The importance of incorporating signal characteristics in the evaluation of noise exposure impacts on marine life.

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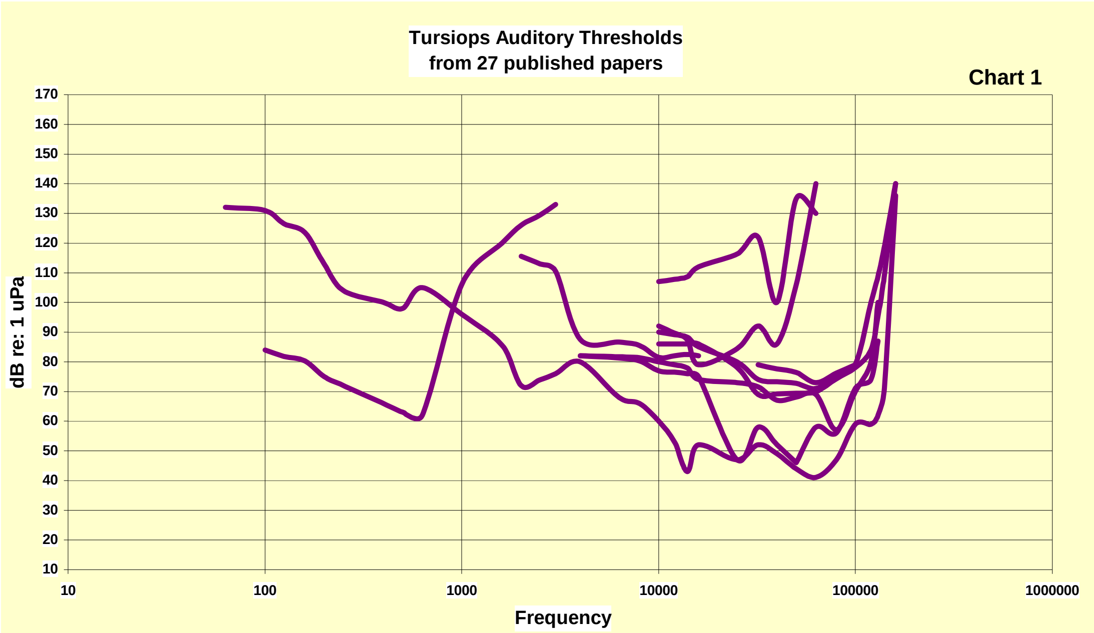
Auditory thresholds are used to establish mitigation guidelines for anthropogenic noise exposure on marine animals. These thresholds are determined using either sinusoidal signals at specific frequencies or band limited, sinusoidal-derived Gaussian noise. Given that the preponderance of naturally occurring noise in the marine environment is sinusoidal, marine animals may have lower thresholds, and thus lower tolerance to non-sinusoidal noise. Fast rise time impulse noise, continuous non-sinusoidal noise, or a combination of these characteristics may induce biological responses at lower levels than sinusoidal noise with an equivalent power density. The author proposes a metric to evaluate and express signal characteristics as a component of determining noise exposure impacts on marine animals.

Introduction

Mitigating for the impacts of anthropogenic noise on marine life is a vexing, and multifaceted problem. While we know that there are impacts of noise exposure when the evidence includes mortalities or unambiguous shifts in wildlife populations consequent to an acoustical event, these unambiguous clues are (fortunately) not so common. In order to avoid the unambiguous evidence, appropriate and safe exposure thresholds are sought. But this task is confounded by the fact that there are no clear biological or auditory thresholds for noise exposure across all potentially impacted species. Even within a single species there does not seem to be any hard and fast threshold guidelines.

One of the greatest challenges in establishing appropriate mitigation levels involves correlating repeatable lab studies on captive animals to wild animal behavior in the open ocean. There are many methods used to determine auditory thresholds in subject species in the lab. And as the subjects are captive, the studies can be tailored and adjusted to yield unambiguous results. But even with this advantage the differences between individuals, testing procedures, testing environments and test signals nonetheless account for a high level of variability in the published auditory thresholds by as much as 50-60dB. (See Chart 1).[1]



Nonetheless policy and practice needs unambiguous guidelines on noise exposure criteria. Until these criteria are crafted we can expect somewhat arbitrary guidelines to be drawn up by the courts to in response to the best contemporary arguments. For example, in the October 2008 US Supreme Court case "Donald Winter / U.S. Navy v. NRDC et.al."[2] among the issues at play were whether the Navy would mitigate to noise exposure levels at 173 dB SEL re: 1 μPa established using "temporary threshold shift" levels of legacy captive dolphins exposed to sinusoid signals,[3] or at 154dB re: 1 μPa established by avoidance behavior of wild right whales to more complex signals.[4]

While the current practice is to express noise exposure – an thus set mitigation thresholds based on amplitude alone, it is clear from the very citations used in the Supreme Court case to set statutory mitigation thresholds that there are other characteristics of sound which are not amplitude dependant which nonetheless induce biological and physiological impacts on the exposed animals.

Correlating lab-derived auditory and behavioral thresholds to field thresholds

A majority of animal audiology studies have relied on exposing animals to calibrated and repeatable stimulus signals in lab settings. As a consequence, either single frequency sinusoids or band limited Gaussian noise has been employed to establish auditory thresholds. The purpose for this is obvious in light of the need to calibrate and reestablish testing conditions between different labs and studies, and then to use these results to inform our understanding on animal perception and perhaps more importantly, to provide guidelines for environmental management policy.

But one of the most fundamental obstacles to establishing mitigation thresholds derived from lab animals in a controlled setting and applying them to animals in the field is that – aside from the field behavioral conditions being necessarily more complex, the signals and acoustic conditions in the field are likewise much more complex than controlled lab conditions.

It is also the case that signals used in the lab are fundamentally dissimilar to the actual signals that animals are exposed to in the field because they are used for different purposes. For example; it is sanguine to assume that sinusoidal signals – either pure tones, or sinusoid-derived Gaussian noise used in laboratory audiometrics correctly models an animal's sensitivity or predicts their response to signals used for human communication systems and environmental exploration.

Additionally, the natural noise of the motion in the ocean is sinusoidal, and it can get quite loud depending on turbulence, weather conditions, surf breaks, and proximity to shallow water hydro-geological variability. Animals living in loud sinusoidal noise fields are not served by sensitivity to sinusoidal noise, so it stands to reason that these animals would have higher thresholds to signal characteristics which would only be noise in their perceptual field.

Some animals are distinctly <u>not</u> sensitive to sine wave stimulus. This feature is exploited by spider kleptoparasites that can forage in a spider's web without alerting the resident by using a "sinusoidal gait."[5]

From a behavioral standpoint it is only expeditious to assume that pure-tone derived masking thresholds are linearly correlated to naturally occurring noise masking if the "masked signals" are more complex than the pure tone signals and/or biologically significant to the animals in the field.

Band limited Gaussian noise is used in auditory threshold testing, but using lab derived auditory thresholds still only serve as a mechanistic proxy for the actual noises that are known to cause biological disruption. This situation has recently been addressed in controlled exposure studies in wild animals. [6,7,8] Testing with actual disruption signals provides the most meaningful data on the impacts of these signals in field conditions on non-captive subjects, but the limitations on these tests include the statutory (as well as ethical) constraints on exposing wild animals to sounds that disrupt and may damage them.

But from these studies, it is clear that animal hearing systems are not just "auditory frequency bins" but include complex ways of discriminating the characteristic differences between biologically useful signals, "safe sounds," noise, and "pernicious sounds."

Animal discrimination of some of these characteristics are most notably exploited in signals used for acoustic harassment devices designed to keep animals from interfering with human enterprise. These include "pingers" used to keep net predators away from fish farms, net beacons to keep beaked whales from net entanglement in fishing operations, and ultrasonic noise generators to harass and scare off mice and rats. Harassment signals do not need to be loud to be effective; they just need to be obnoxious.[9]

Kastelein and Verboom have worked with various non-sinusoid signals to demonstrate variability in discomfort levels, and thus radii of discomfort zones correlated to signal differences.[10]

Hammernik and Wei have also demonstrated that signal characteristics have a bearing on physiological damage, and that signals with a higher "kurtosis" or statistical variability in levels or harmonic content over time produce greater physiological damage than lower kurtosis signals of equal amplitude exposure levels.[11]

In light of the common use of harassing, obnoxious and alarming sounds, and the damage induced by high kurtosis signals, it stands to reason that exposure criteria should be embellished reflect characteristics known to harass or damage the exposed subject.

Signal characteristics that effect marine animals

A bridge between using lab derived threshold data and exposing wild animals to actual signals that are disrupting them involves looking at characteristics and qualities of the signals in addition to frequency band and signal amplitude.

Characteristics to be evaluated:

1. Rise time of impulse signals
2. Periodicity of intermittent signals
3. Kurtosis in terms of spectral bin distribution (from instantaneous FFT of a signal)
4. Kurtosis in terms of amplitude variability over time
5. Kurtosis in terms of spectral and amplitude variability over time.

There has been a recent move to consider cumulative exposure impacts with a time integral as in the use of "Sound Exposure Level" (SEL) defined as:

Energy flux density = $10\log\int_0^T p^2(t)dt$

where "T" is duration of the exposure and "*p*" is pressure.

Bearing in mind that the total acoustical energy flux density also includes particle velocity which integrates an angular vector at the receiver as well:

$$|\overrightarrow{A}| = \sqrt{A_x^2 + A_y^2 + A_z^2}$$

where $|\overrightarrow{A}|$ is the magnitude of the particle vector in the x, y, and z directions, requiring an integration of this component into each of the five characteristics indicated above.

Conclusion

There has been a long history of measuring auditory thresholds using behavioral and physiological test methods. The use of simple, easily quantified signals in these tests has facilitated some degree of repeatability. But the tests only demonstrate the subject's sensitivity to the test signals and do not necessarily reflect the subject's auditory thresholds to the range of signals that they might encounter in their own habitat.

This is particularly important because the results from published auditory threshold tests are increasingly being used to set exposure thresholds and mitigation standards for exposures to human generated noise. Some of these human generated noises, such as underwater communication sonars and other exploration signals are unlike any sounds encountered in nature and may be correlated with marine mammal strandings.[12]

A method of determining behavioral thresholds to these sounds would provide exposure mitigation guidelines more consistent with the actual exposure. Controlled exposure experiments in the field can provide behavioral thresholds of certain species to certain sounds,[13] but establishing a range of thresholds across a range of signals and across a range of subjects would be impractical given the complexity of the testing procedures, variability of field conditions, and variability of the array of subjects.

On the other hand, deriving a metric based on more accurate characterization of signals would facilitate repeatability in lab threshold test settings. This metric could be more practical in correlating field exposures with lab-derived behavioral responses to more complex signals and may prove more useful in establishing realistic mitigation guidelines.

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