**REVIEW OF THE MEASUREMENTS OF SOUND DEGRADATION AND ATTENUATION**

**NOISE**

Background Noise (Bn) is the sound pressure level (SPL) conformed from the value obtained by a root mean square (RMS) of the amplitude of the signal within a given time window and frequency range (Merchant *et al.* 2014).

**SIGNAL to NOISE RATIO**

Signal-to-Noise Ratio has a clear consensus in the definition and formula. It is calculated as SNR = 10log((Ey -Bn)/Bn), where Ey is the ratio of the energy of the test sound. Following the definition of Hardt & Benedict, 2020, this ratio evaluates how much of the energy from the source signal stand out from the energy of the background noise (Dabelsteen, 2002; Holland *et al*. 2002; Lampe *et al*. 2004; Mathevon *et al*. 2005; Darden *et al*. 2008; Barker *et al*. 2009; Mockford *et al*. 2011; Rek, 2013; Vargas-Castro *et al*. 2017; Niederhauser *et al*. 2018).To obtain this measure in SIGPRO, firstly the Bn must be set up, most authors use a duration of one second. Then by cross-correlation of the waveforms, both sounds are aligned and Ey is calculated, and the formula SNR = 10log((Ey -Bn)/Bn) is automatically computed (Dabelsteen *et al*. 1993; Holland *et al*. 1998; Blumenrath & Dabelsteen, 2004; Sabatini *et al*. 2012). This procedure also applies to the calculation of this variable in MATLAB (Stimpert, *et al*. 2020).

**TAIL to SIGNAL RATIO**

Continuing with measures that involve energy changes, Tail-to-Signal Ratio (TSR) measures the amount of energy in the reverberations after the time frame of the source signal, to understand the persistence of the energy of the source signal (Lampe *et al*. 2004; Darden *et al*. 2008; Barker *et al*. 2009; Rek, 2013; Hardt & Benedict, 2020). In the meaning of TSR, multiple authors also include the amount of the signal is elongated by the tail of the tails, thus also reporting those values (Mathevon *et al*. 2005; Nemeth *et al*. 2006; Mockford *et al*. 2011; Sabatini *et al*. 2012; Niederhauser, *et al*. 2018). Nevertheless, multiple studies determine a standard length to measure TSR (*e.g*. Niederhauser *et al*. 2018).

This variable is also consistent in the formula used in literature as SNR: TSR = 10 log((Et − Bn)/(Ey − Bn)), where Et is the ratio of the energy of the tail echoes (Dabelsteen, 2002; Rek, 2013). Mostly to obtain this measure SIGPRO is used, in which firstly the Bn must be set up, most authors use a duration of one second (Blumenrath, *et al*. 2004). Then by cross-correlation of the waveforms, both sounds are aligned, and then the tail is measured using time by backward integration, starting from the end till the point in the recording where the sound disappears in the Bn (Nemeth *et al*. 2006; Rek, 2013). Still from the four principal variables of attenuation and degradation, TSR is the least used, and part of it may be almost exclusivity has been analyzed in SIGPRO, with only a few studies utilizing SIGNAL (Slabbekoorn *et al*. 2007; Tobias *et al*. 2010; Hardt & Benedict, 2020).

RTD

A byproduct of the calculation of the TSR is a variable that multiple authors name as the rate of tail energy decline (RTD) and it represents the tail distribution of energy in quartiles (i.e. 75%, 50%, and 25%) (Blumenrath & Dabelsteen, 2004; Rek, 2013).

**BLUR RATIO**

We describe the Blur Ratio (BR) as the distortion in the amplitude envelopes in the time dimension between the model and the observation sound, without taking into account the attenuation by normalization of the energy of the amplitude envelopes to 1. In a recent review made by Hardt & Benedict, 2020, their consensus of the definition of BR is the ratio of the energy of the observation model (Ex) to the energy of the model (Ey), by also taking account of the energy of Bn: BR = Ex/(Ey – Bn). However, in the literature, there are multiple definitions, one of the first definitions of BR is the distortion of the patterns of the frequency and amplitude over time. Calculated as the product of the energy of the observation signal and the energy of the model signal (Dabelsteen *et al*. 1993 and Holland *et al* 1998; Sabatini *et al*. 2012). However, a clearer meaning in the literature of BR is the amount of time distortion and frequency-dependent attenuation between the aligned amplitude functions of the observation, model signals, and accounting for the Signal to Noise Ratio (SNR) (Lampe *et al*. 2004; Blumenrath & Dabelsteen, 2004; Barker *et al*. 2009; Vargas-Castro *et al.* 2017; Niederhauser *et al*. 2018).

This ratio (BR) has been almost exclusively calculated utilizing SIGPRO with the formula of BR=ExAF/EyAF. First, they align the amplitude envelopes (AF) obtained by Hilbert transformations by a cross-correlation between them. In this position, they determine the energy (SE) and the ratio difference between the energy of the signals (XEAF). The noise effect is accounted for when the values of SNR are below 20 dBs by the calculation of nonbiased ExAF and EyAF, combining the signal AF and Bn in a nonlinear manner as expressed in the methodology of DIGSIG (the predecessor of SIGPRO) (Holland *et al* 1998; Dabelsteen, 2002; Holland *et al*. 2002; Mathevon, *et al*. 2005; Mockford et al. 2011; Vargas-Castro *et al.* 2017). The formula proposed in SIGPRO has been also previously used in one other study utilizing MATLAB by Mercado III *et al*. 2007. Here we employ it in a more streamlined function in R.

**ATTENUATION**

To understand the attenuation measurements, the theoretical definition of attenuation is key and is expressed as the maximum distances within the threshold of Signal to Noise Ratio necessary for discrimination from the receiver (Nemeth & Brumm, 2010; Hardt & Benedict, 2020). This can be expressed as , which is based on Marten & Marler, 1977, and further elaborated by Dooling & Popper, 2007. In this formula, D0 is the model signal and Dcmax is the theoretical maximum communication distance, EA is the excess attenuation caused by spherical spreading (Nemeth & Brumm, 2010). Although in practice, there are two methods 1) measure the ratio in dB of the differences in SPL of the model and observed sound, reported as the observation divided by the model sound or 2) the maximum cross-correlation coefficient between amplitude envelopes of the model and observed sound (Marten & Marler, 1977; Date & Lemon, 1993; Tobias *et al*. 2010; Hardt & Benedict, 2020). In the literature, the values of attenuation by measuring the difference in values of SLP from both signals have been analyzed in MATLAB and SIGNAL by Mercado III *et al*. 2007 and Tobias *et al*. 2010. Even though more recently, a third method was calculated by Garcia Arasco *et al*. 2022, in the R package waRbler. In which the attenuation is the product of the peak amplitude of the observed signal divided by the mean Bn from both silent sections next to the observed signal.

**EXCESS ATTENUATION**

We determine Excess Attenuation (EA) as the extra amount of attenuation from the predicted loss of amplitude by distance as a result of spherical spreading and atmospheric absorption (-6 dBs). We found that almost all definitions in the literature arrive at the same consensus as Hardt & Benedict, 2020, that EA measures the attenuation in excess by normal physical processes such as atmospheric absorption and spherical spreading. However, the formula from this variable has multiple iterations, the most used is calculated as EA = -20log(Kaf) -A, where Kaf is a constant product of the mean difference between amplitude envelopes of the model and observation signal and A is 6 dB by doubling the distance between the microphone and speaker (Holland, *et al*. 2002; Blumenrath, *et al*. 2004; Lampe *et al*. 2004; Mathevon *et al*. 2005; Nemeth *et al*. 2006; Barker *et al*. 2009; Mockford, *et al*. 2011; Sabatini *et al*. 2012; Vargas-Castro *et al*. 2017; Niederhauser *et al*. 2018). However, also in Hardt & Benedict, 2020 they recommend a different iteration of the formula where EA = ls -20log10k(r) – A, where ls is the amplitude of the model signal, but we propose a change into the difference in amplitude from the model and observation signal, and they take more into account the spherical absorption by establishing K as the constant of −10log10(4π) r is the distance in meters, and A is the product of the equation prosed by the IOS 9613–1:1993 (Mouterde *et al*. 2014). Additionally, there have been other attempts to determine the EA formula as the simplification made by Marten & Marler, 1977, where they don't take into consideration the atmospheric attenuation, EA= L1-L2-20log(d2/d1), where L1 and L2 represent the model and observed signal SPL respectively, and d1 and d2 are the distances from microphone to speaker in meters of the model and observed signal correspondingly (Sugiura *et al*. 2006). As BR,here we propose a more streamlined function in R.

EA mainly has been calculated utilizing SIGPRO following the formula of EA = -20log(Kaf) -A. Following the same steps as BR, first, they align the amplitude envelopes (AF) obtained by Hilbert transformations by a cross-correlation between them (Holland *et al* 1998; Mockford *et al*. 2011). Then they obtain the mean difference between amplitude envelopes of the model and the observation signal, (Kaf). As BR, the noise effect is accounted for in Kaf when the values of SNR are below 20 dBs, combining the signal amplitude of AF and Bn in a nonlinear manner as expressed in the methodology of DIGSIG (the predecessor of SIGPRO) (Dabelsteen *et al*. 1993; Holland *et al* 1998; Holland *et al*. 2002; Vargas-Castro *et al*. 2017). Only one paper proceeds to alter the SIGPRO formula, EA = g − 20 log(d/10) −20log(k), where g is the combined microphones gains in dB from the model and the observation sounds and d is the distance from the microphone to the speaker in meters (Darden, *et al*. 2008). Nevertheless, this variable has been calculated not only in SIGPRO, for example in the research from Mouterde *et al*. 2014, utilizing custom-made Matlab scripts, where they calculated EA = ls -20log10k(r) – A, where they utilize spectral envelopes (SF) to obtain ls and A is obtained from the equations from the International Organization for Standardization (ISO 9613–1:1993).

**OTHER MEASUREMENTS**

DIFFERENCES IN MODULATION POWER SPECTRA

The Modulation Power Spectra (MPA) visualizes the distribution of specific spectral and temporal modulations of sounds (Ranjard *et al*. 2010; Mouterde *et al* 2014). To obtain this graph firstly is necessary to decompose the sound into frequency bands using multiple gaussian filters (the size of them determines the spectral and temporal Nyquist limits of the visualization), obtaining narrow-band signals with time-varying amplitude (AF). Next, a correlation matrix is obtained by cross-correlating each amplitude envelope with itself and all other bands, and the functions are compensated by averaging for all functions with equal frequency bands from the different sources (df). Finally, in the cross-correlation matrix where the function of time delay is the x axis, and frequency band offset as the y axis a two-dimensional Fourier transformation results in the modulation spectrum of the source sounds (Singh & Theunissen, 2003; Mouterde *et al* 2014). The MPA has been graphed in MATLAB

SIGNAL-TO-SIGNAL RATIO

The variable of Signal to Signal is a measure of the distortion between samples of sound and is obtained by dividing the second sample of observation signal by the first sample of observation signal from the same test distance, in this case, this variable was measured in SIGNAL (Tobias *et al*. 2010).

SIGNAL CONSISTENCY

A new measurement is the variable Signal Consistency which measures the attenuation variation of a signal by changes in the propagation of the equal time segments. This measurement is the value of each determined signal minus the standard deviation from the maximum cross-correlation coefficient between the amplitude envelopes of the observation and model signals in each determined segment equal time of the signal (Benedict *et al*. 2021). In this case, this measurement was done in the R package seewave.

SPECTROGRAM DISTORTION

To quantify the acoustic degradation over distance in time and frequency, the variable of Spectrogram Distortion calculates the values of the cross-correlation of the spectrograms from the observation and model signal between different distances (Brown & Handford, 2003; Garcia Arasco *et al*. 2022). The cross correlation between spectrogram was done in the R package WarbleR.

MEAN/MAX AMPLITUDE DIFFERENCE

The Mean/Max Amplitude Difference (MAD) measures the difference between amplitudes of the model and observation signals utilizing the formula: MAD = Ay – Axe – Bn, where Ay is the mean or max amplitude of the model signal, and Axe is the amplitude of the model signal (Hardt & Benedict, 2020).

REVERBERATION INDEX

The Reverberation index determines the amount of energy from reverberation in the silent intervals between two signals. Where the values of the SPL of the signals and the intervals in between are multiplied by their duration. Lastly the conversion to an index occurs, however, the author doesn't explain in great detail how to obtain this and what the values mean (Naguib, 2003).

DECAY RATE

To understand the Decay Rate of the reverberations and how it is affected by distance. Firstly, utilizing filters, the frequency band of the model and test sound utilizing are segmented into ten segments the first two being octave intervals of the signal, then the other eight being half octave intervals of the signal. Subsequently, Amplitude Envelopes of each interval are calculated and finally, those values are reported using a least-squares linear regression (Padgham, 2003).

CHANGES IN MODULATION

Each frequency has a different attenuation and degradation rate, to understand the loss of frequencies (modulation) the variable of Changes in Modulation is reported as a percentage of the bantdwidth loss, and this is calculated as the result of dividing the bandwidth of the observation signal by the bandwidth of the model signal and multiplied by 100 (de La Torre & Snowdon, 2002).

CHANGE IN ENTROPY

The Change of the Wiener entropy is relevant as a transmission measurement as this determines the randomness of the frequencies in a signal (Tchernichovski *et al*. 2000). This has been proven a useful cue for the receptor, and the change of values determines the loss of order in the frequencies of the signal (Hansen *et al*. 2005).

CHANGE IN THE SPECTRAL CONTINUITY

As for the variable for Change of Entropy, the Spectral continuity estimates the Weiner entropy, but it also measures his relationship with the frequency contours across time windows, in which the key difference is that Weiner entropy measures variation in Y axis, and the spectral continuity is on X axis. This can be calculated as where T is the selected threshold for the analysis, in which each frequency (fi) in each time window (ti) has their contours values of duration and frequency range calculated and their difference from the other close time windows (Tchernichovski *et al*. 2000).

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