# Appendix C : Calculation of the sound pressure level L and the geometric $A_{geo}$ and atmospheric $A_{atm}$ attenuations

#### 1. Conversion of raw audio data into sound pressure

The audio files recorded by an ARU consist of raw audio files containing one (mono) or two (stereo) vectors of integers  $w_t$ . By knowing the acquisition parameters as well as the ARU technical specifications, raw audio data can be converted into a calibrated signal, allowing a direct reading of the sound pressure  $p_t$  (Pa) and the experimental sound level  $L_{exp_t}$  (dB SPL) in the temporal domain (Merchant et al., 2015) according to:

(pressure (Pa))  

$$p_t = w_t / 2^{bit} * V_{adc} * 1/10^{(S/20)} * 1/10^{(G/20)}$$
 (C1)  
(decibel (dB SPL re20 µPA at 1 m))  
 $L_{eyn,t} = 20 * \log_{10}(p_t/p_{ref})$ 

 $L_{exp_{-}t} = 20 * \log_{10}(p_t / p_{ref})$  $L_{exp_{-}t} = 20 * \log_{10}(w_t / 2^{bit} * V_{adc}) - S - G + dB_{ref} \quad (C2)$ 

with:

- $dB_{ref}$ , the reference value used for the calibration of the microphone, that is, the decibel value of the reference acoustic pressure  $p_{ref} = 20 \ \mu$ Pa. For SM4,  $dB_{ref} = 94 \ dB$
- V<sub>adc</sub>, the voltage range over which the signal received by the microphone is converted. For SM4, V<sub>adc</sub>= 2V<sub>p-p</sub> with V<sub>p-p</sub> the peak-to-peak voltage, that is, +/- 1V.
- *bit*, the quantization range. For SM4, *bit* = 16 bits.
- S, the microphone sensitivity at 1 kHz. For SM4 default internal microphone, S = -35 dBV
- *G*, the total gain. For SM4, this corresponds to the sum of the preamplifier gain (26 dB) and the variable gain. For older SM4s, the preamplifier gain can be 24 dB.

The acoustic pressure  $p_t$  and the experimental sound level  $L_{exp_t}$  given by Eq. C1 and Eq. C2 are both approximations because the formulae assume an equal sensitivity over the entire microphone frequency response, which is not the case for ARUs, including the SM4. In order to approach the value obtained by a calibrated sound level meter, it is necessary to estimate and flatten the frequency response of the ARU. We estimated the SM4 frequency response in an anechoic chamber using a sound source with a flat frequency response (see Appendix D for the detailed procedure). We applied this frequency correction only when necessary, that is, when a comparison with experimental data acquired with the ARU or a simulation of the effective detection distance by the ARU were performed. The correction is not required to estimate the attenuation of a habitat.

### 2. Sound level estimation

The experimental sound level of the white noise was estimated from the mean power spectral density  $P_{f,r}$  of the sound pressure signal  $p_{t,r}$ , which is very similar to Welch's method for spectral density estimation (Welch, 1967). In practice,  $P_{f,r}$  is obtained by: (1) extracting the 22 s section of the audio file corresponding to the ambient sound or the white noise; and (2) computing an average of the  $P_{f,r}$  calculated from the successive non-overlapping frames of 2,048 points apodized by a Hamming window with an amplitude correction. Averaging reduces the contribution of possible brief random events that could increase the signal-to-noise ratio (SNR). Thus, the experimental sound level  $L_{exp_f,r}$  was calculated in the frequency domain following:

$$L_{exp f,r} = 10 * \log_{10}(P_{f,r}/p_{ref}^2)$$
(C3)

with  $L_{exp_f,r}$ , the experimental sound level in dB SPL re20 µPa, which is a function of the frequency f measured at the distance of propagation r.

Due to energy conservation following Parceval's theorem, we worked with the power spectral density (i.e. spectral energy) every time an average or sum was required. In order to simplify the following annotations, henceforth we will not mention the subscripts  $_{f,r}$  for the experimental sound level  $L_{exp}$ .

#### 3. Ambient sound subtraction

The ambient sound is also referred to as background noise in the context of transmission of information. The sound level of the ambient sound Ln was estimated in the same way as the sound level of the white noise (see Eq. C3). Due to overlap between the ambient sound and the white noise, we first subtracted the spectral energy of the ambient sound  $Pn_{f,r}$  from the spectral energy of the propagated signal  $P_{f,r}$  and then kept only the positive values obtained after the subtraction. Thus, the corrected experimental sound level  $L_{exp\_corr}$  corresponding to the experimental sound level  $L_{exp}$  without the contribution of the ambient sound Ln is calculated in the frequency domain as following:

$$L_{exp\_corr} = 10 * \log_{10}((P_{f,r} - Pn_{f,r}) / p_{ref}^{2})$$
(C4)

Negative values were regarded as missing values or *NA* (i.e. not available), as they revealed that the white noise did not emerge above the ambient sound.

#### 4. Geometric attenuation (spreading loss)

We predicted the sound pressure p at the distance r due to the geometric attenuation  $A_{geo}$  as follows:

$$p_{t,r} = p_{t,r0} * (r_0/r)$$
 (time domain)  
$$p_{f,r} = p_{f,r0} * (r_0/r)$$
 (frequency domain)

with  $p_0$  the sound pressure of a spherical wave at the distance  $r_0$ .

We also expressed  $A_{geo}$  in terms of sound level using the following equation, which is independent of frequency:

$$A_{geo} = 20 * \log_{10}(r / r_0) \tag{C5}$$

#### 5. Atmospheric attenuation

We estimated the atmospheric attenuation, which depends on the ambient air temperature (T), the relative humidity (RH) and the barometric pressure (PS), using the following exponential decay law in the frequency domain (ISO 9613-1, 1993; Rossing, 2007):

$$p_{f,r} = p_{f,r0} * \exp(F(T,RH,PS) * f^2 * (r - r_0))$$
(C6)

with F, the function that governs the exponential decay law (Rossing, 2007).

We also expressed  $A_{atm}$  in terms of sound level using the following equation, which is frequencydependent:

$$A_{atm} = 20 * \log_{10}(\exp(F(T,RH,PS) * f^{2} * (r - r_{0})))$$
  

$$A_{atm} = 20 * \log_{10}(\exp(1)) * F(T,RH,PS) * f^{2} * (r - r_{0})$$
  

$$A_{atm} = 8.69 * F(T,RH,PS) * f^{2} * (r - r_{0})$$
(C7)

## References

ISO 9613-1. (1993). *Acoustics—Attenuation of sound during propagation outdoors—Part 1: Calculation of the absorption of sound by the atmosphere*. ISO. <u>https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/01/74/17426.html</u>

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E. (2015). Measuring acoustic habitats. *Methods in Ecology and Evolution*, 6(3), 257–265. https://doi.org/10.1111/2041-210X.12330

Rossing, T. D. (Ed.). (2007). Springer handbook of acoustics. Springer.

Welch, P. (1967). The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. *IEEE Transactions on Audio and Electroacoustics*, *15*(2), 70–73. <u>https://doi.org/10.1109/TAU.1967.1161901</u>