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TOWARDS A SOUND DIFFUSION CHARACTERIZATION IN THE URBAN ENVIRONMENT FROM ISOVIST TOOL TO ACOUSTIC SCATTERING INDICATOR

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1 INTRODUCTION

Architectural morphology is an important factor for the prediction of soundscapes and noise propagation in urban areas. As in room acoustics, the sound field in a street is characterized by the building façades irregularities, as well by its global propagation volume characterization. This paper presents a coupling morphological and acoustical database, developed for spatial information systems, aimed to be used by town planners and architects for urban projects.

To achieve this goal, sound field modelling in urban acoustics has attracted considerable attention in the last decades. Thus, many mathematical and numerical models have been derived to predict the sound field in streets, such as image-sources, ray-tracing or beam-tracing, to compute early propagation paths between sound sources and listener while late reverberation is usually modeled using statistical techniques^{1,2,3}. However, many differences were observed between models and measurements in streets, suggesting that the part of multiple reflections, diffraction and diffusion of sound by building façades could be more significant than expected. As a consequence, those models fail to spatialize sound realistically because they do not accurately simulate diffuse sound field.

Moreover, as most prior systems for geometric acoustic modeling are based on image source or ray tracing methods^{4,5,6,7}, sound travel modelling from source to receiver via a multitude of paths containing reflections, transmissions, and diffractions, is leading to extremely time-consuming simulation processes. Therefore, those models do not generally support large 3D environments real-time computation, particularly in the dynamical application corresponding to a walkthrough simulation within the urban maze.

As a consequence, acoustical simulation systems generally work in “batch” mode, taking several minutes to update the acoustic model for a change of the receiver location, or the acoustical parameters of the environment. In order to avoid this working mode, a real-time environmental computation for acoustics is needed, particularly for Geographical Information Systems implementation, fast enough to be used for dynamic spatial interaction modes.

To achieve this goal, we propose a new method to compute diffusive properties of the urban built network, based on an anthropocentred point of view for acoustic computation. This new model, based on a vision-model analogy, tries to determinate the surrounding acoustic properties of a receiver with isovists fields computational tools.

2 PROBLEMATICAL POSITIONING

2.1 Visibility analysis: an overview

To compute the visibility of the pedestrian all along his pathway, the presented method consists into “concatenating” several partial visibility polygons in order to represents the visual perception of the pedestrian.

From a morphological point of view, open spaces are usually defined as the empty space, the void, between the surrounding buildings. However, although these open spaces are not material components of the physical world, they can be conceived as part and parcel of our urban heritage^{8,9} puts the emphasis on the fundamental motivations of conducting visibility analysis research. He noticed that the key questions “how far can we see”, “how much can we see”, and “how much space is enclosed” are relevant to develop good urban design. Benedikt¹⁰ defines an isovist as “the set of all points visible from a given vantage point in space and with respect to an environment”. This concept has been previously introduced in Tandy¹¹. As mentioned in one of Benedikt¹⁰ footnotes, “readers familiar with Gibson's work will see the affinity of isovists with [ambient] optic arrays”.

The isovist is simply this optic array, with the wavelength and intensity information omitted¹². To sum up, an isovist is usually a 2D bounded polygon which is a useful tool to define and characterize the open space concept.

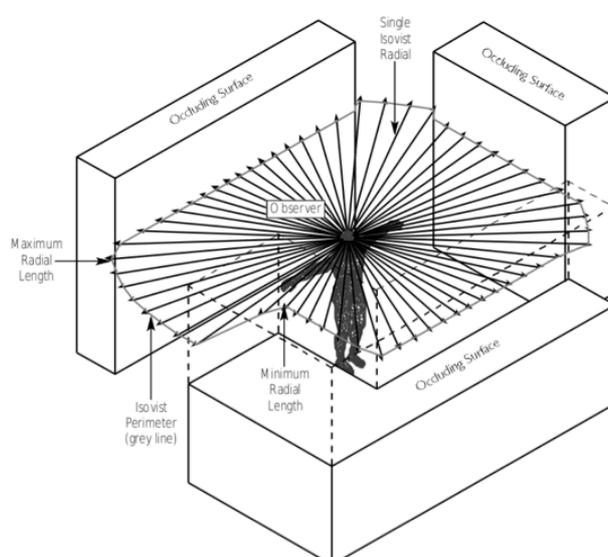


Figure 1: isovist symbolic representation

Several different spatial analysis methods have been defined to study the plenum conception¹³ of urban space: isovist fields^{9,10}, space syntax¹⁴, visibility graphs¹⁵, agent-based approach¹⁶, convex partitions¹⁷, sky opening maps^{8,18} and ambianscape formalization¹⁹. For all reasons developed by Leduc²⁰, we have decided to focus on the well-known 2D isovist fields (vector based approach) method. Indeed, Hillier¹⁴ noticed “human space is in fact full of strategies [...] to reduce the three-dimensional structures to the two dimensions in which human beings move and order space”. Essentially, isovists describe local geometrical properties of spaces with respect to individual observation points and weight all the possible view directions equally. An isovist is a 2D horizontal slice of pedestrian's surrounding space.

2.2 Acoustics and visibility analysis: analogical matching ?

One of the major challenges in geometric acoustic modeling we try to reach through this research work is accurate and efficient computation of a listener morphological fingerprint of an urban networked structure. To achieve this fingerprint analysis^{21,22}, those previous visibility analysis methods enable embodying “space slicing”, aiming to compute geometrical first order diffusion space along a pedestrian pathway. As we want our model to rely on “classical” data of vector type so as to let it be easily and widely repeatable^{23,24}, we will present, in the following use case, a simulation that is only based on both a polygonal buildings layer and a linear pathway layer.

An important contribution of this paper lies on data structures precomputation method that encode surface scattering properties (frontage local diffusivity parametering) in a manner that enables interactive updates of global diffusivity parametering (global street scattering parametering) for an arbitrarily moving receiver location.

Local diffusivity parametering describes frontage local backscattering properties through vertex multiscale densitometrical distribution evaluation at each incidence angle, provided through a fractal technique, the Minkowski sausage, which computational methods are developed further in Woloszyn^{25,26,27,28}.

Thus, global scattering parametering has to be defined through the geometrical properties of spaces from the observation point. Thus, enclosed space analysis is leading to the « Diffusion Volume » expression at each step of the urban soundwalk, through the corresponding isovist indicator. Resulting approximation of direct sound listening can then be « recalculated » through diffusion volume step-by-step computation along the street wandering, with taking the local geometrical characteristics of urban frontages into account.

3 BACKGROUND HYPOTHESIS

3.1 A discreet approach

What needs to be remembered here is that a pedestrian walk in the urban fabric is fundamentally a time-line process. To simplify the model, we have decided to adopt a discrete time approach of the perception mechanism: a slice-time has to be set so as to sequence each pathway. The mean speed of the pedestrian is stable, at each time tick, he reaches a new following position. The continuous linear pathway is thus transformed into a set of ordered punctual equidistant positions. In each of these positions, an isovist is computed and the corresponding polygon is then added to the global isovists field.

3.2 Geometric Limitations

As our system is a research prototype, it has several limitations. First, the 3D model must comprise only planar polyhedron because it is not possible to model the transformations for isovists when reflecting off curved surfaces. Furthermore, Isovists allows only first-order diffusion volume treatment, as the perceived surface collection involved in the diffusion process has to be renewed real-time during the walkthrough. This limitation, mainly audible for highly complex acoustical situations, has to be overtaken in further developments.

Nevertheless, urban applications domain for which our method does work well undertakes limited acoustical effects of any sound source out of the local (viewed) region of the environment.

We integrated the prototype system that allows a user to move through a virtual environment interactively, while spatialized diffusion volume are realtime rendered, according to the user's simulated position in the urban maze.

To test isovists efficiency for modeling global diffusive behaviour in typical urban environments, we choosed a soundpath in a particular heterogeneous built surrounding, thus implying very differenciated morphological situations to be detected.

3.3 Fraunhofer far-field conditions

This work lies on several acoustical hypothesis, which first of them is related to the effective positioning of the pedestrian in the urban fabric. During a walkthrough into the street void, the listener is ususally standing at a certain distance from the reflection planes, namely the urban façades, so that the distance between the structure and the embodying frontage surface (the façade) is large compared to the size of the structure. Therefore, viewed at a large distance compared to the extent of the object, the sound may be accurately modeled as plane waves with different wavefront tilts. This occurs in the Fraunhofer diffraction region²⁹, where, for an incident plane wave, result of scattering from a periodic structure (the façade) can be resumed as an infinite sum of plane scattered waves, mostly harmonics.

In far-field conditions, diffraction of a wave by a periodic structure is due to phase differences that result in constructive and destructive interference³⁰. Observation of diffraction patterns when acoustic waves pass through complex structures is here completed through complex scattering in the diffusion space. The effect of incident plane wave scattering is the creation of far-field secondary waves. These waves, arising from each point on the structure, travel in all directions giving rise to interferential distributions of amplitude and phase³⁰.

3.4 Dimension reduction process

In our particular case, the isovist shape is a polygonal region where there exists at least a point (the view point R) such that for each point P of the polygon, the segment VR lies entirely within the polygonal region. This specificity is due to its relation to the notion of visibility: the isovist polygon may be informally defined as the one whose whole interior is visible from a single view-point, assuming that its boundary is not transparent. Each edge of a polygon defines an interior half-plane, informally defined as a half-plane that contains interior points of the polygon in the vicinity of the edge in question. In the specific case of an isovist polygon, the view-point is located in the intersection of all those interior half-planes. For that reason, but also to convert this bi-dimensional characterization into a mono-dimensional one (efficiency gains), we will focus on the boundary edges of this isovist polygonal region from the view-point point of view.

One must admit that the initial problem (characterize the acoustic diffusion volume) has been simplified a lot with a drastic dimension reduction. The number of random variables under consideration has been divided by 3: from 3D bulk computation to a line integral calculus.

4 GEOACOUSTICAL DIMENSIONING METHODOLOGY

4.1 Diffracted sound pressure distribution

Within the embodying propagation space, quantification of the sound pressure of the scattered acoustic field is provided with the specific angle's frequential polar response, according to an inhomogeneous parametering of the Lamberts law^{31, 32}, following the vertex multiscale densitometrical distribution evaluation of the concerned frontage surface^{25, 26}. This last provides calculation of the mean square diffracted sound pressure P_d by the whole frontage of area S as:

$$P_d^2 = \rho \iint_S \frac{\cos\alpha \cos\alpha_d}{\pi r^2} P^2 dS$$

where r represents the receiver distance from the scattering surfaces, α and α_d , the angles of incident and diffracted sound waves and ρ the energy density distribution of the surrounding façades. Thus, spatial scattering function assumes a tridimensional formulation of the angular distribution function, showing the distribution of the surface's scatterers along every incidence angle of the acoustic source²⁶.

The acoustic field is then expressed through the phonon's density-density distribution $\rho(r)$, involved in the calculation of the mean square diffracted sound pressure P_d by the whole volume for the receiver distance r of the structure²⁷.

To achieve this goal, the structure's neighborhood as a geometrical estimation of its embodying volume²⁸ has to be defined further with a global measure, through α/r distribution laws of the polar response, measured with isovists n^{th} order moment indicators.

4.2 Wave structure factor

The mathematical relationship between the shape and size of those waves output relative to a done spatial structure input can be described by the following spatial Fourier transform³³:

$$F(k) = \sum_{\infty} G_R(k) e^{-j2\pi r}$$

with G_R , the density-density correlation function for reception point R , geometrical parameter of the scattering intensity of the structure.

When measuring several phonons located at different points, the diffraction at each point will be the sum of the waves scattered by each phonon³⁴. So, the expression of this sum with Euler's equation gives us, for the j^{th} phonon at distance r from the diffusive structure:

$$F_{(x,j)} = \sum_j \exp(2\pi i r_j)$$

This wave expression formulates the Fourier transform of equal strength scatterers on all points of the diffraction plane. Continuous expression of this previous equation involves the phonon's density $\rho(r)$ as the following structure factor^{27,28}:

$$F_x = \int_{\text{space}} \rho(r) \exp(2\pi i r) dr$$

As shown through this expression of the structure factor, the diffraction pattern is defined as the spatial Fourier transform of the phonon density.

4.3 Parseval theorem and diffractance angular distribution

Parseval's theorem formulates that the energy in the frequency domain is the same as the energy in the spatial domain³⁵. Consequently, the mean square value on one side of the Fourier transform is proportional to the mean square value on the other side. So do Parseval's theorem allows to express the phonons density distribution as a transform of the spatial distribution of the surface scatterers. This property allows us to express the angular distribution function as a discrete quadratic summation of elementary structure factors³⁶ as following:

$$\int_V \rho(r) dV = \frac{1}{V_D} \sum_x |F_x|$$

where the diffusion volume V_D is a ratio between the square root of the discrete quadratic summation of the structure factors and the angular distribution function.

Diffusion volume V_D , as a ratio between the sum of local frontage scattering contributions and the scattering pressure function at reception point R , can therefore experimentally be obtained by complex measurement of the neighborhood volume of direct reflecting urban surfaces around the listener.

The upper limit of the diffusion domain conditioning the specular condition is then obtained with the asymptotic behavior of phonons distribution law³⁷ as:

$$\rho(k, \omega) \propto \left(\frac{G k}{\omega} \right)^2$$

with k , the concerned diffusion order, and ω , the corresponding wave number. The angular distribution factor G can be directly obtained with the second order of the diffusion volume, given by the corresponding viewpoints density distribution.

However, the angular distribution function $g(r)$ along a characteristic direction of scattering informs on the wave disturbance at a distance r from the object, involving the phonon's average density as:

$$g(\mathbf{r}) = \frac{1}{m} (G(\mathbf{r}) - \bar{m} \rho(\mathbf{r}))$$

This diffractance formulation implies the angular second moment of energy density, the density-density correlation function $G(r)$, taken from the reception point to the urban embodying surfaces, main parameter of the scattering intensity of the diffusive structure. For an incident plane wave, scattering result is an infinite sum of plane-scattered waves, mostly harmonics.

Thus, as the structure factor F_x is the Fourier transform of the scatterers of equal strength on all points at distance r of the diffraction plane, the acoustic diffraction pattern is defined as the Fourier transform of the structure spatial angular density. As phonons density distribution is a transform of the spatial distribution of the surface, second-order phonon density distribution can therefore be deduced from those geometrical indicators all along a pedestrian pathway in the urban environment.

Therefore, phonons angular density-density correlation function $G(r)$ can be deduced from the embodied distances probability distribution, calculated by the corresponding isovists normalized moments in the spatial domain.

4.4 Isovists normalized moments

As diffusion capacity of a complex plane can be directly computed from the Fourier Transform of its spatial structure, the corresponding far-field Fraunhofer diffraction region characterisation allows scattering prediction for many types of spatial configurations, through their isovists probability distribution moments calculation.

According to the Hausdorff moment problem in mathematics, for a bounded input interval (as may be seen below, ours is defined by $[-\pi, +\pi]$), a given infinite sequence of moments is a necessary and sufficient condition to define a probability distribution of this observation space.

The corresponding normalized central moments of the isovists probability distribution are dimensionless quantities, which represent the distribution independently of any linear change of scale.

2nd order moment, variance, characterize the isovist probability distribution.

As the k^{th} standardized moment of a continuous univariate probability distribution x with probability density function $f(x)$ is defined by:

$$G(x) \propto M_p = \int_{x \in X} \left(\frac{x - \bar{x}}{\sigma} \right)^p p(x) dx$$

where respectively average value and standard deviation are defined by:

$$\bar{x} = \int_{x \in X} (x p(x)) dx \quad \sigma = \int_{x \in X} (x - \bar{x})^2 p(x) dx$$

The isovist boundary (from the view-point point of view), can be seen as a continuous function from $[-\pi, +\pi]$ to R^+ . It associates each input azimuth angle α to an output radius' length $r(\alpha)$. In this specific context, the k^{th} standardized moment formula mentioned before may be simplified into:

$$G(x) \propto M_p = \frac{1}{2\pi} \int_{-\pi}^{\pi} \left(\frac{r(\alpha) - \bar{r}}{\sigma} \right)^p d\alpha$$

As written in this last formula, a simple line integral has to be calculated on the classical $[-\pi, +\pi]$ domain of integration.

5 CASE STUDY

The pedestrian pathway we are used to analyze is about 1.6 km length. To characterize it using isovists field tool, we have to sample it into a set of about one thousand harnessing positions. Due to the huge amount of involved geo-processes, this task requires a scalable indicator. The one-dimensional one, resulting from the previous line integral, is enough robust, easy and efficient to be computed.

5.1 Nantes city center (France) as a use case

In order to exhibit the relevance of our model and its potentialities, we have decided to apply it to a pedestrian pathway called "parcours confort" proposed by the Nantes Métropole Tourist Office¹. Nantes is a west-coast located city in France. This tour, accessible to all (even for people in a wheelchair), proposes to those who have some time to spend wandering in Nantes a discovery of the historical city center from medieval to 19th century morphologies.

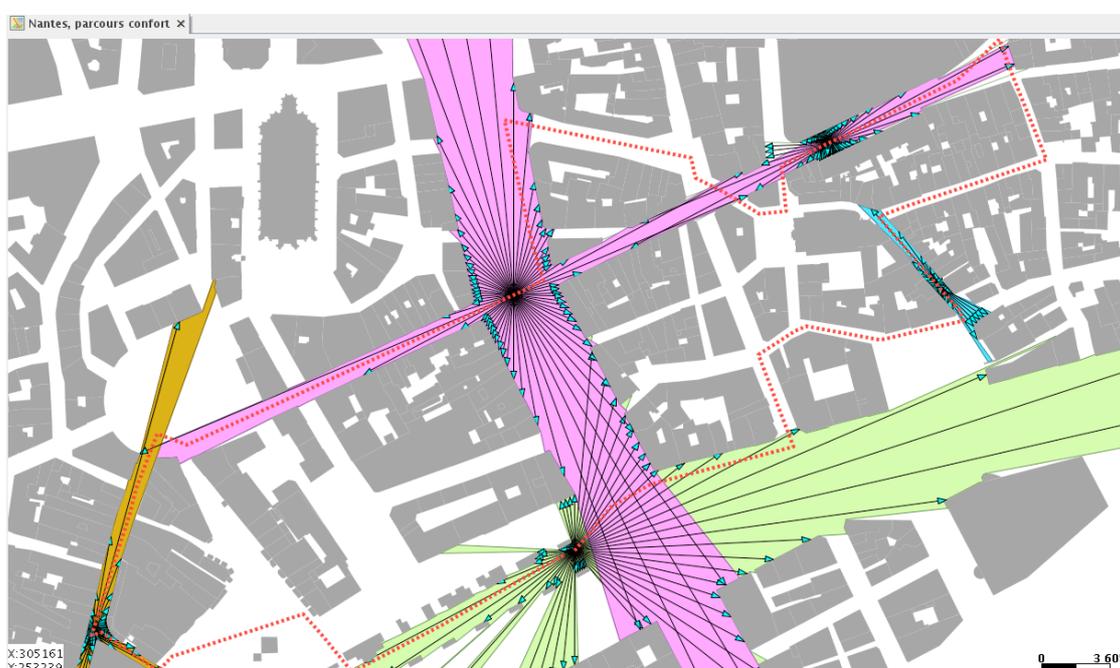


Figure 2: Overview of one of the Nantes Métropole Tourist Office tours in the historical city center (dashed line). This path is sampled into 983 discrete positions. On each of them a full isovist is computed. In this figure, only 5 of them are represented with both polygons and ray tracing techniques.

This 1590 meters long tour starts from the tramway central station Commerce and run through:

- the medieval district called *quartier du Bouffay*,
- the *Cours des 50 otages* main street, named in memory of the fifty hostages who were executed during the Second World War. This boulevard has been redesigned in 1990 by the Italian architect Italo Rota;
- the *Place Royale*, which embeds a 19th century fountain representing the city of Nantes with the Loire River sitting on her feet,
- the *Passage Pommeray*, the only multilevel covered street in Europe, containing a staircase bordered by statues.

1 This tour is available on-line on the website: <http://www.nantes-tourisme.com/>.

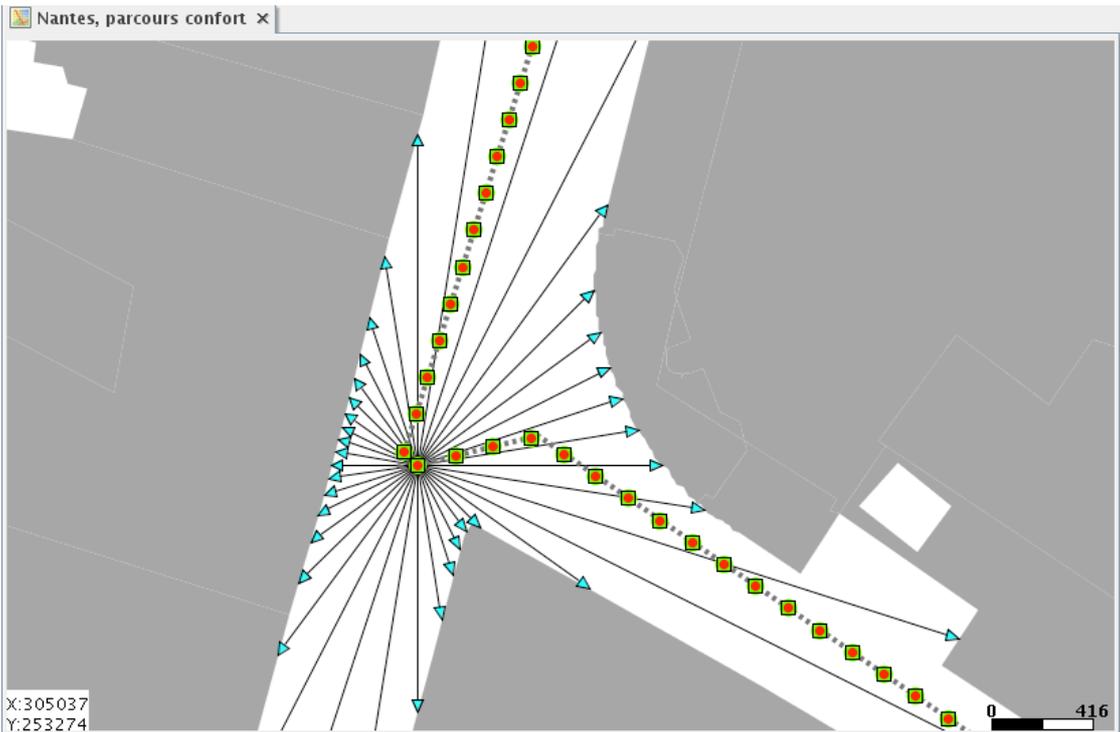


Figure 3: Zoom in a specific place. Discrete path positions are depicted by square-centered discs.

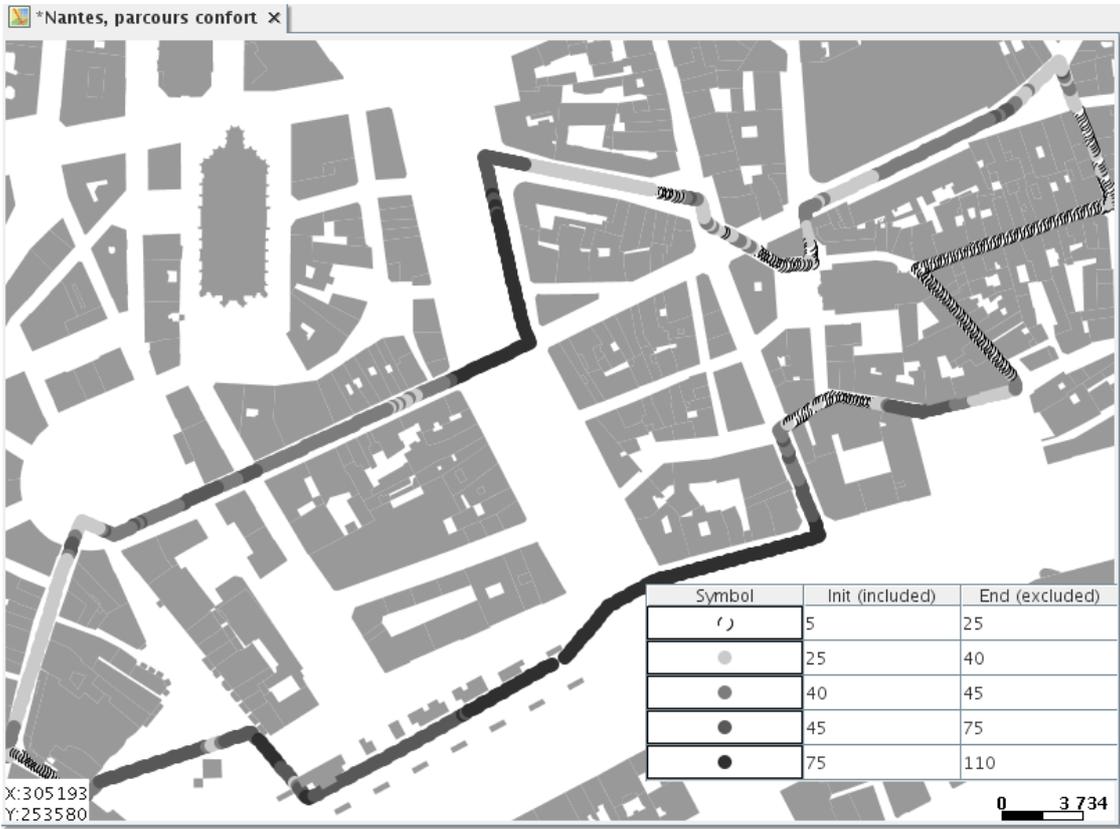


Figure 4: Interval classification of the isovist ray tracing approach with the 2nd order moment indicator. As may be seen in this figure, the values of this indicator in canyon streets (ranges 5-25 and 25-40) differ clearly from the values of the same indicator in open spaces like squares (ranges 45-75 and 75-110).

5.2 Results and discussion

As may be established considering figure 4, this use case present manifold urban morphologies. In a 11m wide street canyon called *rue d'Orléans* (surrounding buildings are about 15 m high), the 2nd order moment value is about 40. In a narrower street canyon of about 6m wide (and with surrounding buildings of about 12m high), such as the one of the east (in this figure) medieval district *Le Bouffay*, this 2nd order moment value is about 10. Lastly, in real open spaces like wide main roads or large square, the corresponding value is greater than 70.

6 CONCLUSION

In this paper, we introduce an efficient technique for incorporating diffusion effects for soundwalks audio simulations into a geographical information system, with isovists algorithms that allow quick computation of diffusion volume within urban environments.

Aimed to simulate urban morphology far-field diffusion behaviour, this powerful information system is able to discriminate local urban morphologies through second-order moment isovists calculation, with sufficient flexibility to permit dynamical diffusion indices real-time calculation for an urban walkthrough.

One potential application for the methods developed in this paper consists into enhancing dynamic auralization with real-time computation of diffusion volume and scattering surfaces through soundscapes convolution with using the calculated tridimensional impulse responses.

Last development perspectives aims to apply this real-time diffusion geoprocessing system to investigate psychophysical characterization of varying diffusive parameters, through real-time auralization and visualization feedback.

Under the generalization condition of this diffusive characterization method to any complex urban configuration, this research work states on diffusion process as a geometrical-dependant phenomenon, confirming the multiscale influence of the built structure, structurally considered as a diffusive system, on urban acoustics.

7 PERSPECTIVES AND FURTHER WORK

7.1 3D impulse responses validation procedure

Experimental validation of this dynamical diffusivity model will be run thanks to a B-Format multisensor method of measurement, in order to characterize a continuous 3-D Impulse response of an urban path. This innovative method of measurement will be applied *in situ* on the same location than the numerical model used for isovists calculation.

During a soundwalk, information system treatment will describe the street diffusion process with providing N^{th} order isovist measurements. Those values will provide the late reverberation distribution law corresponding to the successive diffusion volumes for the receiver pathway, to model a tridimensional impulse response serie of the soundwalk.

Experimental validation measurement system will use a geometrical placement (*xyz*) of the recording systems, derived from the Ambisonics® approach. It consists into acquiring the omnidirectional sound pressure signal (*W*), plus three first-order pressure gradient components, along the three Cartesian axes (*XYZ*). The 4-channel microphone used at this aim records the B-format impulse responses with a sine sweep signal at every point of the street to be characterized during the analyzed soundwalk.

Tridimensional diffusion experimental values will then be compared to the described dynamical isovist 3D impulse responses model in order to validate dynamical diffusivity indicators all along the analyzed pathways.

7.2 Walkthrough auralization process and soundscape psychophysical evaluation

In a second time, the resulting tridimensional impulse responses can then be used as convolution filters to spatialize audio signals according to the computed reverberations between sources and receivers in the urban environment³⁸.

To achieve this goal, 3D impulse responses will be convolved to the reference anechoic urban signal, which makes it possible to re-create the complete three-dimensional information of the street with the soundscape for auralization through a restitution system that preserves its spatial components^{39,40}.

Thus, a real-time auralization and visualization feedback system that uses interactive acoustic simulations will enable us to investigate the psychophysical effects of varying different diffusive parameters⁴¹ conditioned by the urban built environment.

Such an experiment was proceeded within a canyon street in Bordeaux, *Vital Carles* street, in which tridimensional impulse responses were recorded all along of the street, to investigate how the sound field was influenced by the building façades^{42,43}.

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