Bird vocalizations and audible Transmission Line (TL) noise: frequency overlap analysis for two 230 kV TLs

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Abstract: - The present work carries out the analysis in the frequency domain of the overlapping and attenuation of the amplitudes of the weighted power of the vocalizations of 24 bird species distributed in the American continent regarding the amplitudes of the audible noise emitted in 10 tower sites of 230 kV Transmission Lines (TL). The study compares noise measurements from 10 towers, selected according to their location conditions, for which audible noise measurements are made using LAeq and LAF50 weightings, and also a time domain recording of the noise emission was taken with a frequency band between 20 Hz and 20 kHz against 24 bird species' vocalizations recordings. These species were selected by criteria of availability of their vocalizations in the HUMBOLDT Institute's repository, geographic location, and threat category, among others. The analysis shows a frequency band of species' vocalizations whose significant power components start at 200 Hz and extend up to 11 kHz, while for the TL noise, the band starts at 0 Hz and extends up to 200 Hz. No significant interfaces or overlaps are found. Subsequently, a methodology for attenuation estimation is proposed based on the overlapping bands and the absolute amplitudes of the weighted powers adjusted to coincident frequency vectors. A component-by-component attenuation comparison is performed, and an attenuation index is calculated. The results for all vocalizations and all noise signals show a mean attenuation of less than 0.5% and attenuation values between 2.53% and 0.51% for quartiles 1 and 3 for the entire range of signals vocalization for all species. According to the results, it is unlikely that communication is being affected or that some type of mechanism associated with the TL noise is being generated in the species studied.

Key-Words: - OHTL Noise, Birdlife, Bird vocalizations, Environmental impacts, Spectral analysis, Spatial discretization techniques, Short time Fourier transform, Spectrogram, Absolute signal power

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1 Introduction

The emission of audible noise outside the conductors of an energized Transmission Line (TL) is a physical phenomenon widely studied, characterized, and parameterized as input to the design process, with legally established limits and mitigation measures validated by environmental authorities. The interaction of this emission of audible noise with birds has generated special interest in recent years, given the possibility that it causes interference with the vocalizations (songs and calls) that birds use in their social and courtship relationships or mating. If this is the case, it would be necessary to determine precisely at what level they interact and accordingly evaluate whether the control measures and established thresholds are sufficient to mitigate some possible effects.

Typical audible noise measurements for TL are made within the legal framework of environmental compliance, with frequency or temporal weighting filters, and their permitted thresholds are expressed in a single equivalent sound pressure value in dB. However, broad unweighted frequency spectra are essential for certain analyses to verify interactions in specific bands.

This work begins with a general review of the theoretical basis of the noise emission of a transmission line and then presents the maximum emission thresholds established by Colombian regulation. A set of 10 LT towers at 230 kV two circuit corridors were selected according to their technical and environmental conditions. The results of the classic measurements with weighting carried out at these sites with a certified sound level meter are presented. To carry out a broad-spectrum analysis, recordings were made in these same places with a conventional recorder with a frequency range of 20 Hz to 20 kHz. The recordings were made at the points determined by resolution 627 of the Ministry of Environment and Sustainable Development and the IEEE 656 standard, selecting for spectral recordings made at the central point between the axis and the outer phase for spectral analysis, the result of a computational simulation with space discretization techniques is presented, which was developed to corroborate the maximum emission of the LT in the absence of external noise sources, using type A weighting functions, demonstrating regulatory compliance.

The selection of 24 bird species present on the American continent continues, bringing together aspects of the availability of recordings of their vocalizations, previous characterization in environmental studies baselines, geographic location, and threat category, among others. The vocalizations are analyzed using time-frequency transforms, spectrograms, and 3D spectrograms with short-time Fourier Transform; this same analysis is performed for the 10 audible noise recordings from the selected tower sites. Results are presented, and some limitations of these analyses are shown.

Finally, a methodology is proposed to estimate the attenuation of vocalizations originating from noise emission signals based on the overlapping bands and the absolute amplitudes of the weighted powers of each signal adjusted to coincident frequency vectors. This analysis presents the results of the interactions found for the 24 bird species with each of the 10 noise signals. In this way, the findings of this study provide critical insights for policymakers and environmental regulators, particularly in the context of Resolution 627 of 2006. By demonstrating minimal overlap between bird vocalizations and TL noise, this research supports the adequacy of current noise emission thresholds in protecting avian biodiversity. However, future studies should explore species-specific sensitivities to ensure comprehensive conservation strategies.

2 Theoretical Bases of Noise Emission by Lts and Its Typical Measurements

Although the audible noise emitted by Transmission Lines is a phenomenon widely studied, characterized, and controlled from the design stages, there are still strong concerns regarding its possible effects and interrelationships with the environment, especially for infrastructure of 230 kV and higher where the emission levels are higher than those of lower voltages, generating greater perception and increasing concern and complaints on the part of the communities [1].

The noise generated by Transmission Lines is mostly caused by two components: broadband noise and hum noise. The first contains several medium-high frequency components, originating from positive polarity “streamers” that generate local changes in air pressure that generate a surrounding propagation wave [1]. The frequency characteristic for this component is given by the randomness of the “strimers” and their pressure waves, which also generate a random phase relationship. The combination of these phenomena generates the typical “cracking,” “frying,” or “hissing,” which is perceived in the vicinity of an energized LT [1]. The frequency spectrum of this component may have a flat or very gently rising characteristic that extends beyond the typical frequencies of audible noise with components as high as several kHZ.

The second hum component is superimposed on the broadband component, with much more limited frequencies whose main component is associated with twice the fundamental frequency (for the TL of interest: 120 Hz). Physically, this component originates in pressure waves caused by the movement of air ions attracted or repelled by the conductor [1]. Here, two polarities of corona discharge are observed, the positive ones triggered when the conductor's surface reaches a field level. Critical positive electricity generates an attraction of electrons to the conductor and, consequently, a repulsion of ions of this element. A similar process is observed in corona-type discharges initiated in negative polarity; in this cycle, it begins with a negative electric field threshold that creates electrons that adhere to air molecules to form negative ions that are repelled and then attracted with the change. Polarity: this movement is a change in the density and pressure of the air, as evidenced twice in each cycle of the transmission frequency, causing a sound pressure wave double the industrial frequency. The pressure variation is not a pure sinusoidal phenomenon; therefore, components of industrial frequency harmonics are also observed.

Climatic conditions can significantly affect the emission magnitudes of the different components of LT noise; for example, in rainy or very high-humidity weather conditions, the broadband component may be predominant [1]. Physically, the broadband component is generated more intensely by positive polarity streamers. On the other hand, the corona effect, evident in the flashes, generates intense ionization and emits a loud hum [1]. In addition to the physical conditions, the band characteristics of the measurement elements affect the result of the broadband component without significantly impacting the pure tones. Ambient noise can strongly affect measurements in the spectrum below 100 Hz. In relation to the distance from the source, the sound pressure levels of the two noise components have a variation that is inversely proportional to the square root of the distance to the TL. For reference, the noise is attenuated by about 3 dB each time the distance to the LT is doubled [1].

Figure. 1, adapted from [1] presents a typical frequency spectrum of the noise emission of an LT in rainy conditions. The pure tones of 60 Hz, 120 Hz, and 240 Hz are clearly observed, the latter attributed to him; also, bandwidth components are observed that increase in intensity and extend above 10 kHz.

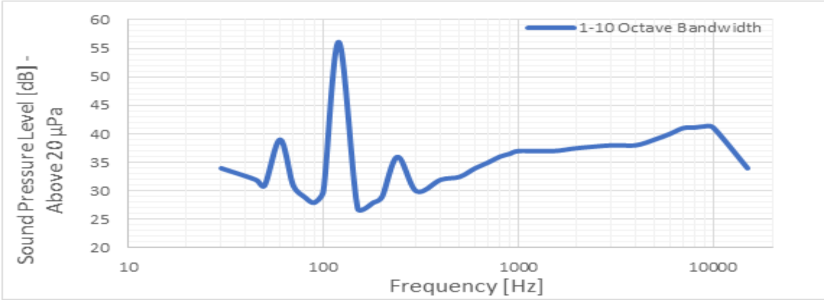

Figure. 1 Frequency spectrum of audible noise emitted by a TL during rain

The two components also differ in the phase correlation of the pressure waves that generate them; for the broadband component, the sources originating in each of the phases of the TL are combined randomly. For its part, the phenomenon that causes the hum has a relationship with the load of the conductor, which is in phase with the voltage; that is, the pressure waves are out of phase by 120°, and when they reach the measurement point, the resulting is a phasor sum of all of them. Thus, the phase would also depend on the time that each incident wave travels from its origin; in addition, the waves reflected by the ground will have a different phase than the component [1]. adapted from [1] presents a diagram of the attenuation of the two noise components with distance. Here, it can be seen how the broadband component, due to its random characteristic, has a homogeneous attenuation, while the hum component has points at which the sum of the waves of the different phases causes the profile to change according to the measurement point.

There are additional elements of the physics of human hearing that are intrinsic to typical noise measurement and evaluation models, one being the wide range of sound pressure variations that the human ear is capable of perceiving. Thus, large noises can be up to a million times higher than the RMS value of very low noise. Taking into account this great sensitivity of the human ear for the representation of sound amplitudes, a compression scale has been developed based on the logarithm of the sound pressure expressed mathematically in decibels (dB). Another element is frequency selectivity, and this organ has greater sensitivity in the mid-range of the audible spectrum (20Hz – 20kHz), where the most relevant information of spoken communication is found, and even more selective in the 200 Hz to 8 kHz band. This characteristic is emulated by noise measurement devices by adjusting the sensitivity of the sound pressure measurement spectrum; for this purpose, some weighted measurement curves are defined: A, B, C, and D. These weightings give greater relevance to frequencies where the ear is more sensitive and reduce those where the ear lowers its sensitivity. In general, the curve most commonly used is Type A, which is normally used for measuring the noise of transmission lines in dB.

2.1 Maximum Audible Noise Emission Thresholds

For the Colombian territory, compliance is mandatory with resolution 627 of 2006 issued by the Ministry of Environment and Sustainable Development, which establishes the national noise emission standard and environmental noise standard for the entire national territory. Chapter II establishes the maximum permissible standards for noise emission levels expressed in Decibels dB(A). For the typical sites where transmission lines are located, the category that applies corresponds to a type D sector: “Suburban or rural area of tranquility and moderate noise.” For this category, a maximum emission standard of 55 dB(A) is defined during the day and 50 dB(A) at night. The daytime and nighttime hours are also determined by the same resolution, such as daytime from 701 to 9:00 p.m. and nighttime from 9:01 p.m. to 7:00 a.m. For transmission lines, these levels must typically be met at the edges of easement strips or safety strips.

2.2 Measurements Based on What is Determined in the Legal Requirements

Within the framework of environmental compliance and in accordance with the environmental instruments or licenses that frame the energy transmission process in Colombia, periodic or specific measurements of audible noise emissions are carried out in accordance with what is determined by resolution 627 of 2006, in general the Measurements are carried out with the weights explained above and thanks to all the prior assurance of the design

Table. I present the LAeq and LAF50 weights measurements for the determined tower sites at 15 m from the LT axis, following the requirements of requirements and the designs of the LTs, it is very rare for a non-compliance with the maximum emission standards to be determined. The resolution 627 of 2006 and IEEE standard 656. As can be seen, the daytime and nighttime emission limits are met quite comfortably in all places.

Table. I Measurements with LAeq and LAF50 weights for the study tower sites

TL Noise Tower	LAeq(dB) - 15 m from axis	LAF50(dB) - 15 m from axis	Measurement schedule
BOGT111B	42	41	daytime
BOGT112B	38.6	38.4	daytime
BOGT142B	34.2	31.3	daytime
BOGT143VB	33	29.5	daytime
BOGT156B	39.5	32.2	daytime
BOGT156VB	37.2	33.4	daytime
BOGV157B	43	33.5	daytime
ParamoT39	41.3	40.8	daytime
RainforestT54BF	44.4	43.8	daytime
RainforestV54BF	51	51	daytime

3 Computational Simulation With Space Discretization Techniques

As part of the proposed study and to complement the analysis of measurements and recordings, a numerical simulation is implemented with space discretization techniques to estimate the propagation of acoustic noise and compliance with maximum emission without external sources; specifically, similar parameters were selected to those present in the RainforestT54BF tower. The simulation is carried out in a two-dimensional domain since, due to the nature of line emission and propagation, there are no changes in sound pressure level in parallel directions. Thus, the simulation is built in two simulation domains of 39x90 m and 20x39 m, used according to the wavelength of the frequencies to be simulated. A plane normal to the TL is established in which 3 conductors are included as noise emission sources, represented by cylinders of radius that tend to zero and infinite length. The Perfectly Matched Layer (PML) approach is used, which generates a layer at the edge of the domains that adds a non-absorbing and non-reflective boundary condition. The physical model of acoustic pressure is based on the solution of the Helmholtz equation; for each frequency of interest, the modeling includes physical parameters of attenuation in the medium with environmental simulation conditions of relative humidity = 53% and temperature 22.72 °C. For case I, phase shifts of 0° upper phase, 120° intermediate phase, and 240° lower phase are assigned; phase shifts are established in the opposite direction for case II.

The Helmholtz equation was selected for its ability to model acoustic wave propagation in complex environments, while the Perfectly Matched Layer (PML) boundary condition minimizes reflections, ensuring accurate simulation results. These choices enhance the generalizability of the findings to other TL configurations and environmental conditions.

The results of the simulations can be seen in Figure. 2. The simulation frequencies, according to the domain dimensions and simulation computational parameters, were 120, 1000, 1258.9, 1584.9, 1995.3, 2511.9, 3162.3, 3981.1, 5011.9, 6309.6, 7943.3, 10000.0 Hz. The results corroborate compliance with the maximum emission thresholds for the different weightings without external noise sources, in accordance with what is expected according to the design criteria.

3.1 Selection of Bird Species for the Study

Interest in analyzing the effects of noise on birds has increased during the last decades (Shannon et al. 2016 [2]), important efforts have been made to carry out experiments both in the laboratory and in the field, which provide information on the way in which that noise can alter the distribution and habitat quality of species (McClure et al. 2013 [3]; Derryberry et al. 2016 [4]), reduce reproductive success (Schroeder et al. 2012 [5]); cause physiological damage (Ryals et al. 1999 [6]; Kaiser et al. 2005 [7]) and cause changes in vocal communication (Slabbekoorn & Peet 2003 [8]; Luther & Derryberry 2012 [9]; Halfwerk & Slabbekoorn 2013 [10]; Ríos-Chelén et al. 2015 [11] Hao & Wörtche 2016 [12]), and how noise generates stress in bird populations.

The hypotheses propose that, in places with high noise levels, some individuals tend to have high hormonal levels of corticosterone compared to individuals who live in rural areas (Cyr & Romero 2009 [13]; Bonier, 2012 [14]) or in some cases it can serve as protection against predators. Nests that are sensitive to noise (Francis et al. 2009 [15]; 2012 [16]), as well as modifying anti-predator alert calls and surveillance patterns (Klett-Mingo et al. 2016 [17]). It can then be argued that the impact of noise on bird communication depends both on the interference in time and space between high noise levels and on the specific acoustic and behavioral characteristics of the species (Slabbekoorn et al. 2012 [18]; Halfwerk & Slabbekoorn 2013 [10]).

In relation to the objective of this research, the review of sources does not provide specific information on the possible impact of noise generated by transmission lines on different species of birds and whether this type of emission can confirm interactions similar to the different hypotheses and results of previous studies of the effects associated with other types of noise. Based on the environmental management plans of the transmission projects, actions are defined to prevent, mitigate, correct, and compensate for the impacts that arise for fauna, reinforcing the relevance of this analysis in the identification of possible residual impacts in order to guarantee the conservation of birdlife in the area of influence of the transmission projects.

The first step is to select a group of species that allows a comparative analysis of the noise spectra of the transmission lines in relation to the sonograms of their vocalizations, seeking to identify possible overlaps in their frequencies.

The process of selecting species and achieving their vocalizations has important restrictions. It would be desirable to structure a large base of sounds classified by type of vocalization, species order, families, threat categories, migration events, or endemic presence structures, among others. However, recording vocalizations is a process that requires great technical expertise and a large number of resources invested, both in time, devices, and personnel. Thus, for this study, it is determined that the first selection condition is the availability of vocalizations. Of the species to be selected to carry out the studies. The vocalizations were analyzed and taken from the sound collection of the HUMBLODT1 institute, where the search for vocalizations of the species of interest was carried out, downloading the available tracks, listening and classification, processing, and analysis. Although the HUMBLODT Institute's bank of vocalizations is very extensive, for the purpose of study, only a few audio tracks fit the required quality parameters and possibility of vocalization isolation.

The second restriction is the prior knowledge and relationship of the TL in operation with birds. For this purpose, species previously studied in the characterization baselines of the environmental studies of the transmission lines or in environmental studies of projects in the licensing process were selected. The endemic or almost endemic characteristic was also an element of relevance and selection, understanding that if there is some type of impact on a species with a focused presence, there

[1] The Instituto de recursos biológicos Alexander von Humboldt is a non-profit civil corporation linked to the Ministry of Environment and Sustainable Development (MADS) of Colombia. Created in 1993 to be the biodiversity research arm of the Environmental System (SINA). Within the framework of the United Nations Convention on Biological Diversity, ratified by Colombia in 1994, the Humboldt Institute generates the knowledge necessary to evaluate the state of biodiversity in Colombia and to make sustainable decisions about it. Additional information can be consulted at http://www.humboldt.org.co/

could be more acute effects; in addition, this element was complemented by the threat category of the species, seeking to include some species at high category (Critically Endangered and Vulnerable) of which a general description is presented in Annex. Finally, the selected species were sought to include a sufficiently wide range of frequencies in their vocalizations to carry out a holistic and significant characterization. For this purpose, some species classified as areas of influence that adequately expanded the frequency bands were included.

The general taxonomic classification of the selected species, common name, the main countries where they have been identified (Bolivia: Bol; Brazil: Bra; Chile: Chi; Colombia: Col; Costa Rica: Cos; Cuba: Cub; Ecuador: Ecu; Guatemala: Gua; Mexico: Méx; Nicaragua: Nic; Panama: Pan; Paraguay: Par; Peru: Per; Puerto Rico: Pue; USA: USA; Venezuela: Ven; South America: Sou, North America: Nor, Europe: Eur, Asia: Ais; Africa: Afr) and the selection characteristic for this study are presented in

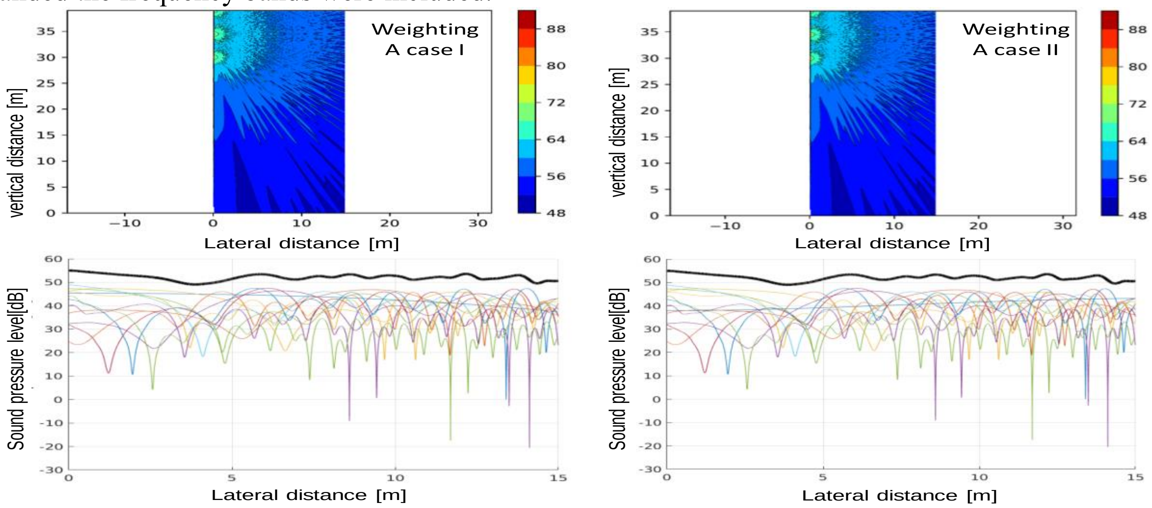

Figure. 2 Side profiles of simulations above Sound pressure levels for type A weighting. Below is the side profile of the Sound Pressure Level for different simulation frequencies, the black line representing the equivalent in type A weighting. Case 1 left, case 2 right

Table. II.

Table II summarizes the selection criteria for each species, including threat status, geographical relevance, and data availability. This approach ensures a representative sample of bird species while addressing ecological and conservation priorities. Here, the same species can have two or more selection characteristics. An additional point that is also highlighted in the table is the number of vocalizations analyzed (# Vowel). It was found that most species had 4 vocalizations for analysis, including different calls and/or songs. However, some species were included with fewer vocalizations available due to the relevance of their ecological conditions or the frequency structure of their vocalization. In this way, sixteen species with 4 vocalizations analyzed were included, four with 3, three with 2, and one with 1 single vocalization, of which 13 are associated with the category of characterized in the baselines, 2 with the level of significant threat, 4 endemic or almost endemic and 6 from the areas of influence.

3.2 Vocalization Analysis Methodology

Once the records of the species' vocalizations determined for study are available, a first analysis of their behavior is carried out in the time-frequency domain. For this step, the team of biologists performs an initial screening of the signals with detailed listening that seeks the specific selection of the intervals of the tracks in which the vocalizations of the analyzed species can be heard and identified as clearly as possible, excluding, to the extent possible, external environmental noises or vocalizations of other birds that may negatively affect the analysis. Due to the type of research proposed and in order to characterize most of the frequency bands of the vocalizations, no type of filtering will be carried out on the signals under study, seeking not to attenuate frequency components that may be relevant within the vocalizations. Analyzed.

Figure. 3

shows the time signals and the respective spectrograms for the species Cardinalis phoeniceus on the left and Ara militaris on the right. Note how selecting the intervals of the signals in which the vocalization of the species under study is identified makes it possible to better characterize the vocalization by reducing the frequencies of environmental noise. This procedure was carried out for each vocalization of the species selected for this research.

Once the soundtracks are adequate, we seek to characterize the vocalizations of each species in the time-frequency and frequency domains to identify the bands in which each emission has its main components. Thus, the frequency spectra of the available vocalizations are studied for each species by analyzing the complete spectrum and focusing on the most significant frequency intervals. For general waveform reference, Figure 5 shows a diagram of the signals in time, frequency, and time-frequency of the vocalizations of the species Catharus minimus; significant components of the spectrum were determined between 1800 and 7500 Hz.

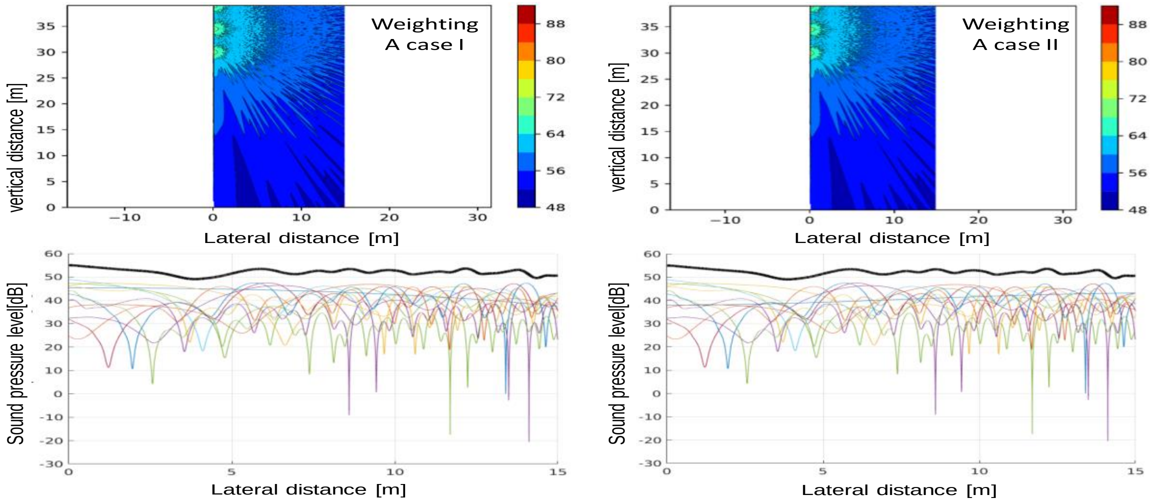

Figure. 2 Side profiles of simulations above Sound pressure levels for type A weighting. Below is the side profile of the Sound Pressure Level for different simulation frequencies, the black line representing the equivalent in type A weighting. Case 1 left, case 2 right

Table. II Bird species and selection characteristic for this study

Order	Family	Species	Common name	Selection feature	Country	# Vocal
Psittaciformes	Psittacidae	*Amazona autumnalis*	Red-lored Parrot	Zone of influence	Col, Ecu, Pan, Cos, Nic, Gua, Mex	4
Psittaciformes	Psittacidae	*Ara ambiguus*	Great Green Macaw	Critically Endangered	Col, Ecu, Pan, Cos, Gua, Nic	2
Psittaciformes	Psittacidae	*Ara militaris*	Military Macaw	Baseline-Vulnerable	Col, Ven, Ecu, Per, Mex, Bol, Par	4
Passeriformes	Passerellidae	*Atlapetes flaviceps*	Yellow-headed Brushfinch	Near Threatened-Endemic	Col	3
Passeriformes	Cardinalidae	*Cardinalis phoeniceus*	Vermilion Cardinal	Baseline - Vulnerable	Col, Ven	4
Passeriformes	Turdidae	*Catharus minimus*	Zorzal Carigrís Gray-cheeked Thrush	Baseline-boreal migratory	Col, Ecu, Pan, Nic, Gua, Mex, USA	4
Passeriformes	Furnariidae	*Clibanornis rufipectus*	Santa Marta Foliage-gleaner	Vulnerable-Endemic	Col	2
Caprimulgiformes	Trochilidae	*Colibri coruscans*	Sparkling Violetear	Baseline	Col, Ecu, Per, Bol, Chi	4

Order	Family	Species	Common name	Selection feature	Country	# Vocal
Passeriformes	Tyrannidae	*Contopus virens*	Eastern Wood-Pewee	Zone of influence	USA, Col, Ven, Ecu, Per, Bol, Pan, Nic, Gua, Mex	4
Piciformes	Capitonidae	*Eubucco richardsoni*	Lemon-throated Barbet	Zone of influence	Col, Ecu, Per, Bol	3
Coraciiformes	Momotidae	*Eumomota superciliosa*	Turquoise-browed Motmot	Baseline	Cos, Nic, Gua	3
Falconiformes	Falconidae	*Falco peregrinus*	Halcon Peregrino Peregrine Falcon	Baseline-boreal migratory	Sou, Nor Eur, Afr, Asi	4
Gruiformes	Rallidae	*Fulica americana*	American Coot	Baseline	Nic, Gua, Mex, USA, Cub, Pue	4
Passeriformes	Icteridae	*Icterus Chrysler*	Yellow-backed Oriole	Zone of influence	Col, Pan, Nic, Gua	4
Pelecaniformes	Ardeidae	*Nyctanassa violacea*	Yellow-crowned Night Heron	Baseline	Col, Ecu, Per, Ven, Nic, Gua, Mex, USA, Cub, Pue, Bra	4
Pelecaniformes	Ardeidae	*Nycticorax nycticorax*	Black-crowned Night Heron	Baseline	Sou, Nor, Eur, Asi	4
Caprimulgiformes	Caprimulgidae	*Nyctidromus albicollis*	Common Pauraque	Baseline	Col, Per, Ecu, Bol, Par, Bra, Ven, Nic, Gua, Mex	4
Psittaciformes	Psittacidae	*Ognorhynchus icterotis*	Yellow-eared Parrot	Vulnerable-Endemic	Col	3
Galliformes	Cracidae	*Ortalis garrula*	Chestnut-winged Chachalaca	Endemic	Col	2
Phoenicopteriformes	Phoenicopteriformes Phoenicopteridae	*Phoenicopterus ruber*	American Flamingo	Baseline	Col, Ven, Cub, Pue, Gua	4
Piciformes	Picidae	*Picumnus cinnamomeus*	Chestnut Piculet	Baseline-Cuasiendemic	Col, Ven	1

Order	Family	Species	Common name	Selection feature	Country	# Vocal
Passeriformes	Turdidae	*Setophaga fusca*	Reinita naranja Blackburnian Warbler	Baseline-boreal migratory	Col, Ecu, Per, Ven, Pan, Nic, Gua, Mex, USA, Cub, Pue	4
Anseriformes	Anatidae	*Spatula discors*	Pato Careto Blue-winged Teal	Zone of influence	Col, Ven, Pan, Gua, Nic, Mex, USA	4
Podicipediformes	Podicipedidae	*Tachybaptus dominicus*	Least Grebe	Zone of influence	Col, Ven, Ecu, Per, Bol, Bra, Pan, Cos, Nic, Gua, Mex	4

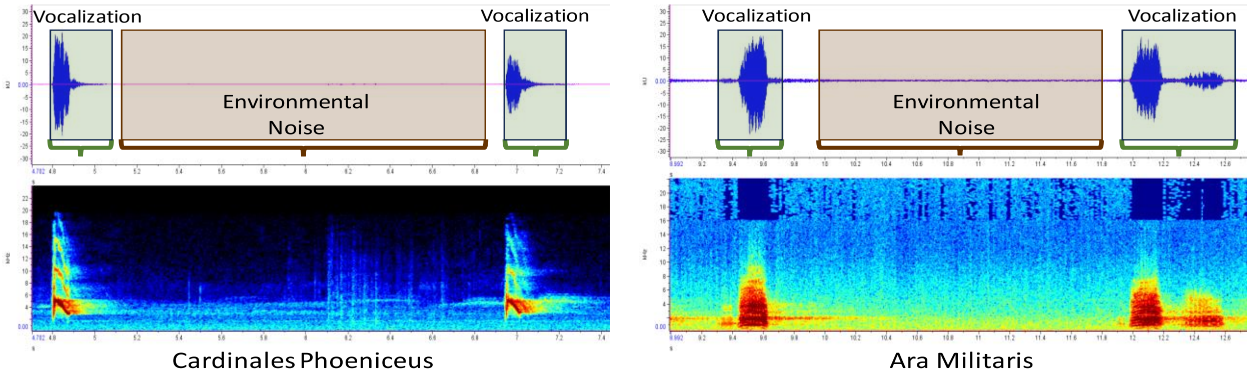

Figure. 3 Signals in time and the respective spectrograms for the species Cardinalis phoeniceus, on the left, and Ara militaris, on the right

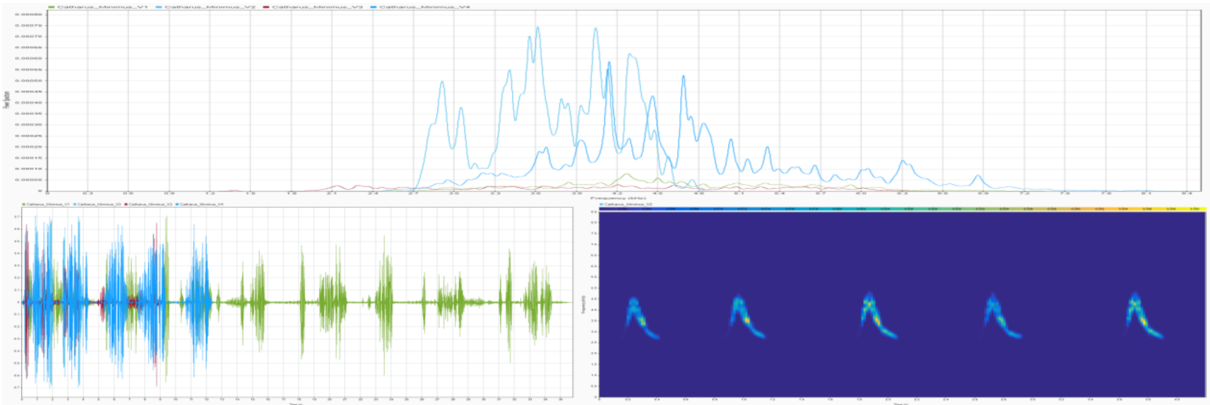

Figure. 4 Frequency spectrum of Catharus minimus vocalizations, bottom left 4 vocalization signals in the time domain, top their respective frequency spectra and bottom right their corresponding spectrograms.

The next step focuses on analyzing the time-frequency behavior of the signals. Here, 2D spectrograms are typically used. However, these representations do not allow analysis with sufficient precision since heat map visualizations can offer results markedly influenced by the susceptibility of the observer and his perception of color intensity, especially at border points. Then, time-frequency-power amplitude spectrum transforms are implemented, which can be presented in a 3D visualization and present adequate resolution and precision for the analysis of interest.

Since these are non-stationary signals, a spectrogram of each signal is sought that shows the temporal evolution of the frequency content it carries. The process begins by dividing the signal into segments of equal lengths, seeking a length adjustment that allows each segment's frequency content to not change significantly or suddenly. The segments may be overlapped with an overlap coefficient determined by the signal's length and the equivalent bandwidth of the spectral window, typically defined here. A Kaiser window is applied to each established segment, and the short-time Fourier transform is then implemented to find its spectrum. Each of the segments is concatenated to form a matrix of transforms; thus, each transform is adjusted and weighted to show the representation of the power of each segment [19] [20].

Figure. 5 presents the spectrogram of the four vocalizations of the Ara militaris species. Using this analysis, it can be seen that the band of interest where the important components of the signal power are found is above 500 Hz and extends up to 5500 Hz, similar to the results found in the frequency spectral analysis. The

Figure. 5 Spectrogram of Ara militaris for 4 vocalizations, with short-time Fourier transform

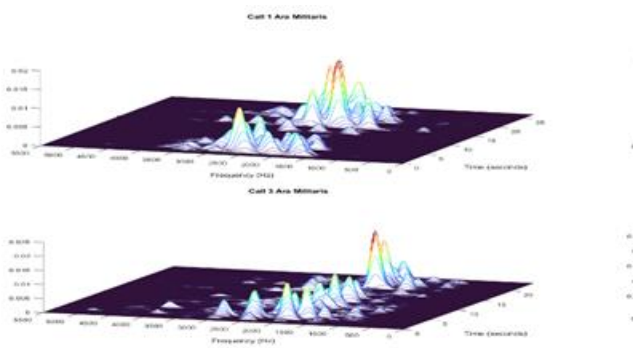

Figure. 6 presents for comparison the analysis of the spectrogram of 4 vocalizations of four different species: Colibri coruscans, Spatula discors, Fulica americana, and Icterius chrysater. The analysis of a wide frequency spectrum is evident; with all species, the spectrum of vocalizations begins at 200 Hz and extends up to 11 kHz. Thus, the short-time Fourier transform (STFT) was applied with a Kaiser window of 512 samples, 50% overlap, and a frequency resolution of 10 Hz. This configuration ensures accurate time-frequency localization while maintaining computational efficiency.

4 Analysis of Noise Measurements on Transmission Lines

Following the analysis process presented for bird songs, we now proceed to develop the same scenario for analyzing noise recordings from Transmission Lines. For these recordings, a similar screening stage was carried out to select intervals in the original signals, avoiding including segments in which the presence of vocalizations of other species, such as dogs, horses, bovines, and unidentified birds, was evident. In addition, avoid intervals in which noises from combustion vehicles or human voices were detected. The Figure. 7 presents the signals in the time domain, the power amplitude spectra in the frequency domain, and the spectrograms using the short-time Fourier transform. The analysis of the different noise signals allows us to reveal components at frequencies close to 120 and 240 Hz, as well as amplitudes of interest close to 60 Hz. Very slight increases in amplitude are observed and sustained between 1 and 11 kHz, and decay suddenly passes the 16 kHz threshold. The harmonics of 300 and 360 Hz are observable, but those of higher frequencies are not perceived. One of the signals presents appreciable amplitudes at 2, 4, 6, 8, and 10 kHz; these may be attributable to external noise that could not be excluded from the tracks. Additionally, very significant components are observed at low frequencies of less than 60 Hz; these components seem to originate from environmental noise, especially wind noise, which is perceptible in some of the recordings and which was impossible to exclude. These last components are not considered an element of uncertainty or deviation in the analysis since, from the characterization of vocalizations presented, it is evident that in bands below 100 Hz, the interaction is virtually null. Regarding short-time Fourier transform spectrograms, it is evident that all power signals have important components that start at frequencies close to 0 Hz and extend up to 200 Hz.

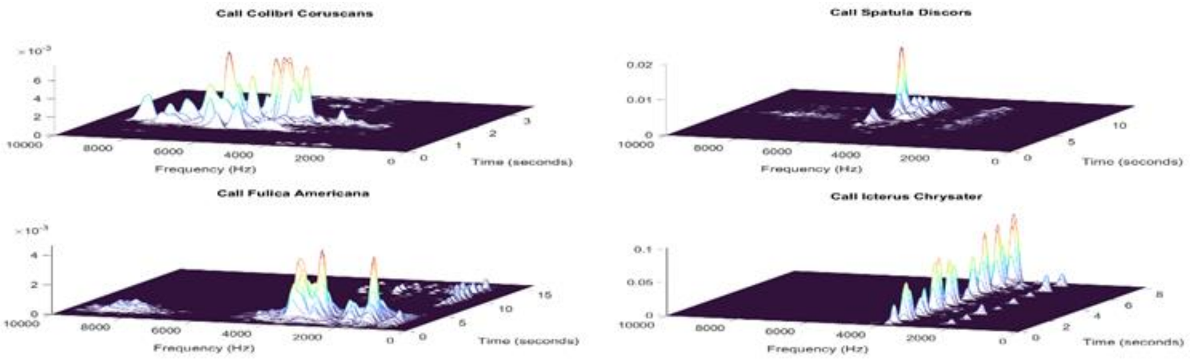

Figure. 5 Spectrogram of Ara militaris for 4 vocalizations, with short-time Fourier transform

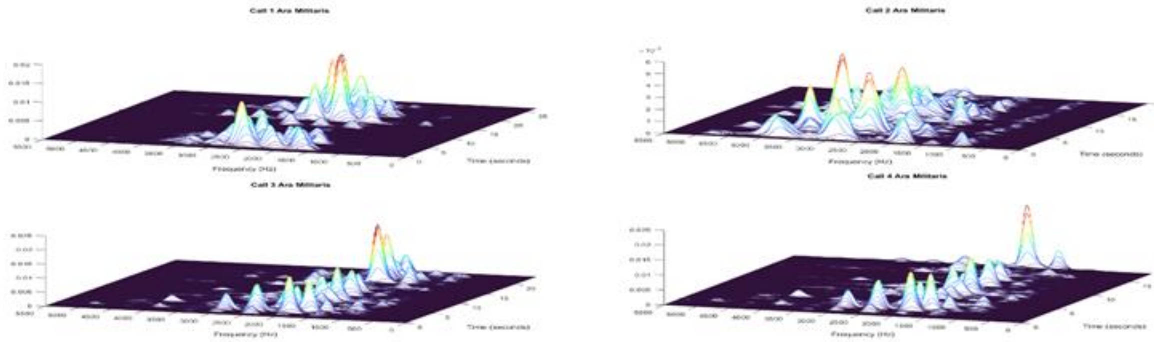

Figure. 6 Spectrogram of Colibri coruscans, Spatula discors, Fulica americana, and Icterius Chrysler vocalizations, with short-time Fourier transform

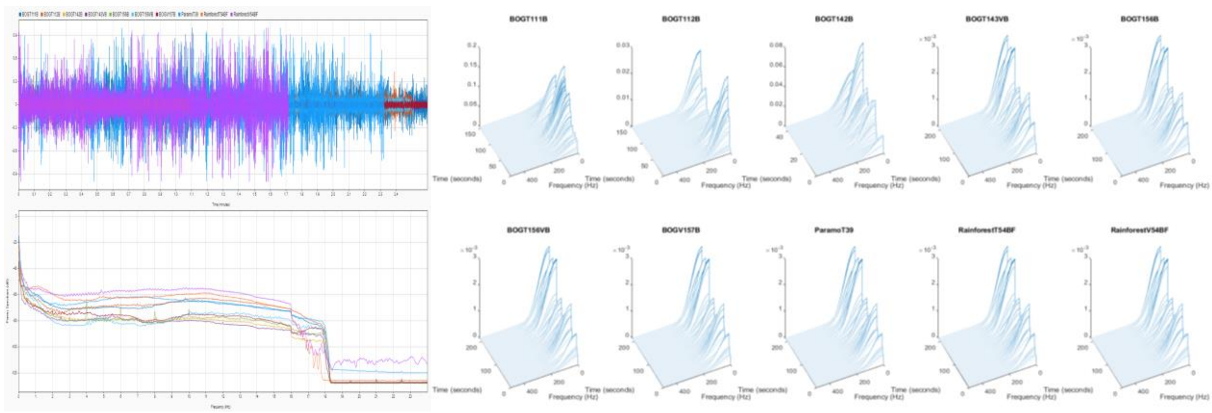

Figure. 7 Signals in time and their respective frequency spectra and spectrogram with short-time Fourier transform for the recorded noise signals.

4.1 Overlay Evaluation Methodology for the Signals Under Study

The 3D time-frequency-power spectral analysis with the short-time Fourier transform contributes to the analysis by clearly showing the frequency bands in which the signal power has the greatest contributions according to its temporal evolution. However, based on this analysis, no important overlap or interaction was identified in any of the vocalization signals of the species with any of the audible noise emissions. Despite its important contribution, this analysis has limitations in carrying out a high-resolution or point-to-point comparison of the frequencies in which overlapping may exist, which may conceal or simply not show these overlapping or interaction bands. Furthermore, the construction and calculation characteristic of the spectrogram that makes it necessary to include analysis windows and band overlap means that the representation includes locally focused intervals, which could again mask the overlap.

To overcome this limitation and achieve a final analysis with greater precision, a methodology of direct comparison of the frequency spectra of the power amplitudes of the vocalization and noise signals, weighted and adjusted, is used. This process allows us to specifically verify the overlap of each frequency in a specific selection interval. However, it is necessary to take into account that when using the signals without any type of filtering, overlaps can be identified in frequency bands that correspond to environmental noise. Present, especially in the interfaces of bands where there is a coincidence of vocalization-noise components.

We start from the concept that the power of a noise signal in the time domain is typically represented by the absolute squares of the signal samples divided by the length of the signal; also, it is typically represented by the square of its RMS amplitude [2. 3]. In the frequency domain using the discrete Fourier transform (DFT), the signal power would be represented by the squares of the absolute values of the DFT amplitudes divided by the number of samples [2] [3].

Taking into account that the specific parameters of the vocalization recording are beyond the control of this research since its source is external institutional repositories, it is impossible to make a direct comparison. Then, a normalization of the power amplitudes of the vocalizations and noise emission must be implemented, for which a weighting process is carried out with the maximum amplitude of the absolute power spectrum of each signal; in this way, a measurement is obtained. The contribution of each amplitude sampled in the spectrum in relation to the maximum amplitude of the signal under study.

An additional problem is the sampling mismatch in the signals at the origin of time and, consequently, their correspondence in frequency, which is again caused by the inability to control the process of recording the vocalizations. Then, with the help of the Nyquist theorem and the time-frequency sampling relationships of the different signals, a coincident frequency vector is calculated and implemented for all vocalizations per species with all the noise emission signals of the TL for the purpose of this analysis, the vector was determined with jumps of 1 Hz. Based on this coincident vector, a component-by-component subtraction of the absolute power amplitudes of the signal of the vocalizations and the signals of each of the noise emissions under study is carried out. The subtraction in each component of the interval of frequency gives a positive value that integrates a decrease in the amplitude of the vocalization signal when it is greater than its corresponding noise signal and is negative when the noise signal has an amplitude greater than that of the vocalization, in the latter case, there is a total attenuation of the vocalization amplitude in that component.

Finally, to estimate with an indicator the attenuation of the components of the noise signal over those of the vocalization at the frequencies where overlapping occurs, a sum of all the absolute values of the amplitudes of the components is generated (note that the negative ones are equivalent to total attenuation of the vocalization and will provide a value of 0) of the attenuated signal and the result is weighted in relation to the sum of all the frequency components of the original power signal of each vocalization. This indicator represents the discrete integral of the total attenuated amplitude relative to the discrete integral of the original signal amplitude for all components. Figure. 8 presents the scheme of the methodological process of constructing the attenuation indicator, and this process is carried out for each vocalization from species 1 to 24 in relation to each noise signal from 1 to 10. The Figure. 9 schematically presents the calculation steps. On the left, the superimposition of all the absolute noise power signals is presented in colors, and in green, the absolute power signals of the 4 vocalizations of the species Colibri coruscant. The detail shows an interaction zone between 120 and 300 Hz at very low amplitudes. On the right is shown the overlay of the attenuated vocalization signal 1 of the same species with the BOGT111B noise signal, in green, superimposed on the weighted absolute power signal of the same unattenuated vocalization, in black. It can be seen that the differences between the attenuated and unattenuated signals are minimal.

Figure. 10 presents the box plots of the results for calculating the attenuation indicator for each vocalization that originates each noise signal, grouped by each species under analysis. For simplicity, the discussion of results is presented with the percentage relationship of the amplitude resulting from the attenuated vocalization in relation to the unattenuated vocalization, which is equivalent to the simple numerical relationship generated by the indicator. The average attenuation indicator for all vocalizations is 99.49%, meaning that the absolute power-weighted signal only attenuates, on average, about 0.5% of its entire frequency amplitude component. Extreme attenuation values between 97% and 93% are observed in less than 2% of the samples, and extremes between 96.5% and 93% are observed in less than 1.5% of the samples. The species that presents the highest attenuation index in its vocalizations is Ortalis garula, where one of the extreme values is close to 93% of the total weighted power signal, but the average value for all their vocalizations is 98.7%. Likewise, it is the species that presents the greatest dispersion. The species that presents the least attenuation in the attenuation index of its vocalizations is Catharus minimus, which is also the one that presents the least dispersions. In relation to the noise signals, the one that generates the greatest attenuations is signal 9 (RainforestV54BF), having a maximum extreme attenuation value of about 93%. The noise signal that presents the least attenuation is signal 3 (BOGT142B). Extreme values of attenuation of the power signals of the vocalizations can be observed between 96% and 93% for three of the signals (BOGT156VB, BOGV157B, and RainforestT54BF) interacting with five species and only for 5 vocalization signals. The attenuation values between quartiles 1-3 for the entire range of vocalization signals of all species are between 97.7% and 99.9%. The total indicator values calculated with the crosses of all vocalizations and all noise signals are 830, which is the universe of statistical analysis. The results obtained indicate an almost marginal attenuation in the absolute power signals of all vocalizations.

5 Conclusions

In an environment in which society is increasingly resistant to the construction of electrical infrastructures and especially LTs at high voltage levels, due, among other reasons, to the growing concern for the preservation of the surrounding ecosystems. It is imperative to broaden the focus of the studies traditionally carried out for the design of these infrastructures, seeking to guarantee the minimum possible impact, not only for people but also for the fauna and flora present in the sites where the electrical systems are located. The fundamental contribution of this work is to deepen the expansion of these horizons of analysis that allow defending, with arguments supported by research, the expansion of electrical infrastructure worldwide, which is the axis of the energy transition required to optimize and make sustainable the supply of energy resources demanded by the planet.

Typical audible noise measurements performed in the framework of environmental compliance for power transmission projects are made with frequency or time-weighted filters, and their results are expressed as a single equivalent sound pressure value in dB. These types of measurements are adequate for the verification of audible noise perceived by the human ear but should be complemented to analyze variables related to wildlife or other non-typical environmental compliance elements. By means of numerical simulations with spatial discretization techniques, some of the noise emission variables can be established to corroborate the variables that are determined and ensured from the design stages. The technical-economic balance is key to their implementation, and under some circumstances, they can complement or even replace direct measurements, providing additional approaches and building new knowledge. For the case study proposed in this research, the results corroborate the compliance with the maximum emission thresholds for the different weightings in the absence of external noise.

According to the review of the state of the art, previous studies of frequency overlapping and attenuation of bird vocalizations due to noise emitted by TL is not a field that has been very developed. In that sense, the results obtained are highly relevant due to their potential for extrapolation to other bird species and the possibility of complementing or reaffirming the actions defined in the framework of the environmental management plans to prevent, mitigate, correct, and compensate for the impacts on the fauna, and to guarantee the conservation of the avifauna in the area of influence of the transmission projects.

The screening and selection of bird vocalization tracks is a relevant element for their frequency analysis, especially in studies like this one in which the application of filters or preprocessing of signals with amplitude modification or modulation can bias the results obtained, the selection of the best quality and clarity tracks contributes to reducing the uncertainty of the analysis and reduces the inclusion of components from other sources that can widely affect the results. The decision not to apply filters in the developed study was key to generating confidence in the results and building an element of contrast for other investigations in which the application of this type of signal processing is decided.

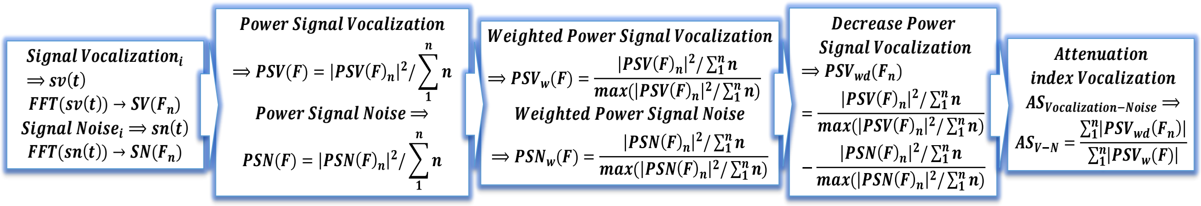

Figure. 8 Outline of the methodological process of construction of the attenuation indicator

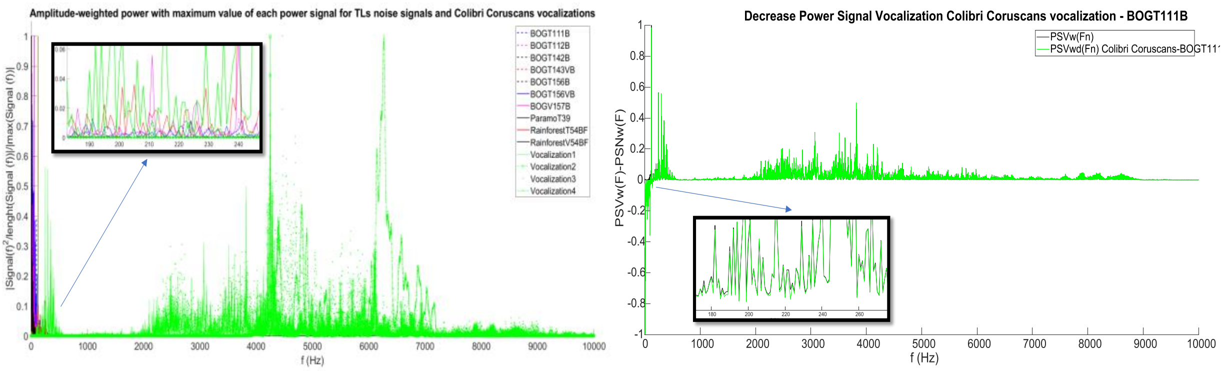

Figure. 9 Graphical representation of the construction of the attenuation indicator

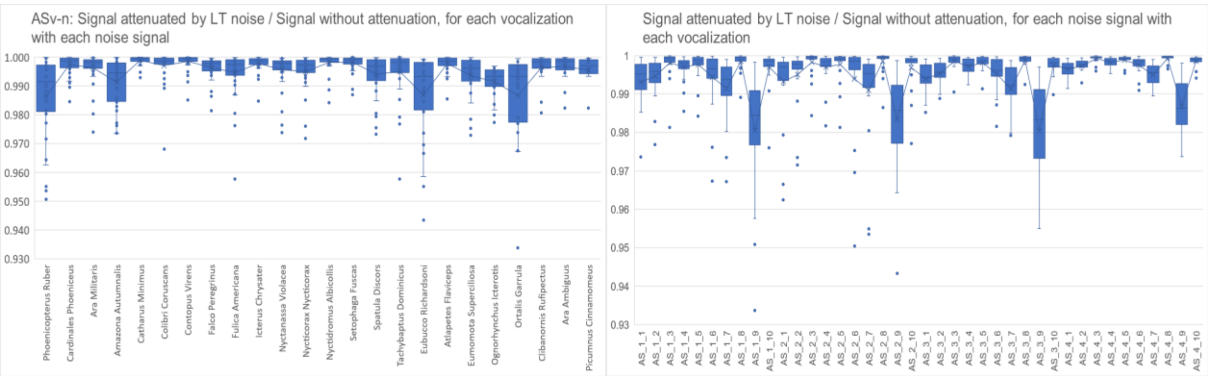

Figure. 10 Results of the calculation of the attenuation indicator for all vocalizations grouped by species on the left and grouped by noise signal on the right

The determination of the conditions for the selection of species is a relevant element in a study like this to avoid biases or biased evaluations. Even with the difficulties of obtaining and classifying vocalizations, it is imperative to include a sufficiently large bank of species in studies like this that provides a sufficiently broad bandwidth for analysis, and that is representative as a whole. This can be as relevant as the number of bird species included.

The time-frequency-power spectral analysis with the short-time Fourier transform contributes important elements to the analysis of vocalization and noise signals, clearly showing the frequency bands in which the signal power has the greatest contributions according to its temporal evolution, overcoming the disadvantages of uncertainty in the reading that has the heat maps of the classical spectrograms. For noise signals, bands of significant amplitude were found at frequencies close to 0 Hz and extending up to 200 Hz; for vocalizations, the band of interest extended from 200 Hz to 11 kHz. However, these techniques do not allow us to identify overlapping or interactions in narrow bands with complete accuracy, especially at interfaces.

The analysis of the different noise signals emitted by the TLs revealed components at frequencies near 120 and 240 Hz, as well as amplitudes of interest near 60 Hz. Very faint increases in amplitude are observed between 1 and 11 kHz and sudden decay past the 16 kHz threshold. Harmonics at 300 and 360 Hz are observable, but those at higher frequencies are not clearly perceived. The presence of significant components at low frequencies below 60 Hz seems to be due to environmental noise, especially wind noise, which is perceptible in some of the recordings. These results corroborated the theoretical assumptions of noise emission by TLs.

The proposed analysis methodology of direct comparison of the frequency spectra of the absolute power amplitudes of the vocalization and noise signals, weighted and adjusted with a homogeneous frequency vector, together with the construction of the attenuation indicator, proved to be a robust technique to determine the possible impact of noise emitted by TLs on the vocalizations of the bird species under study, its level of accuracy and resolution complemented and provided clear and repeatable analysis elements for the audio signals in this and future studies.

The average attenuation indicator for all vocalizations was 99.49%. Extreme attenuation values between 97% and 93% were observed in less than 2% of the samples, and extreme values between 96.5% and 93% in less than 1.5% of the samples. The species that presented the highest attenuation rate in its vocalizations is Ortalis garula, where one of the extreme values is close to 93% of the total weighted power signal, but the average value for all its vocalizations is 98.7%. Extreme values of attenuation of vocalization power signals between 96% and 93% could be observed for three of the signals (BOGT156VB, BOGV157B, and RainforestT54BF) interacting with five species and only for 5 vocalization signals. Attenuation values between quartiles 1-3 for the entire range of vocalization signals for all species are between 97.7% and 99.9%. The total indicator values calculated with the crossovers of all vocalizations and all noise signals are 830, which constituted the universe of the statistical analysis.

The results obtained indicate an almost marginal attenuation in the absolute power signals of all the vocalizations in relation to their total power. The frequency bands in which components interact or overlap between the analyzed vocalizations and the noise emissions are around 200 Hz and extend up to 500 Hz for the significant components. This interval is a very narrow band of the vocalizations in which the phenomenon occurs, as its significant components extend over several kHz. Under these conditions and taking into account the results of the calculated attenuation indicator, it is unlikely that communication is being affected or that some type of compensation mechanism associated with the TL noise is being generated in the species studied. Nevertheless, it is necessary to develop additional studies in this line of research to increase the knowledge base and give greater statistical weight to the conclusions and hypotheses obtained here. In this way, While the study shows minimal frequency overlap, the potential for cumulative effects on bird behavior and reproduction remains an area for further investigation. Future research should explore the long-term impacts of TL noise on species-specific stress levels, mating success, and habitat selection.

As a final remark, While the simulations demonstrate engineering rigor, they are limited by the assumption of uniform environmental conditions. Future studies should incorporate variable humidity and temperature profiles to further enhance the accuracy and generalizability of the results.

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