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Acquisition Module for a Wireless Acoustic Sensor Network Suitable for Argentinian Urban Environments

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ABSTRACT

Urban noise is a main component in the deterioration of life quality for people in urban areas. This problem mainly affects those who periodically travel through high traffic areas. The first step in reducing environmental noise is to characterize the urban setting with acoustic metrology for its diagnosis and control. This document exposes the design, construction and characterization of a wireless urban noise measurement module. The device works as a low-cost node with the capacity to be replicated for the deployment of a network of wireless acoustic sensors that allows the elaboration of dynamic urban noise maps. Each module consists of an electrical autonomy system, a single board computer and a MEMS microphone. The project also includes the design of a web portal to display measurement results in real time. The low-cost system was calibrated and compared with a class 1 sound level meter used to measure urban noise in the Autonomous City of Buenos Aires (CABA). Global differences of less than 1 dB were obtained. Urban noise was measured near the National University of Tres de Febrero following guidelines of ISO 1996-2 standard. The performance obtained in the evaluation instance and the results of the comparison were satisfactory.

Keywords: acoustic sensor, WASN, urban noise, noise map, smart city.

INTRODUCTION

Currently, of the 7.5 billion people living in the world, 55% live in urban areas. It is estimated that this value will increase to 68% by 2050 according to a study carried out by the United Nations (United Nations, 2018). As the world continues to evolve, the sustainable development of urban areas becomes of great importance to guarantee the quality of life of its inhabitants, taking into account economic, social and environmental parameters. In this scenario, Argentina is one of the most urbanized countries in the world and the second in Latin America according to reports released by the Economic Commission for Latin America and the Caribbean. In recent years, there has been a paradigm shift in the management of urban areas thanks to the development driven by the Information and Communication Technology revolution (ICTs). The ICTs are fundamental for the creation of smart cities that address one or more of the following aspects (Manville et al., 2014): smart government systems, people, life, mobility, economy and/or environment (including control and pollution monitoring).

The continuous growth in the number of inhabitants has led to an expansion of transport systems. This causes a considerable increase in environmental pollution, a cause for concern due to the negative effect of atmospheric and noise pollution (Goines et al., 2007). The World Health Organization (WHO) estimates that more than 40% of European citizens are exposed to excessive levels of traffic noise during the day, and more than 30% at night (World Health Organization, 2011). The impact of environmental noise on people is not harmless and several studies prove that diseases caused by the effect of this phenomenon produce loss of years of healthy life (Guski et al., 2017) (for example, permanent hearing loss, tinnitus, adverse outcomes in birth). Road traffic is one of the main noise sources in urban areas, increasing tiredness and altering sleep patterns (Öhrström et al., 2006).

As part of the environmental actions carried out in Argentina for awareness and action on pollution generated by urban noise and in compliance with CABA's LAw 1,540, a survey of sound pressure levels was carried out in the city. It shows the emission levels produced by mobile sources such as automobiles and railways. The Ministry of Environment and Public Space of CABA developed a noise map that covers 203 km², following the simulation and validation method with acoustic measurements according to international standards. The city government provided five dedicated measurement stations designed for the task, taking into account long exposure times and various weather conditions. With this study, the Daytime Map was obtained, which represents the noise levels recorded in the City between 07:01 AM and 10:00 PM, and the Nighttime Map for the hours between 10:01 PM and 07:00 AM.

Traditionally, noise measurements have been carried out by professionals using certified sound level meters for a certain period of time according to the guidelines established by international regulations. However, this approach becomes difficult to scale up when it comes to addressing current demand, especially for real-time surveying and display of results over large areas. Despite this and thanks to the development of technology within the framework of the Internet of Things (IoT), it has been possible to solve these problems through the deployment of wireless acoustic sensor networks (WASN). WASNs enable the automatic generation of dynamic noise maps in urban areas from controlled measurements, while reducing the cost of noise mapping compared to the corresponding expert update of the static noise map every five years.

Thanks to the European Parliament Directive 2002/49/CE, the interest in generating better wireless networks of acoustic sensors, with greater autonomy and quality, grew considerably (European Directive, 2002). There are two large groups of works or projects that were carried out: those where nodes are developed with commercial acoustic measurement devices and those that use commercial technologies to create custom nodes. The first group consists primarily of novel developments using soundmeters and dedicated systems connected to a mobile, telecommunication or local area network. Mietlicki et al. showed the advantages of a hybrid wireless sensor network using low and high precision equipment in different areas, connected with 3G technology to a database to save the results (Mietlicki et al., 2015). This work forms one of the first publications under the RUMEUR and HARMONICA projects from Paris, which are one of the first in the region to consider a web portal to ensure that information can be shared with the public (Mietlicki et al., 2014).

The other group uses embedded and low cost technology taking advantage of the growing improvement of the IoT. The work presented by Bertalucci et al. consists of a low cost system to measure and compare noise level differences before and after structural interventions in urban areas (Bertalucci et al., 2018). This was the first article presented by the LIFE MONZA project, a pioneer system that uses 3G technology and low cost technologies for sound measurement.

A similar project was presented by Mydlarz et al. in 2019 called Sounds of New York City, SONYC (Mydlarz et al., 2019). They used commercially available technology such as a MEMS microphone (working at a 48 kHz sampling rate and 16 bit depth) and a Raspberry Pi as the main computer, to record environmental noise and post-process outside the network. Nodes were distributed in various urban locations over an extended period, with the aim of collecting urban acoustic data, then processing it to provide meaningful information to change urban policies and develop action plans. This work presents the development of an urban noise acquisition module with a replicable design for the deployment of a Network of Wireless Acoustic Sensors. Free access and low cost technologies are used without neglecting the tolerances and sensitivities required by international regulations.

MATERIALS AND METHODS

The sensor network is made up of nodes that connect to the internet simultaneously. Each one includes an electrical autonomy system, a low-cost microphone and a single board computer for data capture, frequency response compensation, data adaptation and the uploading of results to the cloud server. Figure 1 shows a simplified block diagram of the components present in each node and then each part is explained in detail.

Main module hardware

A Raspberry Pi model 3B+ is used as a single board computer (SBC) due to its small dimensions, wireless connection ability, community support and computation capacity. The transducer is a low-cost commercial MEMS microphone model INMP 441, which contains an ADC and a I2S interface for data transfer. The transducer is commonly used for voice frequency ranges and devices such as tablets, computers and cell-phones.

Main module software

Data collection and signal processing codes were extracted from a previous thesis work, developed by a member of the investigation group (Iaquinta Tomas, 2020). Different formatting and average functions were developed to upload all the results and coefficients to a Google Firestore platform database. In addition, various alternatives were delivered to control contingencies and ensure that the module is as autonomous as possible in the face of possible failures (low quality internet connection, complete discharge of the battery, among others).With measurements made in an uncontrolled environment, the transfer function of the used transducer was found, so that the inverse filter could be added to obtain a flat frequency response.

Design of the electrical autonomy system

This section of the node consists of four main parts: a battery, a solar panel, a charging regulator and a voltage adapter. To determine the battery capacity, a power consumption of the SBC needed to be estimated and a minimum autonomy time assumed. These values were set to 500 mA per hour on average and 24 hours of runtime. Local market products were selected to satisfy these conditions. A combo of solar panel and charging regulator was sought to fit the desired parameters, charge the battery in as little time as possible and provide discharging protection circuits. Finally, the voltage regulator adapts the output of the charging voltage to values that can be handled by the Raspberry Pi. Figure 2 shows the final block diagram showing all the required hardware for the module.

Module housing and mounting

Two IP-65 boxes were used to store all the components. The first one is a small PVC

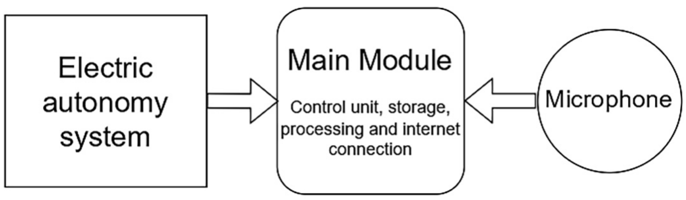

Figure 1. Block diagram of the urban noise acoustic sensor

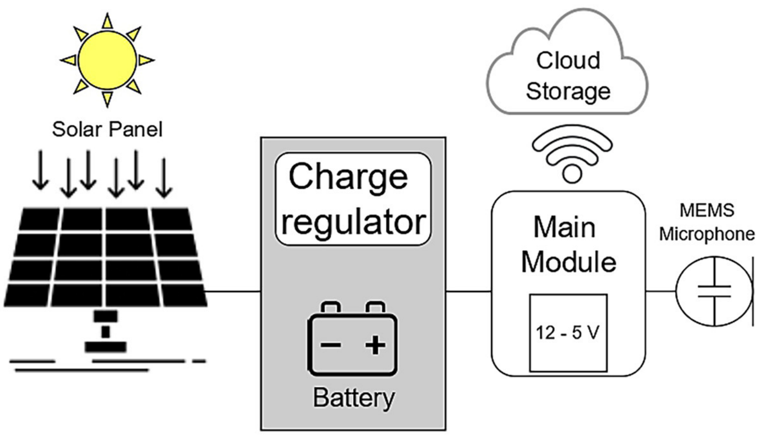

Figure 2. Final block diagram of the urban noise acoustic sensor

enclosure and contains only the SBC and voltage regulator. Two plastic cable clamps are used to ensure that input cables for power supply and microphone's output do not present a risk of water or dust entering. The microphone is protected with an „anti-pop" filter, which impact on the measurements is underestimated, but future research should consider its effect. The second cabinet is a larger one and it is made out of metal, since it contains the battery and the charge regulator. An aluminum frame was designed and assembled to facilitate the mobility and installation of the electrical autonomy system. These two compartments are joined with a UTP CAT 5 type cable.

Website design

The collected data must be presented in such a way that it can be easily interpreted by anyone interested in the subject. This is why it was decided to hire a third party to be in charge of setting up a web portal with all the project information. The main section shows the levels recorded in the last 24 hours, the last level input measured by the module, its location and operating status. The design also contemplates relevant information about the project, the investigation group and the members. The web page takes the results from the Google Cloud Firestore server. The unique timestamps from each database entry are the key elements that provide order in the results shown. Figure 3 shows the constructed node: [a] the electrical autonomy system and [b] the main capture and processing part.

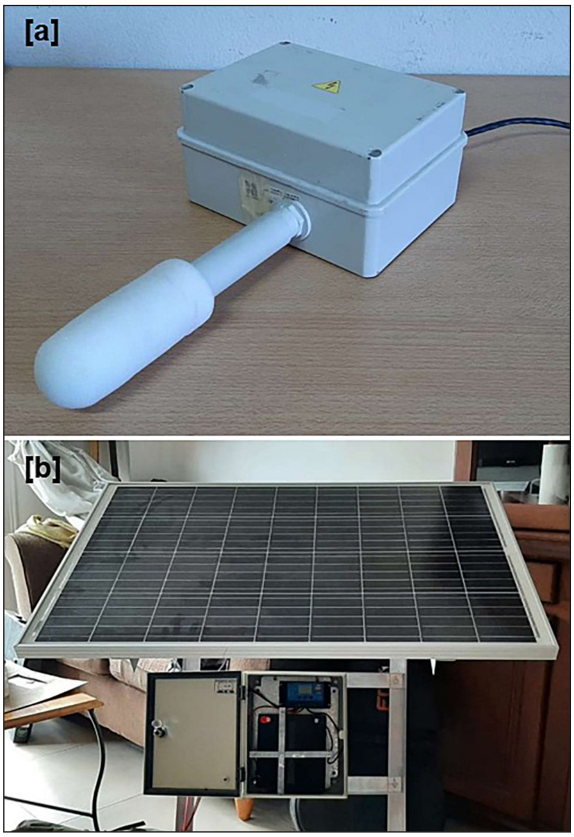

Figure 3. Final design and construction of the node. [a] the electrical autonomy system and [b] the main capture and processing part

MEASUREMENTS

After building the main module and installing the drivers for the recognition of the MEMS microphone, an exploratory and stability test was executed analyzing the usage of CPU, RAM memory and processor temperature. A statistical analysis of the data showed that both RAM and CPU percentages were not affected by the continuous functionality of the software. The temperature values of the main processor showed the need for a cooling system if the ambient temperature exceeds 40°C.

After being able to access measurement equipment, the device under test was calibrated with the Svantek Calibrator model SV-30-A and compared with an Earthworks M50 measurement microphone to compensate for the frequency response. Figures 4 and 5 show the methodology for obtaining the transfer function and the result obtained after smoothing the curve. With the equipment already compensated, comparison measurements were made with an urban noise station used in CABA. The main purpose of this part of the project is to analyze the results obtained with different time and frequency weightings. The sound signal used for this instance was pink noise in various SPL, so that the sensibility could also be compared.

After constructing the electrical autonomy system, a test of stability and effectiveness was carried out. This process only consisted of installing the device on the rooftop of a building, having previously analyzed the movement of the sun to maximize exposition. The main part of the module was installed several meters away from the electrical autonomy system to ensure internet connection. The test showed the efficiency of the autonomy system by providing continuous energy through more than three weeks, even with more than two consecutive days of cloudy weather.

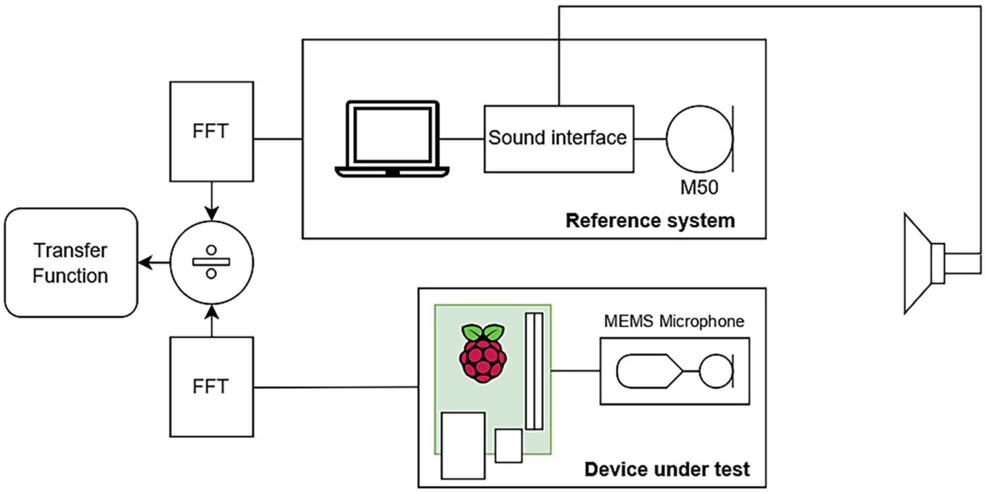

Figure 4. Block diagram of the connection of the devices to obtain the microphone transfer function of the developed module

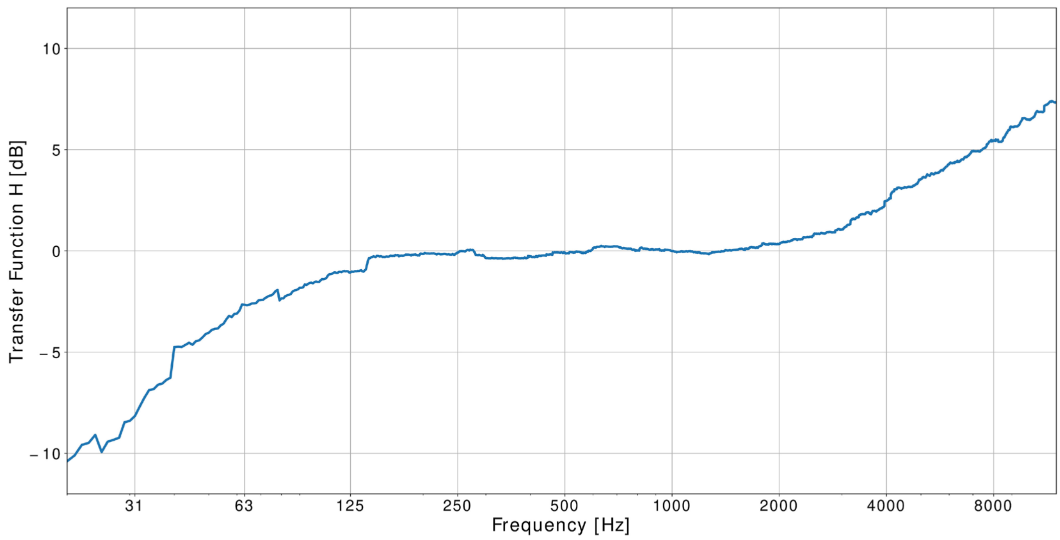

Figure 5. Microphone transfer function smoothed and normalized at 1 kHz

Once the correct operation of the system was verified, the equipment was moved to the Caseros IV Headquarters, located at San Martín Avenue 2508 in Caseros, Tres de Febrero, Buenos Aires Province of Argentina. This was the first real measurement and its main purpose was to determine the noise levels at the area following the ISO 1996 standard (ISO 1996, 2001). The establishment is located on a corner and one of its faces is exposed to the Av. San Martín tunnel, through which a large number of vehicles pass at all times during the day, and it is less than 30 meters from a pedestrian crossing of the San Martín railway. The aim of this measurement was to expose the team to a real application and to be able to evaluate the exposure to urban acoustic noise of those who work in said building. The main results were taken from the first ten days, however the module was able to continue working for more than 3 months with no interruption. For this application, the following configuration was applied:

- frequency weighting: A
- time weighting: Slow
- frequency filtering: octave band
- measurement time: 120 seconds

The integration time window was modified to facilitate post-processing and database management. Modifying this parameter helps to visualize the data on the web page, avoiding showing excess information.

The thesis work of Eng. Stasi entitled „Comparative study between predictive models of vehicular traffic noise and validation measurements in the Autonomous City of Buenos Aires", analyzes the differences between vehicular traffic models for the development of acoustic maps (Stasi Agustín, 2017). The document unifies the number of measurements for acoustic models validation to obtain descriptors that contemplate a single total measurement period for the analysis. Through knowledge of the maximum error, it is possible to use a smaller number of measurement days as a representative value for the analysis of the descriptors to be evaluated. The conclusions of this work are used to justify the use of ten days of measurement for the calculation and exposition of the parameters named above.

RESULTS

This section shows the results obtained in the comparison between the device under construction and the measurement module used in CABA. Then, the results of the first ten days at the UnTreF headquarters Caseros IV are presented.

Comparison with professional equipment

The log files (logger) provided by both devices were used for comparison. The timestamps helped to perform integrations on coincident time intervals. The subtraction between the levels obtained by the equipment developed in this work (calibrated and compensated) and the sound level meter is presented below. Figure 6 shows the temporal levels obtained in the measurement of pink noise of variable intensity. This figure also serves as an example of the work done on all measurements to ensure that the values being analyzed match over time.

This representation demonstrates the similarity of response between the sound level meter used as standard and the developed module. In order to verify this statement, a statistical study of the values obtained is carried out. The Pearson correlation coefficient (r) is calculated for the equivalent continuous sound levels (Leq) recorded, obtaining an r value of 0.941, this correlation being significant with $p < 0.001$. The standard deviation of the analyzed Leq values is 8.9 dB for the sound level meter used as reference and 8.4 dB for the wireless acquisition module. This means that there is more variation in the values measured by the sound level meter, which exposes the differences in the dynamic range and noise floor of the class 1 transducer compared to the MEMS microphone.

Third octave band analysis

For the frequency response characterization of the device, the values obtained with the

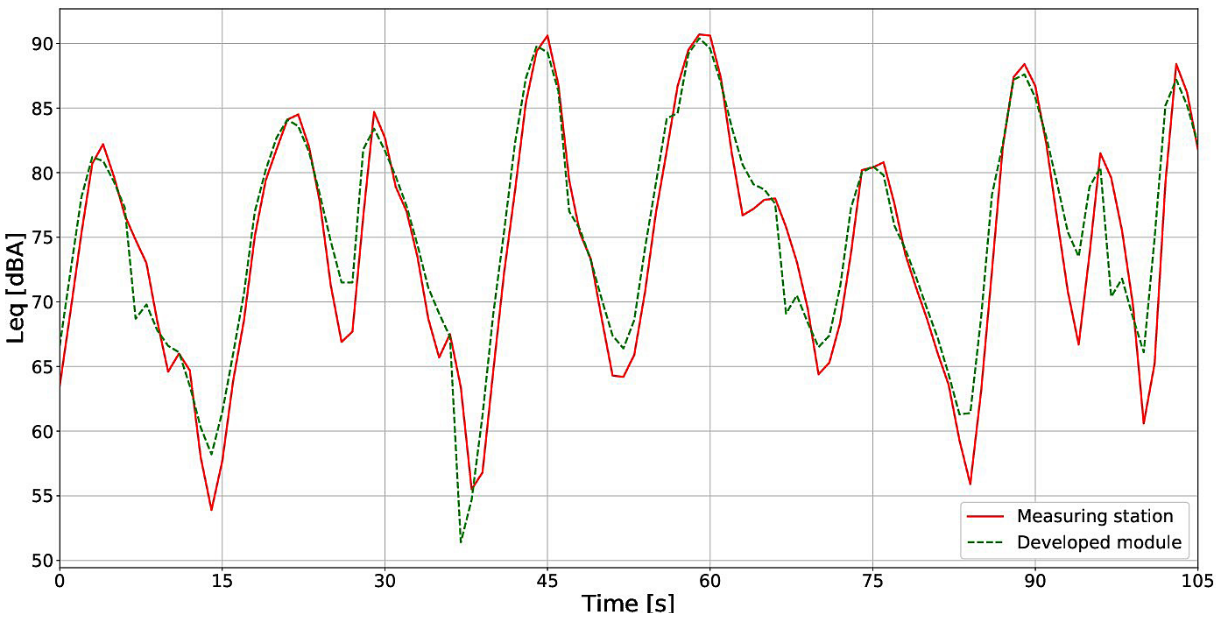

Figure 6. Temporal response of both devices to the same sound source with pink noise reproducing with variable level

measurements of the sound level meter used as reference are subtracted. This operation is repeated for each third-octave band in which the meters were configured and for each of the measurements. Figure 7 shows the results of the time-varying pink noise measurement.

Global results

Within the same time intervals, global Leq values of both devices were obtained and subtracted to analyze the differences. As the module developed in this work contemplates a frequency response compensation, minimal to no differences are expected. Table 1 shows the global results obtained after this procedure. The measurements are presented according to the measured signal, the frequency weighting (A or Z) and the time weighting (slow or fast). The global values expose the offset generated by the difference between values across the third-octave bands found above. These results contemplate differences of less than 2 dB, as in the works analyzed in the state of the art that inspired this project (Mietlicki et al., 2015).

In-situ measurement Caseros IV

The following results correspond to ten consecutive days of uninterrupted measurement, from Friday, July 16 to Monday, July 26, 2021. During this period, there were days with adverse weather conditions, but previous experiences show that this type of phenomena does not significantly affect the performance of the electrical autonomy system. The ambient temperature was kept between -2 and 27°C so the processor was not in danger of failure due to overheating. Heavy rainfall and entire cloudy days were recorded, but these weather events did not negatively affect the normal operation of the device. Figure 8 shows all the values recorded throughout the specified period. The A-weighted equivalent continuous sound level of the entire measurement was 72.2 dBA.

Urban behavior can be characterized with the information presented in this figure. During business days (Monday to Friday), the values recorded are higher than those measured during weekends (for example, days 17, 18, 24 and 25). A clear decrease in the level measured during the early mornings is also observed, mainly caused by the

Table 1. Difference of global values

Measured sound and configuration	Leq difference [dB]
Background noise A S	0.2
Pink noise A S	-0.1
Pink noise Z S	-0.1
Pink noise A F	-0.3
Dynamic pink noise A S	0

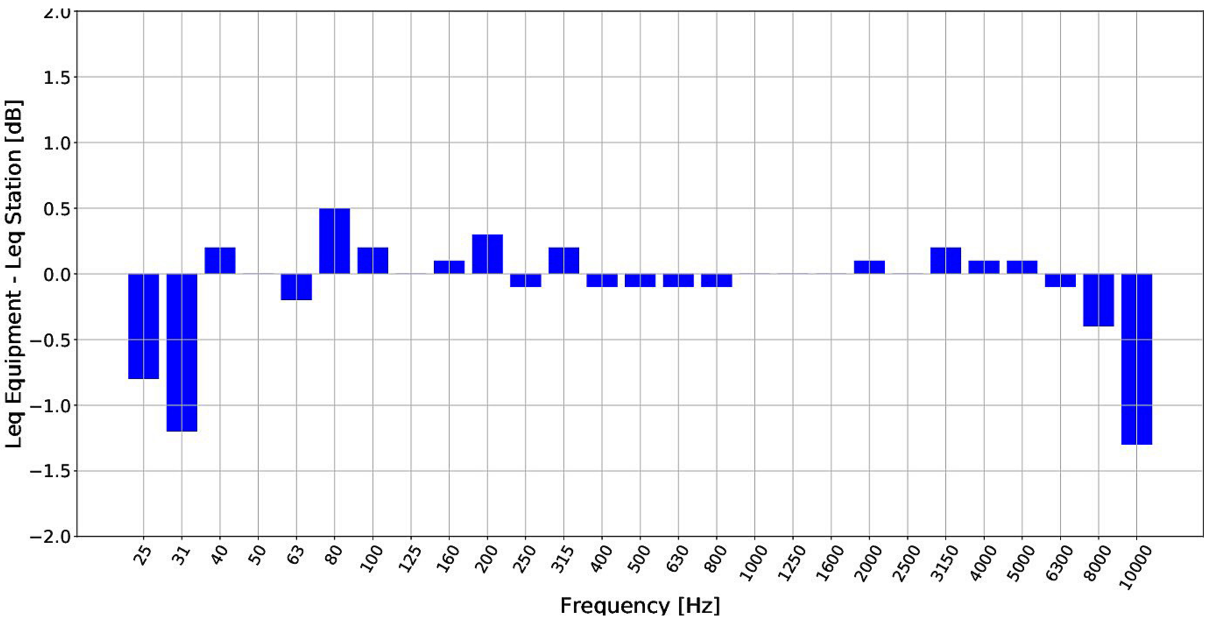

Figure 7. Difference between the values obtained by the equipment and by the sound level meter when measuring pink noise with time-varying amplitude, configured with Slow time weighting and A frequency weighting

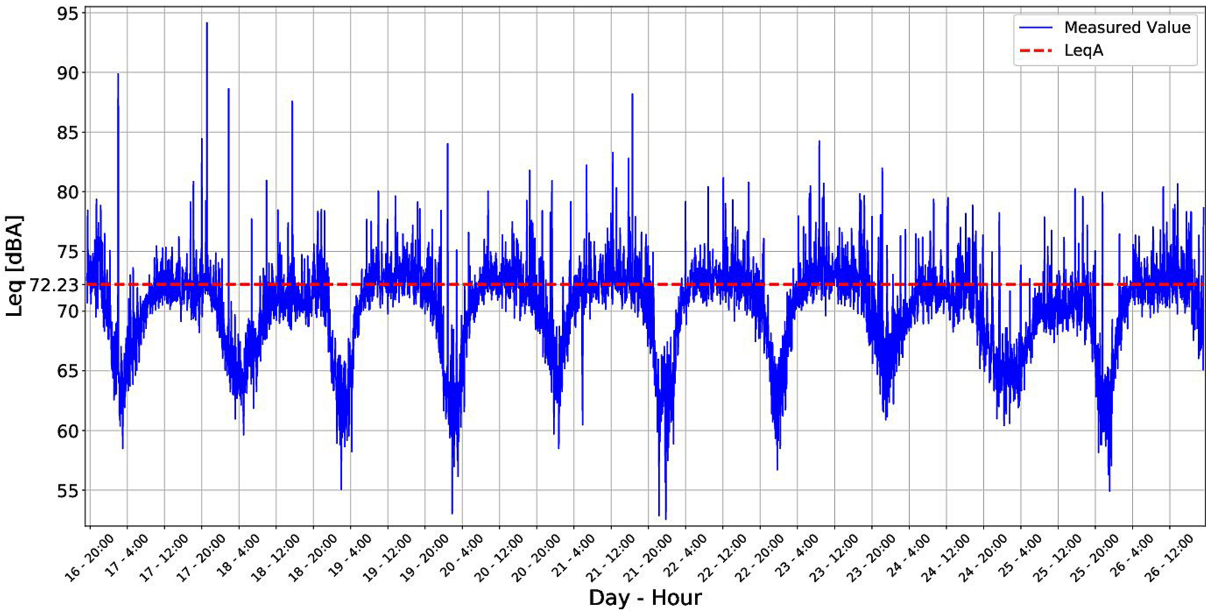

Figure 8. Values recorded in the 10 days of measurement in Caseros IV

decrease in vehicular traffic. One of the elements that stands out in this temporal graph is the presence of anomalous acoustic events, which exceed up to 18 dB of the calculated Leq level. The presence of these peaks is due to various phenomena such as noisy vehicles passing through the nearby tunnel, which acts as an acoustic resonator. The vehicles that had the greatest impact were ambulances and fire trucks with their high-intensity tonal sirens. This tunnel is the union between the northern and southern part of Caseros City, so it is heavily transited by heavy and private vehicles whose impact on acoustic pollution does not go unnoticed. Another noise source is the diesel powered San Martin train and its pedestrian railway crossing. Through the same railway, a cargo train usually passes and generates a very particular sound contamination.

However, as stated in the thesis of Eng. Martín Crapa entitled „Design of a methodology to estimate the influence of anomalous events on the noise levels of road traffic in urban areas", the presence of these anomalies does not generate a pronounced impact in the final Leq value

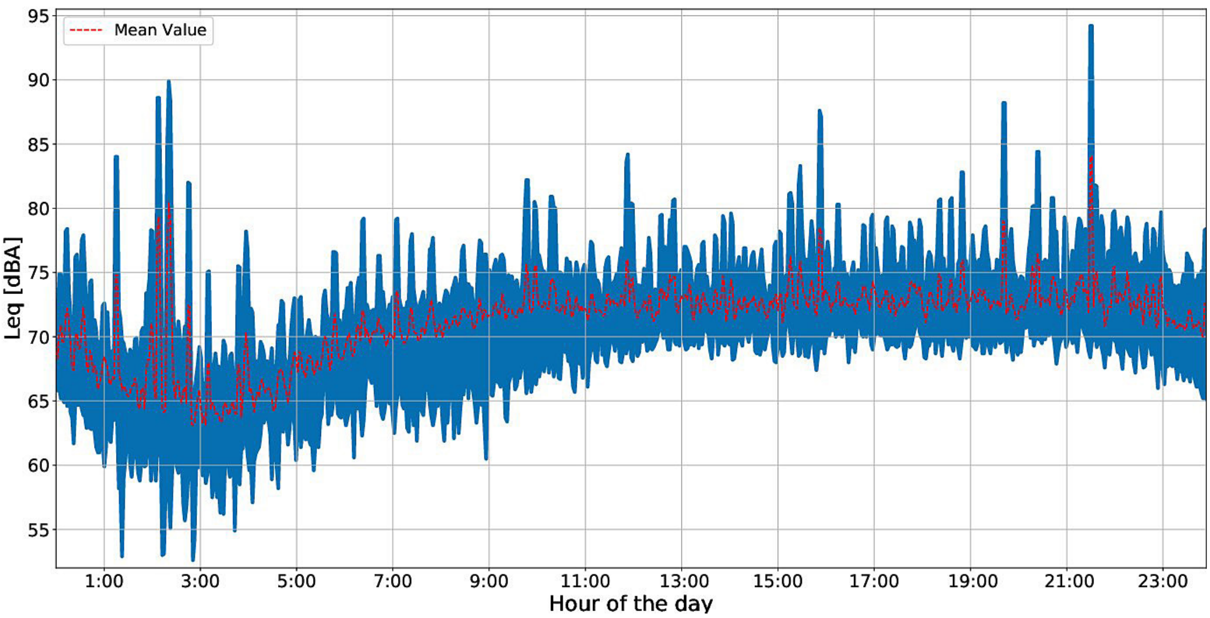

Figure 9. Average values recorded in a week in Caseros IV building

Table 2. Calculated values of Lday and Lnight obtained after 10 days of measurement

Parameter	Value obtained [dB]
Lday	73.1
Lnight	69.7

or similar acoustic indicators (Crapa, 2019). Figure 9 shows a curve composed of the 10 full days average measurement. With a database entry every 2 minutes, 720 daily and 5040 weekly entries were captured. It is of interest to know the Leq value at each moment of the day throughout the week, represented by the dotted red line. The shaded parts of the figure delimit the maximum and minimum values recorded.

The main curve is strongly influenced by the peak levels that represent sporadic situations, which will be attenuated over time once longer measurements are made. Another parameter of interest is the equivalent day (Lday) and night (Lnight) levels, used in the urban noise map of the Autonomous City of Buenos Aires. The parameters were calculated considering the integration periods for the day (07:00 to 22:00) and for the night (22:00 to 07:00), as established by the ISO 1996 standard. The period for determining these acoustic indicators is three months. However, as established above, with measurements of ten continuous days, values similar to the values obtained in the measurement period established in the regulations are achieved. Table 2 shows the values obtained for these indicators.

CONCLUSIONS

A low-cost wireless urban noise acquisition module was successfully developed, capable of being easily replicated for the deployment of an acoustic sensor network. Beneficial differences are observed in the cost of this module (USD 350) compared to dedicated stations (> USD 7000).

The price differences lie mainly in the transducer, since the capsules used in professional equipment are subjected to laboratory tests following rigorous international standards. In addition, these microphones have certain features for precision measurements that exceed those required in certain specific applications. That is why it is necessary to question and analyze the need of laboratory transducers to carry out urban noise measurements, considering the need for a large number of units and a small budget that is not enough to cover the demand. A compromise relationship is observed in which a more exhaustive analysis of available alternatives would offer solutions that can satisfy the economic and precision aspects involved.

The station proposed in this work is positioned as a viable and economical alternative for surveying noise pollution levels in cities. This is due to low-cost, high-reliability components, and the use of freely available platforms that are flexible and efficient enough for a potential multi-station deployment. The final price of the module and every component is listed in Annex A. Long uninterrupted work times demonstrated the stability and good design of the electrical autonomy system, even contemplating the days where the weather conditions were not ideal. The single board computer met the requirements and all its features provided comfort and good performance in different weather conditions and usage configurations. However, the use of flash-type memories in this model reduces the useful life of the file management system, so it is necessary to evaluate alternatives that reduce the exhaustive and constant use of reading and writing actions. Another parameter to take into account is the consumption of electrical energy, which can be reduced by characterizing and limiting the hardware to be used. This would reduce the cost of each module since a smaller solar panel and a smaller capacity battery would be enough, facilitating portability and installation in streets and residential areas.

After compensating the frequency response of the microphone used in the sensor, similar results were obtained comparing it with the Class 1 sound level meter used in the Autonomous City of Buenos Aires to measure urban noise. For all the signals analyzed, Leq differences of less than 1 dB were archived. Further comparative testing in controlled laboratory environments is needed to characterize sensitivity and temperature impact in the transducer. For the applications established in this work, the sensor meets the requirements, despite being designed for consumer electronics and optimized for a specific frequency range, different from that used in urban noise as indicated in its data sheet.

It was possible to add a web portal design to the project, showing information about it and only one parameter in real time, for which greater investment is necessary so that more data can be exposed that can be easily interpreted by the interested public. By doing so, all the processed data can be used and the computational, energy and monetary cost of each node can be justified.

The final system falls within the framework of the Internet of Things (IoT) to control environmental variables and phenomena, since it consists of a number of basic operating blocks with various functionalities aimed at detecting and monitoring noise pollution. Thanks to the Internet connection, the visualization of the data will provide valuable information to deal with the problem of urban noise, to be able to put together action plans and follow them up after applying them.

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