Signal kurtosis as a predictor of biological impacts from noise exposure.

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Abstract

Anthropogenic noise is compromising the habitat for marine mammals, fish, and other marine organisms. Determining acceptable exposure thresholds is confounded by the fact that marine animals have adapted to some exceedingly loud naturally occurring sounds, whereas exposure to certain anthropogenic noises at equivalent or lower amplitudes causes harm. It is clear that exposure mitigation thresholds cannot be established by signal amplitude alone; rather signal qualities should be considered when attempting to predict noise exposure impacts.

This paper presents a proposed metric that expresses signal qualities which may be subjectively evaluated in terms such as "smooth," "rough," "shrill," or "pleasant." There is a correlation to these subjective terms with a numeric value derived from "kurtosis" which is a measure of the "peakedness" of the data distribution. There is also a correlation between high kurtosis signals and hearing trauma, even in situations where the subjects are exposed to equal energy, (Qiu et.al 2006) establishing kurtosis as an important variable in noise exposure regulation.

Introduction

Just as our terrestrial habitat is easily served by visual senses due to the transparency of air as a light transmission channel, the ocean is easily served by acoustical senses due to the efficiency that water transmits sound. This has resulted in a myriad of acoustic-sensory adaptations by aquatic biota; from complex bio-sonar to long distance acoustical communication. (Cornell, 2005)

As human enterprise has expanded into the ocean it has brought with it the sounds of industrialization. In the past 50 years anthropogenic noise in the ocean has increased by as much as 10 -15dB in some locations. (Ross 1976, 1993). While the increase in broadband anthropogenic noise may mask significant bioacoustic communication channels (Clark et.al 2009) the public, and thus legislative and regulatory bodies were not alerted to the potential disruptions of anthropogenic noise until noises were implicated in catastrophic strandings of cetaceans. (NOAA, US Navy 2001).

It was largely a consequence of these strandings that ocean noise regulation became a prioritized public concern (McCarthy 2004). While there were many theories about the causes of the strandings, and many variables to consider such as signal source, exposure level, exposure onset envelope, hearing ranges of the subject animals, propagation characteristics of the habitat, behavior patterns of the animals during the disruption, and even phases of the moon, for lack of a more refined understanding of the catastrophic events, regulatory protocol under the U.S. National Marine Fisheries Service (NMFS), the U.S. Marine Mammal Commission (MMC), the Canadian Department of Fisheries and Oceans (DFO), the International Whaling Commission (IWC), and the United Nations Environmental Program (UNEP) among others have established permissible noise exposure standards on regulatory thresholds based on net or accumulated acoustical energy alone , known as the “Equivalent Energy Hypothesis” (Atherly and Martin, 1970) with only a cursory inclusion of the hearing thresholds and perceptual bandwidth of the receiver, and without considering characteristics of the noise. The hearing regime of the receiver has been proposed as a modifier to regulatory exposure thresholds (Southall et. al. 2007) but has yet to be adopted.

There is a natural as well as an academic understanding that emotional and psychological responses to sound are correlated with signal qualities (Kumar 2008), but quantifying the impacts of sound characteristics becomes a complex multivariate challenge with signal amplitude, signal envelope, frequency and harmonic components, and temporal variability when the biological response is on a continuum between mild avoidance to life-threatening (or life-ending) flight.

We humans do know nonetheless that some sounds are easy to listen to, while others are obnoxious. Even while containing the same frequency components and being of the same amplitude the sound of a high note bowed on a violin is much more tolerable than fingernails being scraped across a blackboard. It is the more subtle modulations of the signal – at least from a quantifiable standpoint, that render a sound intolerable (Halpern et.al.1986). However there are noises that are anxiety producing not due to association (such as babies screaming, earthquakes and avalanches, or fire alarms) but because they are dissonant and highly variable in the frequency and/or time domain - and perhaps associated with something out of control.

Expressing the characteristics of a signal amplitude, signal envelope, frequency and harmonic components, and temporal variability into a single metric would be a complicated integral of physical properties which would not easily yield an unambiguous numeric suitable for setting regulatory thresholds. But by looking at the input variables from a statistical standpoint a single numeric can be derived which could prove much more adapted to setting noise exposure metrics.

Kurtosis

Kurtosis (β) describes the shape of a probability distribution on an x-y graph. It is equated with the “peakedness” of the curve as a product of the distribution of observed data around the mean.

$$\beta = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - \bar{X}}{S}\right)^4$$

Where:

> n = the number of elements in the distribution.
> S = Standard deviation

X= are the discreet peaks in data stream (for sound, the pressure/time waveform) over some interval of time.

Kurtosis then is an expression weather the data are peaked or flat relative to a Gaussian distribution. Datasets with a high kurtosis (β >3) tend to have a distinct peak near the mean, declining rapidly below and above the mean (leptokurtic). Data with low kurtosis (β <3) tend to have a low rise around the mean (platykurtic). Gaussian distribution β = 3 (mesokurtic).

Kurtosis then is correlated to a high degree of variability in either a static or streaming dataset. If an acoustical input is used as a streaming data set then a 1kHz sinusoid would be platykurtic, band-limited pink noise or would be mesokurtic, and grinding brakes would be leptokurtic. Other leptokurtic sounds would include babies screaming, earthquakes and avalanches, or fire alarms mentioned above.

In terms of an expression of impacts, signals with higher temporal kurtosis β(t) consistently caused higher hearing trauma and hair-cell damage than lower kurtosis signals with equal energy with a direct correlation between kurtosis and degree of damage. (Hamernik et.al. 2003).

While these are physiological impacts, at the gross levels of exposure (noise exposures lasted 24 h/day for five days and were interrupted once daily for approximately 20–30 minutes for AEP testing) it would not be a reach to correlate nervous system compromise as a consequence of the exposures regime, although these studies did not examine cortisol levels as a function of kurtosis.

Unfortunately, there is not a direct linear relationship between kurtosis and physiological impacts; rather in studies with chinchillas physiological damage was dependent on a threshold of energy level exposure, where below a certain threshold of equivalent noise exposure (L_{eq}=90 dBA) there was equivalent trauma regardless of whether the exposure was Gaussian or nonGaussian. For exposure levels of Leq>90 dBA nonGaussian noise produced increased trauma relative to Gaussian noise (Qui et.al 2006).

Given that there is a correlation between kurtosis and antagonistic or anxiety-producing characteristics of sound as well as a correlation between kurtosis and hearing trauma, we believe that a kurtosis metric would be useful in predicting aversive responses and potential for physiological damage to humans and other animals from sound exposure.

Methods

As of this writing the project is still in development. It is being developed on a National Instruments "LabView" virtual instruments platform which takes data channels from digitized analog inputs and facilitates conforming the data channels into computer processing channels which can be further manipulated for various channel interactions, control, and displays. We are using this software platform in conjunction with a National Instruments "Sound and Vibration Toolkit" which includes a suite of useful signal processing tools such as input processing associated with common acoustical and vector sensors, and sound analysis tools such as a Fast Fourier Transform analysis. Through capture, gain, and filter building blocks data can be routed into "real time" processing and displays, or stored in various arrays for time-dependent analysis.

For input conditioning we are using a National Instruments brand mdl.# "NI PXI-1031" PXI bus chassis containing a mdl.# "NI PXI-8101" Celeron 575 2.0 GHz Controller and operating system and a mdl.# NI PXI-4461, two channel signal conditioning amplifier and 24 Bit, Analog to Digital converter with a sample rate of 204.8 kS/s.

After calibrating the gain of the input channel the data is sent to a Fast Fourier Transform (FFT) analysis tool which drops the entire signal across 33x1/3 octave filter bins which are windowed though a Hanning window. The output of each of the filter bins is placed into an array as a dataset to evaluate the "instantaneous" frequency kurtosis $\beta(f)$ of the signal at each sample time t_s of the system.

The amplitude numeric of each bin is also placed into an averaging array so that each bin average can be analyzed over a time interval i across the bin query frequency f_Q - which is related to the bin center frequency "f" by:

$$f_Q = \left(\frac{1}{n} \sum_{i=1/f}^{n} f \right)$$

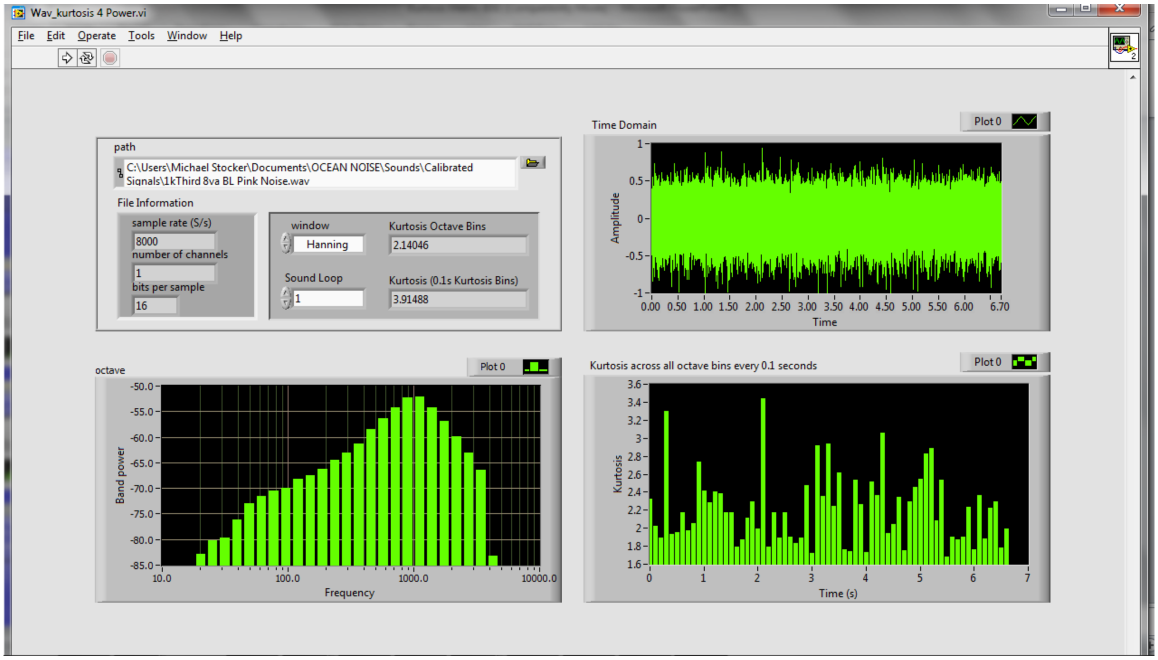
The sample time t_s of the analysis is associated with the low frequency cutoff f_L of the system bandwidth by being higher than twice the lowest required frequency. The sampling frequency f_s of the system is greater than twice the highest required signal frequency f_H so that the bandwidth of the system is defined by:

$$t_s > 2 * f_L \text{ and } f_s > 2 * f_H$$

The average output of each bin is sent to an array and analyzed over the cumulative time window "T" typically one second to yield signal kurtosis in the time domain $\beta(t)$

The input of the system is fed directly to a screen which displays the signal in a time-spectral "waterfall" graphic based on a 2 Hz - 50 kHz FFT analysis with the "X" axis representing frequency, the "Y" axis representing amplitude displayed across a 1 second time window on the "Z" axis with a query rate of 2ms, yielding a graphic that gives a visual representation of the signal variability.

The instrument has also been adapted to display (as selected) other common noise exposure metrics such as broad-band RMS level, maximum instantaneous peak level, and Sound Exposure Level (SEL) to allow for use of the kurtosis metric in conjunction with established noise exposure standards.



Working demonstration of the “Kurtosis Metric” development platform can also be seen online here: http://ocr.org/portfolio/kurtosis/

Discussion

As this instrument is still in development as of this writing we have not been able to do much more than subjective testing on the concept – substantiated by the literature. We do believe that using the kurtosis metric will increase our understanding of how and why some sounds are obnoxious and others are not. We have yet to determine if the level dependence (Qui et.al 2006) is due to physiological constraints or if there is some linear correlation to trauma, kurtosis, and signal amplitude.

As the behavioral and physiological significance of signal kurtosis is explored in the marine environment it may allow us to tailor nose exposure regulations to more accurately reflect the impacts of noise exposure on marine animals. The kurtosis metric can also be used both in designing service signals such as surveillance and communication sonars that are less antagonistic.

Citations:

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