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NOISE CONTROL FOR A BETTER ENVIRONMENT

Structural Vibrations Induced by Infrasound from Pipelines. Case Studies in the Mountains of the Peruvian Andes

Montano, Walter A.[1]
'Joseph Sauveur' Acoustics Laboratory-ARQUICUST
Luis Clavarino 1227. Gualeguaychu. E2820. Entre Rios, Argentina
Gushiken Uesu, Elena I.[2]
ARQUICUST
Tomás Ramsey 930 #805. Magdalena. 17 Lima. Lima, Peru

ABSTRACT

In the case of low levels of ambient noise, as low as 30 dBA, it is possible that sound radiation from the structure of the houses can be perceived by people. In this Paper, acoustic measurements were made in locations 2600 meters above sea level in the mountains of the Peruvian Andes. The results of the acoustic measurements, made inside and outside of the dwellings subjected to structural vibrations, are presented here. The pumping station and its industrial site are more than 250 meters from the houses, so the vibrations are caused by the mechanical energy that propagates solidly through the ground and from the pipes that carry mining effluents from the mountains down to the valley. As it is well known that the values in dBA do not report the real impact of noise, a direct study of the sound levels and the acceleration of the vibrations had to be conducted. A statistical procedure was developed to identify the anomalous sounds based on percentile sound levels, finding a solution to categorize the impact of low frequency noise and infrasound, and thus improving on the methods proposed in ISO 1996-2: 2017.

Keywords: Infrasound, Structural Vibration, Annoyance
I-INCE Classification of Subject Number: 49

1. INTRODUCTION

There are two big problems when measuring an alleged annoying noise that comes from industry: determining the specific sound level and getting the low-frequency attenuation by using the "A" filter. It has been observed in most of the Noise Protocols around the world that the common practice is using just one SLM at the suspect affected dwelling, but in order to conduct a Legal Acoustics Assessment, this is not enough. It may be a good practice to measure both places simultaneously: at the receiver point and near the noise emitter. This action should manage auditory skills, where low-frequency noise is a health problem.

2. FORENSIC ACOUSTICS FOR ILFN MEASUREMENTS

Both the WHO and the I-INCE [1] warn about the problems of using the dBA as a single descriptor to measure infrasound and low-frequency noise (ILFN); technician

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[1] wmontano@arquicust.com
[2] arquicust@arquicust.com

or untrained persons with no proper training into these particular acoustics problem, they could arrive at mistaken conclusions.

This Paper presents the results of one ILFN assessment by means of Forensic tools applied to environmental acoustic measurements. The reason for this method was because it was not clear whether the noise inside the dwellings was airborne or from the ground; also, there was less certainty if the acoustic emission was from the industrial facility under study. The work was carried out near a sewage treatment plant (the only source of noise/vibration in the area) that is 2,600 meters above sea level. Three SLM were used: one inside the house, another outside the house right above a buried pipeline, and a final one at the fence's plant limit. Also, two Vibrometers were used.

It should be considered that Acoustics for noise measurements is a new branch of Forensic Sciences, and legal noise assessment is intended under Audit activity. Therefore, it is important to get a chain custody to keep the noise data safe, simultaneously using more than one SLM as a way to correlate a sound emission from a specific sound emitter.

The assessment was requested by the Authorities, so it was mandatory to use just dBA measurements. However, in order to do a Forensic Acoustics audit, ISO standards needed to be used for the noise/vibration assessments in order to rule out the alleged annoyance. In order to avoid any future complaints, the study was conducted during continuous 48 hours as follow:

Table 1: Intervals time where the plant was on duty and off duty

Plant on duty	**Plant off duty**	**Plant on duty**
day #1: 9 am - day #2: 5 am	day #2: 5 am to 7 pm	day #2: 7 pm – day #3: 9 am

Fig. 1 shows: (a) instruments in the house, (b) instruments above the buried pipeline.

Figure 1: (a) the indoor and (b) the outdoor monitoring stations

3. ACOUSTICAL INSTRUMENTATION

The acoustical instrumentations used were the following:

- Indoor. Sound level meter analyzer with one-third-octave band, CESVA® instruments, a class 1 SC420® model, it records for each 125 ms (8 samples per second): the time history, $L_{\mathrm{A},T}$, $L_{\mathrm{C},T}$, $L_{\mathrm{Z},T}$, L from10 Hz to 20 kHz, and other descriptors.
- Outdoor. Sound level meter analyzers with one-third-octave band, BSWA® instruments, a class 1 308® model, they record for each 500 ms (2 samples per second): the time history, $L_{\mathrm{A},T}$, $L_{\mathrm{C},T}$, $L_{\mathrm{Z},T}$, L from 6.8 Hz to 20 kHz.

- Vibrometer, CESVA® instruments, a class 1 VC431® model, 500 mV/g triaxial accelerometer AC032® model.
- A class 1 sound calibrator, AIHUA® AWA6223F Multifrequency model.
- Weather meter, a KESTREL® 4500NV.

4. DIRECTIONS OF THE ILFN MEASUREMENTS CONDUCTED

This section is a summary of the empirical method applied in order to keep the work's repeatability and reliability, as well as some specific definitions.

4.1 The ISO series 1996: Measurement and assessment of environmental noise

For years, acousticians have pondered how to eliminate unwanted sound, which is the sound which doesn't belong to the noise source of interest. Some of the most common practices have been:

- To conduct measurements on holidays, because of low levels of urban noise.
- To turn on/off sound sources, though this is impossible to do on industrial sites or with machines under mandatory continuous work orders.

The last actualization of the two parts of ISO 1996 Standard was established with a group of informative instructions, one of which has been resolved by the author previously [4] [5]: "*Record the time history of the noise to be measured and use statistical or other methods to exclude unwanted sound.*" [3]

4.2 The big "Q": How to determine the *specific sound* from a *total sound* file

It is well known that the time interval of the measurement made with a SLM corresponds to the *total sound* level; therefore, it is necessary to extract the *unwanted sound* that does not belong to the *specific sound* from the emitters under study. This problem can be simplified to consider the measurements in two large groups: (i) *Total sound* with a few spurious *unwanted sound* events, and (ii) *Total sound* with many spurious *unwanted sound* events. This Paper presents an empirical method to exclude the *unwanted sound*, by a computer program, considering them outliers.

4.3 A new idea of "basal noise" applied to environmental noise measurement

It is common to find the "basal noise" concept in medical jargon, but it is possible to use it in environmental noise measurements. According to Cambridge on-line dictionary, *basal* shall be understand as "*forming the bottom layer of something*".

For years the statistical L_{A90} (or L_{A95}) level has been used as a notion of *background noise*, or more recently, representative of the *residual sound* value, true only when the emitter is off, and the issue (The big Q) is how to estimate the *specific sound* which is in the *total sound*, so a priori, it seems impossible to do it.

Actually, the *specific sound* level and others noise levels are part of the *total sound*, so the noise from other sources not interested are "mounted" onto the *specific sound*, because they overlap; then it is possible to do an empirical statement: Beneath a statistical value, all sound levels are part of the *specific sound* and other noises impossible to identify, such as faraway noise sources and natural ones (birds, pets, weather, etc.).

The *environmental basal noise* concept appears to be useful for the empirical model presented in this Paper, it means that the *specific sound* should be appraised by a statistical value, for instance, all the sound levels below these reference percentile level belong to *environmental basal noise* (where the *specific sound* is included), on the contrary they will be consider as outliers.

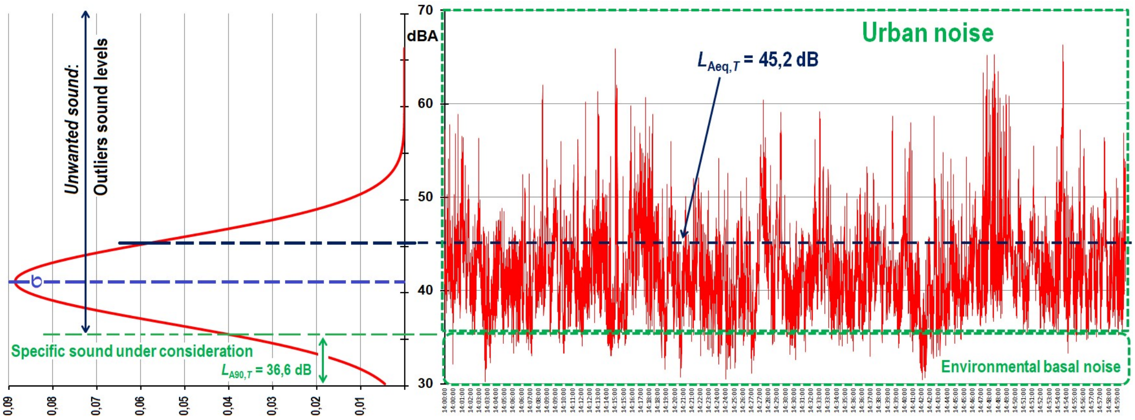
4.4 The “unwanted sound” as outlier sound events which need to be extracted

Fig. 1 shows the L_A time-history sound level each 125 ms like dots, instead of "seeing" it as a continuous line, the 60-minute interval between 6 pm and 7 pm, with a working plant. The noise emissions from the industrial facility under consideration are steady, so one can assume that the *environmental basal noise* (including the *specific sound*) is beneath a statistical value noise level.

In order to explain the inferences, Fig. 1 shows the normal distribution curve of the measurement but rotated, because in this way it’s easy to see its positive skewness. It can be observed that there is a concentration of sound levels below L_{A90} (36.6 dBA), that should be appraised as the *specific sound*, so for statistical reasons if it is possible to remove the outliers sound levels, then one may considerer the L_{A90} value as a threshold of *unwanted sound* in order to exclude those spikes which don’t belong to the *specific sound* under consideration.

The *environmental basal noise* is a better choice to identify the idea of *specific sound*, because *background noise* is close to the meaning of *residual sound*.

Figure 1: Normal distribution of *total sound*: From 2 pm to 3 pm. Plant on duty



In Fig. 1, it is easy to see the *environmental basal noise* idea: The normal distribution curve doesn’t have values below 30 dBA, it is not truncated, and this is because it is the minimum sound level measured by SLM; this is the concept of *environmental basal noise*, so beneath the statistical L_{A90} value there are high probability to estimate the *specific sound* level under consideration.

5. NOT INFORMATION OF ILFN LEVELS BY USING dBA

It is well known among acousticians that global dBA measurements are insufficient to assess a noise problem, but the worldwide legislation is based on that descriptor. This is the reason why it is important to considerer *Forensic Acoustics*, so enhancing the acoustics study by others noise descriptors or vibration data will be imperative.

Fig. 2 shows the time-history of indoor noise (a) and indoor vibration level (b) on right axis both correlated with affluent flow on left axis.

Fig. 2-b, per each second, shows that vibration emission has a strong dependence on mechanical energy emitted from the buried pipeline, but it is not the same with noise level emission: although the sound level fluctuates with the volume of affluence (Fig. 2-a), when the plant is off duty the sound level increases, because of the urban noise.

Figure 2: (a) Noise levels time-history - (b) Vibration levels time-history

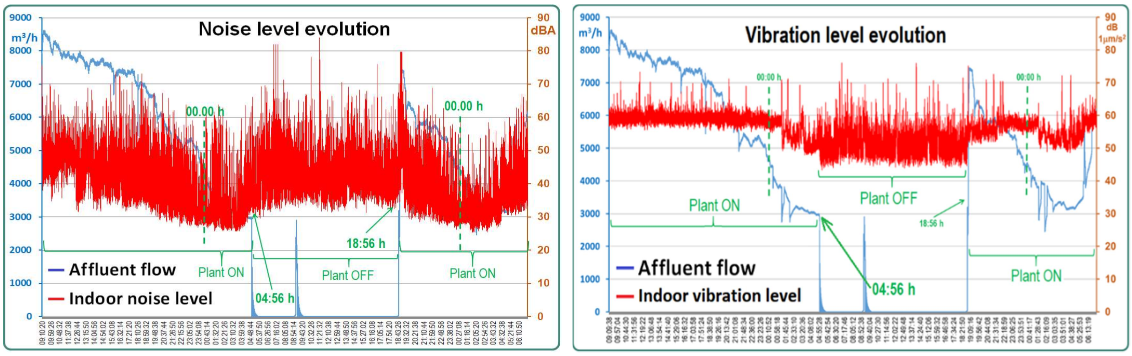
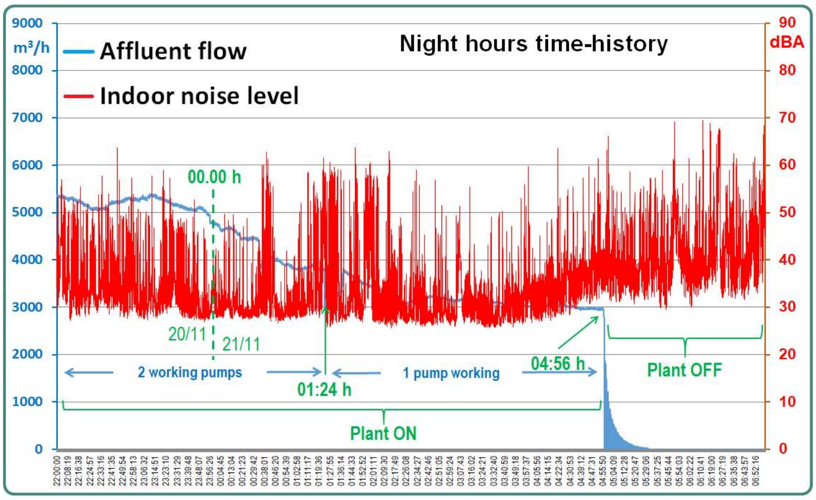


Fig. 3 displays, per each second, a zoom during night hours when the plant was turned off, where it is interesting to see how the sound level in dBA increases.

Figure 3: Indoor dBA noise level time-history. Plant was turning off (re dB 20 μPa)



Because of the low noise level inside the dwellings, the stakeholders claim indoor hum annoyance and rattling windows; for this reason, a specific ILFN analysis had been conducted during night hours in order to discard urban noise.

5.1 Determining the groundborne infrasound noise from the buried pipeline

Fig. 4 shows, per each second, the time-history of @10 Hz level evolution (on right axis) correlated with affluent flow (on left axis).

Figure 4: Time-history of indoor infrasound @10 Hz (re dB 20 μPa)

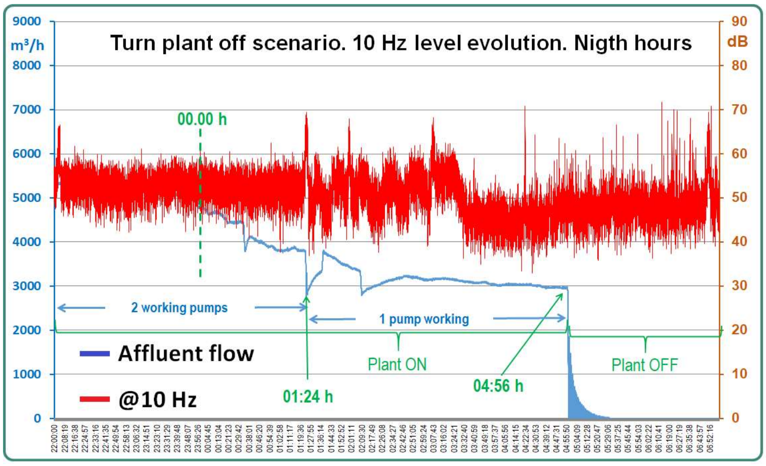


Fig. 4 displays the 10 Hz sound level has not straight dependence with mechanical energy from buried pipeline, and when the plant is OFF duty, it increases lightly because of the atmospheric infrasound effect in that morning hour.

5.2 Determining the groundborne low-frequency noise from the buried pipeline

Fig. 5 shows, per each second, the time-history of @25 Hz level evolution (on right axis) correlated with affluent flow (on left axis).

Figure 5: Time-history of indoor low-frequency @25 Hz (re dB 20 µPa)

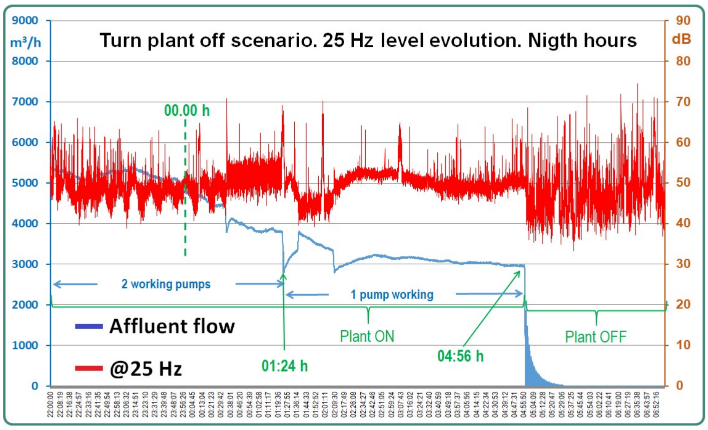


Fig. 5 displays that 25 Hz sound level has strong dependence with the acoustic energy radiated from the house's walls, meaning a structural vibration induced by the groundborne mechanical energy from buried pipeline; when the plant is off duty, the 25 Hz sound level freely oscillate showing a big variance among maximum and minimum.

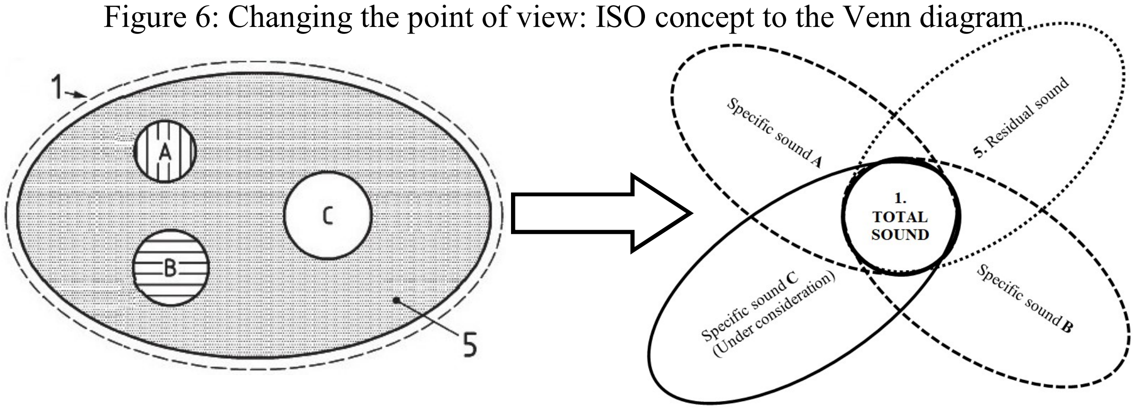
6. HOW TO ESTIMATE THE *SPECIFIC SOUND* LEVEL USING DISCRETE MATHEMATICS

The author have been presented in [4] a mathematical reasoning in order to simply exclude the *unwanted sound* from the *total sound* file by means of discrete mathematics.

6.1 Expanding the scope of ISO sound designation to a Venn diagram

ISO 1996-1 [2] presents an important concept to understand the acoustics complexity of the *total sound*, in the sense of showing its intrinsic components, but the easy way to find out one possible solution is transforming the ISO sound designation into a manageable mathematical algorithm; the first immediate inferences of their categorical proposition is making a conversion to a Venn diagram [6], Fig. 6 shows the assumed obversion.

Figure 6: Changing the point of view: ISO concept to the Venn diagram



This categorical logic permits a more convenient way of assessing the *specific sound* of ISO categorical propositions by drawing Venn diagrams, the idea showed in Fig. 2 is fairly straightforward, and the particular affirmative proposition asserts that the *total sound* is a member of all classes. Mathematical thinking of the *total sound* simplified like a set collection, allowing it to be considered through a possible computer program, with low complexity by discrete mathematics.

$$\textit{Total sound} = \textit{Residual sound} \cap \textit{Specific sound}\ \mathbf{A} \cap \textit{Specific sound}\ \mathbf{B} \cap \textit{Specific sound}\ \mathbf{C} \quad \text{Eq. 1}$$

Equation 1 shows the *total sound* as an intersection subset, and it is the results of overlapping the others. Using Eq. 1, one can estimate the *specific sound* as follow:

$$\textit{Specific sound C} = \{\textit{Total sound}\} - \{\textit{Residual sound} \cap \textit{Specific sound A} \cap \textit{Specific sound B}\} \quad \text{Eq. 2}$$

Equation 2 shows the *specific sound* under consideration is the *total sound* when the others are excluded, it means that the *specific sound* should be appraised by a statistical level (such as L_{A90}), for instance, all the sound levels below these reference percentile belong to *environmental basal noise*, on the contrary they will be consider as outlier.

6.2 Inference: Estimating the *specific sound* using a statistical percentile level

A practical way of appraising the possible sound pressure level of Fig. 1 measurement is s to assume that the L_{A90} or L_{A95} have should been the "specific sound level," it means to use a single statistical value as the equivalent estimator.

Table 2: Appraising the *specific sound* level considering one statistical value. Plant on duty from 2 pm to 3 pm (re dB 20 µPa)

	***Total sound* level measured ≡ $L_{\mathrm{eq},T}$**	**Appraised #1 *specific sound* level ≈ $L_{\mathrm{A90},T}$**	**Appraised #2 *specific sound* level ≈ $L_{\mathrm{A95},T}$**
$L_{\mathrm{Aeq},T}$	45.2	36.6	35.5
$L_{\mathrm{Ceq},T}$	59.7	unknown	unknown
$L_{\mathrm{Zeq},T}$	63.6	unknown	unknown

The issue is, which one of those two statistical values should be chosen as representative of the *specific sound*? Moreover, how should one know the low-frequency level or the infrasound level under this assumption? It is impossible to know them because it doesn't have the complete data of the whole *specific sound* time-history, but just one single "representative" value?

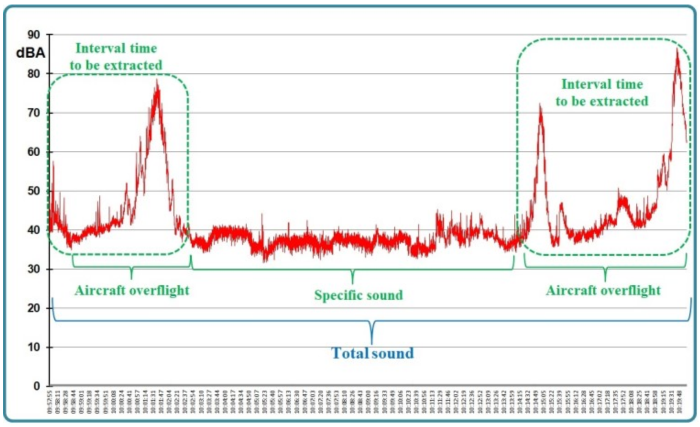
7. EMPIRICAL METHOD TO DETECT AND REMOVE THE OUTLIERS

This section contains a summary, a brief explanation of the empiric method applied to develop the functions and procedures which were programmed into VBA computer language included in Excel®, because it is easy to use its large library for mathematic and statistical function, no further programming needed.

7.1 Excluding outliers from a total sound file with a few spurious unwanted sound events

The measurements belonging to the first group (presented in sub-section 4.2-i) are simple to analyze, because it's easy to see the unwanted sound into the time-history file, so to exclude the unwanted sound, it is only necessary to extract the sound levels from the time interval in which the spurious noise is present.

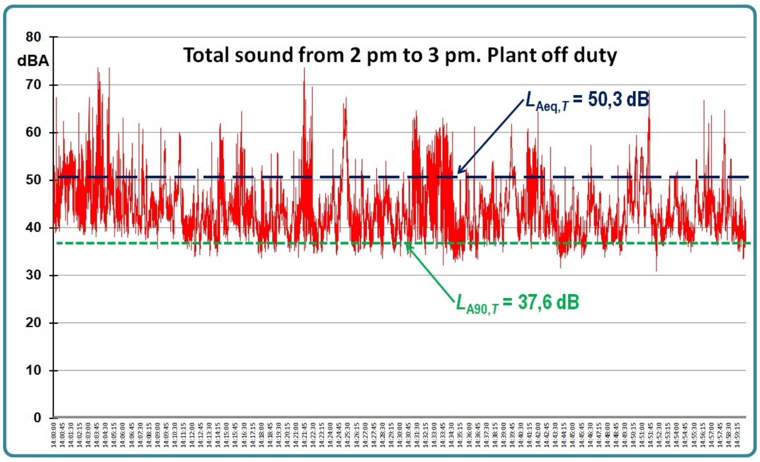
Figure 7: Time-history file with a few spurious noise events (re dB 20 μPa)



7.2 Excluding the outliers from a total sound file with bunch spurious unwanted sound events

The measurements belonging to the second group (presented in sub-section 4.2-ii) are difficult to analyze, because it is impossible to extract them "by hand" each individual unwanted noise (the outliers) above L_{A90}, as one can see in Fig. 8.

Figure 8: Time-history file with bunch spurious noise. Plant off duty (re dB 20 μPa)



7.3 Excluding the unwanted sound by means of outliers concept

The simplest procedure to exclude the unwanted sound, it is not consider those sound events which do not belong to the *specific sound*, removing them -statistically speaking- as if they were outliers.

There are a number of methods and algorithms to remove the outliers [7] [8] [9], for the particular procedure presented here, generating and separating a vector with the *specific sound* noise from the vector containing the *total sound* data, it will have to consider one threshold value (such as the statistical value L_{A90}) from which all the noise levels that exceed it shall be considered "outliers." The resulting vector contains the time-history of the *specific sound*, and it will be a "smooth signal."

Other authors (in the field of physics or other sciences) use similar procedure [10] [11], but instead of deeming it "outlier removal," they often use other synonymous terms such as "spikes removal," "removal of spurious," etc.

7.4 Defining the threshold for exclude the outliers by a statistical value

A particular macro was written to obtain the equivalent-continuous sound pressure level, using the spreadsheet with the *total sound* time-history (one data for each

125 ms) in dBA, dBC and dBZ; the "Percentile" function included in Excel® was used to calculate the statistical noise level. Tab. 3 shows the final results:

Table 3: *Total sound* level: From 2 pm to 3 pm. Plant on duty (re dB 20 μPa)

$L_{\mathrm{Aeq},T}$	$L_{\mathrm{A10},T}$	$L_{\mathrm{A90},T}$	$L_{\mathrm{A95},T}$	$L_{\mathrm{Ceq},T}$	$L_{\mathrm{Zeq},T}$
45.2	47.5	36.6	35.5	59.7	63.6

The L_{A90} is the estimated value is to be considered as an Estimator, in this case the threshold, values from which each individual LA125ms level that exceed it, and these L_{A125ms} will be excluded.

7.5 The *total sound* time-history contained into a spreadsheet. Matrix size

The SLM writes a file in txt format ($\mathrm{TS}_{[i;j]}$ matrix) where each row has 47 elements with this format: A=[Time stamp; L_Z; L_C; L_A; $L_{10\mathrm{Hz}}$… $L_{20\mathrm{kHz}}$], so the matrix size of a single 60-minutes measurement is equal to:

$$8\ \text{(samples)} \cdot 60\ \text{(seconds)} \cdot 60\ \text{(minutes)} \cdot 47\ \text{(elements)} = 1{,}353{,}600\ \text{matrix's elements} \quad \text{Eq. 3}$$

According to this, the resulting $\mathrm{TS}_{[i;j]}$ matrix is [i = 28,200 rows ; j = 47 columns], and always the $\mathrm{TS}_{[i;4]}$ element it will be the L_A value, because all the elements into row *i* column *4* are the L_A sound level of each 125 ms measurement.

7.6 Modular programming for the mathematic empirical model

The author presents in [4] [5] [12] a similar set of procedures, in this Paper an updated version is presented. A new concept about modular programming has been incorporated, because a matrix structure is more flexible for Set Theory, which is the empirical idea to write automatic software for removing the outliers.

7.6.1 Module A: Excluding the unwanted sound. Outlier's detection

Before running the detection-processing algorithm using the $\mathrm{TS}_{[i;j]}$ matrix (contained into a spreadsheet in text format), Module A calculates the L_{A90} that it will be the threshold value. The simplest procedure to exclude the unwanted sound is to remove the spikes and not consider those sound events which do not belong to the *specific sound*. A decision structure asks whether each $\mathrm{TS}_{[i;4]}$ value is greater than the threshold:

- If $\mathrm{TS}_{[i;4]} \rightarrow L_A > L_{\mathrm{A90}}$ threshold value: the program discard the actual row and goes to next one, it seeks the $\mathrm{TS}_{[i+1;4]}$ asking again the same conditional.
- If $\mathrm{TS}_{[i;4]} \rightarrow L_A \leq L_{\mathrm{A90}}$ threshold value: the program copies its whole row into a $\mathrm{SS}_{[i;j]}$ matrix, it seeks the $\mathrm{TS}_{[i+1;4]}$ asking again the same conditional.

When the conditional doesn't find no more data in TS $_{[i;4]}$, the program activates Module B. So the only "filtering" used here is to exclude the outlier's spikes [13] which exceed the L_{A90} threshold value: There is no frequency filtering; therefore, what is being "filtered" is the L_A outliers contained in the *total sound* matrix file.

7.6.2 Module B: Building the *specific sound* time-history. Low-frequency tones identification

The building-processing algorithm uses the $\mathrm{SS}_{[i;j]}$ matrix, which contains all L_{A125ms} values. The processing is performed consecutively in all 34 frequency one-third-octave bands between 10 and 20 kHz, this macro calculates the equivalent-continuous sound pressure level in dBA, dBC and dBZ; the "Percentile" function included in

Excel® was used to calculate the statistical noise level. Tab. 4 shows the final *specific sound* results using the $SS_{[i;j]}$ matrix.

Table 4: *Specific sound* level: From 2 pm to 3 pm. Plant on duty (re dB 20 µPa)

$L_{Aeq,T}$	$L_{A10,T}$	$L_{A90,T}$	$L_{A95,T}$	$L_{Ceq,T}$	$L_{Zeq,T}$
35.3	36.5	32.6	31.5	54.4	60.6

Fig. 9-a shows the resulting *specific sound* time-history, it is a smooth line because all outliers and spikes belonging to the unwanted sound were removed.

Figure 9: (a) *Specific sound* time-history - (b) Spectrum comparison (re dB 20 µPa)

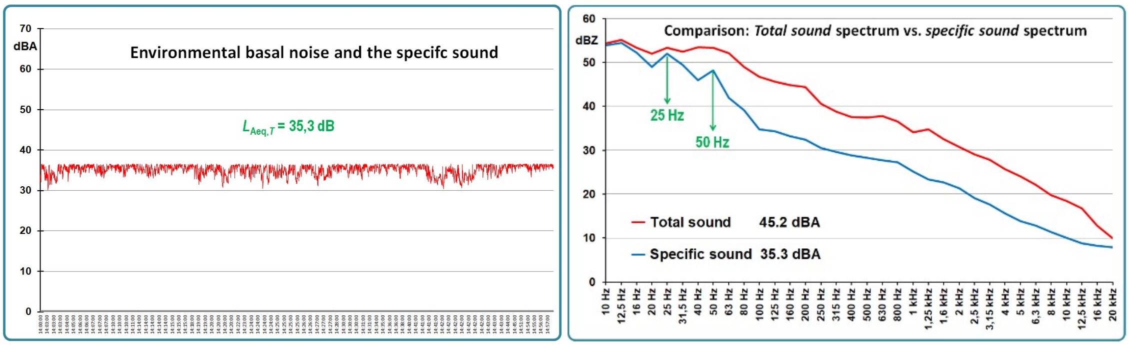


Fig. 9-b shows a comparison between the *specific sound* spectrum vs. *total sound* spectrum of the same measurement with plant on duty from 2 pm to 3 pm, where it can be seen how, after application of the empiric method to remove the outliers, two tonal sounds appear in low-frequency band, those they were masked by urban noise.

7.6.3 Module C: Statistical validation of the empirical method

It is important to justify mathematically the truthfulness of the estimated *specific sound* level, by mean of simply statistical tools such as Deviation and Variance; it is possible to calculate them with 95% accuracy. Tab. 5 resumes the calculation (using the functions included in Excel®), of these statistical functions applied to both.

Table 5: Statistical analysis of *total sound* vs. *specific sound*. Plant on duty

Classification	Deviation	Variance	Observation
$L_{Aeq,T}$ Total sound	4.51	20.3	60 minutes
$L_{Aeq,T}$ Specific sound	1.25	1.56	6 minutes
Difference	-3.26	-18.74	

Tab. 5 displays the benefits of applying the proposed empiric method, because of the Deviation and Variance reduction, and then *specific sound* levels result more reliable as consequence of not considering the outliers.

Another issue to analyze is the sound level due to outlier's removal, to consider the acoustic energy is possible to appraise the actual acoustics energy immission: For this particular case a difference of 3 dBZ means 100% less energy. Tab. 6 resumes and displays the *total sound* and the *specific sound*: The difference among each noise descriptor.

Table 6: Total sound vs. specific sound ECPL difference (re dB 20 μPa)

Classification	$L_{\mathrm{Aeq},T}$	$L_{\mathrm{Ceq},T}$	$L_{\mathrm{Zeq},T}$
Total sound	45.2	59.7	63.6
Specific sound	35.3	54.4	60.6
Difference	-9.9	-5.3	-3.0

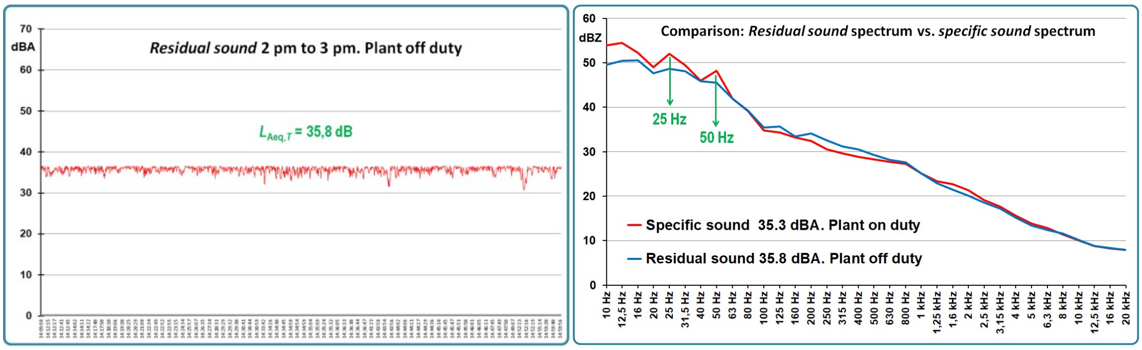
NOTE: If an inexperienced person, or an acoustician without proper training, would give the *total sound* level measured by the SLM like valid, in this example the direct result is 45.2 dBA, the Report would be wrong because this value should be informed as it if were the noise level from the noise source under consideration. An even worse situation would be if one compares the *total sound* value in dBA against legal limits.

8. STRUCTURAL VIBRATION DUE TO GROUNDBORNE ILFN IMMISSION

In order to validate the empirical method as a tool to demonstrate the ILFN immission from the buried pipeline (that produce structural vibration), this empirical method was applied to the matrix containing the *total sound* measurement (see Fig. 8) between 2 pm and 3 pm when the plant was out of service (off duty).

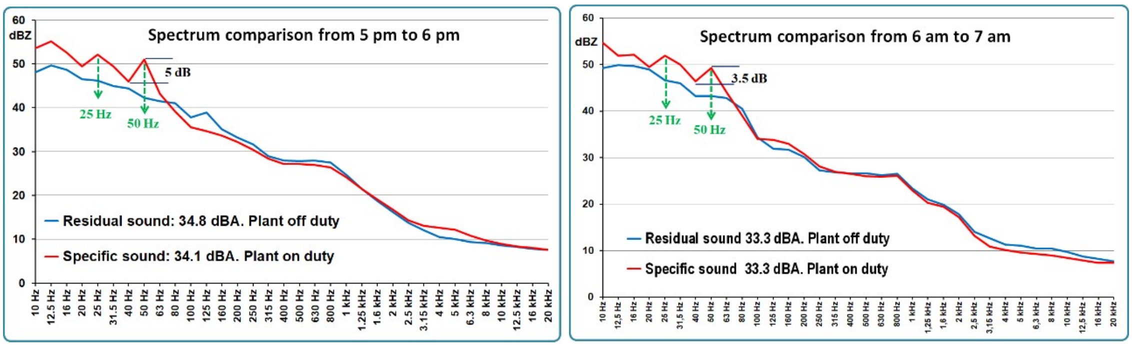
Fig. 10 show two graphics: (a) it displays the time-history of the *residual sound* level, after applying the empirical method to *total sound* file presented in Fig. 8. (b) It displays a comparison between the *specific sound* spectrum with plant on duty from 2 pm to 3 pm (it registered on day #1) vs. *residual sound* spectrum with plant off duty from 2 pm to 3 pm (it registered on day #2).

Figure 10: (a) *Residual sound* time-history - (b) Spectrum comparison (re dB 20 μPa)



The spectrum comparison in Fig. 10-b demonstrates that when the plant is on duty, the mechanical energy from the buried pipeline is capable to induce structural vibration on 25 Hz and 50 Hz. Fig. 11 show the same comparison but during different hours.

Figure 11: Spectrum comparison. Plant on duty vs. off duty (re dB 20 μPa)



9. CONCLUSIONS

The empirical method presented here and the algorithm developed have been used efficaciously for more than seven years, not only at industrial facilities far from city noise but also in urban sites with noise sources of stationary sound emissions, such as air conditioners, fans, generators, etc. and where traffic and other spurious noises should not be taken into account. For obvious reasons of space, it is not possible to show the VBA source code.

As one can see the graphics of figures 10 and 11, inside the dwelling is a very low noise level, the sound level pressure being almost the same with the plant on duty and off duty. The assessment of low-frequency noise radiated from the house's walls was more clear after using the empirical method, because of the structural vibration. It was reported to the Authorities that the buried pipeline is responsible for the phenomena. The purpose of this Paper is to share to the acoustician community that it is possible to achieve a standardized method, in the sense that an algorithm could be agreed among specialists for having an "universal computer program" to determine the *specific sound* contained in the *total sound* file.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

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