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# PROPOSAL OF A METHOD FOR ASSESSING THE AUDIBILITY OF SIREN-DRIVEN ALERT SYSTEMS

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## 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 the emitted sound level by the sirens is known, it is nevertheless difficult to evaluate their audibility across a given zone, especially in complex urban environments. An experimental protocol has been deployed around a siren installed in a city in the south of France to assess its audibility perceptually and through modelling. This protocol relies on (1) sound level measurements during source activation, using the NoiseCapture smartphone application, (2) perceptual information survey (siren audibility, perceived sound level, masking by passing vehicles), and (3) sound environment simulation using NoiseModelling. The results of this study validate the use of CNOSSOS-EU model integrated in NoiseModelling to evaluate the audibility of a warning system located in an urban environment within a radius of 2.8 kilometers around the siren rather than the sole consideration of the distance and even if we are far from its range of validity. Finally, a metric linking audibility to modelled 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]. 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. The effectiveness of early warning systems is one of the main risk reduction strategies for communities vulnerable to natural disasters [2].

The effectiveness of sirens heavily depends on them being properly heard by as many people as possible [3, 4]. Traditionally, the structure and densification of the siren networks have been based on technical constraints rather than on an effort to optimize their sonic spatial coverage [5]. 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 [2]. This zoning is usually mapped by concentric circles around the sirens whose distances would represent theoretical sound levels threshold values generally around 800 m, 1.6 km, and 2.4 km for the maximum distances [6, 7]. 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 [8, 9].

In this study, we evaluate the CNOSSOS-EU model [10], embedded in NoiseModelling, an open-source noise mapping tool, to carry out the sound mapping of a siren-driven warning system in the city of Saint-Martin-de-Londres, Hérault department in France. We propose a methodology that involves perceptual data and establishes

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a relation between audibility, numerical simulation, and measured sound levels when assessing the spatial coverage of siren warning systems. For this purpose, we collected acoustic and perceptual data during an experiment in the study area which was then compared to the simulated sound levels. Section 3 presents the results obtained through a correlation test between each data set. Finally, the consequences in terms of estimation of siren audibility by modeling are reviewed in section 4.

## 2. METHODS

### 2.1 Case study

Saint-Martin-de-Londres is a municipality of about 3000 inhabitants approximately 30 km to the north of Montpellier in the south of France. The experiment took place on October 6, 2021 at 12:15 during the siren's activation which is part of a monthly exercise to ensure the proper functioning of the siren. We evaluate a warning siren installed on a mast near a municipal building, it is 10 meters above the ground and it is activated for 1 minute and 41 seconds emitting a tonal acoustic signal of 135 decibels 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 (see 2). Its theoretical spatial extent is around 3 km.

25 students of the Natural Risks Management Master of the University Paul Valéry Montpellier 3 were deployed at various distances around the siren as indicated in figure 1. The farthest source-participant distance was of approximately 2.5 km. The participants were asked to measure the sound level at their corresponding location as well as to fill a questionnaire regarding the audibility of the siren. Participants were equipped with NoiseCapture, an open-source Android application to measure sound levels on a smartphone [11]. Simultaneously, participants responded to a questionnaire, which was intended to evaluate their perception of the siren.

### 2.2 Tools

### 2.2.1 *Questionnaire*

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

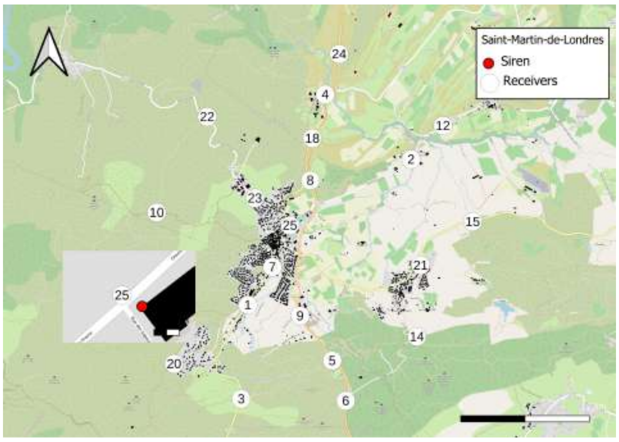

**Figure 1**. Map of Saint-Martin-de-Londres. The siren is represented by a red point. The participants were positioned at the white points.

### 2.2.2 *Acoustic measurements*

Sound level measurements were performed by the participants using NoiseCapture [1], a free Android application designed to perform acoustic measurements and share the user's sound environment using the built-in microphone on their cellphone or an external microphone [11]. Some of the data collected was the 1-second measured sound level by one-third octave band, the equivalent sound level in dB(A) $LA_{eq}$, an identifier of the measuring device and its GPS position at the time of the measurement. The GPS track associated with the measuring has a temporal resolution of 1 second and a mean spatial accuracy of approximately 6 meters. Participants were equipped with a 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 measurement was done using a class 1

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[1] `https://noise-planet.org/noisecapture.html`

**Figure 2**. Photography of the siren.

| Parameter | Buildings | DEM | Ground | Meteorological conditions | Horizontal diffraction | Vertical diffraction | Reflection order |
|---|---|---|---|---|---|---|---|
| Input | Yes | Yes | Yes | Real | Yes | Yes | 2 |

**Table 1**. Input parameters in NoiseModelling

sound level meter 10 meters away from the source during the activation of the siren.

By visual inspection of the ensemble of measurements, we noticed that the 400 Hz one-third octave band was the most prominent during the activation of the source, which is in accordance with the characteristics of the siren. Therefore, we will consider the equivalent sound level in this one-third octave band as the sound level of the siren at a given evaluation point and we will be, from now on, referring to it as $L400$. Due to some wind gusts during the activation of the siren, the measuring conditions were not ideal. Also, incorrect handling of the measuring device by the participants corrupted some of the collected data. In total, 5 out of 25 measurements were not exploitable. By observing the temporal evolution of the sound level at each location, we manually determined an equivalent sound level for the 400 Hz one-third octave band during the activation of the siren by averaging the distance to the siren. This sound level is referred to as $L400_{Obs}$ hereafter.

### 2.2.3 *Numerical modelling*

The numerical modelling of the siren was performed using NoiseModelling, an open-source tool that integrates the CNOSSOS-EU propagation model, a standardized model for the elaboration of strategic noise maps [12]. Using the exact location of the participants, provided by Noise-Capture, we generated a layer of 20 receiver points distributed in the study area representing each participant respectively.

The siren was modeled as a source point with an emission sound level of 135 dB at 400 Hz, which is the closest one-third band to 380 Hz, the real fundamental frequency of the source. The modeled signal is considered to be tonal and constant at its fundamental frequency. This is an assumption, compared to the actual warning signal of sirens in France, which gradually increases over a period of 3 seconds in sound level and frequency, settles down at its maximum power and frequency for 58 seconds and then decreases for the last 40 seconds. The input parameters for the sound propagation model are presented in table 1

The geometry of the buildings, the ground topography, and the digital elevation model were retrieved from the BD TOPO ©databases départementale 2018 [2] and BD ALTI ©25m 2021 [3] 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. Diffractions from vertical and horizontal building edges were taken into account in the model, as well as reflections of second order from facades within 500 meters of the receiving point.

The directions of the favorable conditions of propagation were estimated on the basis of meteorological forecasts[4], as well as field experience. The values retained

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[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`

| 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 |

**Table 2**. Probability of occurrence of favorable conditions

for each of the cardinal directions are presented in table 2.

## 3. RESULTS

### 3.1 Cartographic representations

Sound levels for each configuration are calculated on a regular grid of 951610 (305X312) receiving points, each point being up to 20 meters away from the next point. The resulting sound level map is presented in Figure3.

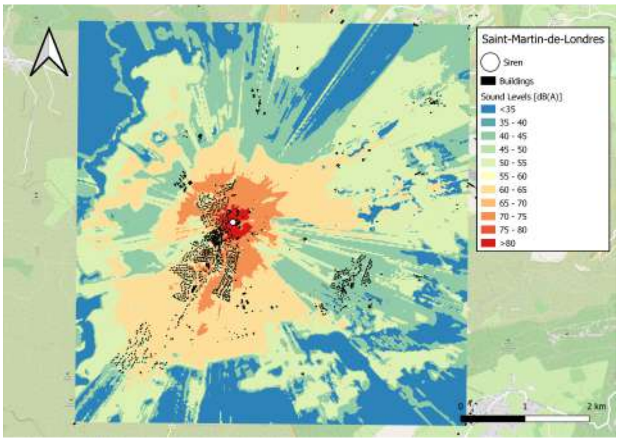

**Figure 3**. Cartographic representation of the siren sound propagation

Figure 3 shows a decrease in the sound level as the distance increases from the source, but this reduction is neither monotonic nor uniform. Isophone lines are far from concentric, which may question the theoretical threshold approach validity. This result shows that the sound levels are impacted not only by the distance to the source but also by external factors such as the topography, the presence of buildings, the digital elevation model, and wind and temperature gradients.

We present the audibility values from the perceptual data set in Figure 4. Again, distance does not appear to be the only factor impacting the audibility of the siren, as some participants informed having heard the siren at a medium level while being located farther than others with a lower level of audibility. The following section discusses in more detail the links between acoustic measurements, perception, and simulations.

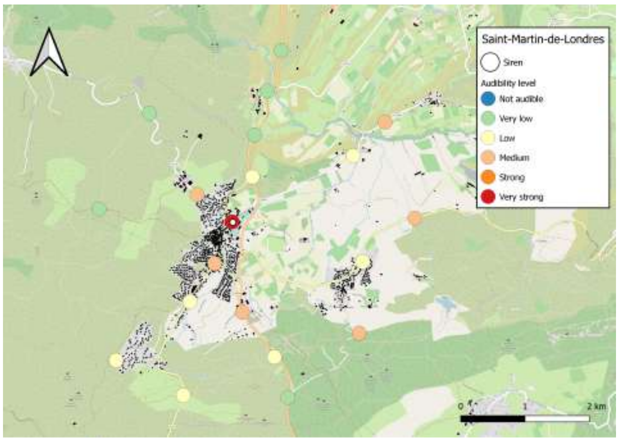

**Figure 4**. Mapping of siren audibility as reported by participants

### 3.2 Cross analysis: Acoustic measurements, perception, modeling

We performed a cross-analysis between our 3 different data sets: acoustic measurements, simulated noise levels, and perceptual data. The aim is to compare the different approaches, we observed the Spearman and Pearson correlation coefficients. Spearman is somewhat more appropriate than Pearson for our specific case where the dataset is not linearly distributed and includes a sample that is very close to the sound source. For this section we introduce 5 indicators representing different measured and collected information during the experiment :

- *L400*: Equivalent sound level at the 400 Hz one-third octave band of measured levels;
- $L_{400-315}$: Difference between the 400 Hz 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;
- $L400_{Obs}$: 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;
- *PrcvdSL*: Perceived sound level of the siren indicated by the participants.

### 3.2.1 *Measurements vs. perception*

The correlation between the *Audibility* and $L400_{Obs}$ ($r_{Spearman} = 0.33$ and $p - value = 0.15$; $r_{Pearson} = 0.54$ and $p - value = 0.13$) suggests a correct interpretation of the audibility question by the participants, as well as the expected link between audibility and sound level. At this stage, it is not possible to determine whether the other part of the non-linear dependency is due to measurement errors, or to a non-linear relationship between the two variables. The correlation between *Audibility* and the emergence of the signal with respect to $L_{400-315}$ ($r_{Spearman} = 0.41$ and $p - value = 0.06$; $r_{Pearson} = 0.56$ and $p - value = 0.01$) being more significant than the correlation between *Audibility* and $L400_{Obs}$ 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*

Simulated sound levels *L400* are better correlated with $L400_{Obs}$ ($r_{Spearman} = 0.48$ and $p - value = 0.03$; $r_{Pearson} = 0.69$ and $p - value = 6x10^-3$) than with the classical concentric circles approach ($r_{Spearman} = 0.37$ and $p - value = 0.1$; $r_{Pearson} = 0.78$ and $p - value = 4.48x10^-5$). This indicates that relying on a modelling approach that accounts for the effects of sound propagation, such as CNOSSOS-EU embedded in NoiseModelling, could better represent the propagation of siren sound levels over a territory with complex topography and buildings.

### 3.2.3 *Perception vs. simulation*

Finally, we evaluated the correlation between the reported audibility of the siren *Audibility* and the simulated sound levels *L400* in order to investigate the potential of an advanced sound modelling approach to improve the estimation of the audibility of the siren. There is a more significant correlation between *L400* and *Audibility* ($r_{Spearman} = 0.57$ and $p - value = 0.01$; $r_{Pearson} = 0.71$, and $p - value = 5x10^-3$) than there is between the classical concentric circles approach and *Audibility* ($r_{Spearman} = 0.18$ and $p - value = 0.45$; $r_{Pearson} = 0.62$, and $p - value = 0.01$). Moreover, the correlation between *L400* and *PrcvdSL* ($r_{Spearman} = 0.55$ and $p - value = 0.01$; $r_{Pearson} = 0.63$, and $p - value = 0.003$) is more significant than the correlation between the simulated sound levels using the concetric circles approach and *PrcvdSL* ($r_{Spearman} = 0.28$ and $p - value = 0.24$; $r_{Pearson} = 0.58$, and $p - value = 0.01$ ). This leads us to believe that a more complex, detailed modelling, such as the one under study, is more suited to estimate the two perceptual variables *Audibility* and *PrcvdSL*.

## 3.3 Towards an audibility cartography

After evaluating the relevance of using the CNOSSOS-EU model, embedded in NoiseModelling, to estimate the siren audibility, we propose a metric to map this audibility on a territory. To do so, it is fundamental that this metric represents the percentage of people hearing the siren as a function of the estimated sound level.

We have the sound level estimated by NoiseModelling as well as the audibility level, between 1 and 6, for each of the 20 participants. We set a 10 dB(A) wide sound level interval in our data set and we evaluated the proportion of participants exposed to the corresponding sound level interval 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 dB(A) and 50 dB(A) informed an audibility score of 3 or more, then this percentage is 50%. Figure 5 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 6; and the simulated sound levels. Audibility levels indicating ”None”, ”Strong” and ”Very strong” audibility were not sufficiently informed by the participants to produce such curves.

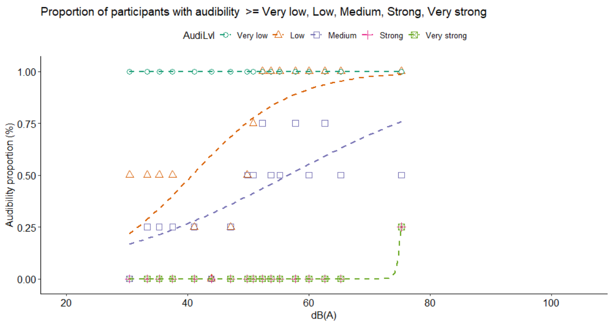

**Figure 5**. Audibility proportion curves (%) of the siren as a function of the sound level in decibels, for ”Very low”, ”Low”, ”Medium”, ”Strong” and ”Very strong” audibility level.

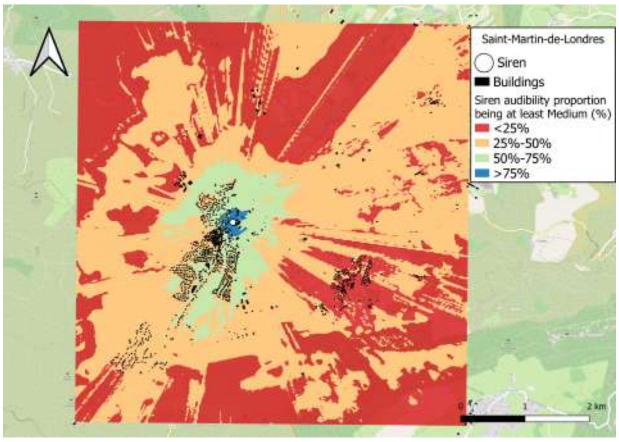

**Figure 6**. Audibility cartography showing the percentage of at least medium audibility

By visual analysis, we notice that the siren is always heard at least at a ”Very low” level. 50% of the participants exposed to a sound level ranging between $[40 - 50dB(A)]$ indicated that the siren was audible at a ”Low” level, while 50% of the participants exposed to a sound level ranging between $[60 - 70dB(A)]$ indicated that the siren was audible at a ”Medium” level. By relating the percentage of participants having indicated a certain audibility level to the sound level interval to which they were exposed, we produced a map of the audibility as shown in Figure 6 for ”Medium” audibility.

## 4. CONCLUSIONS

We assessed the relevance of the CNOSSOS-EU model, embedded in NoiseModelling, to estimate the perceived audibility of a siren. The conclusions are as follows:

1. CNOSSOS-EU modeling approach outperforms the classical concentric circles approach to estimate the sound levels distribution of the siren over a territory with complex topography and buildings;
2. The CNOSSOS-EU approach also improves the estimation of the perceived audibility *Audibility* and the perceived loudness of the siren *PrcvdSL* ;
3. A metric for deriving the audibility of the siren in the function of sound levels is proposed. This opens the possibility to the production of audibility maps that could be useful to understand the problem of siren audibility and therefore optimize the structuring and densification of siren-driven warning systems.

The *Audibility Curves* issued from this experiment combine the perceptual and simulated data in order to produce an audibility cartography of the siren, therefore leading to a better understanding of the problem of siren coverage. In the future, this procedure can be implemented towards a broader problem: Optimization of warning siren system placement [13] using a model that accounts for the significance of the acoustic properties of the siren, the propagation medium, and the background sound level.

## 5. ACKNOWLEDGMENTS

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