

Impact of multiple reflections on urban acoustics

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Abstract. Understanding how the urban form contributes to noise is important for the successful acoustic design of cities. The amplification of sound is mainly due to the multiple reflections that occur between the high and parallel walls of urban canyons. This study explores the use of ray tracing at the urban scale through the measurement and simulation of three configurations. These are referred to as “1D”, “2D” and “3D”. Impulse response measurements performed at points located on the top of the façades show an increase of 6 dB for the “2D” case and 11 dB for the “3D” case. These results are consistent with ray tracing simulations. This kind of simulation is useful to determine the influence of the street aspect ratio on the sound level. Since specular reflections are related to geometry, a spatialized representation is proposed and discussed.

1. Introduction and context

Urban form design must take into account the physical behavior of light, heat, fluids, and sound [1]. At the city scale, the study of the sound field is complex: the sources are multiple and the propagation phenomena are difficult to interpret [2]. In urban canyons, the built surfaces are high, parallel, and acoustically very reflective. The shape of the street contributes to the amplification of sound, on both pedestrians and high points of buildings [3]. At this local scale, the sound level is determined by the multiple reflections [4]. Reflections on urban façades are mostly specular [5] and can therefore be studied by geometric acoustics [6]. These techniques provide information that guides decision in the design process [7]. This work explores the relevance of ray tracing methods in the acoustical study of the urban environment.

Three common urban configurations with the same dimensions are studied. The first, referred to as “1D”, corresponds to an open view façade. The second, “2D”, represents an urban canyon. The third, “3D”, stands for a small square or a courtyard. The impulse response from a source located at human height is measured on the top of the façade. The sound level differences observed in each case allow quantifying the impact of multiple reflections. The measurement results are used to validate the ray tracing simulation. Simulations allow modifying the aspect ratio and observing its influence on the sound level. First, the results indicate beyond which street width the effect of reflections in a canyon becomes negligible, in other words, the limit between the “2D” and “1D” configurations. In the same way, the depth beyond which a closed “3D” street can be considered as an open “2D” street is studied. Finally, a spatialized representation of multiple reflections is presented to discuss the design aspects of such spaces.



2. Description of cases and method

The three spaces shown in Figure 1 correspond to an open view façade of a modern building, a downtown narrow street, and a courtyard in a university campus. Their dimensions are similar and their façades are considered smooth.

The impulse response is the signal recorded at a receiver point R after an impulse emitted at a source point S. This measurement provides all the temporal and frequency information on how the energy propagates between the two points and is performed using standard room acoustics equipment. A microphone (Brüel & Kjær type 2250) is placed on the façade (Figure 1). The source (Brüel & Kjær Omnipower type 4292-L), an omnidirectional loudspeaker, is positioned at 1.80 m above the ground, and 2.5 m from the microphone façade. The emitted impulse is an exponential signal (e-sweep), which reduces the influence of ambient noise [8]. The measurements were carried out under optimal conditions, in the absence of people, with ambient noise lower than 40 dB, and during a windless day with temperatures around 20°C

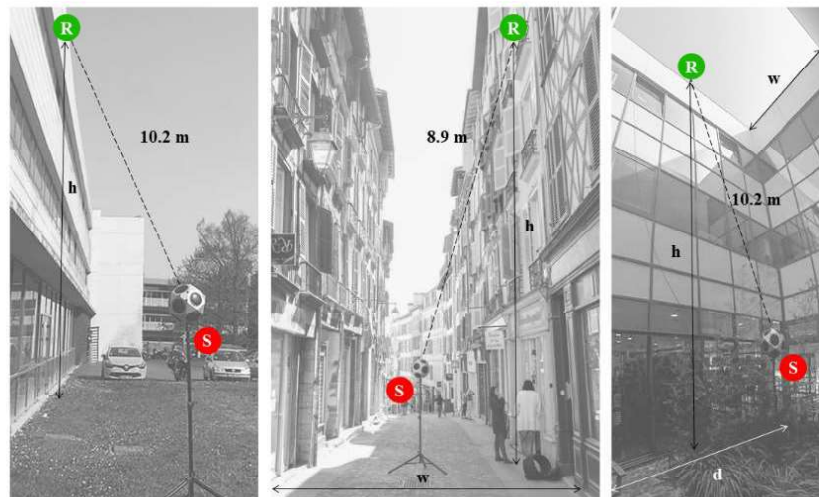


Figure 1. Pictures of the measured configurations (a) “1D” with $h = 11.7$ m, (b) “2D” with $h = 10.3$ m and $w = 5$ m, (c) “3D” with $h = 11.7$ m, $w = 5$ m and $d = 8$ m.

Figure 2 shows the impulse responses recorded in the three configurations. Each one contains a first peak, which corresponds to direct sound. Its delay is equivalent to the distance between the source and the receiver divided by the speed of sound (340 m s^{-1} in the air): the direct sound is recorded with a delay of 29 ms, 26 ms, and 30 ms respectively. The following peaks represent the reflections. Figure 2a exhibits only one of them, which is the consequence of the reflection on the ground. Figure 2b has more and Figure 2c over a longer period. The sound level, expressed in decibels, is calculated by the logarithmic ratio between the squared pressure integral of the impulse response (Figure 2) and the reference constant squared value of $2 \cdot 10^{-5}$ Pa.

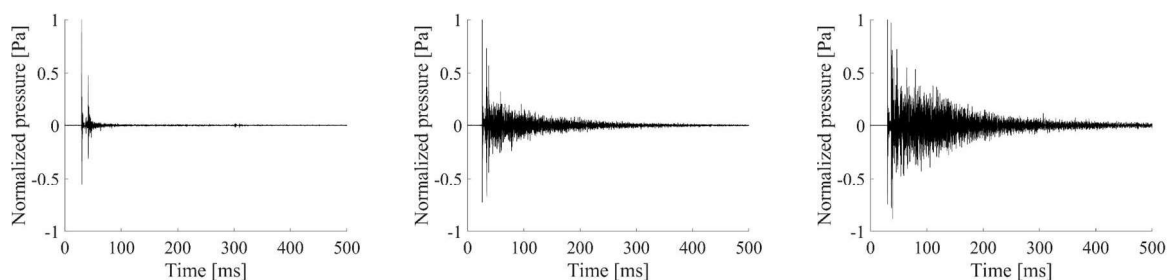


Figure 2. Normalized echograms, measured in (a) “1D” (b) “2D” (c) “3D” configurations.

Ray tracing consists of casting a large number of rays from the source point, which are successively reflected on the surfaces of the geometry and intercepted by a sphere around the receiver point. The accuracy of the calculation depends on three parameters: the number of rays [9], the quality of the distribution [10], and the size of the receiver [9]. To minimize the computation time, *Embree*, an open-source ray tracing library for x86 CPU is used [11]. The source definition relies on a stratified Monte Carlo that ensures a homogeneous random distribution of rays [10]. When performing ray tracing in an urban geometry, many rays can be reflected toward the sky, there is thus no formula to estimate the size of the ideal receiver [9]. In the simulations, 10^9 rays are emitted and the receiver is a sphere with a radius of 0.5 m.

The stop criterion is twofold: either the ray is reflected toward the sky or its travel time exceeds 500 ms, which corresponds to the duration of the measurement (Figure 2). The absorption coefficient α taken for all surfaces in the model corresponds to that of smooth concrete and is 0.01.

Equation (1) gives the sound intensity I (J m^{-2}) of a ray intercepted by the receiver. The parameter s is the distance (m) traveled inside the receiver, W the source power (W), α_k the absorption coefficients of the k walls intercepted during reflections, N the number of rays launched, and r the radius (m) of the sphere [12]. To determine the sound level L_I in decibels at the receiver, the formula in equation (2) is used with n the number of intercepted rays [10].

$$I = \frac{3 s W \prod_k (1 - \alpha_k)}{4 \pi N r^3} \quad (1)$$

$$L_I = 10 \log_{10} \left(\frac{\sum_n I_n}{10^{-12}} \right) \quad (2)$$

3. Results

3.1. First observations and ray tracing validation

The measured and simulated sound levels are presented in Table 1, taking the “1D” configuration values as a reference.

The differences between measurement and simulation “1D” and “2D” are less than 1 dB. The simulated sound level in case “3D” is 1.7 dB higher than the measured value. This is probably due to a vegetalized square ground that is more absorbent than the material taken for the simulation.

Compared to an open view building, a canyon street increases the sound level by about 6 dB, while the courtyard increases it by more than 11 dB. These first results show the impact of multiple reflections on sound levels and validate the use of ray tracing in further studies.

Table 1. Measured and simulated sound levels.

	“1D” configuration	“2D” configuration	“3D” configuration
Measurement	104.0 dB <i>reference</i>	110.3 dB <i>+6.3 dB</i>	115.4 dB <i>+11.4 dB</i>
Simulation	103.7 dB <i>reference</i>	109.6 dB <i>+5.9 dB</i>	117.1 dB <i>+13.4 dB</i>

3.2. Use of ray tracing for the study of urban configurations

Additional simulations were performed to determine the limits between the three configurations (Figure 3). The source and receiver positions are fixed, while the aspect ratio of the geometry changes. In the first case (Figure 3a), the width of the “2D” street varies from 5 to 30 m with 5 m steps. In the second (Figure 3b), the width is fixed at 5 m and the depth of the “3D” configuration changes from 10 to 30 m with 20 m steps. Increasing the distance between façades reduces the sound level at the receiver due to a higher probability of the ray to be reflected toward the sky. The results can be summarized as follows:

- From a width of 15 m or more (Figure 3a), the impact of multiple reflections on the opposite façade is less than 1 dB, the street can be assimilated to the “2D” configuration.
- From a length of 60 m (Figure 3b), the reflections on the walls closing the side of the canyon no longer have any impact on the street center: only the effects on the opposite façade remain, which are equal to 5 dB. This value is the same as the one previously observed on the 5 m wide “2D” street in Figure 3a.

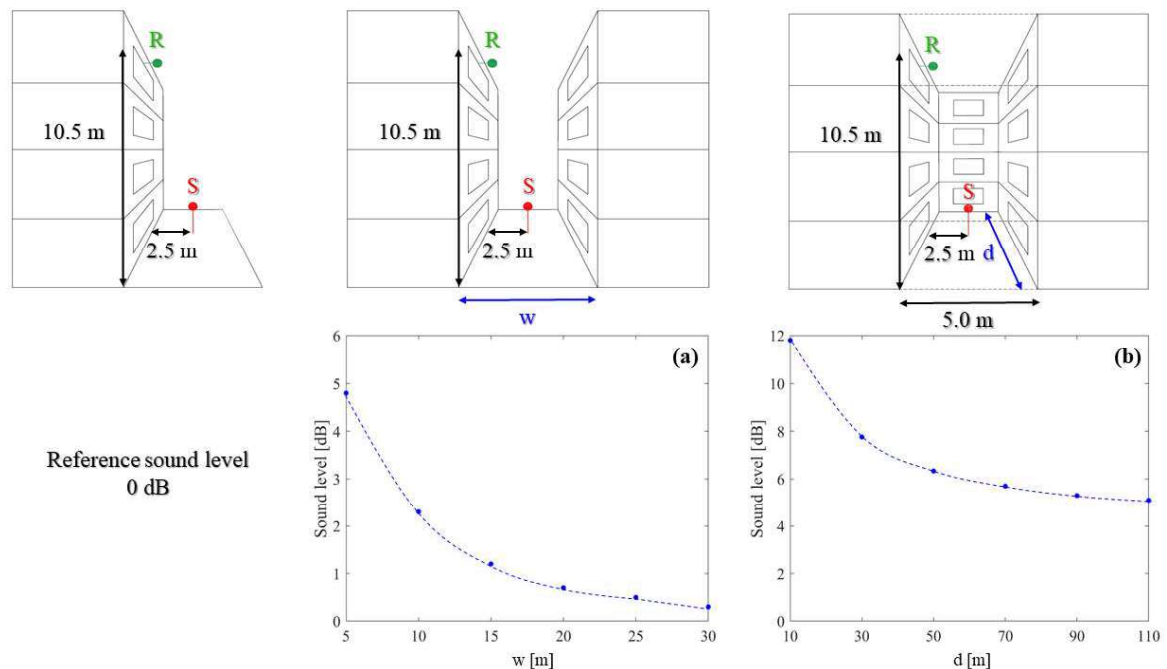


Figure 3. Sound levels simulated at the receiver: (a) in an urban canyon of 5 to 30 m width, (b) in an inner courtyard of 10 to 110 m depth.

3.3. Spatialized representation of the multiple reflections

Figure 4 is a spatialized representation of the multiple reflections. It shows, in isometry, the last point of contact with the geometry of each ray intercepted at receiver R , for the three configurations. The points are colored according to the number of reflections the ray undergoes before reaching the receiver. Reflections come from different places: the early reflections (in red) are originated at the mid-section of the geometry, while the late ones (in blue) come from the top of walls. Direct rays are limited to a single red point at the source S .

The “1D” configuration contains two areas of sound reflection, which are common to the other two configurations. The first area of reflection is located on the ground and corresponds to the second peak of the measured impulse response (Figure 2). The second one, similar to a stretched disk, is located below the receiver at the top of the wall. This is due to the fact that the receiver is spherical: it can intercept some rays after the first reflection on the façade.

In the “2D” configuration, rays also come from a vertical line on the opposite façade. The “3D” case is more complex. The sidewalls increase the reflections and multiply the directions of incidence at the receiver.

A temporal (Figure 2) and a spatial representation of the impulse response could be used together in a process of design: one gives the information on how the sound is perceived and the other illustrates the role of the geometry. It can be used for several applications such as the disposition of absorbent panels or the modification of the architecture.

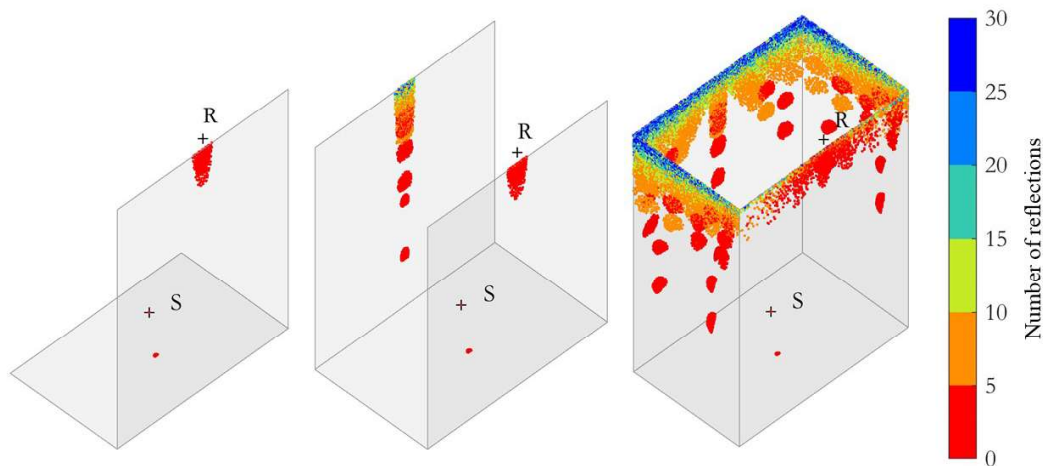


Figure 4. The last contact point of each ray intercepted by the receiver in the three configurations: “1D” “2D” and “3D” (100 000 rays).

4. Conclusion

This work explores the use of ray tracing for acoustical analysis in urban environments. The work on three simple urban configurations showed good agreement between measurement and simulation, allowing the study to be extended to other cases of different dimensions. The “2D” case amplifies the sound found in the “1D” case by 6 dB and the “3D” case by 11 dB. Further simulations show that this amplification decreases as the vertical elements of the scene move away. Thus, from a width of 15 m, the effect of the “2D” canyon façades drops off completely. Similarly, from a depth of 60 m, the effects of the lateral elements of the “3D” case are negligible regarding the center of the street. It can then be considered as a “2D” case.

The spatialized representation of the multiple reflections is based on the colorization of the last contact point of each ray before its interception by the receiver. The image obtained allows to imagine a work on the main areas on which reflections appear. The method could orientate the design and quickly test the efficiency of solutions by combining both the analysis of the sound level and the visual analysis of the multiple reflections on the geometry.

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