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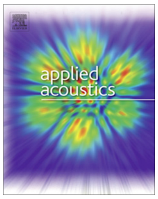

Practical implementation of auditory time and frequency weighting in marine bioacoustics

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ABSTRACT

Much effort is currently directed at describing the behavioral reactions of marine mammals following exposure to sound with the aim of deriving generalized thresholds and dose-response functions. The perceived loudness of a given sound is a candidate for a common metric for sound exposure. The loudness of a signal relates to various factors, including the stimulus duration and frequency content, and it can be approximated by an appropriate time and frequency weighting of the signal. Auditory frequency weighting is achieved by applying a frequency weighting function (band-pass filter), with a frequency response resembling the shape of an inverted audiogram. Temporal weighting may be achieved by computing the running rms-average (L_{eq}) with a time constant that is comparable to that of the mammalian auditory system. The practical implementation of such weighting functions are presented in the form of Matlab functions. These functions generate output signals that are weighted according to current recommendations for different groups of marine mammals. With these functions, it is possible to derive the weighted peak L_{eq} of a signal, which is likely to be a good proxy for the loudness of the signal. Ultimately, this weighted level is conjectured to be a predictor of behavioral response of marine mammals to the sound.

1. Introduction

A central concept in auditory psychophysics is loudness. Loudness is a measure of how loud a sound is perceived to be by the listener (human or animal), and is closely related to the intensity of the sound. Everything else being equal (i.e., for constant signal duration, frequency spectrum, envelope etc.), and for the same individual, there is a monotonic relationship between signal intensity and perceived loudness. However, as soon as other signal parameters change, loudness is likely to change as well, despite a constant signal intensity. If the frequency spectrum is changed, the change in perceived loudness is related to the shape of the audiogram and the fact that the sensitivity of ears varies across frequencies. The perceived loudness of short signals changes with changes in the duration of the signal, related to the temporal integration of the ear and the auditory pathway. This temporal integration phenomenon reflects the fact that the mammalian ear is better described as a detector of energy, rather than an intensity detector, for signals shorter than some hundreds of milliseconds e.g. [1–3].

Loudness is also a central concept for assessing the impact of noise on both humans and animals, and lies at the core of standards for human community noise regulation. These standards specify how measurements should be weighted, in both frequency and time, so that they reflect, as closely as possible, the perceived loudness of the noise under investigation (see [4] for a review of how auditory frequency weighting has developed in both humans and marine mammals). A seminal publication, with respect to marine mammals, was Southall *et al.* [5], which established noise exposure criteria for marine mammals. This publication provided the first systematic review of studies of temporary hearing loss in marine mammals and advocated the application of auditory frequency weighting in assessments related to marine mammals. More specifically, a series of "M-weighting" curves were derived, one for each of five functionally different groups of marine mammals [5]. The M-weighting curves have since been replaced by several iterations of new curves [6,7], which have been gradually adapted with the emergence of an increasing amount of new experimental evidence.

The marine mammal auditory weighting curves were originally developed to assess the risk of injury to individuals. In particular, they were developed to define group-wide exposure limits, based on the criteria of temporary and permanent threshold shifts (TTS and PTS). The original criteria [5], as well as subsequent ones [6,7], were formulated in terms of "sound exposure level" (SEL), which is a measure of total acoustic energy cumulated over the

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duration of exposure (to some upper limit, currently 24 h), and weighted with an appropriate auditory weighting curve. This approach seems reasonable, as experimental data support weighted, cumulated SEL as the best overall predictor of likelihood of TTS [8,9]. Thus, auditory frequency weighting can be implemented by applying weighting to the frequency spectrum of the total signal that the animal is exposed to, and then summing the energy across the frequency spectrum, as described in Section 2.

In addition to criteria and thresholds for injury, it is also desirable, if possible, to derive generalized response thresholds for behavioral reactions to sound. However, this goal appears more difficult to achieve. Thus, even though it was one of the intentions behind the initial review [5], the authors refrained from providing actual thresholds. There are many reasons why this task is more difficult than deriving exposure limits for TTS/PTS. One of the difficulties is related to behavioral reactions being a continuum of many different types of reactions, and another the likelihood that behavioral responses depend on other factors than just loudness, such as context and physiological state of the animal e.g., [10,11]. However, it seems reasonable to conjecture some sort of general correlation (even if just on average) between the loudness of a sound and the likelihood of response to that sound. This approach has been suggested for harbor porpoises (*Phocoena phocoena*), supported by a review of experimental data from observational studies in the field [8]. Reaction thresholds were compared across several different types of sound sources (pile driving, seal scarers, and gill net pingers) by considering the integration time of the porpoise ear [8]. Integration time was included by adopting a correction factor, which was determined by the duration of the given sound, taking advantage of the observed relation between duration and thresholds for short sounds (below the time constant of the ear, roughly 125 ms), where the threshold decreases by 3 dB for each doubling of the duration. Similarly, when the spacing between pulses is much shorter than 125 ms, the threshold decreases by 3 dB for each doubling of the pulse rate (see [8] for further details). Comparison across sounds with different frequency spectra was achieved by comparing levels above the hearing threshold at the signal peak frequency (also known as sensation level), rather than comparing absolute sound levels. Comparing sensation levels is a crude way of performing an auditory frequency weighting with a curve identical to the inverted audiogram. However, while this approach works well for pure tone signals, it is less applicable to broad-band signals.

The key inference from [8] and the line of reasoning above is that, for a given marine mammal species, a generalized response threshold could be expressed in terms of loudness of the sound. A threshold expressed solely in terms of loudness is attractive because of its simplicity. However, this approach is limited as not all complexities of the responses may be captured. Such complexities are for example seen in several studies on larger baleen and beaked whales, which indicate that the distance to the source also could be an important parameter (see [12] for a recent example). Nevertheless, the conjecture of loudness being an important determinant in behavioral responses could and should be tested experimentally by measuring behavioral responses to a wide range of different sounds, and with thresholds expressed as estimated loudness of the received sounds. However, to do this, better tools to estimate the loudness of sounds, – by means of appropriate frequency weighting and temporal weighting of the signals, – are needed. Thus, this technical note describes a practical implementation of such tools. Two different functions are provided that perform auditory temporal and frequency weighting, respectively. These functions are described in general, as well as being presented in Matlab/Octave code. Complete source codes of the functions are included as electronic Supplementary material.

2. Weighting in the frequency domain – Auditory filter functions

A basis for the weighting of auditory frequency is recommendations of the U.S. National Marine Fisheries Service [7] (henceforth referred to as the NMFS recommendations). These curves are the result of a large review of all available experimental data to date and are thus adopted here without further justification. All weighting curves are described by the following general equation:

$$W_f = 10^{C/10} \cdot \frac{(f/f_1)^{2a}}{[1+(f/f_1)]^{a}[1+(f/f_2)]^{b}} \tag{1}$$

where f is the frequency in Hz, while a, b, $f1$, $f2$ and C are the species group specific constants listed in Table 1. Note, Eq. (1) differs slightly from the corresponding Eq. (1) in the NMFS recommendations [7] in that it is expressed here in linear units of power (for convenience), whereas it is expressed in units of dB in [7]. Fig. 1 shows the weighting functions for the five different groups defined by the NMFS [7].

For short signals, where one might only be interested in the frequency weighted cumulated energy of the signal ($L_{E,\ weighted}$), the weighting is performed directly on the power density spectrum or third-octave spectrum (whatever is relevant in the particular application) and $L_{E,\ weighted}$ is obtained by summing (integrating) across the entire frequency range. For the power density spectrum P (in linear units), $L_{E,\ weighted}$ is obtained as:

$$L_{E,\ weighted} = 10\log_{10}\int_0^{\frac{fs}{2}} P_f \mathrm{W_f} df \tag{2}$$

where fs is the sampling rate. For the third-octave spectrum $TOL(f)$, in units of dB re. 1 μPa, $L_{E,\ weighted}$ is found by summing across n third-octave bands, each with center frequency f_i:

$$L_{E,\ weighted} = 10\log_{10}\left(\sum_{i=1}^{n} 0.23 f_i W_f(f_i) \cdot 10^{\frac{TOL(f_i)}{10}}\right) \tag{3}$$

For longer signals, however, one might be interested in assessing the total $L_{E,\ weighted}$ of the signal and the instantaneous intensity of the weighted signal (i.e., the development of signal intensity with time). This is particularly important when frequency weighting is followed by temporal weighting, as described in Section 3 below. If one ignores the negligible phase distortion of the frequency weighting function, W_f, then the weighted version of a signal, s, can be obtained by the inverse Fourier transform of the product between the complex Fourier transform of the signal and the appropriate frequency weighting function.

$$s' = F^{-1}\{F\{s\}\sqrt{W_f}\} \tag{4}$$

Frequency weighting must be applied in linear units of amplitude (pressure), which is achieved by taking the square root of W_f (which has the unit of intensity).

2.1. Practical implementation of frequency weighting

A practical implementation of Eq. (4) in Matlab is provided in Supplementary material S2 in the form of a Matlab function "NOAAweighted". The central steps are described here. The function will accept as input, a real-valued signal, *sig*, sampled at a rate of *fs* (Hz), and will return the signal *sfilt*, which is the corresponding signal after it has been weighted by the selected type of filter (termed *filtertype*). Legal inputs for *filtertype* are 'HF', 'MF', 'LF', 'Otariid', and 'Phocid'.

```
s = NOAAweighted(sig, fs, filtertype)
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