DOI: 10.61782/fa.2025.0132

FORUM ACUSTICUM EURONOISE 2025

ANALYSIS OF THE RECONSTRUCTED ACOUSTIC ENVIRONMENT OF A PORTUGUESE ROMANESQUE CATHEDRAL IN THE 16TH CENTURY BY NUMERICAL MODELLING

Paulo Amado Mendes[1*] **Luís Godinho**[1] **Diogo Mateus**[1]
Andreia Pereira[1] **Denilson Ramos**[1] **Anna Gaspar**[1]
[1] University of Coimbra, ISISE, ARISE, Department of Civil Engineering, Coimbra, Portugal

ABSTRACT

In Portugal, the acoustic characterization of historic churches has been relatively unexplored. In some cases, there are documented modifications performed along the centuries that significantly have changed the original acoustic environment of the religious spaces. It is thus very interesting to analyze the consequences of those modifications on the acoustic heritage that can be nowadays "experienced".
In the present study, the Old Cathedral of Coimbra, a Romanesque Church from the 12th century that has been modified during different periods, is first analyzed in its present condition. Therefore, a 3D numerical model has been built, the acoustic properties of the still-present materials have been studied and the main acoustic quality parameters have been numerically evaluated. An experimental in situ campaign has been carried out and the obtained data has been used in the calibration of the numerical model.
Then, following multidisciplinary art history research from the 16th century period, the numerical reconstruction of the acoustic environment is sought in order to analyze the significant acoustic influence of dominant structures present in early days, such as a low and a high-choir. The main results of this numerical acoustic study are herein presented.

Keywords: *acoustics of historical places, 3D numerical modelling, in situ experimental survey*

[*]***Corresponding author***: pamendes@dec.uc.pt.

1. INTRODUCTION

In the last decades, there has been a significant interest in the acoustic study of historical places, with special focus in churches and religious spaces [1-3], showing the importance of holistic approaches in the study of these significant heritage buildings and its relationships with clergy and faithful communities. More recently, different studies have been using simulation and virtual techniques in order to analyze the acoustic environment of reconstructed historical places, the influence of the presence of architectural elements that are no longer present in these places or even the evolution of the acoustics of different Cathedrals, which have continuously changed over the centuries [4-6].
These approaches have not yet been adopted in the acoustic study of Portuguese churches, but a recent interdisciplinary project, involving the Old Cathedral of Coimbra, proposed to evaluate in situ the main acoustic parameters characterizing the current situation of this 12th century Portuguese cathedral, and to use these parameters in the calibration of a 3D computational acoustic model. Then, using computational acoustic simulation, the acoustic behavior of this historical space, after the reconstruction (or retro-incorporation) of the main changes made to that space, since the 16th century, could be analyzed and the evaluation of the main acoustic parameters characterizing the acoustic situation of the cathedral space on that date.
In this paper, first, a brief description of the Old Cathedral of Coimbra is given, and the whole process to construct an efficient and accurate 3D acoustic model, its materials' definition and its calibration with onsite acoustic measurements is presented. Later, the main identified changes performed in this historical building, corresponding to the 16th century scenario, are introduced, and the analysis of the reconstructed acoustic environment is performed, by

geometrical acoustical simulation, highlighting the great influence of once existing low and high choirs, and how different locations in the space and distinct user communities may have had their needs and sound perception affected.

2. OLD CATHEDRAL OF COIMBRA 3D ACOUSTIC MODEL

2.1 Digital geometrical model

The Old Cathedral of Saint Mary of Coimbra, in Portugal, is classified as international Romanesque architectural style, and dated from the 12th century [7]. It is one of the most important Portuguese religious spaces of this style, having played an important role for Christian Church in Coimbra, almost from the foundation of Portugal as a kingdom. This important religious heritage building has presented an impressive renovation dynamic along the centuries, with several documented restoration campaigns, held until the first half of the 20th century.
The building of the Old Cathedral of Coimbra presents nowadays an approximate rectangular plan shape, divided into three vaulted naves, a transept that sections the naves transversally, complemented with three small chapels, being the central the high altar (see Figure 1).

Figure 1. Old Cathedral of Coimbra contemporary inner view of the central nave facing the high altar.

The maximum length of the Cathedral corresponds to the central nave, from door to the high altar, of about 40 m, and the length of the transept if approximately 22 m. The total width of the space is less than 15 m, with the central nave being slightly wider than the lateral ones. The central nave and the transept nave are the highest naves, with a height of about 17 m, and a 23 m high dome is formed in their intersection; the two lateral vaulted naves have approximately a 10 m free height, since they present two triforiums or galleries in a second floor. The estimated inner volume of this religious space is about 11000 m^3.
Initially, a detailed laser-photogrammetric survey of the Old Cathedral of Coimbra was performed, giving rise to a huge cloud of points defining the geometry and volume of the inner space. This refined 3D spatial data was then progressively organized and simplified in order to create a 3D digital model (a general outside view can be seen in Figure 2).

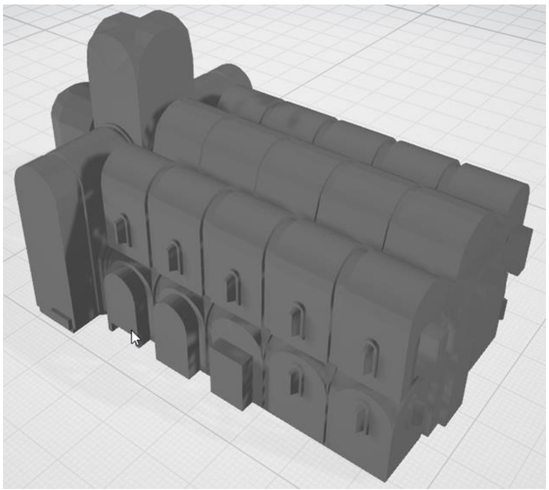


Figure 2. 3D general view of digital model of the Old Cathedral of Coimbra.

This simplified 3D geometrical model of the Old Cathedral of Coimbra, with approximately 36000 nodes and 12000 polygons, has been verified onsite for geometrical accuracy of the building elements, representing a compromise between detail and geometric simplification compatible with the detail and accuracy of the computational model responsible for the acoustic simulations,

2.2 Acoustic properties of materials

Based on an extensive onsite inspection and photographic surveying, all the materials of the exposed building elements and decorated surfaces of all spaces in the Old Cathedral of Coimbra were identified and cataloged, with the correspondence to the flat polygons of the geometrical model being accurately performed. Also, both the sound absorption coefficients and sound scattering coefficients of all surfaces were assigned, for each frequency octave band, based in usual values found in the bibliography [8-12].

2.3 In situ acoustic measurements

The acoustic characterization of the contemporary configuration of the Old Cathedral of Coimbra was done by experimentally evaluating, onsite, a set of quality acoustic parameters. Acoustic measurements were performed in the unoccupied religious space, with impulse responses (IR) being obtained in accordance with the guidelines defined in the standard ISO 3382-1 [13]. An excitation point was considered, coincident with one of the usual locations of the main sound sources in religious celebrations, in the high or main altar (source F1), and placed at a height of 1,5 m (Figure 3). A set of 12 receiver positions has been considered, distributed throughout the faithful audience area, in the ground floor, and 4 additional receiver positions in the triforiums, in the second floor, with all microphones being placed at a height of 1,2 m above the floor.

Figure 3. Acoustic measurements with sound source in the high altar (source F1).

For the source F1 position, and for each microphone position, impulse responses were registered for an MLS (Maximum Length Sequence) acoustic signal, generated by the digital recording system, controlled by dBBATI32 software, and emitted by a dodecahedral sound source after amplification. Environmental conditions (e.g. temperature and relative humidity) were registered along the measurement campaign in order to control the sound velocity in air and its absorption in the calibration process of the geometrical models for the simulations.

At this stage, the digital processing of the acoustic measurements enabled the computation, in octave frequency bands from 125 to 4000 Hz, of the following acoustic quantities: Reverberation Time (RT) and Early Decay Time (EDT), in seconds, related to the perceived reverberance of the acoustic space; and Definition (D_{50}, in %) and Clarity (C_{80}, in dB), related to the perceived clarity of sound (for speech and music, respectively) subjective listener aspect. The average values of these acoustic quantities in all receiver positions are resumed in Table 1.

Table 1. Acoustic parameters in octaves obtained through in situ acoustic measurements, with source F1 position (average values in all receivers).

Freq. (Hz)	125	250	500	1000	2000	4000
RT (s)	5,02	4,98	4,87	4,44	3,79	2,66
EDT (s)	4,86	4,92	4,76	4,44	3,68	2,55
D_{50} (%)	13,3	8,6	10,4	12,7	16,2	26,2
C_{80} (dB)	-7,4	-8,7	-8,0	-7,3	-5,7	-2,8

2.4 Calibration of the 3D acoustic model

After performing the onsite experimental campaign, the previously described 3D acoustic model of the Old Cathedral of Coimbra can be adjusted and calibrated in order to make the virtual model correctly reproduce the current acoustic conditions of the space. The numerical simulations of the sound field in the religious space are carried out by an in-house implemented MATLAB ray tracing code, based on geometrical acoustics theory [14-17]. In fact, as it was already mentioned, in the construction of the acoustic model, there is a certain level of detail that cannot be considered in the definition of the building elements and decorative surfaces, which can usually be compensated by the iterative adjustment of sound absorption and scattering coefficients, and successive comparison of different (frequency-dependent) acoustic parameters obtained numerically and during the onsite acoustic measurements.

In the present case, this iterative process was carried out with minor adjustments in the sound absorption and scattering coefficients of the larger exposed areas (in stone), in octave bands in the frequency range from 125 to 4000 Hz, and without modifying the geometrical configuration of the model. In this calibration process, an agreement between simulated and experimentally measured acoustic parameters was pursued, based on getting JND (just noticeable differences) differences as low as possible, preferably below 1.

The definitions of JND adopted in this study correspond to the expressions stated in the standard ISO 3382-1 [13],

complemented with the recommendations given by Martellotta [18] for large reverberant spaces, such as churches, and they can be summarized as: 5% of the reference value, for RT and EDT; 5% for D_{50}; 1.5 dB for C_{80}; and 8.5% of the reference T_S value, when assessing center time, T_S.
A good adjustment has been achieved, with average #JND values, in the frequency range 125-4000 Hz, for the four measured acoustic parameters averaged in all receiver positions, not exceeding 1, with only occasional higher discrepancies at specific octave band and mainly for the case of EDT acoustic parameter. After the successful calibration of the 3D acoustic model, the simulated acoustic parameters are shown in Table 2, and the frequency values for reverberation times and clarity plotted in Figure 4.

Table 2. Acoustic parameters and JND in octaves obtained by simulation after model calibration, with source F1 position (average values in all receivers).

Freq. (Hz)	125	250	500	1000	2000	4000
RT (s)	5,37	5,23	4,75	3,92	3,48	2,41
EDT (s)	5,71	5,51	4,90	3,97	3,59	2,52
D_{50} (%)	9,9	10,3	11,3	13,8	16,9	24,3
C_{80} (dB)	-8,3	-8,0	-7,9	-6,6	-5,3	-3,0

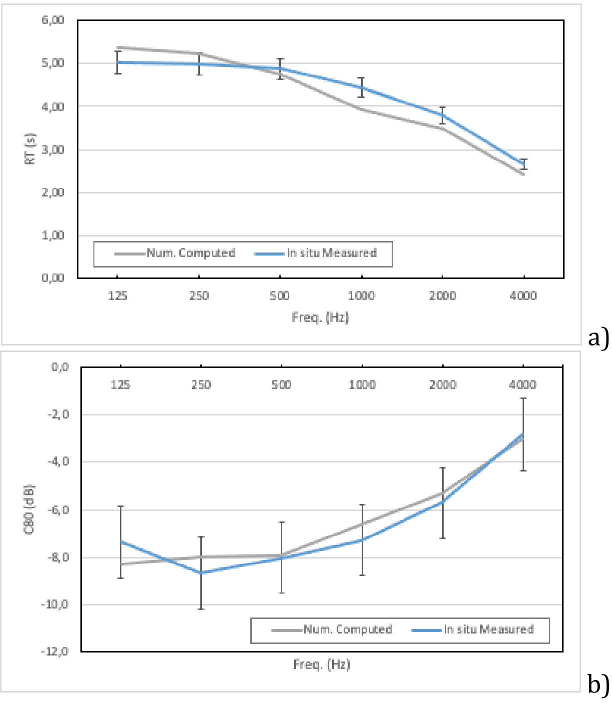


Figure 4. Comparison of measured in situ and simulated acoustic parameters: a) RT (s); b) C_{80} (dB).

3. RECONSTRUCTION OF THE 16TH CENTURY ACOUSTIC ENVIRONMENT

3.1 Virtual reconstruction

Given the interdisciplinary character of the present study, also involving Musicology and Art History disciplines, an important period of time to be better understood, in terms of the acoustic behavior of the Old Cathedral of Coimbra, is the 16th century acoustic environment, in the context of musical liturgy ceremonies of the deceased. Therefore, among several changes in the space of the Cathedral since that period, that could be identified in bibliographic and iconographic sources, the ones that could generate a significant impact in the worship and acoustic environment and that should be further studied were the presence of a low choir, in the central nave at the ground level, and the presence of a high choir, also in the central nave, but at the higher level, levelled with the triforiums (see the modified 3D digital virtual model incorporating both choir structures, and the schematic representation identifying both elements). Both choirs have similar rectangular shapes, about 10 m*5 m, and wooden benches and three wooden walls due to clergy privacy.

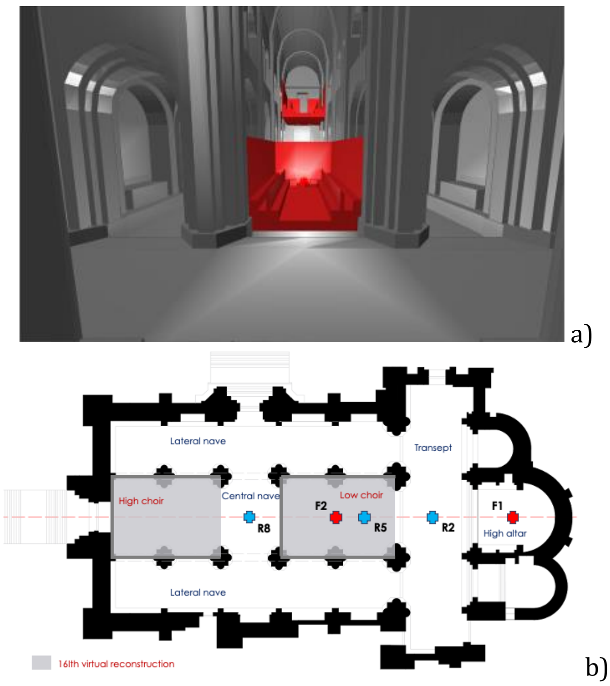


Figure 5. Reconstruction of the 16th Old Cathedral: a) inner view of digital model with low and high choirs; b) schematic representation of ground plan.

Therefore, the initial 3D acoustic model of the Old Cathedral of Coimbra has been modified, in order to retro-incorporate the once existing low and high choirs, important structures that were used to accommodate, in a reserved enclosure, the clergy for prayer, preaching or chant.

3.2 Analysis of the 16th century acoustic environment

Consequently, the 16th century spatial configuration and sound space should be digitally reconstructed, and numerical simulations should allow for this virtual recreation. Additionally, along with the change in the global sound field of the cathedral due to those modifications in architecture, the perceived acoustic conditions, at specific locations, should be analyzed and better understood.
In this particular 16th century scenario, the sound source location has changed to the center of the low choir (source position F2), in coherence with the musical role of the choir in the context of the liturgical ceremony. Also, let us consider the specific location of three important receiver locations, namely: receiver position R2, located in the transept, in front of the low choir; receiver position R5, placed inside the low choir, representing the clergy location during the ceremony; and receiver position R8, located in the central nave, but outside the low choir, representing a generic position of the faithful audience.

3.2.1 Average acoustic parameters

Let us analyze, first, the single number frequency averaging (500-1000 Hz [13]) of the already defined acoustic parameters, and let us consider the following additional parameters: Center Time (T_S, in milliseconds), and nondimensional Bass Ratio (BR) and Speech Transmission Index (STI).
In Table 3, the simulated acoustic parameters are given for the 3 receiver positions and the corresponding values for spatial averages of all receiver positions distributed in the religious space.

Table 3. Simulated acoustic parameters (average 500-1000 Hz) in reconstructed Old Cathedral, with source located in low choir F2.

Receiver	RT_m (s)	EDT_m (s)	T_{Sm} (ms)	D_{50m} (%)	C_{80m} (dB)	BR (-)	STI (-)
R2	4,33	3,71	209,9	39,9	-1,2	0,67	0,50
R5	3,94	1,26	72,3	75,5	6,0	0,64	0,71
R8	4,35	4,65	372,1	6,8	-7,5	0,70	0,34
Avg. all recs.	4,27	4,16	322,2	16,0	-6,3	0,68	0,36

It becomes evident that receiver position R5, inside the low choir, presents the best acoustic parameters (lower EDT_m and T_{Sm} values, higher D_{50m}, and C_{80m} values, and higher STI value, which can be classified as Good in the subjective intelligibility scale [12]), followed by the receiver located in the transept (R2), but receiver position R8, located in the faithful audience area, exhibits a significant decrease in the quality of the acoustic parameters (high EDT_m and T_{Sm} values, very low D_{50m}, C_{80m} and STI values, being classified with a Poor intelligibility) and it is very similar to the average values in all receivers.
This is also highlighted if an analysis of the #JND differences is carried out (Table 4), comparing the acoustic parameters in the three receiver positions and the spatial average values in all receivers. In fact, the higher #JND values corresponding to R5 receiver position represent the higher differences from the average values in all receivers.

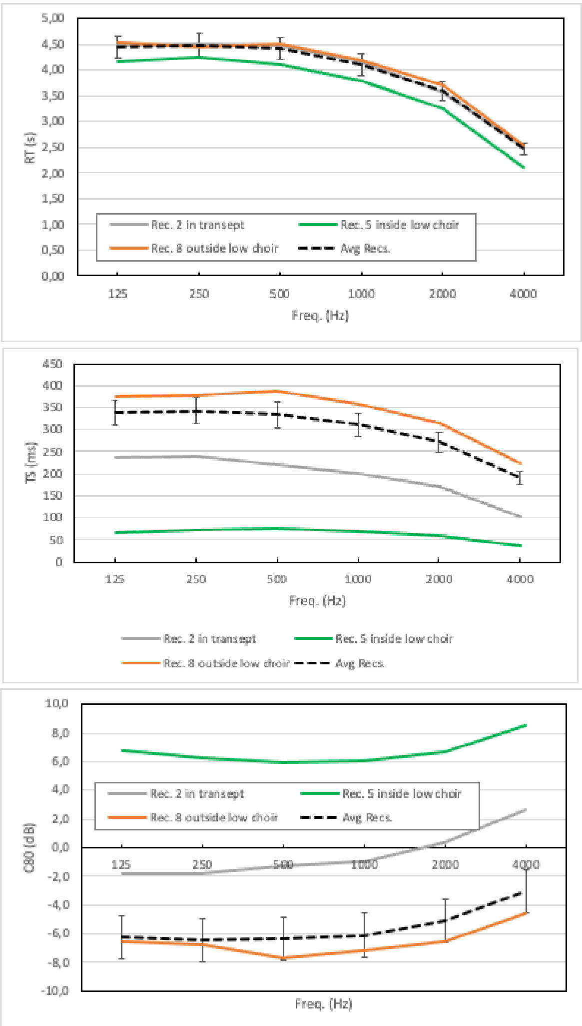
Table 4. Differences in #JND between acoustic parameters in receiver points and average values in all receivers, with source located in low choir F2.

#JND / Receiver	RT_m (s)	EDT_m (s)	T_{Sm} (ms)	D_{50m} (%)	C_{80m} (dB)
R2	0,3	-2,2	-4,1	4,8	3,4
R5	-1,5	-13,9	-9,1	11,9	8,1
R8	0,4	2,4	1,8	-1,8	-0,8

3.2.2 Frequency-dependent acoustic parameters

Instead of analyzing the single number frequency averaging values, the acoustic parameters can be compared, for the same receiver positions (R2, R5 and R8), but in octave frequency bands, in the range 125-4000 Hz. Figure 6 illustrates the evolution with frequency of three selected acoustic parameters, specifically, the reverberation time (RT), the center time (T_S) and clarity for music (C_{80}), obtained by simulation when the space is excited by a sound source located in the low choir, at source position F2.
The same trend as in the single number values previous analysis can be identified in Figure 6, with the receiver position also located inside the low choir (R5) presenting better acoustic quality parameters, followed by interesting values in the case of the receiver position locate in the transept (R2), and the worst acoustic parameters being evaluated in receiver position R8, outside the low choir, and close to the spatially averaged values in all receiver positions. As expected, the improvement in the acoustic parameters, along the frequency range, is most noticeable in the case of center time (T_S) and clarity for music (C_{80}), and the variation in the reverberation time (RT) is only slightly larger than 1 JND at each octave frequency band.
The significant reduction in center time (T_S) and the clear increase in clarity for music (C_{80}), for receivers R5 and R2, highlight both the strong improvement in sound perception,

speech intelligibility and musical clarity that could, indeed, benefit the clergy community when compared to the sound perception that was experienced by the faithful audience, as well as demonstrates the strong influence of the presence of the low choir and high choir structures in sound field of the 16th century reconstructed religious space.



a)

b)

c)

Figure 6. Simulated acoustic parameters in reconstructed Old Cathedral in different locations, in transept (R2), inside low choir (R5) and faithful area (R8), and source located in low choir F2 source position: a) RT (s); b) T_S (ms); c) C_{80} (dB).

4. FINAL CONSIDERATIONS

In the present work, a 3D digital acoustic model of the Old Cathedral of Coimbra is firstly described and the calibration process, with onsite acoustic measurements, presented in detail. This acoustic model has been used in the retro-incorporation of two important volumetric elements that were part of this cathedral in the 16th century, as in many other European cathedrals, one low choir, at ground level, and one elevated high choir, in the opposite side from the high altar. The strong acoustic influence of these dominant structures has been demonstrated by the analyses of the numerical simulations based in geometrical acoustics theory, which also reinforce the significant differences that may have been experienced by the clergy and faithful communities during the 16th century acoustic configuration of this religious space during certain liturgical ceremonies.

5. ACKNOWLEDGMENTS

This work was funded by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020 (doi.org/10.54499/UIDB/04029/2020), and under the Associated Laboratory for Advanced Production and Intelligent Systems (ARISE) under reference LA/P/0112/2020.
Funding was also obtained within the scope of the project “Seeing what the past (heard) saw. Spatial and acoustic reconstruction of the Old Cathedral of Coimbra (16th century)”, a Research and Development Seed Project, funded through the Santander Financing Competition for Interdisciplinary Projects for the Post-COVID19 pandemic phase, within the scope of the Strategic Areas of the University of Coimbra.

6. REFERENCES

[1] S. Girón, L. Álvarez-Morales, and T. Zamarreño: “Church acoustics: A state-of-the-art review after several decades of research”, *Journal of Sound and Vibration*, 411, pp. 378–408, 2017.

[2] A. P. González, “El estudio acústico de los edificios históricos desde una perspectiva global. Conferência plenária”, in *Proc. of Acústica 2020* (online), pp. 25-38, 2020.

[3] F. Aletta and J. Kang (eds.): *Historical Acoustics. Relationships between People and Sound over Time*, special issue published in *Acoustics*, MDPI, 2020.

[4] F. Martellotta, T. Zamarreño García, and S. Girón Borrero, "Virtual reconstruction of Spanish Cathedrals: the sound of choir and other weakly coupled volumes in Seville Cathedral", in *Proc. of EuroRegio 2016* (Porto, Portugal), EAA- SPA, 10 p., 2016.

[5] A. Alonso, R. Suárez, and J. J. Sendra, "Acoustical influence of different locations of the choir in the cathedral of Granada from a subjective and objective overview", in *Proc. of ICSV 2016-23rd International Congress on Sound and Vibration* (Athens, Greece), 8 p., 2016.

[6] S. S. Mullins and B. F. G. Katz: "The Past Has Ears at Notre-Dame Cathedral: An Interdisciplinary project in Digital Archaeoacoustics", *Acoustics Today*, 20(2), pp. 49-58, 2024.

[7] M. L. Craveiro: *A Sé velha de Coimbra*, DRCC, 2011.

[8] M. Vorländer: *Auralization, fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality*, Berlin: Springer-Verlag, 2008.

[9] T. J. Cox and P. D'Antonio: *Acoustic absorbers and diffusers: theory, design and application*, Crc Press.X, 2009.

[10] F. Martellotta: "Identifying acoustical coupling by measurements and prediction-models for St. Peter's Basilica in Rome", *The Journal of the Acoustical Society of America*, 126(3), pp. 1175-1186, 2009.

[11] F. Martellotta, S. Crociata and M. D'Alba: "On site validation of sound absorption measurements of occupied pews", *Applied Acoustics*, 72, 12 (2011), pp. 923-933, 2011.

[12] L. Álvarez-Morales, T. Zamarreño, S. Girón and M. Galindo, M.: "A methodology for the study of the acoustic environment of Catholic cathedrals: Application to the Cathedral of Malaga", *Building and Environment*, 72, pp. 102-115, 2014.

[13] ISO 3382-1:2009(E). Acoustics-measurement of room acoustic parameters, Part 1: Performance spaces. Geneva, ISO, 2009.

[14] E. Brandão, R. Dal Fiume, G. Morgado, W. D. A. Fonseca and P. Mareze, "A ray tracing algorithm developed at the acoustical engineering course of UFSM in Brazil", in *Prof. of ICA 2019* (Aachen, Germany), pp. 4638-4645, 2019.

[15] J. H. Rindel, "Modelling the directional characteristics of sound reflections", in *Proc. of Joint Baltic-Nordic Acoustics Meeting*, (Mariehamn, Aland), pp. BNAM2004-1-8, 2004.

[16] T. J. Cox, B. I. Dalenback, P. D'Antonio, J. J. Embrechts, J. Y. Jeon, E. Mommertz and M. Vorländer: "A tutorial on scattering and diffusion coefficients for room acoustic surfaces", *Acta Acustica united with Acustica*, 92(1), pp. 1-15, 2006.

[17] S. Lesoinne: *Méthodes D'accélération du tir de Rayons Sonores Pour la Simulation en Acoustique des Salles. Doctoral dissertation*, Université de Liège (Belgium), 2014.

[18] F. Martellotta: "The just noticeable difference of center time and clarity index in large reverberant spaces", *The Journal of the Acoustical Society of America*, 128(2), 654-663, 2010.