Damage Potential Index: A single numeric expression for noise exposure impacts?

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Abstract

Regulatory noise exposure thresholds are currently based exclusively on exposure amplitude. These thresholds were only recently bracketed in the frequency domain by auditory bands of marine mammals in a set of “M weighting” curves. While these curves are an improvement on understanding and applying regulatory thresholds for “Level B” behavioral disturbance exposures, the suite of regulatory guidelines still falls short of expressing actual damage or disruption potential of any particular noise exposure.

A correlation between signal kurtosis (of amplitude variability over time) and hearing damage has been well established – with overall signal amplitude remaining an important variable. Understanding that regulators prefer single numeric “go/no go” thresholds has likely been a factor in not adopting any more nuanced expressions of exposure damage potential. We are proposing a single numeric that integrates both amplitude and kurtosis in the time/frequency domain as a “damage potential index” which would more accurately express the impacts of a disturbing or damaging sound.

Kurtosis as a predictor of noise impacts

One clear predictor of stressful sound is their “unpredictability,” or variability over time. This can be expressed in amplitude variability, and amplitude/frequency variability. A statistical expression of this is “Kurtosis,” (β) which 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.

$$\beta = \frac{1}{N}\sum_{\infty}^{N}\left(\frac{X_i - \overline{X}}{S}\right)^4$$

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.

It has been established that in equal-energy settings, high kurtosis signals are correlated to higher physiological impacts, as well as behavioral disruptions, so it stands to reason that this metric should be considered in the context of noise exposure guidelines. But one of the difficulties in applying a kurtosis dimension to exposure regulatory guidelines is that kurtosis is only an indicator of sound quality, without being indexed to exposure amplitude, which is also correlated to physiological damage and behavioral disruption.

Sound pressure kurtosis, then is:

$$\beta = \frac{\mu_4}{{\mu_2}^2}, \text{where } \mu_4 = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[p(t) - \bar{p}]^4\, dt$$

μ_2 and p^{-} are sound pressure variance and mean sound pressure, respectively, in the same time interval.

Wavelet Analysis

Wavelets are mathematical functions used to examine data in the time-frequency domain by cutting the data up and examining them in scalable units. This allows for a scaled analysis of the signal while dis-including noise. Wavelets also allow for signal analysis without distorting the input signals (FFT steep filters create a lot of spurious side-band information).

Continuous Wavelet Transform (CWT) decomposes a signal *f(t)* in the time-frequency domain and is defined as:

$$W(a,b) = \int_{-\infty}^{\infty} f(t)\frac{1}{\sqrt{a}}\,\psi\left(\frac{t-b}{a}\right)dt$$

Where *ψ(t)* is the wavelet kernel function along with the continuous scaling parameter *a* and the time shifting parameter *b*. *W(a,b)* refers to the CWT coefficient. The procedure involves adopting an prototype wavelet function, or “mother wavelet” informed by the subject signal.

Temporal analysis is performed with a contracted, high-frequency version of the prototype wavelet, while frequency analysis is performed with a dilated, low-frequency version of the same wavelet. Because the original signal or function can be represented in terms of a wavelet expansion (using coefficients in a linear combination of the wavelet functions), data operations can be performed using just the corresponding wavelet coefficients.

A kurtosis integral

While Kurtosis is a good predictor of noise impacts, it is energy independent, and thus can’t be used exclusively as a predictor of noise impacts. But we are proposing that it should be used as an integral of signal amplitude to derive a more accurate representation of **characteristic** noise impacts to express a **“damage potential index.”**

$$L'_{Meq} = L_{Meq} + \lambda_{Log10}\left(\frac{\beta}{\beta G}\right)$$

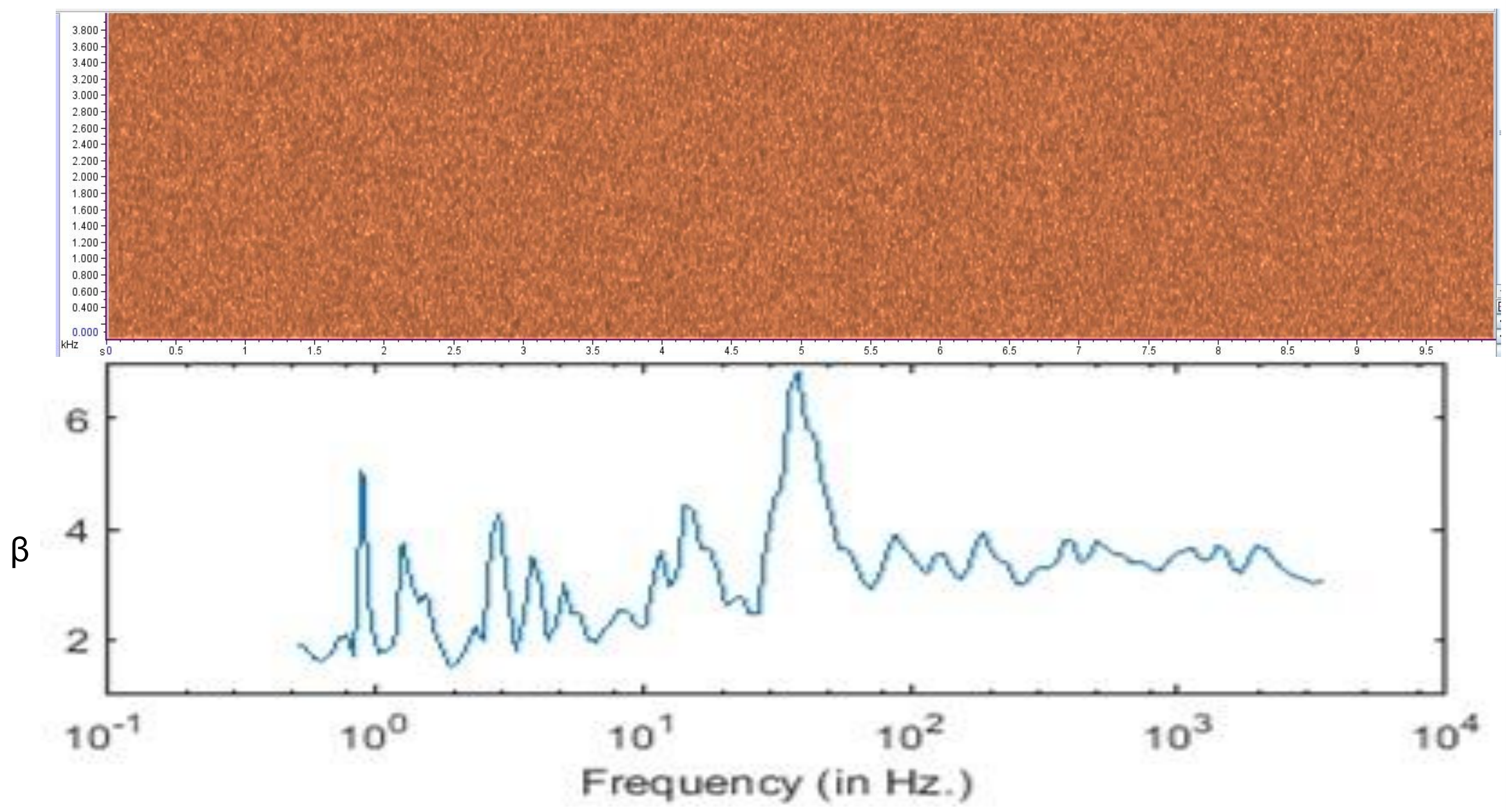
Where:
L'_{Meq} is the kurtosis corrected L_{Meq} “M derived equivalent exposure level”
λ is a positive constant to be determined from dose-response correlation studies,
β is the signal exposure kurtosis, and
β_G is the kurtosis of Gaussian noise (typically 3)

The undetermined factor *λ* can be derived from the numerous studies of kurtosis-correlated behavioral disruptions, temporary (TTS) and permanent threshold shift (PTS) in marine mammals exposed to various noises.

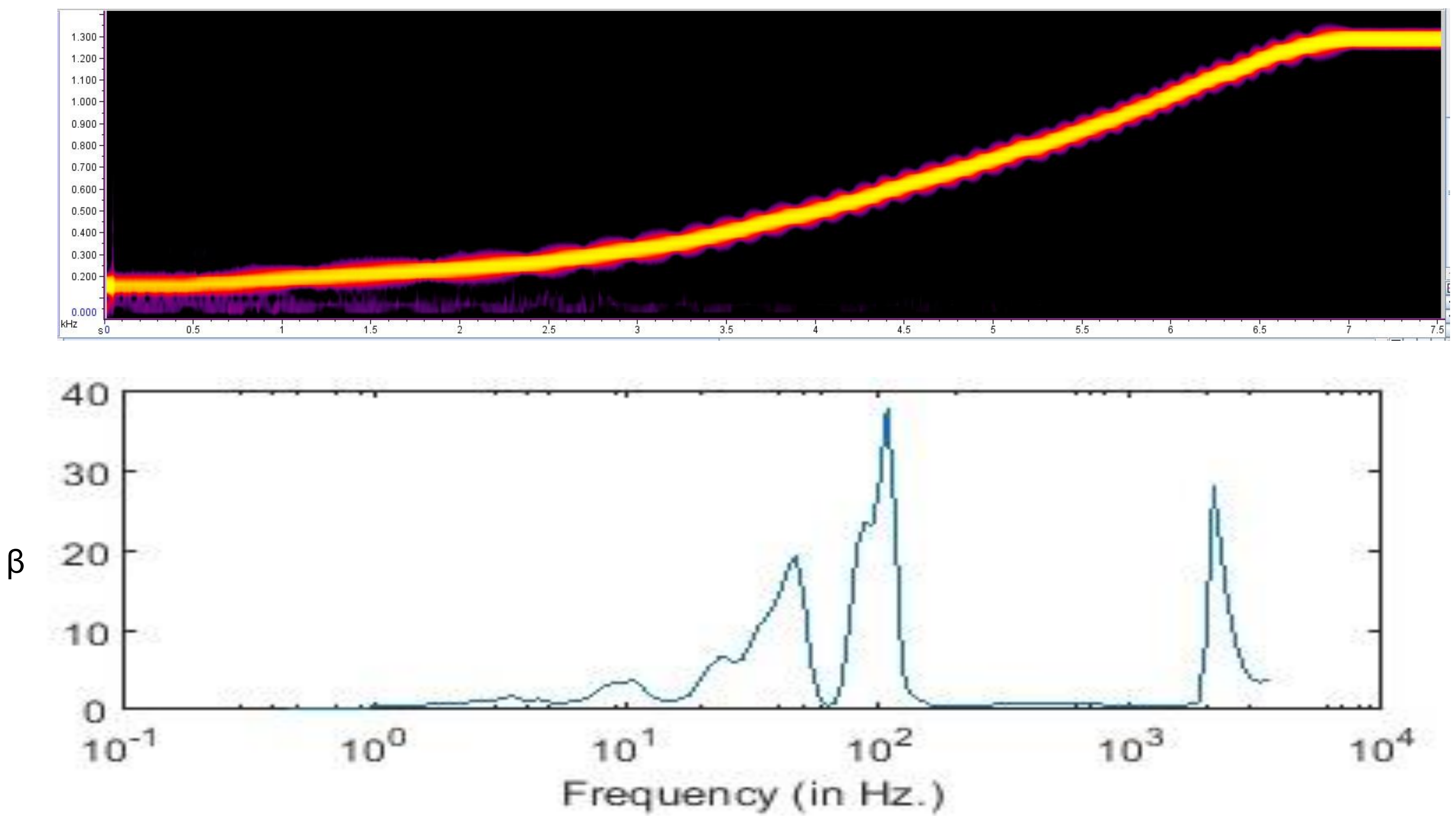
Some results

The following graphics are four spectrograms/histograms of signals at equivalent energy densities:

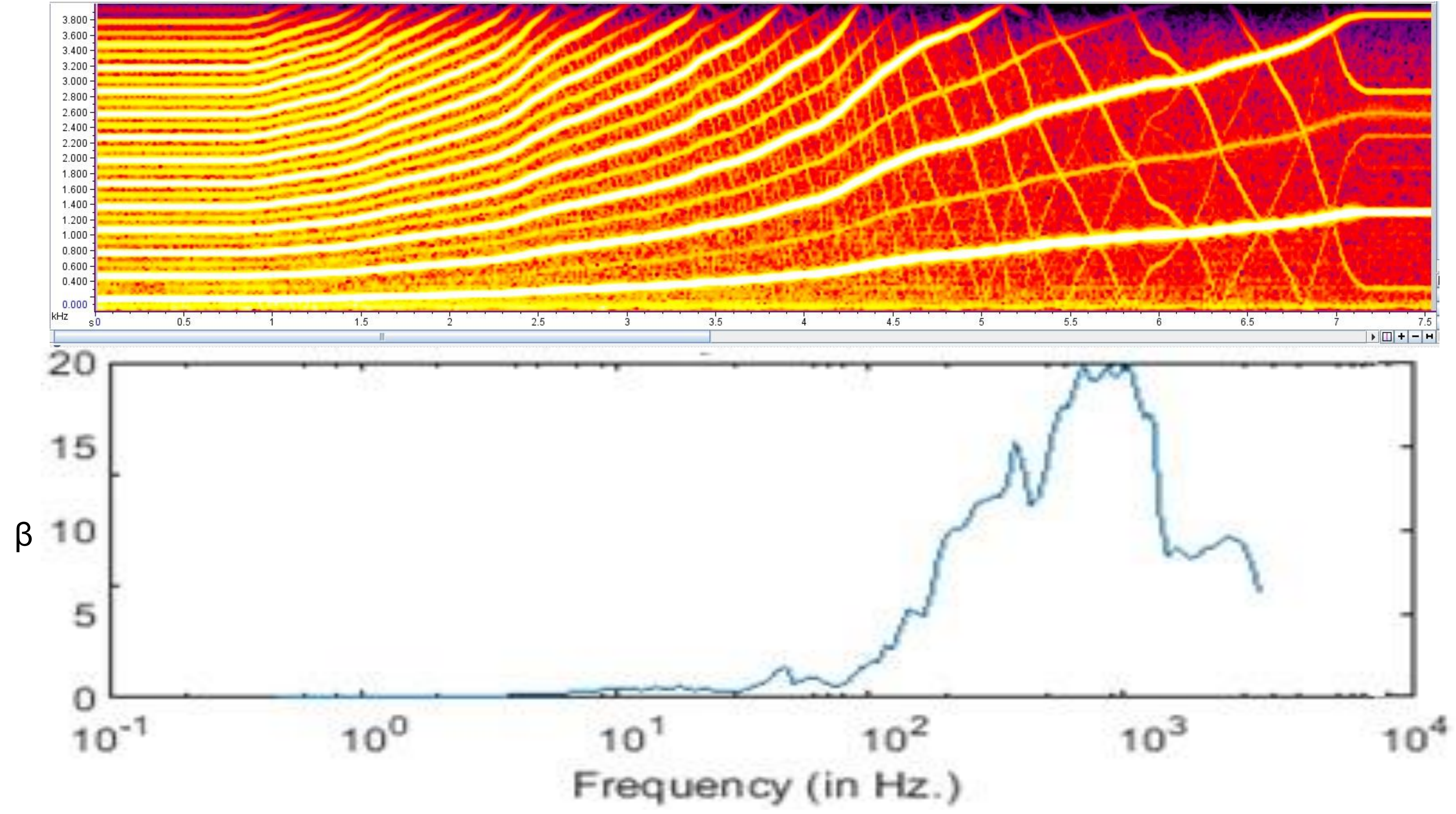
Gaussian Noise



Swept Sine Wave



Swept Square Wave



Audio Frequency Shift Key (AFSK) Signal