



HAL
open science

Case study on the audibility of siren-driven alert systems

Jonathan Siliézar, Pierre Aumond, Arnaud Can, Paul Chapron, Matthieu Péroche

► To cite this version:

Jonathan Siliézar, Pierre Aumond, Arnaud Can, Paul Chapron, Matthieu Péroche. Case study on the audibility of siren-driven alert systems. *Noise Mapping*, 2023, 10 (1), 10.1515/noise-2022-0165 . hal-04494199

HAL Id: hal-04494199

<https://hal.science/hal-04494199v1>

Submitted on 29 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Research Article

Jonathan Siliézar*, Pierre Aumond, Arnaud Can, Paul Chapron, and Matthieu Péroche

Case study on the audibility of siren-driven alert systems

<https://doi.org/10.1515/noise-2022-0165>

received January 18, 2023; accepted May 04, 2023

Abstract: The civil security sirens are used by the authorities in a wide range of countries to signal an imminent or ongoing threat. Even if their sound level is known, it is nevertheless difficult to evaluate their audibility across a given zone, especially in complex urban environments. An experimental protocol was deployed around a siren installed in a town in France, to assess its audibility perceptually and through modeling. Sound level measurements during source activation were made with the NoiseCapture smartphone application at different distances and on several axes by a group of 25 participants. They were also asked to fill in a questionnaire on perceptual information about the siren such as its audibility, the perceived sound level, or the masking of the siren by passing vehicles. A comparison between acoustic measurement levels using NoiseCapture and simulated sound levels using NoiseModelling was performed. The results of this study validate the use of the Common Noise Assessment Methods in Europe model to evaluate the audibility of a warning system located in an urban environment within a radius of 2.8 km around the siren. Finally, a metric linking audibility to modeled sound level is proposed, enabling the development of siren audibility maps in the study area.

Keywords: warning sirens, audibility of sound sources, noise mapping, NoiseModelling, audibility maps

1 Introduction

Sirens are indispensable warning vectors to alert the population of the arrival of an imminent risk: earthquakes, tsunamis, fires, or terrorist attacks [1,2]. Triggered in time, civil security sirens remain a centralized, redundant, and efficient vector to warn the population of an imminent threat and of the need to inform oneself. They produce both collective and individual reactions, they are efficient to alert a whole population, day and night, they leave no time for hesitation, and they require immediate reactions [3]. The effectiveness of early warning systems is one of the main risk reduction strategies for communities vulnerable to natural disasters [4,5].

Although the effectiveness of sirens heavily depends on them being properly heard by as many people as possible [5,6], the structure and densification of the siren network are mostly based on technical constraints rather than on an effort to optimize their sonic spatial coverage [7]. The authorities in charge of triggering alert sirens, from the local to the national level, do not have precise knowledge of the theoretical spatial coverage of the sound signal [4]. This zoning is usually mapped by concentric circles around the sirens whose distances would represent theoretical sound level threshold values generally around 800 m, 1.6 km, and 2.4 km for the maximum distances [8–10]. This mapping does not capture the complexity of sound propagation and its effect on the spatial coverage of the alarm sound, which is influenced by many environmental factors such as terrain, buildings, and weather conditions [11,12]. When evaluating the spatial coverage of an alarm siren in complex environments, the impact of environmental conditions and urban geometry can be modeled by the sound wave attenuation factor which describes the relationship between signal level and distance in terms of the number of decibels the signal is reduced each time the distance between the source and the receiver is doubled. Since the attenuation factor is highly dependent on the geometry of urban configurations, a higher attenuation factor will seriously reduce the effective range of air raid sirens [13]. The optimum location for siren

* **Corresponding author: Jonathan Siliézar**, Université Gustave Eiffel, CEREMA, UMRAE, F-44344 Bouguenais, France, e-mail: jonathan.siliezar-montoya@univ-eiffel.fr

Pierre Aumond, Arnaud Can: Université Gustave Eiffel, CEREMA, UMRAE, F-44344 Bouguenais, France

Paul Chapron: LASTIG, IGN/ENSG, Université Gustave Eiffel, 73 Avenue de Paris, 94165 Saint-Mandé, France

Matthieu Péroche: LAGAM, Université Paul Valéry, Rte de Mende, 34090 Montpellier, France

warning systems was also studied by Wanniarachchi and Lakmal [14]. The authors set up a methodology involving geographic information system (GIS) tools, local authorities' census information, and field surveys with community members to identify the locations and current conditions of the siren system. Siren location-related data were stored and analyzed using GIS software and the modeling of the warning system was carried out using buffer areas around each siren (500, 1,000, and 1,500 m). The surveys led to a mapping of the zones where the siren was audible indicating coverage of 1 km around the base of each tower and suggested several factors to be taken into account when evaluating the optimal locations for warning systems such as the elevation of the ground and the geographical conditions of the study area and weather conditions.

During the past few years, fast-computing simplified numerical methods have been developed in order to study sound propagation under different types of conditions [15]. In 2017, a GIS-based methodology [16] aiming to refine spatial extent and coverage estimations of sirens by calculating mean siren decibel levels for all buildings in the city and relating those levels to population information was introduced by Reed *et al.* using the SPreAD-GIS noise model [17] that predicts sound level loss due to environmental factors. Even though this noise model has several limitations, including processing time or the inability to input source height into the model, the authors could conclude that approximately 97% of the population should hear sirens at a level of 80 dB or higher in this case study. In 2021, a model to calculate the spatial coverage of warning sirens installed in public transport systems through the overlapping of General Transit Feed Specification real-time data and flood hazard inundation areas [18] suggested that approximately 70% of the population in the target area could be reached using a 70 dB siren. Again, this study was limited by the nonconsideration of external factors such as land cover, buildings, or elevation. Although these numerical approaches have shown consistency with measured sound levels, physical characterization of the signal spatial coverage is not always confronted with perceptual data about the audibility of the siren.

While there is an inherent relation between siren sound levels and their audibility, numerous studies have also underlined the role of external factors regarding the audibility of warning sirens such as background noise [19–21]. Contrasts between warning signals and background

noise can have an impact on its attention demand, thus directly affecting the audibility of the siren [22]. As mentioned in Patterson's paper [23], due to the inherent variability of noise and auditory processing, the detection of a warning signal does not occur at one precise signal level but increases in function of the signal level over a range of about 20 dB. As a consequence, this article recommends a 15 dB difference in the warning signal level with respect to the threshold imposed by the background noise as the lower limit for adequate detection of the signal. The audibility of outdoor sirens considering signal frequency, masking noise, and other external factors was studied by Volkmann and Graham [24] involving acoustic measures and audibility surveys in residential areas. The results presented in this study suggested that for the siren to be completely audible, its basic sound level should be at least 80 dB for a 400 Hz signal and that it needs to have an emission level of 132 dB at 100 ft (30 m). Volkmann and Graham's study [24] also highlighted the diversity of variables (land cover, buildings, atmospheric conditions) that needed to be accounted for in the determination of an efficient siren-driven warning system. Since the date of publication of this study in 1942, we now have access to numerical modeling tools that allow us to take these factors into account, such as those presented in the previous paragraph.

It is therefore essential to establish a methodology that involves perceptual data and establishes a relation between audibility, numerical simulation, and measured sound levels when assessing the spatial coverage of siren warning systems. This is the aim of this article. In Section 2, we propose a methodology on a case study located in the city of Saint-Martin-de-Londres, Hérault department in France, whose relevance will be evaluated to carry out the sound mapping of a siren-driven warning system. We collected acoustic and perceptual data during an experiment in the study area which was then compared with calculations carried out using NoiseModelling, a noise mapping software that embeds the Common Noise Assessment Methods in Europe (CNOSSOS-EU) propagation model. Section 3 presents the results obtained through a correlation test between each dataset. We discuss the technical limitations of this study as well as the perspectives on the future development of the methodology in Section 4. Finally, the consequences in terms of estimation of siren audibility by modeling are reviewed in Section 5.

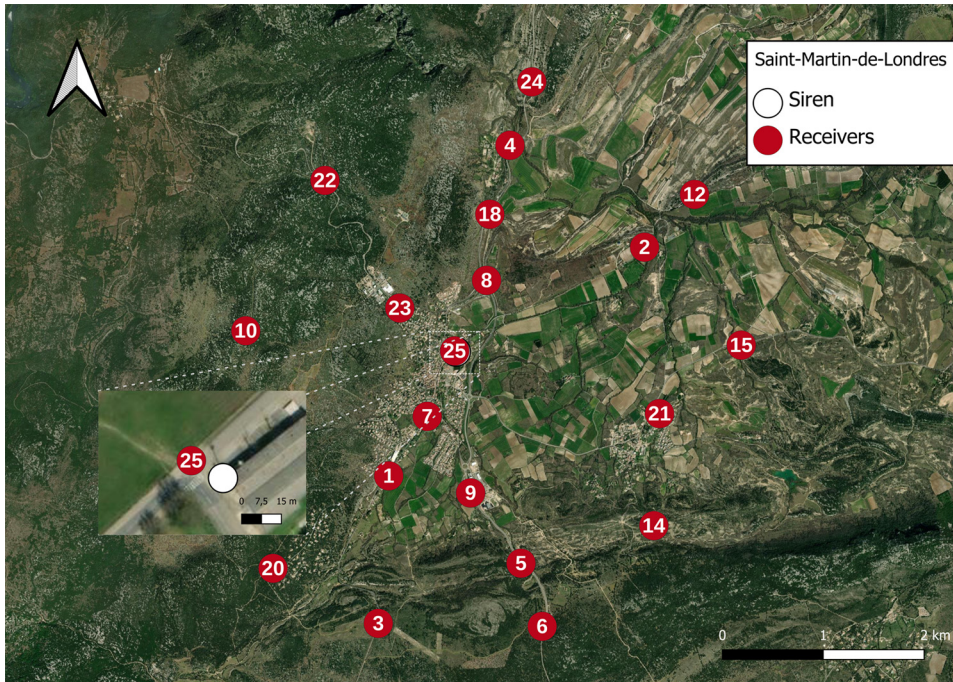


Figure 1: Map of Saint-Martin-de-Londres. The siren is represented by a white point. The participants were positioned at the red points.

2 Methods

2.1 Case study

The study area is located in Saint-Martin-de-Londres, a municipality of about 3,000 inhabitants approximately 30 km north of Montpellier, France. The municipality has a warning siren installed on a mast near a municipal building. The experiment took place on October 6, 2021, at 12:15 during the siren's activation of about 1 min and 41 s, as part of the monthly exercise in France every first Wednesday of the month to ensure that they are functioning properly.

Twenty-five participants (Natural Risks Management Master students of the University Paul-Valéry Montpellier 3) were deployed at variable distances all around the siren at the points indicated in Figure 1. The farthest participants were approximately 2.5 km from the siren's location. Sound level measurements and perceptual data regarding the audibility of the siren were collected simultaneously. For this purpose, participants were equipped with NoiseCapture, an open-source Android application to measure sound levels on a smartphone [25]. Participants responded simultaneously to a questionnaire, in order to evaluate their perception of the siren. The relationship between these two series of

data is addressed in Section 3.2.1. The siren was located on a mast 10 m above the ground and activated for 1 min and 41 s emitting a tonal acoustic signal of 135 dB at a fundamental frequency of 380 Hz. It is composed of an 8-horn-type loudspeaker array in a 360° disposition, therefore ensuring an omnidirectional behavior during activation (Figure 2). Its theoretical spatial extent is around 3 km.

2.2 Tools

2.2.1 Questionnaire

A questionnaire asking about the perception of the siren and the background noise present in the sound environment, as well as information about the traffic flow during the siren activation, was distributed to each participant. This questionnaire was distributed to the participants in the form of a paper that was retrieved at the end of the experience and then tabulated into a spreadsheet. The participants were asked to rate on a semantic differential scale ranging from "Very low" to "Very strong" on the categories "Sound level of the siren," "Siren audibility," "Masking of the siren by passing road vehicles," and "Background noise sound level." Responses were encoded by a value ranging from 1 to 5.



Figure 2: Photography of the siren.

2.2.2 Acoustic measurements

Sound level measurements were achieved thanks to NoiseCapture¹, a free Android application designed to perform acoustic measurements and share the user's sound environment using the microphone on their cell phone [25]. The data obtained by the NoiseCapture application contain the measured sound level by frequency band (1s, third octave), the equivalent sound level over the duration of a measurement in dB(A), an identifier of the measuring device, and its global positioning system (GPS) position at the time of the measurement. The GPS track associated with the sound recording has a temporal resolution of 1s and a mean spatial accuracy of approximately 6 m.

Participants were equipped with the micW i436 calibrated measurement microphone, an omnidirectional microphone with a sensitivity of 6.3 mV/Pa, and a signal-to-noise ratio of 62 dB (1 Pa A-weighted). In addition, a reference

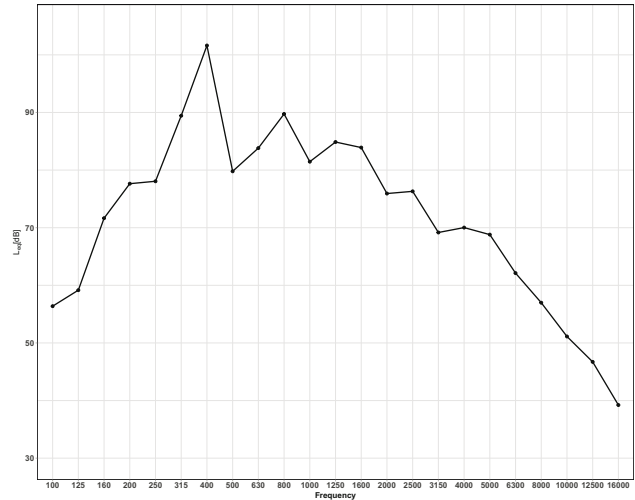


Figure 3: Equivalent sound level per one-third octave band of calibrated sound level meter at 10 m of the siren during its activation.

measurement was made with a class 1 sound level meter near the source when the siren was activated.

Figure 3 shows the equivalent sound level per one-third octave band during the activation of the siren measured by the sound level meter at 10 m distance from the sound source. We can notice that the 400 Hz one-third octave band was the most prominent at the moment of the activation of the siren, which is in accordance with the characteristics of the siren. The equivalent sound level in this one-third octave band will be considered to be the sound level of the siren at a given evaluation point and will be referred to as L_{400} in the following.

The measurement conditions were not ideal, with some wind gusts during the activation of the siren. In addition, the method used to measure noise levels is potentially relatively sensitive to the acquisition conditions, with smartphones held in the hands of participants. In consequence, the sound level of the siren at a given evaluation point, named $L_{400_{obs}}$ hereafter, was determined manually from the temporal evolution of the 400 Hz one-third octave. This choice was done carefully observing the temporal emergence of the measured L_{400} one-third octave band with respect to L_{315} and the activation of the siren (estimated using a sound speed of 340 m/s). The main reason to select an equivalent level for the 400 Hz one-third octave was the fact that during the activation of the alarm and considering that its main frequency is located at 400 Hz, the 315 Hz band should not show any visible change in level since it is not concerned by the alarm frequency extent (while higher frequencies may contain harmonics of the fundamental frequency of 380 Hz). The time series for L_{400} one-third octave band, the emergence (L_{400} with respect to L_{315}), and the

¹ <https://noise-planet.org/noisecapture.html>.

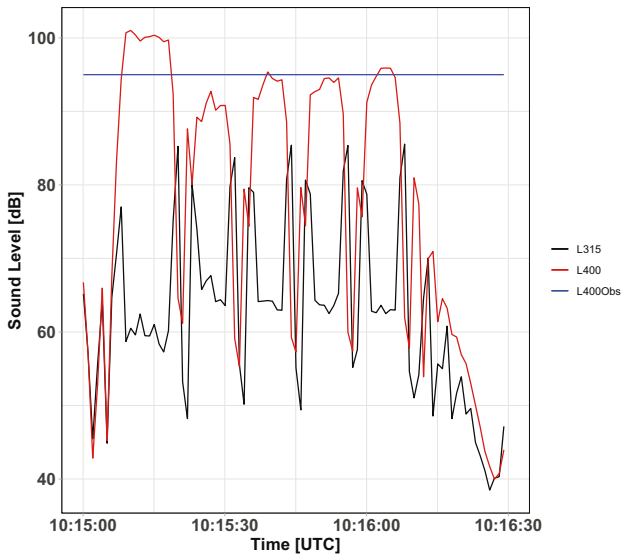


Figure 4: Temporal evolution of sound levels at 315 and 400 Hz for the nearest point to the siren (point 25). The blue line indicates the observed sound level manually selected as the equivalent sound level at the time of the alert. For the temporal evolution of each measuring point, please refer to the Appendix section.

observed equivalent sound level $L_{400_{Obs}}$ are shown in Figure 4 and Appendix. During the processing of the measured acoustic data, we noticed that 5 out of the 25 measurements were not exploitable due to corrupted data from inadequate handling of the measuring device by the participant, wind, or overall non-optimal conditions. These measurements were then manually removed from the dataset. The technical limitations of this manual approach are discussed in Section 4.

2.2.3 Numerical modeling

The sound propagation calculation in the study area is performed using NoiseModelling, which integrates the sound propagation model CNOSSOS-EU, a standardized model for the elaboration of strategic noise maps [26]. Using the geographic location provided by the NoiseCapture data collected during the experiment, we generated a layer of 20 receiver points distributed in the study area at every location of the participants during the experiment.

The siren was modeled by a source point placed at its exact location, with a sound level of 135 dB at 400 Hz since it is the closest one to 380 Hz, which is the fundamental frequency of the source. The modeled signal is considered tonal at the siren's fundamental frequency and constant.

This is an assumption, compared to the actual signal of warning sirens in France, which emit a signal that

gradually increases over a period of 3 s in sound level and frequency, until it stabilizes at its maximum power and frequency of 380 Hz for 58 s, and decreases for the last 40 s. This simplification is discussed in Section 4. Two different numerical modeling configurations are considered:

- Configuration 1: A first, simple configuration aiming to replicate the classic concentric circle approach taking into account only the geometric divergence;
- Configuration 2: A second, more complex approach that considers the sound propagation conditions on the study area, as taken into account within the CNOSSOS-EU model.

The objective is twofold: first, to visualize the difference in the spatial distribution of sound levels resulting from the two configurations, and, second, to evaluate the validity of each configuration for estimating sound levels and siren audibility. Figure 5 shows the input parameters for each configuration.

The input data and calculation parameters used for configuration 2 are as follows. The geometry of the buildings, the ground topography, and the digital elevation model come from the BD TOPO ©databases départementale 2018² and BD ALTI ©25 m 2021³ from IGN (French National Mapping Agency), respectively. The absorption factor G for soil was assigned to the ground layer according to the recommended values given by CNOSSOS-EU.

Diffraction from vertical and horizontal building edges were taken into account, as well as reflections 2 from facades within 500 m of the receiving point.

The directions of the favorable conditions for propagation were estimated on the basis of meteorological forecasts, as well as field experience. The values retained for each of the cardinal directions are presented in Table 1. The wind direction as informed by⁴ is presented in Figure 6.

3 Results

3.1 Cartographic representations

Sound levels are calculated with the two configurations on a regular grid of 95,160 (305×312) receiving points, each point being up to 20 m from the next point. The

² <https://geoservices.ign.fr/bdtopo>.

³ <https://geoservices.ign.fr/bdalti>.

⁴ <https://www.infoclimat.fr/observations-meteo/archives/6/octobre/2021/saint-martin-de-londres/000QM.html?graphiques>.

Name	Buildings	DEM	Ground	Meteorological conditions	Horizontal diffraction	Vertical diffraction	Reflection order
Configuration 1	No	No	No	Unfavourable	No	No	0
Configuration 2	Yes	Yes	Yes	Favourable	Yes	Yes	2

Figure 5: Input parameters for each configuration.

Table 1: Probability of occurrence of favorable conditions

Direction	North east				South east				South west				North west			
Slice	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Value	0	0	0	0.4	0.9	0.9	0.9	0.9	0.7	0.5	0.3	0.1	0	0	0	0

resulting noise maps are shown for each configuration in Figures 7 and 8.

Results for configuration 1 are shown in Figure 7. The concentric circle's approach does not take into consideration how the complexity of the urban geometry affects the propagation of sound waves, and external factors such as ground absorption, wind, and temperature gradients, or horizontal and vertical diffractions, are not accounted for in the sound level calculation. Instead, isophone lines decrease only in the function of distance. For configuration 2, even though Figure 8 highlights a decrease in the sound levels as the distance increases from the source, this reduction is neither monotonic nor uniform. Isophone lines are far from concentric which may question the theoretical threshold approach generally used to characterize siren noise spatial coverage. This cartographic representation suggests that the sound

levels are impacted not only by the distance to the sound source but also by the topography of the zone, the presence of buildings, the digital elevation model, and wind and temperature vertical gradients.

A closer look at Figure 8 reveals an abrupt decrease in the sound level near the landfill site of the city (about 45° northeast from the siren), where a mound interferes with the sound wave propagation. The decrease on the sound levels can be explained by the vertical diffraction to which the wave is exposed due to the topography of the site. In detail, the vertical surface created by the mound produces a masking effect, resulting in lower levels on the receivers just behind the area. This is a clear example of the impact of the topography on sound wave propagation and it is discussed in Section 4.

Figure 9 represents the audibility values from the perceptual dataset. Distances does not appear to be the only parameter impacting the audibility of the siren, as some participants perceived the siren at a medium level while being located farther than others perceived the siren at a low level, for example on the east part of the study area. Bias could be due to the propagation model but also due to the different perceptions of each participant. The following section discusses in more detail the links between acoustic measurements, perception, and simulations.

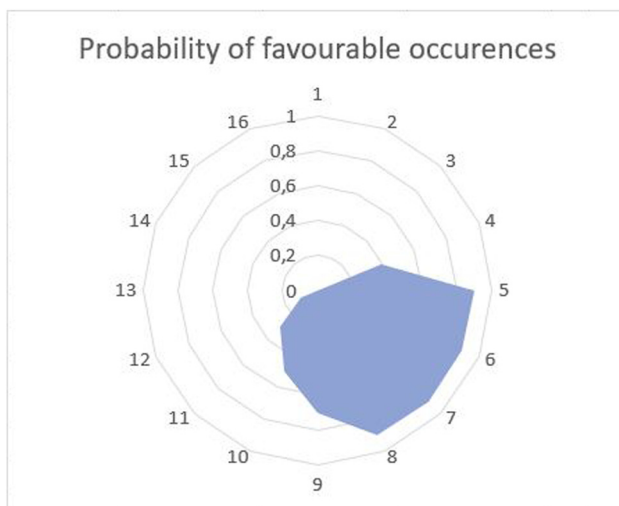


Figure 6: Probability of occurrence of favorable conditions on 6 October 2021.

3.2 Cross analysis: Acoustic measurements, perception, modeling

A cross-analysis has been performed between acoustic measurements, simulated noise levels, and perceptual data in order to compare the different modeling approaches. The Spearman correlation coefficient is calculated to establish the monotonic relationship between each dataset and so it is more adequate for our particular case considering our data. In this section, we introduce five indicators

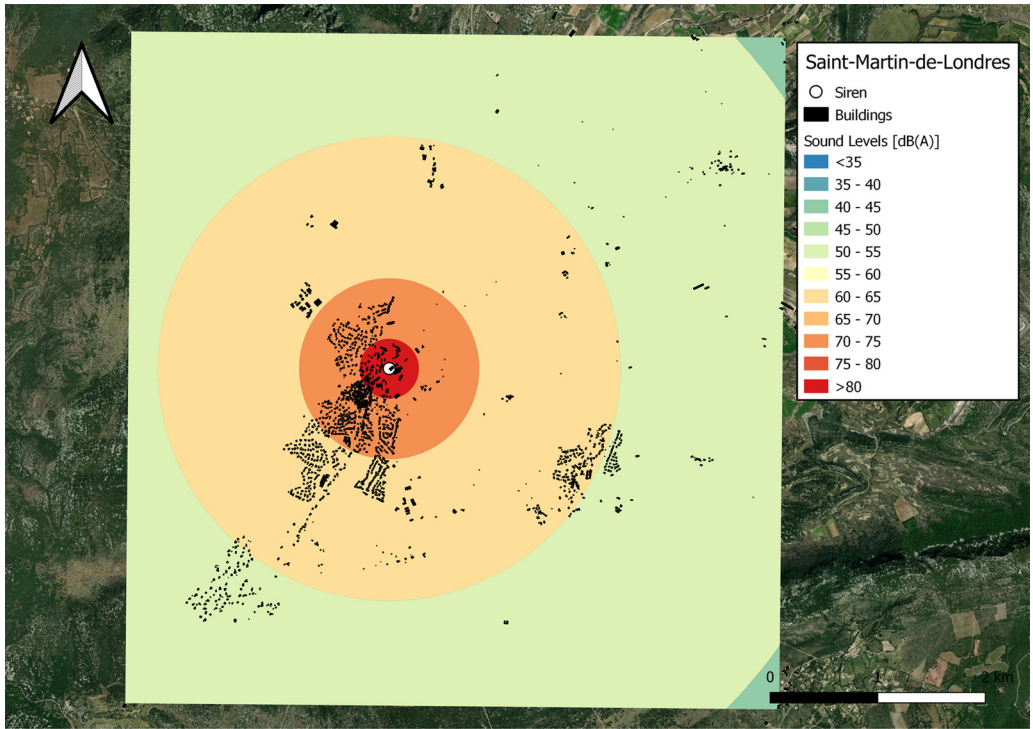


Figure 7: Cartographic representations of the siren sound propagation: Configuration 1.

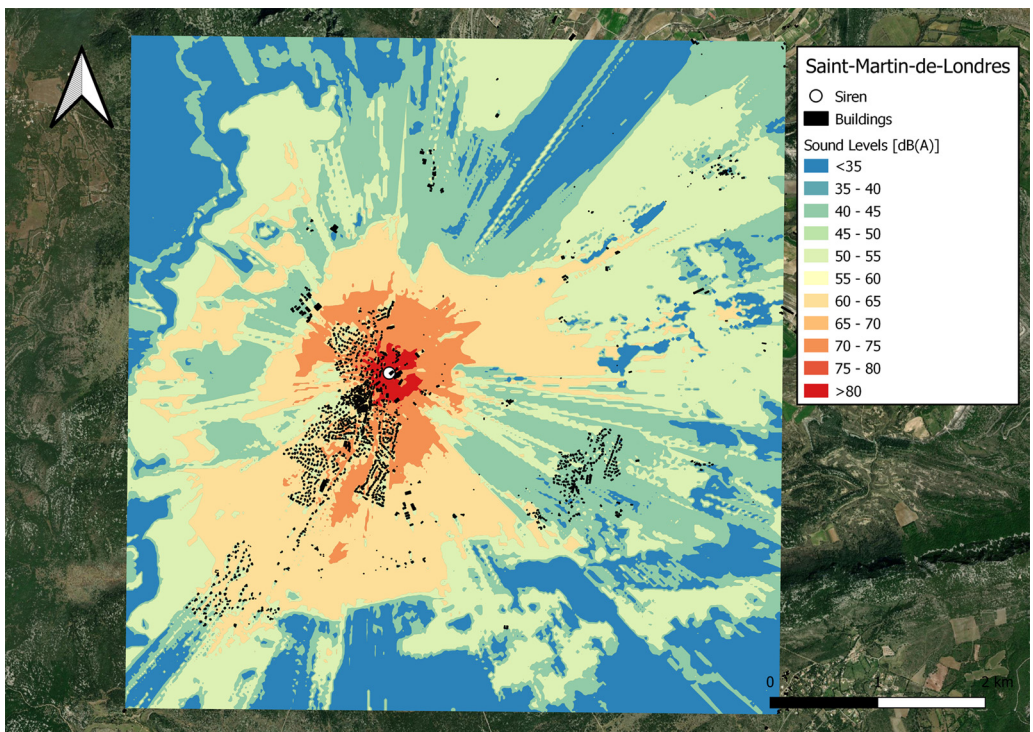


Figure 8: Cartographic representations of the siren sound propagation: Configuration 2.

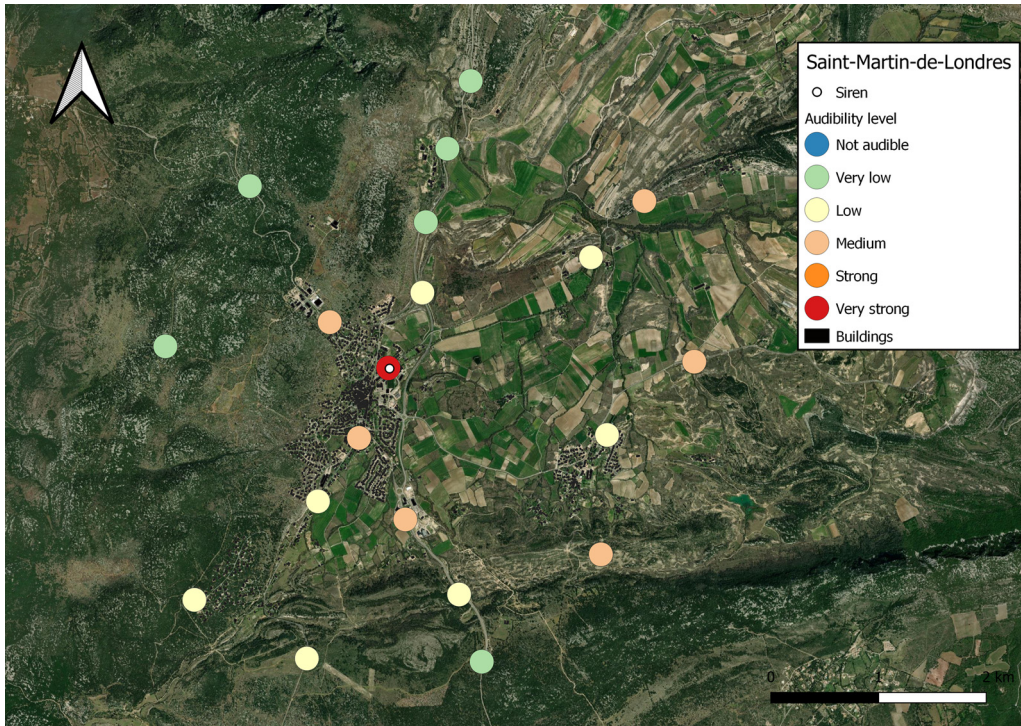


Figure 9: Mapping of siren audibility as reported by participants.

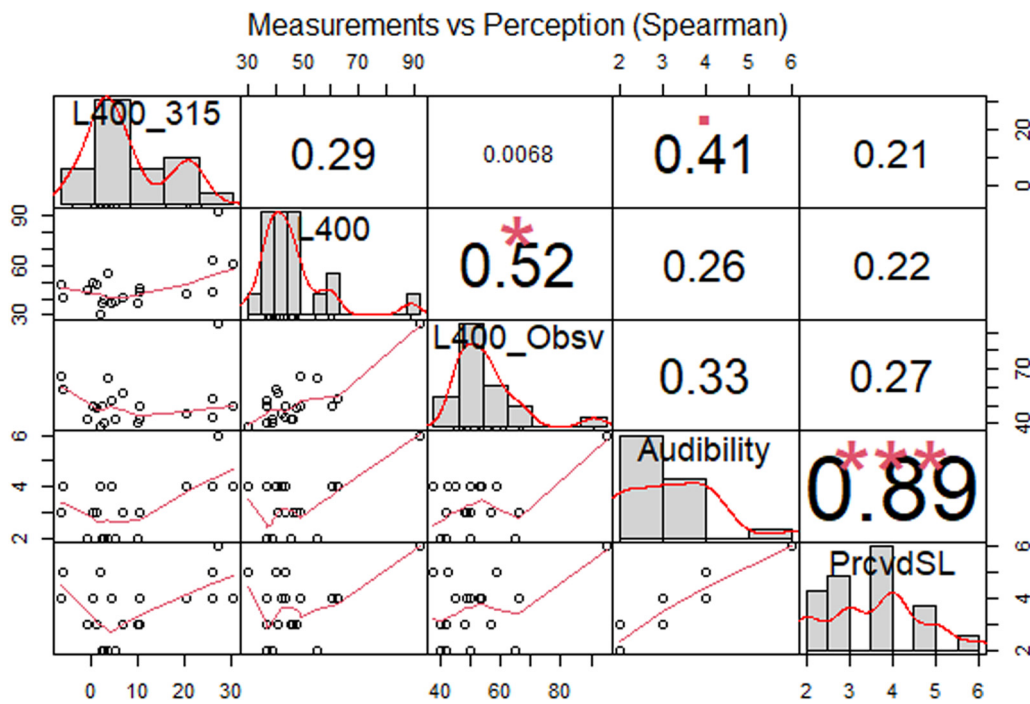


Figure 10: Spearman correlation chart between measurements and perception. The red line indicates the best fit to each set of points.

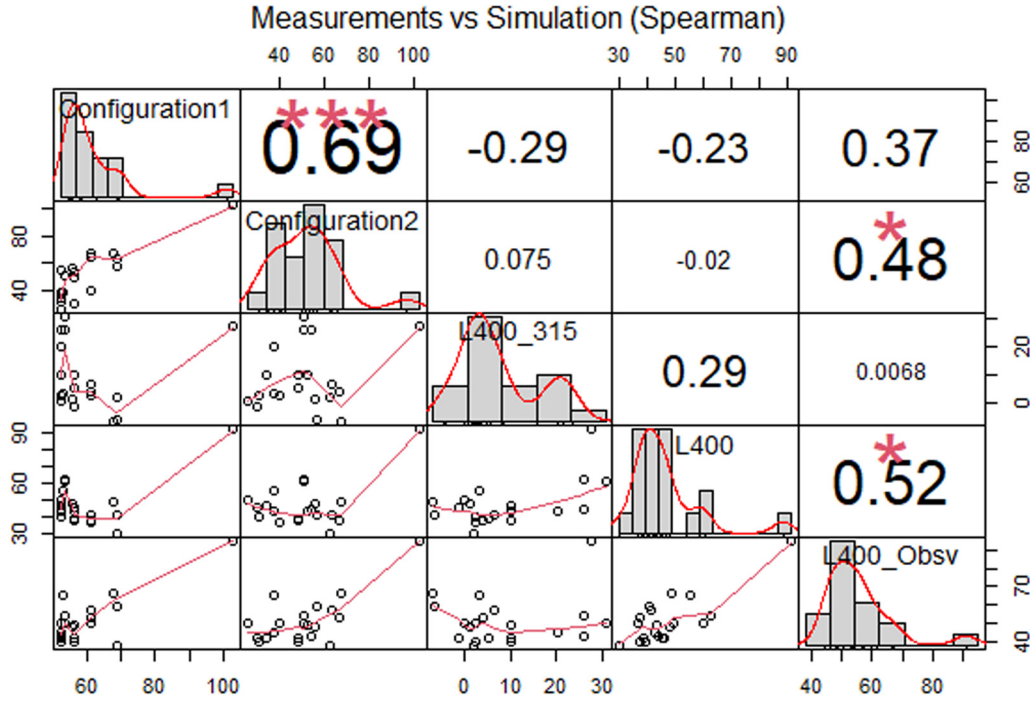


Figure 11: Spearman correlation chart between measurements and simulation. The red line indicates the best fit to each set of points.

representing different measured and collected information during the experiment:

- L_{400} : Equivalent sound level at the 400 Hz one-third octave band of measured levels;
- $L_{400-315}$: Difference between the 400 and 315 Hz one-third octave bands of measured levels, which is an indicator of the spectrum emergence of the signal as explained in Section 2.2.2;
- $L_{400_{Obs}}$: Manually chosen sound level corresponding to the sound level of the siren at a given point for the 400 Hz one-third octave band;
- *Audibility*: Perceived audibility indicated by the participants; and
- *PrcvdSL*: Perceived sound level of the siren indicated by the participants.

3.2.1 Measurements vs perception

Figure 10 shows the Spearman correlation ($r_{\text{Spearman}} = 0.33$ and $p\text{-value} < 1$; $r_{\text{Pearson}} = 0.54$ and $p\text{-value} < 0.01$) between *Audibility* and $L_{400_{Obs}}$ as well as the correlation between *Audibility* and $L_{400-315}$ ($r_{\text{Spearman}} = 0.41$ and $p\text{-value} < 0.1$; $r_{\text{Pearson}} = 0.54$ and $p\text{-value} < 0.01$).

Despite the non-optimal acquisition conditions, the correlation between $L_{400_{Obs}}$ and *Audibility* indicates a

correct interpretation of the audibility question by the participants, as well as the expected link between audibility and sound level. However, it is not possible at this stage to determine whether the other part of the non-linear dependency between *Audibility* and $L_{400_{Obs}}$ is due to measurement errors, or to a nonlinear relationship. The correlation between *Audibility* and $L_{400-315}$ being more significant than the correlation between *Audibility* and $L_{400_{Obs}}$ may suggest that the audibility of the siren is better explained through the spectral emergence of the source rather than only its sound level.

3.2.2 Measurements vs simulation

The Spearman correlation coefficient between the two configurations and $L_{400_{Obs}}$ is presented in Figure 11. The 30 s configuration ($r_{\text{Spearman}} = 0.48$ and $p\text{-value} < 0.05$; $r_{\text{Pearson}} = 0.69$ and $p\text{-value} < 0.001$) is significantly more correlated with $L_{400_{Observed}}$ than configuration 1 ($r_{\text{Spearman}} = 0.37$ and $p\text{-value} < 1$; $r_{\text{Pearson}} = 0.78$ and $p\text{-value} < 0.001$). As a result, relying on a modeling approach that captures the effects of sound propagation, such as NoiseModelling, seems to better represent the sound level distribution of the siren over a territory with complex topography and buildings.

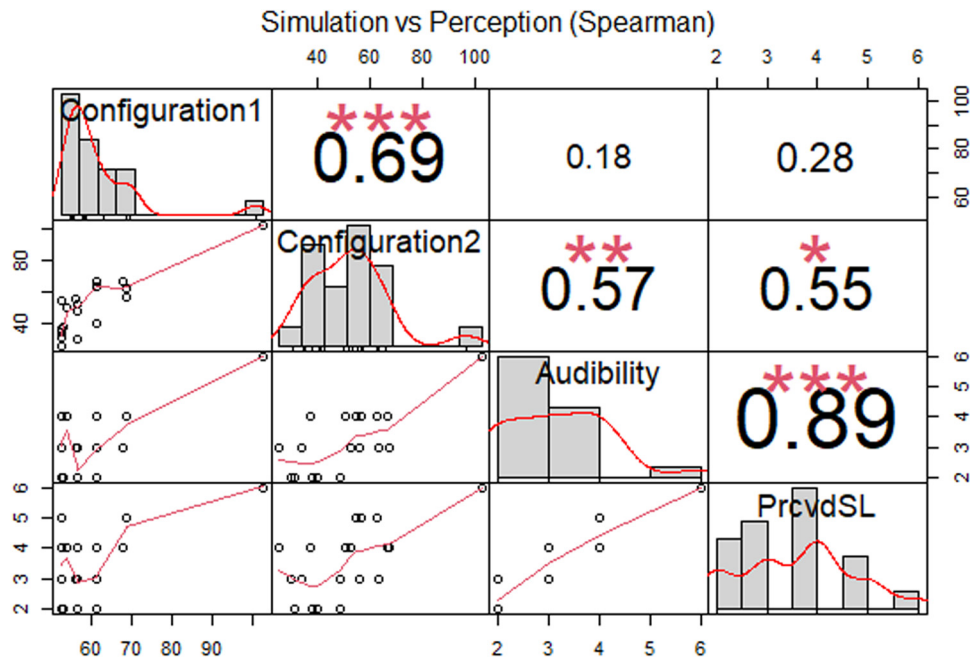


Figure 12: Spearman correlation chart between perception and simulation. The red line indicates the best fit to each set of points.

3.2.3 Perception vs simulation

Finally, the correlation between the reported audibility of the siren and the simulated sound levels is evaluated, in order to investigate the potential of an advanced noise modeling approach, as carried out by configuration 2, to improve the estimation of the audibility of the siren, compared with the basic concentric approach from configuration 1. Results are reported in Figure 12.

Although configuration 1 is better correlated with the perceived sound level *PrcvdSL* ($r_{\text{Spearman}} = 0.28$ and $p\text{-value} < 0.1$; $r_{\text{Pearson}} = 0.58$, and $p\text{-value} < 0.01$) than with audibility ($r_{\text{Spearman}} = 0.18$ and $p\text{-value} < 0.1$; $r_{\text{Pearson}} = 0.62$, and $p\text{-value} < 0.01$), configuration 2 is better correlated with audibility ($r_{\text{Spearman}} = 0.57$ and $p\text{-value} < 0.01$; $r_{\text{Pearson}} = 0.71$, and $p\text{-value} < 0.001$) and *PrcvdSL* ($r_{\text{Spearman}} = 0.55$ and $p\text{-value} < 0.01$; $r_{\text{Pearson}} = 0.63$, and $p\text{-value} < 0.01$) than configuration 1. Therefore, a more complex, detailed modeling, such as configuration 2, better estimates the two perceptual variables (*Audibility* and *PrcvdSL*).

3.3 Toward a cartography of audibility

The validation of the CNOSSOS-EU model to estimate siren audibility suggests the possibility of mapping this audibility on a territory. To do so, it is fundamental to use a metric that represents the percentage of people hearing

the siren as a function of the estimated sound level; this is what is proposed in this section.

For each of the 20 participants, the sound level estimated by NoiseModelling and the audibility level, estimated between 1 and 5, are available. From these 20 pairs

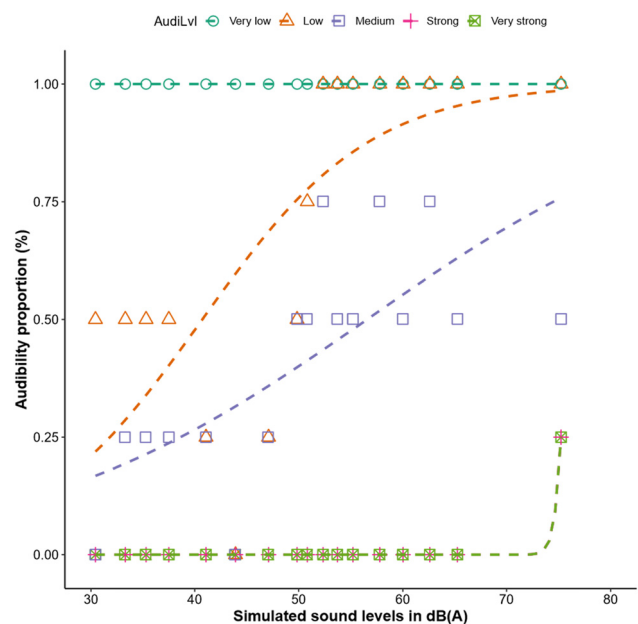


Figure 13: Audibility proportion curves (%) of the siren as a function of the sound level in decibels, for “Very low,” “Low,” “Medium,” “Strong,” and “Very strong” audibility level.

of values, it is possible to estimate, for each 10 dB(A) wide sound level interval, the proportion of the participants exposed to this sound level having informed an audibility score higher than a given value. For example, if 5 out of 10 participants who were exposed to a sound level between 40 and 50 dB(A) heard the siren at an audibility threshold of 3 or more, then this percentage is 50%. Figure 13 introduces the *Audibility Curves*, a metric linking the perceptual data informed by the participants for “Very Low,” “Low,” and “Medium” audibility levels, corresponding to audibility levels of 2, 3, and 4, respectively, on a scale of 1 to 5, and the simulated sound levels. Audibility levels indicating “Strong” and “Very strong” audibility were not sufficiently informed by the participants to produce such curves. In order to define the minimum and maximum values of the 10 dB(A) intervals in Figure 13, we set a condition of four individuals per interval, meaning that sampling is done by shifting from the lowest simulated value to the highest simulated value making sure that in each interval, we have at least four pairs of values (audibility informed by the participants and simulated sound levels). We chose to fit the points with a sigmoid curve, considering that its shape depicts better the audibility function characteristics: low variation at both ends of the sound level domain, and a more or less smooth transition between high and low audibility levels.

From Figure 13, we notice that the siren is always heard at least at a “Very low” level. Fifty percent of the participants exposed to a sound level ranging between 40 and 50 dB(A) indicated that the siren was audible at a “Low” level, while 50% of the participants exposed to a sound level ranging between 60 and 70 dB(A) indicated that the siren was audible at a “Medium” level. By relating a percentage of participants having indicated a certain audibility level to the sound level to which they were exposed, it is then possible to produce a map of the audibility in the modeling approach, as shown in Figure 14 for “Low” audibility and in Figure 15 for “Medium” audibility.

4 Discussion

A methodology involving on-site measurements, numerical simulation, and perceptual data is proposed to assess the audibility of a warning siren system through the evaluation of its spatial coverage. The acoustic measurements were performed by a group of participants equipped with the NoiseCapture application and some calibrated microphones. Alongside the measured data, we obtained perceptual data through a questionnaire filled out by each

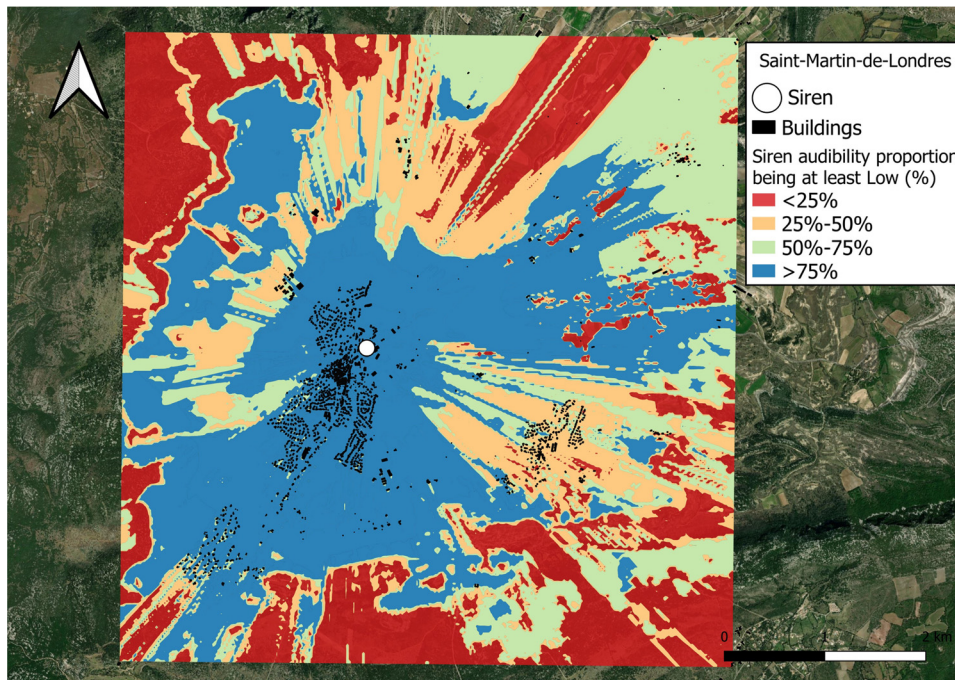


Figure 14: Audibility cartography showing the percentage of at least low audibility.

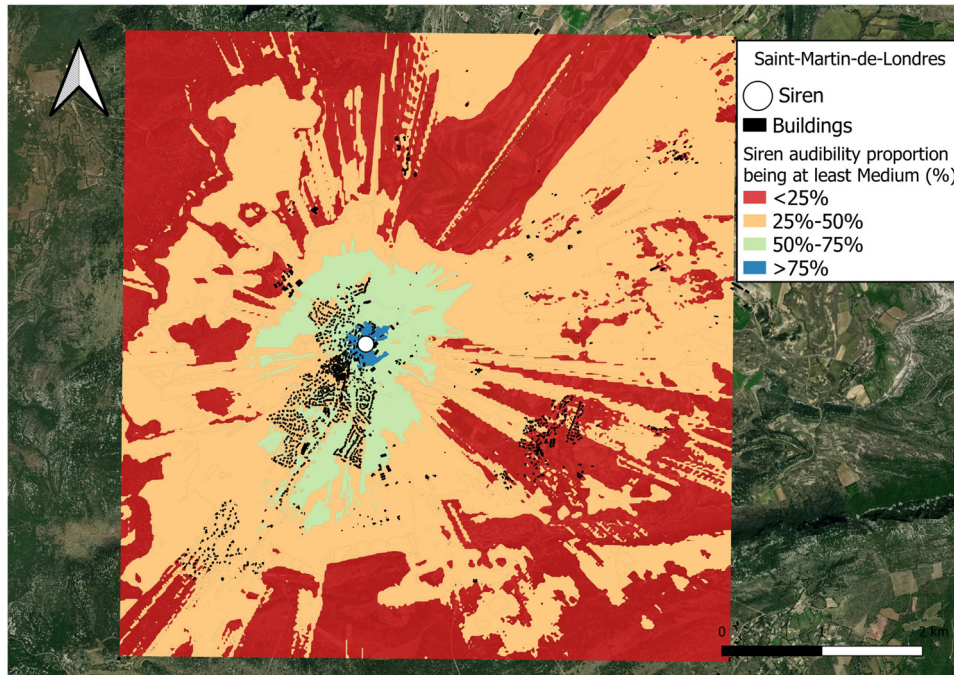


Figure 15: Audibility cartography showing the percentage of at least medium audibility.

participant regarding the audibility of the siren as well as the global sound level at each measuring point. Two numerical models were set up in the study area using NoiseModelling to determine the most adequate set of parameters to carry out the cartography of the sound environment during the activation of the siren. This showed the added value of relying on complete modeling of sound propagation, as considered under the CNOSSOS-EU approach, to assess the spatial coverage of the siren sound signal, compared to a classical concentric circle approach.

Rather than the classical concentric circle approach, the methodology herein presented accounts for the urban morphology complexity interacting with the sound wave propagation. We set up a realistic numerical model of the sound environment using the CNOSSOS-EU model embedded into NoiseModelling that considered the presence of buildings, ground absorption coefficient, digital elevation model, meteorological conditions, and horizontal and vertical diffractions. This approach has to be balanced by the fact that the CNOSSOS-EU propagation model proposed in the Environmental Noise Directive 2002/49/EC has been shown to significantly underestimate the effect of a soft berm next to a highway [27], which is the case for this particular study area. Through a correlation test between the simulated and measured sound levels, the results that emerged from the present study suggested that a more robust, complex simulation is more

adequate when representing the sound environment of an alarm siren (3.2.2). In line with the initial hypothesis, the results showed that the concentric circle's approach, historically used to evaluate siren warning systems, does not accurately represent the sound propagation of a siren in an urban geometry. These results suggest the need to consider the complexity of an urban environment when assessing the audibility of a siren warning system by considering not only simulated and measured data but also perceptual data.

We introduced the audibility curves as a metric to link simulated sound levels and perceived audibility. The results are consistent with the findings by Reed *et al.* [17] and Nishino *et al.* [18], where the authors inform that, for a siren at 80 dB or more, 97% of the population is expected to hear the signal and that, for a 70 dB siren, approximately 70% of the population in the target area could be reached, respectively. Similarly, our results are in line with the results presented in Volkmann and Graham's study [24] that suggest a minimum sound level of 80 dB for the siren to be audible.

This study also confirms in this specific case the validity of CNOSSOS-EU employed beyond its theoretical threshold distance (800 m) [28] through the correlation tests presented in Section 3. These experiments indicate that simple signals such as those of warning sirens can be heard to greater distances than the previously mentioned (800 m) as the furthest measuring point was located at

2.8 km of the siren; nonetheless, participants placed at further distances indicated having heard the siren at a very low level. This statement is solely valid for the particular study case herein presented. To choose a representative sound level for the siren in each measuring point, we perform a visual analysis of each time series in the dataset, and by evaluating the emergence of the 400 Hz one-third octave band with respect to the 315 Hz band, we propose an equivalent sound level $L_{400\text{Obs}}$. No automatic procedure (e.g. cross-correlation) was found for this step because our small number of observations did not accept the presence of multiple outliers and strong wind gusts disturbed the measurement.

Section 3.2.3 proposes a first step toward the consideration of the emergence of the siren with respect to background noise. The results showed a bigger correlation between audibility and $L_{400-315}$, which indicates that audibility could be better described by considering the emergence rather than only measured sound levels. Even if there is a significant relation between the sound level of a source and its audibility, numerous studies suggest that the sole consideration of the sound level does not suffice to describe the audibility of a siren in urban areas as perception involves more complex mechanisms like the presence of background noise and source temporal emergence [29]. In the future, it could be possible to include the background noise to improve the quality and relevance of the audibility curves using either a stochastic methodology [30] that allows for the study of the competition between typical urban sound sources or a road traffic noise model such as QSIDE [31]. According to Keast [32], siren warning systems are effective indoors as well despite the sound attenuation introduced by buildings structures. Therefore, the audibility cartography herein proposed remains relevant both outdoors and indoors as this study case is oriented to solve a choice-making problem concerning the optimal placement of warning sirens in urban areas. In other words, audibility maps indoor would be similar but with a lower level of audibility depending on the building characteristics, which also depend on the country. In the future, a more detailed study on indoor siren audibility could be pursued. The audibility tests were conducted in a listening situation, which makes the sound sources certainly more audible than in a real emergency case where the participants perform an activity. This assumption does not affect the relative audibility of the evaluation points concerning each other. Use in a real-life situation would require determining the transfer function between audibility in a listening situation and audibility in a real-life situation, which is beyond the scope of this study as it would require more specific experimentation as in the study of Filipan *et al.* [33], where the authors

propose a biologically inspired computational model for auditory sensory saliency based on spectrotemporal modulations to detect salient events. As for the problem of detecting the emergence of a sound source among background noise, it would be necessary to develop a more accurate siren audibility assessment model that takes into consideration the background noise, such as traffic, that may be present during the activation of the sound source and its interaction with the sound source of interest. Future work will (i) establish a more robust experimental protocol with more participants all equipped with calibrated microphones to avoid corrupted data and (ii) propose a refined perceptual model accounting for background noise masking to achieve a stronger validation.

Also, the conclusions reported in this study must be balanced by the fact that this protocol was limited by the quantity and quality of the data collected at the time of the experiment as well as the fact that we did not consider the siren's time-dependent characteristic.

5 Conclusions

In this article, the relevance of the CNOSSOS-EU model, here embedded with NoiseModelling, to estimate the perceived audibility of a siren, is evaluated experimentally. The conclusions are as follows:

1. CNOSSOS-EU modeling approach outperforms the classical concentric circle approach to estimate the sound level distribution of the siren over a territory with complex topography and buildings;
2. The CNOSSOS-EU approach also improves the estimation of the perceptual variable audibility and perceived loudness of the siren;
3. A metric for deriving the audibility of the siren in the function of sound levels is proposed. This allows the production of a cartography of the audibility and, therefore, leads up to a better understanding of the audibility.

Finally, through a combination of perceptual and simulated data, we propose a metric for deriving the audibility of the siren in the function of sound levels. This allows us to produce audibility cartography, therefore, leading up to a better understanding of the problem. In the future, this methodology can be implemented toward a broader problem: Optimization of warning siren system placement [34] using a model that accounts for the significance of the acoustic properties of the siren, the propagation medium, and the background sound level.

Acknowledgments: Jonathan Siliézar's thesis is co-financed by the Gustave Eiffel University and the Pays-de-la-Loire region. The authors would like to thank the students of the Master Gestion des Catastrophes et des Risques Naturels (GCRN) of the University Paul-Valéry Montpellier 3 who participated in the experimentation.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Conflict of interest: Authors state no conflict of interest.

References

- [1] Douvinet J. L'alerte par sirènes: une priorité discutable en France. *Annales de géographie*. 2020;731:5–32. (in French)
- [2] Douvinet J, Serra-Llobet A, Kondolf M, Bopp E, Péroche M. Why keep alert sirens in France? *Nat Hazards Earth Syst Sci*. 2020;1–22.
- [3] Douvinet J, Serra-Llobet A, Bopp E, Kondolf GM. Are sirens effective tools to alert the population in France? *Nat Hazards Earth Syst Sci*. 2021;21:2899–920.
- [4] Bopp E, Gisclard B, Weiss K, Martin G, Douvinet J. How to improve alert systems: The technical, human, environmental and structural aspects. *Aust J Emerg Manag*. 2021;36(1):67–75.
- [5] Leonard GS, Johnston DM, Paton D, Christianson A, Becker J, Keys H. Developing effective warning systems: Ongoing research at Ruapehu volcano, New Zealand. *J Volcanol Geotherm Res*. 2008;172:199–215.
- [6] Couling M. Tsunami risk perception and preparedness on the east coast of New Zealand during the 2009 Samoan 30 Tsunami warning. *Nat Hazards*. 2014;71:973–86.
- [7] Current J, O'Kelly M. Locating emergency warning sirens. *Decis Sci*. 1992;23(1):221–34.
- [8] Stimers M. A GIS-based approach to analyzing warning siren networks: an analysis of Riley and Wabaunsee counties, Kansas. The 29th Annual Applied Geography Conference; 2006 Oct 11–14; Tempa (FL), USA. Kent State University, 2006. p. 186–95.
- [9] Mathews AJ, Ellis EA. An evaluation of tornado siren coverage in Stillwater, Oklahoma: Optimal GIS methods for a spatially explicit interpretation. *Appl Geogr*. 2016;68:28–36.
- [10] Rosas-Bermejo EN, Rafael-Valdivia G, PaucarCurasma R. Analysis of sound propagation for outdoor emergency speakers networks. 2016 IEEE ANDESCON; 2016 Oct 19–21; Arequipa, Peru. IEEE, 2017. p. 1–4.
- [11] Webster B. Emergency siren sound propagation and coverage optimization analysis [dissertation]. Redlands (CA): University of Redlands; 2014.
- [12] Attenborough K, Li KM, Horoshenkov K. *Predicting Outdoor Sound*. London, UK: CRC Press; 2014.
- [13] Wiener FM, Malme CI, Gogos CM. Sound propagation in urban areas. *J Acoust Sciety Am*. 1965;37(4):738–47.
- [14] Wanniarachchi KH, Lakmal AH. Optimum locations suitability: Analysis for tsunami warning centres. 13th International Research Conference; Holistic Approach to National Growth and Security; 2020 Oct 15–16; Ratmalana, Sri Lanka. General Sir John Kotelawala Defence University, 2020. p. 45–54.
- [15] Bérengier M, Gauvreau B, Blanc-Benon P, Juvé D. Outdoor sound propagation: A short review on analytical and numerical approaches. *Acta Acust U Acust*. 2003;89:980–91.
- [16] Mathews AJ, Haffner M, Ellis EA. GIS-based 65 modeling of tornado siren sound propagation: Refining spatial extent and coverage estimations. *Int J Disaster Risk Reduct*. 2017;23:36–44.
- [17] Reed SE, Boggs JL, Mann JP. *SPreAD-GIS: 70 an ArcGIS toolbox for modeling the propagation of engine noise in a wildland setting*. San Francisco (CA), USA: Wilderness Society; 2010.
- [18] Nishino A, Kodaka A, Nakajima M, Kohtake N. A model for calculating the spatial coverage of audible disaster warnings using GTFSS realtime data. *Sustainability*. 2021;13:13471.
- [19] Giguère C, Laroche C, Osman A, Zheng Y. Optimal installation of audible warning systems in the noisy work-place. In: Griefahn B, editor. *The 9th Congress of the International Comission on the Biological Effects of Noise: Noise as a Public Health Problem*; 2008 Jul 21–25; Mashantucket (CT), USA. ICBEN, 2008. p. 197–204.
- [20] Wilkins PA. A field study to assess the effects of wearing hearing protectors on the perception of warning sounds in an industrial environment. *Appl Acoust*. 1984;17(6):413–37. Elsevier.
- [21] El Sawaf O, Arz J-P, Grimault N, Chevret P. Audibility of warning signals: methods to evaluate the combined effects of hearing protectors and hearing impairment. *INTER-NOISE: Noise Control for a Better Environment*; 2019 Jun 16–19; Madrid, Spain. Spanish Acoustical Society (SEA), 2019.
- [22] Wilkins PA, Martin AM. The role of acoustical characteristics in the perception of warning sounds and the effects of wearing hearing protection. *J Sound Vib*. 1985;100:181–90.
- [23] Patterson RD. *Guidelines for auditory warning systems on civil aircraft*. London, UK: Civil Aviation Authority; 1982.
- [24] Volkmann JE, Graham ML. A survey on air raid alarm signals. *J Acoust Soc America*. 1942;14(1):1–9.
- [25] Guillaume G, Aumond P, Bocher E, Can A, Écotière D, Fortin N, et al. Noisecapture smartphone application as pedagogical support for education and public awareness. *J Acoust Soc Am*. 2022;151(5):3255–65.
- [26] Commission Directive (EU) 2015/996 of 19 May 2015 establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of 110 the Council (Text with EEA relevance); May 2015.
- [27] Attenborough K, Van Renterghem T. Adequacy of engineering predictions of soft ground effect. *Forum Acusticum*; 2020 Dec 7–11; online. EAA, 2020. p. 863–8.
- [28] Kephelopoulos S, Paviotti M, Anfosso-Lédée F. Common noise assessment methods in Europe (CNOSSOEU). Publications Office of the European Union; 2012.
- [29] Ball LM. Air raid siren field tests. *J Acoust Soc Am*. 1942;14:10–3.
- [30] Aumond P, Jacquesson L, Can A. Probabilistic modeling framework for multisource sound mapping. *Appl Acoust*. 2018;139:34–43.

- [31] Kluizenaar Y, de Gidlöf-Gunnarsson A, Botteldooren D, Bockstael A, Janssen SA, Vos H, et al. Annoyance and disturbed sleep due to road traffic noise: the importance of the least exposed side – QSIDE. INTER-NOISE: Noise Control for Quality of Life; 2013 Sep 15–18; Innsbruck, Austria. Austrian Noise Abatement Association, 2013.
- [32] Keast DN. Outdoor sirens: How do they work for people indoors? *J Acoust Soc Am.* 1987;82(S1):S48–8.
- [33] Filipan K, De Coensel B, Aumond P, Can A, Lavandier C, Botteldooren D. Auditory sensory saliency as a better predictor of change than sound amplitude in pleasantness assessment of reproduced urban soundscapes. *Build Environ.* 2019;148:730–41.
- [34] Goto H, Murray AT. Acoustical properties in emergency warning siren coverage planning. *Comput Environ Urban Syst.* 2020;81:101477.

Appendix

In Figure A1, we present the temporal evolution of the $L_{400}Point25$ as well as the $L_{400}Obs$ level accounting for the manually chosen level corresponding to the sound level of the siren. $L_{400}Point25$ as well as the $L_{400}Obs$ level accounting for the manually chosen level corresponding to the sound level of the siren.

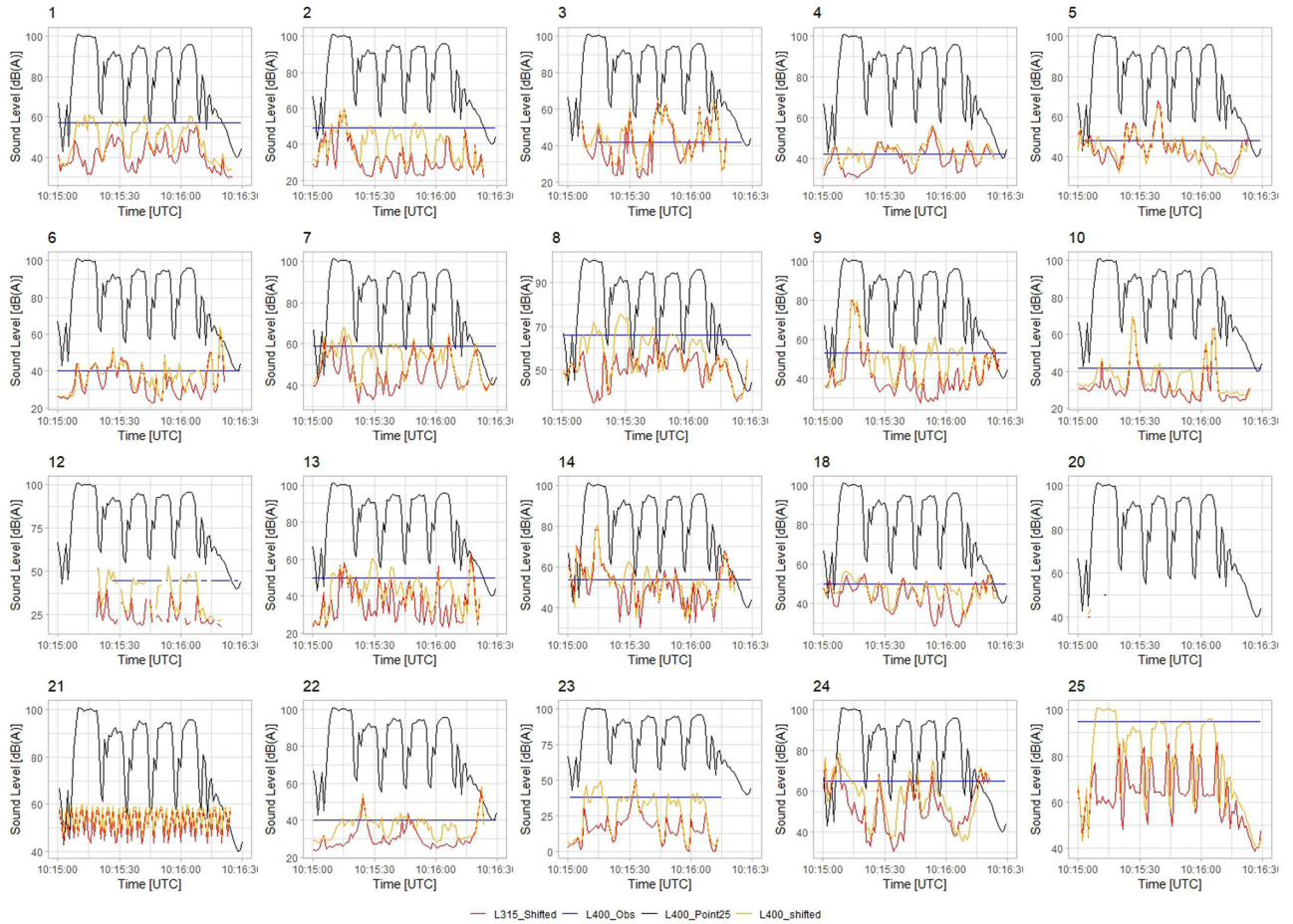


Figure A1: Shifted time series of each measurement point. $L_{400}Shifted$ and $L_{315}Shifted$ represent the shifted L_{400} and L_{315} evaluation point, respectively. $L_{400}Point25$ represents the measured L_{400} for the nearest point to the siren (25). Finally, $L_{400}Obs$ represents the manually chosen level corresponding to the sound level of the siren.