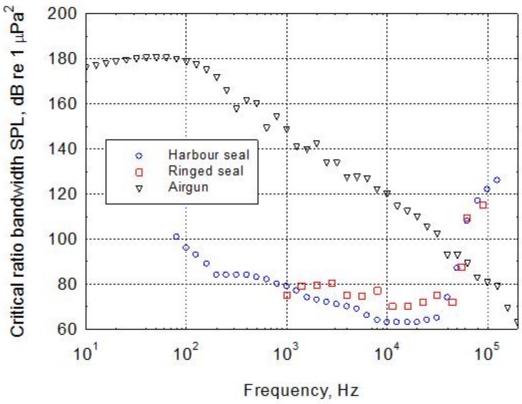

Figure 7. Spectrum of the estimated SPL per critical ratio bandwidth of the Ringed Seal due to noise radiated from the airgun operated by Harris et al (2001) at the range where SEL = 180 dB re 1 μPa^2.s, and audiograms for the Harbour Seal (Nedwell et al, 2004) and Ringed Seal (Terhune & Ronald, 1975a).

Turtles

For their two experiments with turtle subjects in Jervoise Bay, the airgun used by McCauley et al (2000) had the following properties: Q = 103 MPa (1500 pounds per square inch), V = 328 cc (20 cubic inches), and N = 1. The seafloor was 9 to 10 m deep, and the hydrophone was inside or attached to the turtle cage. It was reported that SEL exceeding 155 dB re 1 μPa^2.s caused the turtles to noticeably increase their swimming activity, and this finding is interpreted here to conclude that this SEL produced a DRS of 6.

For McCauley's airgun, the relation between SEL and SPL during the turtle experiments was reported to be

$$\mathrm{SEL(McCauley)} = \mathrm{SPL} - 11 \qquad (8)$$

which indicates that their average pulse duration was approximately 80 msec. Their results for wideband SEL at horizontal ranges of 5, 10 and 30 m are shown here in Figure 8 (a further result at 350 m is too far away to be relevant to the present study). On fitting Equation (7) to these data it is found that A = 186 and B = 16.7. The coefficient B is (again) somewhat less than 20, indicating that reflections by the seabed had a noticeable effect on PL. For this scenario, the Cochrane model yielded an SEL at 1 m of 193 dB re 1 μPa^2.s. The SEL SD to be presented is therefore the Cochrane spectrum at 1 m, reduced by 193 – 155 = 38 dB. It can be seen from Figure 8 that SEL equalled 155 dB re 1 μPa^2.s at a range of approximately 70 m.

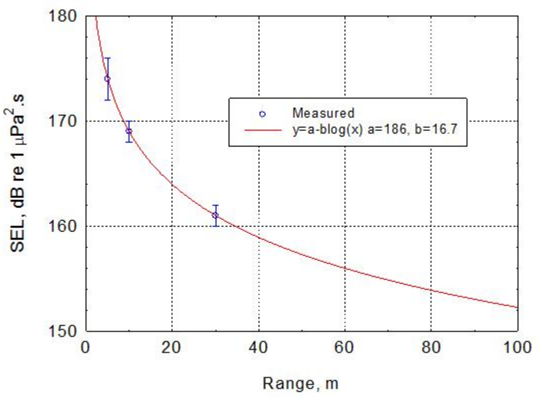

Figure 8. Measured results and a fitted curve for Sound Exposure Level (SEL) from the airgun used by McCauley et al (2000).

The resulting spectrum of SEL SD, to a maximum frequency of 10 kHz, is shown in Figure 9. If the effect of surface interference were included, the curves would decrease as frequency decreases from 100 to 10 Hz. In the absence of a geoacoustic model of the seabed it is impossible however to quantify that decrease.

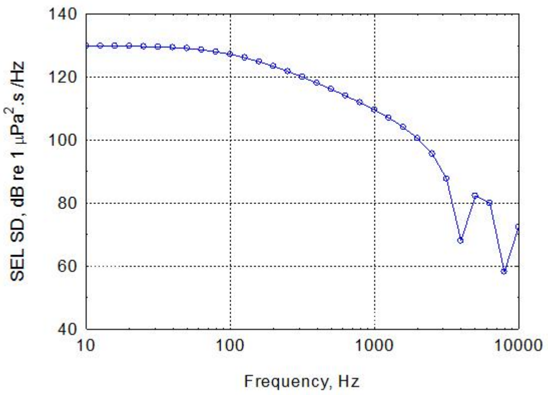

Figure 9. Estimated Sound Exposure Level spectral density of the airgun used by McCauley et al (2000) at the range where SEL = 155 dB re 1 μPa^2.s. Surface interference effects are neglected.

A spectrum of the estimated SPL per critical ratio bandwidth of the turtle, due to noise radiated from McCauley's airgun at the range where SEL = 155 dB re 1 μPa^2.s, is shown in Figure 10. We recall that the turtle CRBW is given by the function associated with the turquoise curve in Figure 4. Each point on the curve in Figure 10 was obtained by adding 10 log (CRBW /T) to the SEL SD in Figure 9. It is evident that for this SPL spectrum, NSR has a maximum in the frequency band of the turtles' best hearing. The maximum NSRs are 30 dB and 50 dB for the Green and Loggerhead turtles respectively.

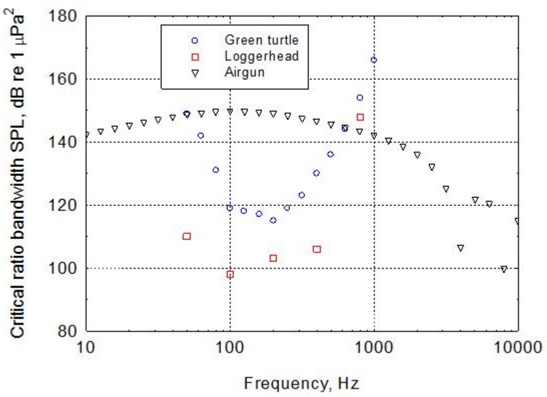

Figure 10. Audiograms for the Green Turtle (Tech Environmental, 2006) and Loggerhead Turtle (Martin et al, 2012), and spectra of the estimated SPL per critical ratio bandwidth of either turtle due to noise radiated from the airgun operated by McCauley et al (2000) at the range where SEL = 155 dB re 1 μPa^2.s..

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CONCLUSIONS

Noise Sensation Ratios to which Ringed Seals have been subjected without causing extensive or prolonged (and thus illegal) disturbance decrease from an estimated 80 dB at 100 Hz to zero dB at around 50 kHz. In the frequency band for their best hearing (10-20 kHz) NSR is approximately 40 dB. For the Green and Loggerhead turtles the maximum legal NSRs in the frequency band for their best hearing are 30 dB and 50 dB respectively. It may be that Green turtle ears have a smaller dynamic range than those of other animals. An NSR of 50 dB is similar to the ratio that humans encounter during medium-level conversational speech.

For seals and turtles, noise exposure criteria should be based on NSR rather than wideband SPL. The usefulness of doing so for other animal groups should also be examined.

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