Mapping the Sound Environment of Andorra and Escaldes-Engordany by Means of a 3D City Model Platform

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Abstract: In the new paradigm of the smart cities world, public opinion is one of the most important issues in the new conception of urban space and its corresponding regulations. The data collection in terms of environmental noise cannot only be related to the value of the equivalent noise level L_{Aeq} of the places of interest. According to WHO reports, the different types of noise (traffic, anthropomorphic, industrial, and others) have different effects on citizens; the focus of this study is to use the identification of noise sources and their single impacts on background urban noise to develop a visualization tool that can represent all this information in real time. This work used a 3D model platform to visualize the acoustic measurements recorded at three strategic positions over the country by means of a sound map. This was a pilot project in terms of noise source identification. The visualization method presented in this work supports the understanding of the data collected and helps the space-time interpretation of the events. In the study of soundscape, it is essential not only to have the information of the events that have occurred, but also to have the relations established between them and their location. The platform visualizes the measured noise and differentiates four types of noise, the equivalent acoustic level measured and the salience of the event with respect to background noise by means of the calculation of SNR (Signal-to-Noise), providing better data both in terms of quantity and quality and allowing policy-makers to make better-informed decisions on how to minimize the impact of environmental noise on people.

Keywords: acoustic source; sound mapping; smart city; 3D model platform; acoustic monitoring; L_{Aeq}; SNR

1. Introduction

While the rise of Big Data is transforming both industry and academia, some of the challenges that have appeared as part of this new paradigm have become full research lines themselves. The classic roles of data analysts are turning into more heterogeneous skill sets involving not only the processing and interpretation of data, but also its disclosure to a wider public. Moreover, the data consumer profile is evolving as well and is increasingly demanding access to a greater volume of data, which is more diverse in content. Data democratization is unveiling the need to develop new visualization tools, suitable for users with less expertise in data interpretation or a non-technical background. In this context, an easy-to-understand showcase of complex information [1] may be remarkably useful for policy-makers who are responsible for developing and implementing policies and regulations, as well as among the citizenship in terms of raising awareness and engaging the community.

The Actuatech Foundation is an Andorran public institution, which in collaboration with the Andorran stakeholders, neighboring universities, and the Massachusetts Institute of Technology (MIT), is backing innovation projects that make an impact on local society and on the economic development of the country through, among others, the implementation of a CityScopeplatform [2], a national DataHub, a BlockchainLabor a DroneLab. The same concept of a 3D city platform has already been exploited to visualize an interactive overview of the rooftop photovoltaic potential in Andorran buildings [3] and generate a discussion on the viability of public subsidy policies or organize workshops with local schools [4].

Many research works have emerged in the last few years showing how noise exposure [5,6] should be prevented in order to avoid several health effects such as sleep disturbance [7,8], annoyance [9], cardiovascular effects [10], learning impairment [11–13], and hypertension ischemic heart disease [14]. Prevention includes understanding, even in real time, the noise levels in the area, and thus, the recent application consists of using wireless sensor networks (WASN) for noise monitoring [15,16], representing a modern and inexpensive solution to fulfil the mandatory noise maps and action plans [17]. Preventing also the means to avoid expensive, and not always accepted, acoustic barriers, which are the most widespread solutions to mitigate the noise produced by the main sources [18]: railway traffic [19,20], airports [21,22], and industrial plants [23–25]. Recent developments in the field are moving the attention towards sonic crystals used as acoustic barriers.

In recent years, as a result of the advances in sensor technology and communications, there has been a boom in projects aimed at monitoring several parameters of cities, especially noise, with the goal of complying with the European Noise Directive (END) [26], which has led to information display platforms for the general public. In Barcelona, an environmental noise monitoring network was deployed in order to manage the resources effectively, to measure the impact of urban infrastructures on the citizens and the environment [27,28], integrating the information via Sentilo to be spread to citizens by means of the web of the Barcelona City Council. There are other alternatives such as the DYNAMAPproject [29], which has deployed two pilots, one in Milan [16] and one in Rome [30], evaluating the noise coming from road infrastructures, and, after integrating the information coming from all the nodes from the WASN, the data were available for the public by means of a GIS platform [31]. Other projects under development, such as the Sounds of New York City project [32], have deployed 56 low-cost acoustic nodes around the city with the final goal of both monitoring the urban noise, as well as performing a real-time multi-label classification, despite not being online in the acoustic nodes. Most of the other projects associated with the monitoring of noise and air pollutants developed the concept of a noise map, which is a precise visualization throughout time variations, but cannot assume the integration of other information rather than the noise level, represented by the equivalent level (L_{Aeq}) or another parameter associated with the Sound Pressure Level (SPL), and none of them by means of a 3D platform.

Following the concept of the CityScope Andorra, in collaboration with La Salle Campus Barcelona and the Observatory of Sustainability of Andorra (OBSA), the Actuatech Foundation is working on a project to analyze the noise pollution that is currently affecting the population of Andorra and to find a way to minimize any harmful effects it may produce. An initial study [33] characterized and classified the topology and intensity of noise events in strategic points of Andorra, with raw acoustic data collected with a digital recorder, while this work is centered on the initial exploration of data visualization to provide citizens and public administrations with a general overview of the noise pollution situation. The Andorran Government and the municipality of Escaldes-Engordany aim to create a real-time monitoring system together with several sources' data integration, in order to increase the knowledge of the urban dynamics data for future policies' design. This project addresses a part of this wide goal. More specifically, the work developed in this project is aligned with the national strategy that the Ministry of Environment and Sustainability is currently developing in terms of noise pollution. The aim of the Ministry is to identify and monitor the noise sources, analyze them until they can be modeled, while they are mapped in order to visualize the effects of noise pollution, and improve

the mitigation policies to reduce the impact in selected areas of the country. Moreover, the Ministry of Tourism is currently developing and implementing the National Strategic Plan of Tourism and Commerce 2015–2019 [34], which includes actions to reduce noise pollution. This strategic plan, developed jointly with the Ministry of Environment, has both the goal of developing a sustainability label and improving the indicators related to the experience of tourism. Within this context, this project focuses on providing a new visualization tool to display relevant results to address more suitable measures and city interventions in order to reduce noise pollution and increase the quality of the environment and the welfare of the area [35–37].

Moreover, the work presented in this paper intends to be used both in the field of the policy-makers, to take better-informed decisions on how to minimize the impact of environmental noise on people, but also to support researchers to visualize the acoustic data recorded and the timeline of the events. The visualization method proposed supports the understanding of the acoustic data collected and helps the space-time interpretation of the events, previously labeled or identified. Soundscape and urban designers require tools to simulate before the design proposals and to evaluate after it, and this is a visualization instrument to be used both in the previous estimations for an urban design, but also for the evaluation of any urban environment under study.

This paper is structured as follows. Section 2 gives the details of the acoustic data collection and basic dataset analysis. In Section 3, we describe the methodology followed to classify the types of noise source to be mapped and the types of events that included each category. Section 4 describes the analysis of the real operation audio collected. Section 5 works on the calculations required to map the different types of sound detected, as the Signal-to-Noise Ratio (SNR), the equivalent level L_{Aeq}, and the visualization of the measurements conducted. Section 6 states the conclusions of the advantages of the new noise visualization proposed and the future work related to this paper to improve it.

2. Real Operation Andorra Acoustic Data

Currently, a number of seasonal campaigns were undertaken by the Government in specific measurement points around the country. Based on the L_{Aeq} measures, a qualitative indicator is calculated in order to provide indicators (good, moderate, bad, . . .) of the quality of the environment in terms of noise pollution [37]. However, these measures are neither in real time, nor do they consider the type of sound that has been proven to have a significant effect besides the equivalent level; hence, the task of analyzing health and welfare impacts on citizens and tourists/visitors becomes more difficult. This information was used to select the three pilot areas under study where the recordings were conducted [33].

2.1. Measurement Equipment Requirements

Several different types of equipment were required for the recording. Since one of the goals of this project was to analyze raw data, a sound level meter was not necessary for this purpose. Instead, a ZOOM H4n digital recorder [38] was used to perform the documentation of noises. With the help of a 1.5-m tripod (where the sensor was placed), we intended to nullify the bouncing effect of the ground to achieve a clean and reliable sound map. As can be presumed from Figure 1, there were buildings or walls behind the sensor, which were kept at a minimum distance of 2 m to avoid also the bounding effect. It is also to be noted that the correct inclination for the sensor to be placed to achieve omnidirectionality was 45°, and that during all recordings on both days, it strictly remained at that angle.

In order to obtain the most accurate and complete analysis possible, notes were taken every time that a sound that could be confused was detected. This process was done manually by an expert technician, observing every event along with a timestamp to make the identification easier once the data were classified in a computer.

2.2. Recording Locations in Andorra and Escaldes-Engordany

The project started recording in three different locations, which corresponded to three nodes with a substantial volume of both traffic and pedestrians, carefully selected to provide as much relevant data as possible [33]. The length of each of the recordings was 10 min, and they were conducted all along the day (not at night) on 2 March and 15 April 2018, in the winter. For more details about the recording campaign, the reader is referred to [33].

- Location (a), found at $42°30'24.0''$ N $1°32'02.5''$ E (see Figure 2a), is a key point connecting the three main roads of Andorra in the capital [35,36]; it has the heaviest traffic during rush time, especially during weekdays. The principal source of noise was expected to be traffic, so it should have constant high equivalent levels of noise and a lower variation of noise sources compared to other areas during the mentioned rush hours and will only decrease as the day goes by.
- Location (b), found at $42°30'30.8''$ N $1°32'02.8''$ E (see Figure 2b), is the intersection between a main road named CG-3, which leads the traffic from Andorra La Vella and Escaldes-Engordany to the northern part of the country, with a wide pedestrian and commercial axis. This is not only a traffic area like Location (a), but one of the most common promenade points for Andorrans and also for tourists. In this area, the number of potential noise sources is wider also during the entire day, which consequently increased our interest in obtaining effective mapping results. Location (b) is of great interest since it recently became the biggest pedestrian area in the country, making it a key point to study the noises that occur in and around it.
- Location (c), found at $42°30'32.3''$ N $1°31'43.9''$ E (see Figure 2c), is also the crossing of a main road and the final part of a pedestrian and commercial street, similar to Location (b). The difference with Location (b) that this street is not totally pedestrianized, since it depends on traffic lights for people to cross the road. Therefore, we expected a high variability of noise sources during the day as reported in Location (b), but with the additional street works detected during both days of the recording campaign due to different circumstances, creating a totally different noise dynamics for further analysis.

These three locations were selected to analyze noise source identification in three different scenarios from Andorra and Escaldes-Engordany. The Ministry of Environment has these locations in its focus for for future urban noise interventions and to propose noise mitigation measures.
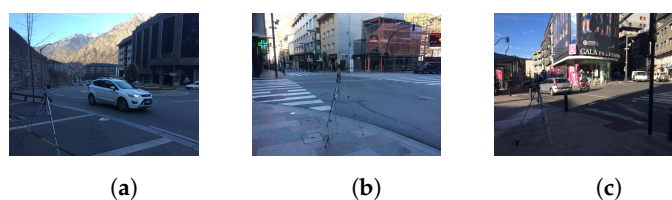

(**a**)   (**b**)   (**c**)

Figure 1. The images above show the three places where the recordings took place and how the equipment was placed in order to achieve reliable data. (**a**) Ctra.de l'Obac, 19; (**b**) Av.Carlemany, 121; (**c**) Av. Meritxell, 73.

(**a**)   (**b**)   (**c**)

Figure 2. The images above show the three places where the recordings took place from a satellite perspective from Google maps (map data: Google 2019). (**a**) Ctra. de l'Obac, 19; (**b**) Av. Carlemany, 121; (**c**) Av. Meritxell, 73.

3. Data Description and Categorization

In this section, we describe how raw acoustic data were labeled to identify the different types of noise events that occurred in the three pilot locations, and then, we describe the four groups of noise events designed for the noise mapping in the 3D city platform.

3.1. Exhaustive Labeling of Events

This subsection is dedicated to emphasizing the complexity of the labeling process itself. Although a relatively simple job in theory, it was done very carefully in order to generate a database from which we would later calculate important parameters such as the duration of each event or the SNR (see Equation (2)). To accomplish such precision, the labeling was carried out using the Audacity freeware software, which allowed us to zoom in to the audio samples and detect sounds as short as milliseconds in length. Even though labels will be later grouped into four main categories for visualization and conceptual purposes, a total of 43 different sounds were used to label all the different events that occurred in both of the recorded time-frames. This number was not defined prior to the recordings, but increased as the labeling process advanced, meaning that the database was as detailed as it could be. The different nature among the four big classes used to categorize all the events, explained in Section 3.2, was an important factor to take into consideration. While vehicles were found in all areas, other more subtle or specific sounds appeared occasionally over time such as walkie-talkies, people whistling, noises from metal tools used in roadworks carried out in the surroundings, or dogs barking in a pedestrian area.

There were some sounds that were barely perceptible or negligible as they were masked behind a louder noise such as a person whistling or a vehicle accelerating. It is important to mention that a special label was used as common traffic background noise, since it was rare to find any moment with no noise at all. The label for that was called RTN, standing for Road Traffic Noise. In these cases, if there was a different perceptible noise, no matter how light it was, the label that prevailed was the other perceptible. However, in a scenario in which two or more sounds overlapped, the COMPLEXlabel was used in order to discard that sample, as it would provide false information when being processed afterwards and the conclusions could be misleading. The reader is referred to the work [33] for the entire list and details of the 43 noise sources found in these three Andorran locations.

3.2. Categorization of Street Noise Events

In order to better understand the noise dynamics and their sources at each of the three measurement locations, different categories of types of events were defined. These categories were selected to comprise the most common and problematic sources of noise in different classes that would later facilitate the analysis and interpretation for the data visualization.

Four categories were defined:

- Vehicles: Noise sources coming from any kind of vehicle, albeit without an engine. This category was chosen as all of the measurement points have a road nearby where a significant density of vehicles circulate every day, so traffic plays an important role in acoustic pollution.
- Works: Noise sources related to street or construction jobs. This category is defined to consider construction works located near the recording points and helps to characterize the contribution of construction to the impact of sound on the population.
- City life: Noise sources from typical events occurring in an urban area (other than vehicles) that helps to provide a wider context to the measurements taken and the local surroundings. This category comprises noise events coming from traffic light emitters, sirens, or music coming from commerce or cars.
- People: Human noise sources. This category is important as some of the measurement areas have pedestrian or half-pedestrian zones highly frequented by both residents and tourists, so it is expected that in this category, human noise sources will be one of the most significant or frequent labels identified during the measurement periods.

4. Analysis of the Real Operation Audio Collected

In this section, the metrics used to describe the acoustic sound events found in the labeling process conducted over the raw acoustic data are briefly described. The duration, the L_{Aeq}, the SNR, and the timestamp, crucial for a precise real-time noise mapping, were used to describe each and all of the noise events identified. For more details about the deep events' analysis, the reader is referred to [33].

- Duration: This was evaluated in fractions of a second and corresponds to the time that the 3D visualization platform would spend to show its values.
- L_{Aeq}: This is also known as the time-average or equivalent sound level [39], and it stands for the equivalent of the total sound energy measured over a limited period of time.
- SNR: The Signal-to-Noise Ratio is the relation between any noise event's evaluated power and the power of the previous and the posterior Road-Traffic Noise (RTN) surrounding the event under study. For more details about the calculus of the SNR, the reader is referred to [40].

$$P_x = \sum_{t=1}^{N} \left(\frac{x(t)^2}{N} \right), \tag{1}$$

where N corresponds to the number of samples and $x(t)$ stands for the time-dependent event under study. The value of SNR is calculated as the following equation:

$$SNR = 10 log_{10} \left(\frac{P_{NE}}{P_{RTN}} \right), \tag{2}$$

where P_{NE} corresponds to the noise event power and P_{RTN} relates to the previous and posterior RTN surrounding the event under study. It should be pointed out that when calculating both powers, N may not have the same size without an impact on the result, because it is normalized by N in the final part of the calculation.

This dataset contains events with negative SNR; this can happen when the surrounding vehicle noise was louder than the labeled event noise or that the event sound was weak, assuming the fact that the noises were labeled only if they were heard. Despite that negative SNR events may have a low impact on humans, we represent them to enrich the diversity of types of events found in the dataset, assuming that at a certain moment, the same type of event can occur with a higher or a lower SNR.

5. Methodology and Visualization

The proposed visualization is a projection of the noise event measurements over the Andorra 3D city model used by the Actuatech Foundation, which is displayed as a series of circles that change shape,

size, and color depending on the noise characteristics over the 3D city model in Figure 3. The main goal is to develop an introductory tool, specifically targeted at people without a technical background in the field, facilitating the understanding of the acoustic pollution topology and promoting discussions about mitigation actions and policies.

5.1. First Visualization Approach

Acoustic pollution is typically represented by means of noise maps, where the area is colored according to noise equivalent levels. This leads to a spatial representation where a unique magnitude is displayed and colors are interpolated from single measurement points using specific models. The initial design of this visualization was intended to break with this classic noise mapping representation. The need to display magnitudes other than the equivalent level led us to target measurement points and use geometric and color transformations to represent variations in those variables. Moreover, the project is not focused on analyzing the spatial spread of the sound, but segregating noise events into specific categories and observing the predominance and parameters of each category.
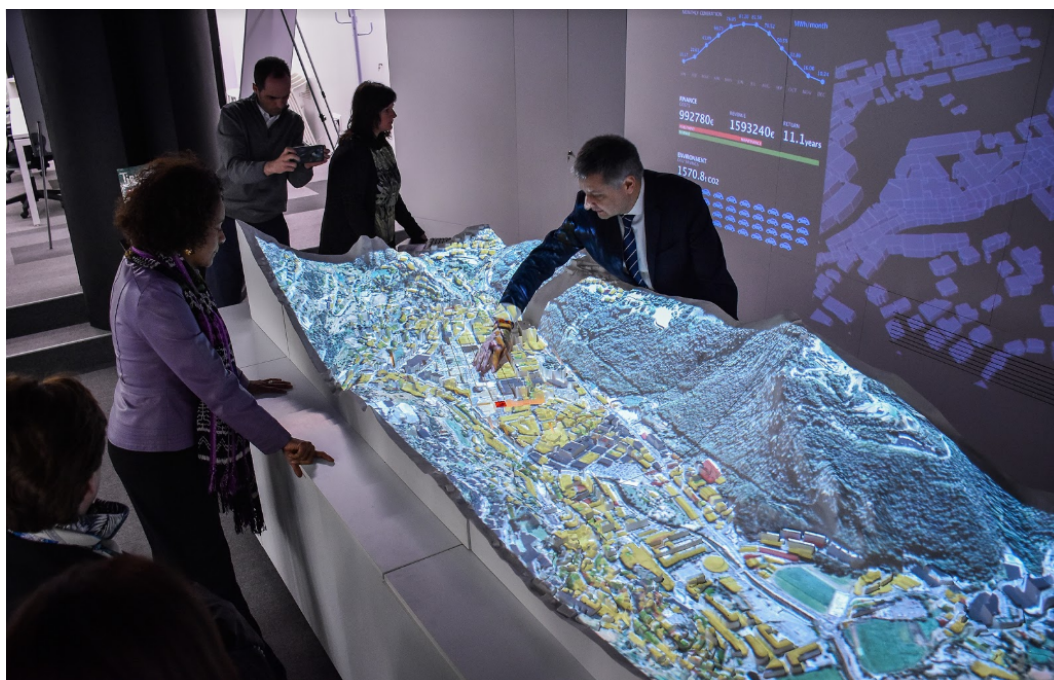

Figure 3. Discussion about the Andorra 3D city model between the Minister of Economy, Innovation and Competitiveness and the Ambassador of La Francophonie.

Due to the fact that humans are very sensitive to detecting and recognizing small deviations from the circular form [41], a straightforward visualization was to represent single sound events as concentric circles aligned in the measurement location. The color of each circle was assigned according to the category to which the sound was associated, resulting in four different possible colors in each location. Different colors were deliberately chosen in order to facilitate their visualization. The radius of the circle was assigned according to the calculated SNR of the sound event in dB. Although the logarithmic scale is complex to understand, especially in visual comparative terms, the fact that it keeps visualization within an appropriate range while respecting the 3D model platform restrictions makes it an effective method to represent the data within an appropriate margin of values. A slight random ripple was also applied to each circle to add some visual dynamism.

A missing piece in the visualization was identified after implementing this first approach. Although the radius of the circle represented the SNR, a representation of the equivalent continuous sound pressure level (L_{Aeq}) was not included. This value was especially important in comparative

terms because it allowed the locations to be easily identified with the highest impact of the noise as a whole.

5.2. Visualization Approach Including L_{Aeq}

A slight modification of the first approach included the L_{Aeq} into the visualization, which enriched the data projection into the 3D city model (see Figure 4). The radius of the circles was set according to the L_{Aeq} value; meanwhile, the SNR was represented by varying the ripple amplitude. The ripple became a direct informative element of the visualization instead of being purely aesthetic and was not generated randomly any longer, but with a defined oscillation frequency. All these measurements and variations were related to the time series recorded and labeled. This approach had three main limitations:

- When a sound event occurred, the circle rippled according to the event's SNR. The visual effect looked harmonic in a single circle scenario, but it became cluttered when multiple circles were overlapped.
- Any SNR bigger than 3 dB produced a ripple amplitude more than twice the radius of the circle. If the sound events were susceptible to reaching more than 20 dB, the circle would overpass 3D surface bounds and become totally useless in terms of the interpretation.
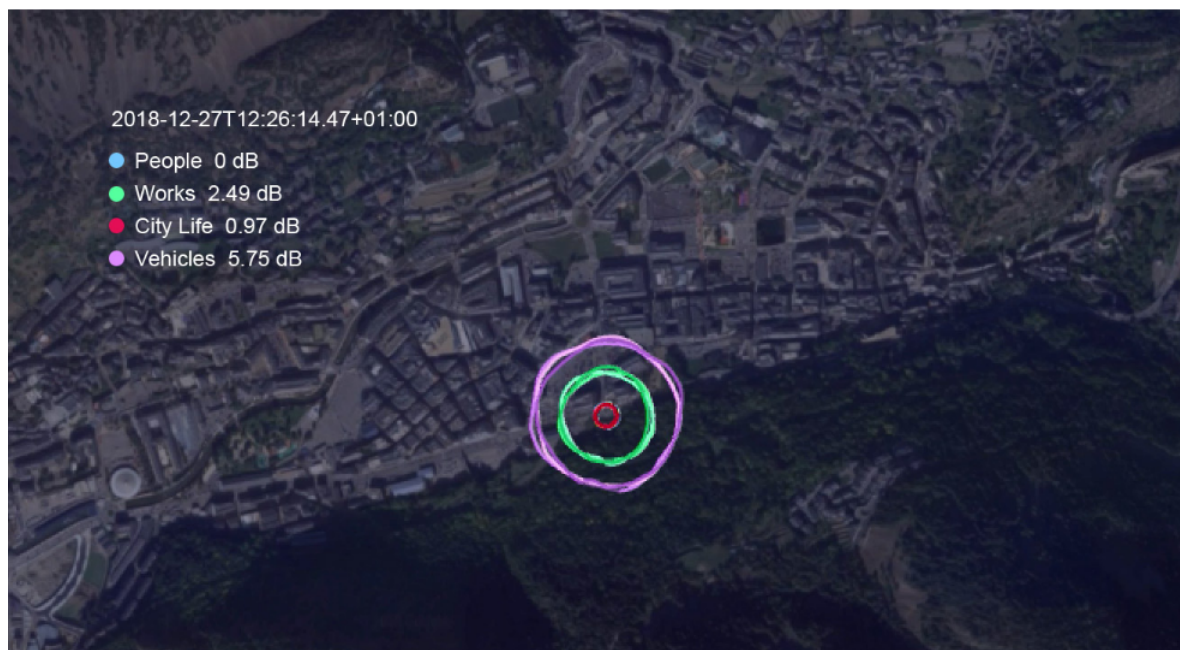- Negative SNR values cannot be represented in terms of ripple amplitude.

Figure 4. Single location noise event visualization.

A discussion on how to overcome these limitations led us to consider new visualization strategies. The ripple's origin was not set at the circle's radius distance, but instead displaced by half of its amplitude; the minimum crests of all ripples matched the circle's radius value, which was common in all ripples. The SNR representation was downscaled to a limited range of magnitudes, depending on the visualization platform size, to the detriment of the real ratio between equivalent noise and sound event levels. It was considered to represent negative SNR values with the ripple inside the circle radius, the ripple's amplitude being larger the lower the SNR. While this workaround represent all recorded events, it may introduce a cognitive bias and create confusion in order to understand the impact of very low level sounds, so it was decided to not represent events with negative SNR.

Another limitation comes with the events with negative SNR. A proposed solution, shown in Figure 5, could be to represent positive SNR as an outside ripple and negative SNR as an inside ripple,

the ripple's amplitude being larger when the SNR is smaller. While this solution represents all recorded sounds, it may introduce a cognitive bias and create confusion in order to understand the impact of very low level sounds.
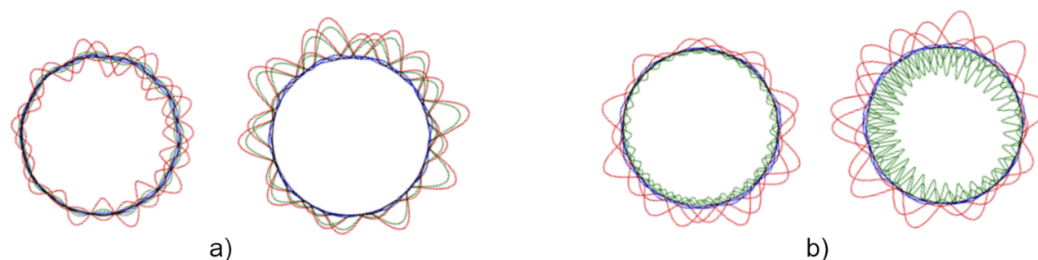

Figure 5. (**a**) Centered vs. displaced ripple's origin and (**b**) negative ripple representation (−0.12 dB and −2.45 dB).

5.3. Implementation of the Visualization over the 3D City Model

The visualization was developed in Processing [42], a Java-based open-source programming language and integrated development environment that serves as a tool for teaching and producing multimedia and interactive digital design projects. Processing allows full control on graphics usage, including shaders, and has dozens of libraries implemented to work with IO components, computer vision, timing control, or multiple file types. The images produced by Processing were mapped over the 3D city model of Andorra and Escaldes-Engordany.

The input of the simulation was a CSV file with a record for each one of the captured sound events, ordered chronologically following the recorded and labeled time-series (see Table 1). Every event was defined by 4 fields, which are common to the list in Section 4:

- ANE (Anomalous Noise Event): categorization label for every sound event. The label was indexed and grouped by the 4 categories described in Section 3.2.
- SNR: Signal-to-Noise relation in dB of the event over the RTN.
- L_{Aeq}: equivalent noise level.
- TS: Timestamp of the event captured in the format hh:mm:ss,d. Even if the resolution could be higher, a decisecond was chosen, as it was considered enough for representational goals.

Table 1. Sample of the input data. TS, Timestamp.

ANE	SNR	L_{Aeq}	TS
BARK (dog barking)	6.745	62.6	00:12:23.4
CMPLX (complex)	1.365	63.1	00:12:34.1
RTN	0	62.8	00:13:18.6
BRAK (brake)	9.734	64.5	00:13:32.8

The input data were loaded during the initialization stage. While a stream loaded by chunks would make more sense in a real-time animation, the input data were actually a preprocessed file with clustering and corrections applied beforehand. Loading the whole file at once was an easier approach in terms of data architecture, which implies a few extra benefits such as global statistics and the possibility to add timeline controls. Data loading and manipulation would be restructured once the operation enabled a real-time data integration.

Figure 6 shows the final visualization, a projection of different animated circles located on the 3D city model at the spot where they were measured and varying their diameter and ripple's amplitude depending on the sound measurements at each point of the timeline. No controls were provided at the moment, other than stopping and resuming the animation, but simple timeline control options are on the roadmap for the development in the short term.
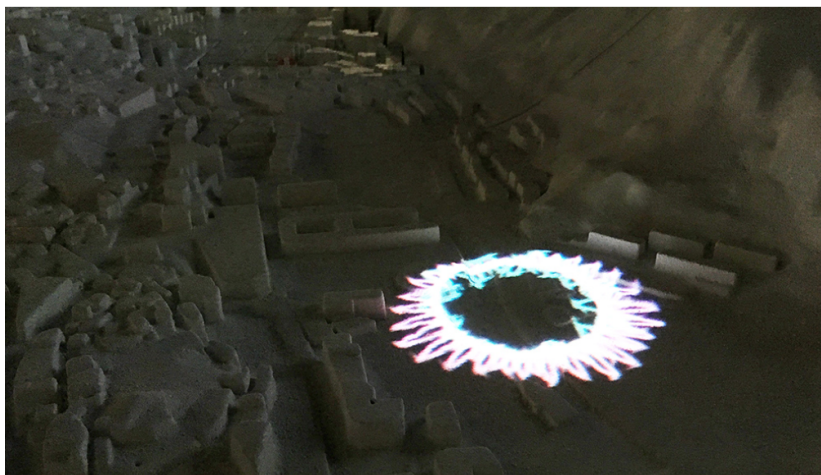
Figure 6. Sound circles on the 3D model.

6. Conclusions

In a noise measurement system with source identification, it is crucial to be able to distinguish clearly and accurately the origin of sounds. The way these results are shown to people is equally important, since the measurements taken are often not easily understood by non-expert observers. The proposed visualization does not provide a deep understanding of noise effects to the population or the environment, but gives a big picture on sound events and their variations through colors, shapes, and sizes. This information can be shared easily with all public and any non-expert audience and allow them to compare where, when, and what is happening in their city. Having this kind of easy-to-understand visualizations on a 3D city model, in which the noise events can be spatially and temporally crossed with other sources and layers of information, has a great potential to foster interpretation and discussion about the impact of noise pollution events and sound landscapes on the city. Moreover, the proposed visualization method can improve the design of future soundscapes, as well as support the analysis of the existing ones.

This approach could help to understand collaboratively the noise problem and raise awareness in different types of stakeholders, as well as help to explore and discuss potential measures and interventions and support decision-making processes, or promote social and behavioral changes of citizens. Currently, the Andorran Government is working with the different municipalities with the goal of creating a national acoustic register, because all administrations are working now only based on noise equivalent levels L_{Aeq}. The work presented in this paper is contributing to the exploration of the diversity of noise sources in the different areas of study and the interest to include more information about the measurements in the acoustic cadaster to widen the analysis over the Andorran territory, in this project, but in any other locations in the future.

Future work of this project will focus on the implementation of the automatic class detection system, which is already working in other environments with two classes developed by the same signal processing research group. The second of the future lines is the development of real-time operation with a network of acoustic sensors deployed in Andorra and Escaldes-Engordany, in order to enable the real-time monitoring of the acoustic environment of the country.

Author Contributions: R.M.A.-P. designed the recording campaign and wrote a part of the paper. M.V. supported the design of the experiments in the cities of Andorra la Vella and Escaldes-Engordany, and wrote the part about visualization. M.P. helped with the location-deciding of the recording campaign and wrote the part of the paper related to policies and future work in Andorra by the government. R.G.A. conducted most of the recording campaign and conducted the tests, and also wrote a part of the paper.

Abbreviations

The following abbreviations are used in this manuscript:

ANE	Anomalous Noise Event
END	Environmental Noise Directive
L_{Aeq}	Equivalent Level A-weighted filter
OBSA	Observatori de la Sostenibilitat d'Andorra
RTN	Road Traffic Noise
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
WASN	Wireless Acoustic Sensor Network
WSN	Wireless Sensor Network

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