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VIRTUAL ACOUSTICS OF THE CATHEDRAL OF CADIZ

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ABSTRACT

Among heritage buildings, cathedrals best reflect European cultural identity. In addition to liturgical activities, with the concurrence of the faithful, cathedrals, in spite of their long reverberation times, develop other cultural activities, with a large audience, and have become spaces of the utmost interest for tourism, with a massive influx of tourists. This paper presents a summary of the Final Degree Project in Fundamentals of Architecture of the first author and describes the process of architectural analysis of the cathedral of Cadiz towards the development of a virtual model of the site. The simulated results are compared with those measured in situ for the preeminent position of the source: the high altar.

RESUMEN

Entre los edificios patrimoniales que mejor reflejan la identidad cultural europea están las catedrales. Además de las actividades litúrgicas, con la concurrencia de los fieles, en ellas se desarrollan, a pesar de sus largos tiempos de reverberación, otras actividades culturales, con numerosa audiencia, y se han convertido en espacios del máximo interés turístico, con masiva afluencia de turistas. En este trabajo se hace un resumen del Trabajo Fin de Grado en Fundamentos de Arquitectura del primer autor. En él se describe el proceso de análisis arquitectónico de la catedral de Cádiz con el objetivo de elaborar un modelo virtual del recinto y se comparan los resultados simulados con los medidos in situ, para la posición preminente de la fuente sonora: el altar mayor.

INTRODUCTION

In recent decades, the acoustic aspects of worship places have been the object of study by the scientific community [1]. New technologies have recently been incorporated both in the procedures for the characterisation of the acoustic field by in situ measurement, and when modelling said behaviour in order to reconstruct the acoustic intangible heritage associated with these enclosures, both in the current state and in past or future possible intervention or remodelling [2-4]. In the official studies of Architecture, students must complete a Final Degree Project (FDP) to obtain the degree in Fundamentals of Architecture before accessing the Master's De-

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gree in Architecture. To this end, certain students who have taken the optional subject of Applied Acoustics to Architecture and Urban Planning of the School of Architecture of Seville have opted to develop their FDP in relation to the line of room acoustics developed by the research group TEP-130 of the University of Seville. This paper summarizes one of these FDPs, in which the creation and contrast of an acoustic model of the Cathedral of Cadiz is discussed. The model development process is followed and certain aspects of the learning process are highlighted that students have assimilated into their training, and the results achieved are presented.
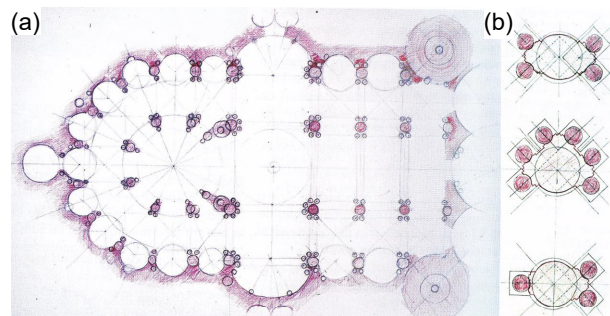

Figure 1. (a) Aplication of variable modulation of columns to all the ground plan. (b) In descending order: main pilaster, composed pilaster in the intersection of the transept, and triangular pilaster for the ambulatory (drawings by Vicente Acero).

DESCRIPTION OF THE CATHEDRAL OF CADIZ

The historical framework, in which the construction of the new Cathedral of Cadiz (c. XVII) was considered, coincides with a time when the city acquired major importance due, among other factors, to the economic boom of trade with the Spanish Indies. The old Cathedral, which was enlarged in 1572, was considered insufficient in the face of such growth. In 1595, space was reserved for the new Cathedral in the neighbourhood of *El Pópulo* which would have meant the demolition of a large part of the city. However, it was decided to rebuild the Old Cathedral in 1600, which would open for worship in 1602. Finally, a place was chosen for the new Cathedral situated near the Old Cathedral, in a consolidated zone of the urban area, which would entail a major undertaking to make space for a building of such great volume and would provide the city with a new façade. In 1721, the project by Vicente Acero was chosen. In 1729, this architect bade farewell to the work due to technical differences of opinion; Acero was succeeded by Gaspar and Torcuato Cayón, Manuel Machuca Vargas, and then by Juan Daura, who finished the work in 1863 [5]. The composition by Acero of the ground plan (85x60 m) is based on a module composed of a pilaster and a series of attached columns; this module adapts to all the necessary variants (Fig.1). On this level, there is a central nave of a greater height (29 m) and two lateral naves (19 m), which join in the ambulatory into which up to 15 chapels open. At the intersection of the central nave with the transept is the main dome (46 m high). The architect's intention to grant a double centrality, which manifests itself in the equal treatment of this dome and that of the presbytery, can be perceived in the ground plan. The small difference in length between the central nave and the transept highlights this duality. Together, they configure an internal volume of approximately 66,000 m^3. The flooring is of marble from which rise the huge pilasters, supported by black and red marble pedestals. The shafts of the columns are made of white fluted marble. Reaching upwards from the capitals are the arches of oyster stone which is the same material as that used in the vaults of the naves, the transept, and the domes. In the presbytery, there is a shrine that is composed of a marble base and columns, topped with an oyster stone dome. The choir, the pews, and the gates are made of wood (Fig. 2).

DEVELOPMENT OF THE ACOUSTIC MODEL

The basic information employed is that of the digital planimetry facilitated by the architect of the cathedral, J. J. Jiménez-Mata, and the photographs taken during the on-site measurement session. The 3D geometrical model (Fig. 3), subsequent to the simplification of its ground plan and

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its architecture with acoustic criteria, is created with Google Sketchup [6], since this is a simple and intuitive tool that can be exported, through the use of the SU^{2}CATT plugin [7], for the Catt-Acoustic simulation programme [8]. This tool takes advantage of the symmetry of the space by modelling half and applying the automatic symmetry operation to generate the complete model. In the modelling process, a full understanding of the project by Acero is crucial and the key lies in finding of the ground plan and pilasters of Fig. 1. The first step consists of simplifying the sections of the original pilasters, by taking the equivalence of areas as criteria, so that the volume of the space remains unaffected. With these pillars placed in their position on the ground plan, the simplification of the perimeter of the cathedral (Fig. 4) can be undertaken in order to avoid the appearance of a great number of planes of small, acoustically insignificant dimensions. The geometric simplification is offset by assigning the absorption and dispersion coefficients to the planes of the model.

The various elements are classified into layers (pillars, walls, vaults, doors, windows ...): one for each type of acoustic material. These elements are then extruded until the arches that make up the vaults are raised (Fig. 5). The arches are built from three points: the two starting points and their key point. In the process of approximation via planes, a good

Figure 2. Indoor view to the high altar, where the shrine can be observed.
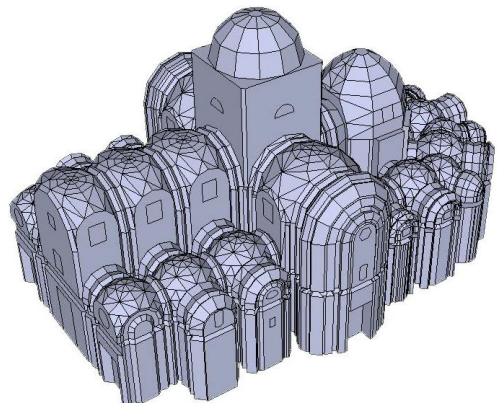
Figure 3. 3D Model carried out by SkechUp: external view.

compromise is obtained by dividing them into six parts. From the arches that define the vaults (usually four), these vaults are constructed by tracing two arches from the midpoints of said arches (Fig. 6, red arches), and passing through the key of the vault. These two arches are copied and rotated 45º (Fig. 6, blue arches) and also divided into six parts. By joining these parts, octagons are created (as seen in the ground plan) (Fig. 6, yellow planes). In order to complete the vault, it suffices to join the various vertices. When implementing the ambulatory, a problem arises due to the design of the section of the pilasters: in Fig. 7 the correspondence in the pair A-A' between the two opposing pilasters can be observed, which facilitates the construction of the arches. However, no such correspondence occurs in the pairs B-B 'and C-C', due to an inadequate simplification of their sections. In the lower part of the same figure appears the modification that facilitates the implementation of the ambulatory arches.

In Fig. 8 (a) the finished half of the model is shown, in the absence of the application of the symmetry in SkechUp for its completion, and in Fig. 8 (b) the complete model is presented after
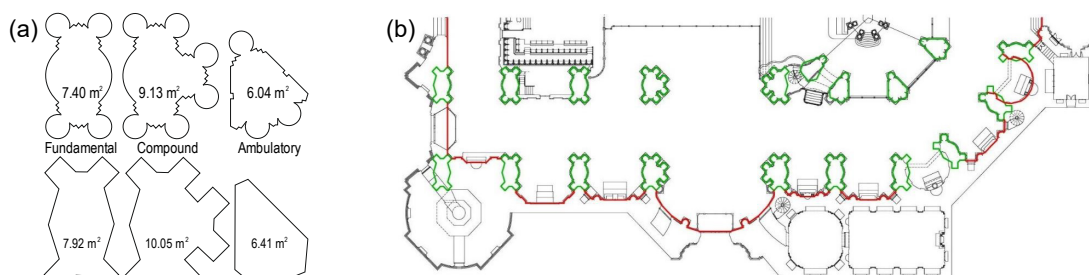

Figure 4. (a) Tipology of pilasters, simplifications and areas; (b) simplification of the ground plan perimeter.

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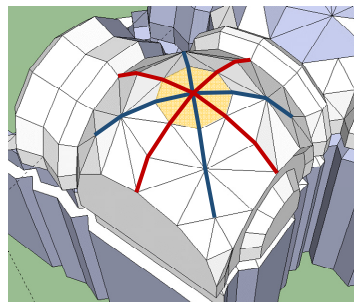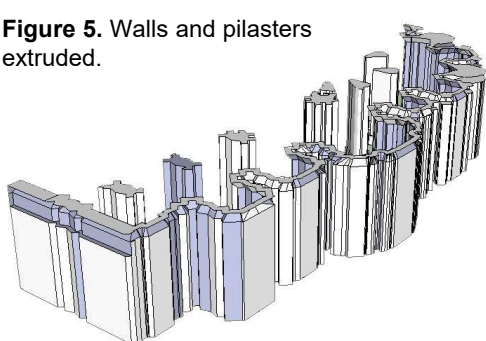**24 al 26 de octubre**

Figure 5. Walls and pilasters extruded.

Figure 6. Drawing of the domes.

Figure 7. Adjustment of sections of pilasters from the ambulatory.

its input and debugging in CATT. The acoustic material is then assigned to each layer. Table 1 identifies the materials with their assigned colours in Fig. 8 (b) and the absorption and dispersion coefficients.

When locating the source and receivers, it is important to maintain the relative position of these with respect to the source in the model (Fig. 9 (a)). Although measurements were taken with several positions of the source, only that source located in the main altar (S1) and the receivers that receive direct sound (R1-R14) are considered here (Fig. 9(b)).

The values of the acoustic coefficients are not accurately known, and their measurement is not straightforward, especially when it comes to materials used in enclosures such as this cathedral. In addition, the geometric simplifications made on creating the model add yet another uncertainty factor when assigning the values for the simulation, and hence we compensate for these simplifications. If the measured values of the reverberation time are known, as is the case, the software allows these values to be entered for each octave band ("*measured*" in Fig. 10), which then serve as an objective. The absorption and/or dispersion coefficients of those materials with a higher uncertainty are modified slightly until the simulated values ("*simulated*" in Fig. 10) approach those of the target. In a first approach, this adjustment is made in an interactive way with an abbreviated calculation, before launching a complete calculation (which takes about 17 h). The model is considered to be well adjusted if the measured and simulated reverberation time does not differ by more than 1 JND for each octave band (Table 2). In this case, these differences are less than 0.5 JND (Fig. 10).
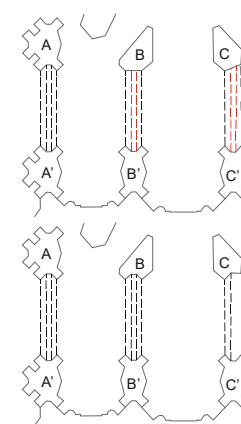
(a)

(b)

Table 1. Coefficient of absorption (upper row) and dispertion (lower row) of the materials. At the right, area (m^2) and colour of each material.

Frequency (Hz)	125	250	500	1000	2000	4000	Area
Glass	0.08	0.04	0.03	0.02	0.01	0.01	178
	0.15	0.15	0.15	0.15	0.15	0.15	
Oyster stone	0.04	0.04	0.04	0.04	0.05	0.05	18834
	0.15	0.20	0.25	0.30	0.35	0.40	
Marble	0.01	0.01	0.01	0.02	0.02	0.02	581
	0.15	0.15	0.15	0.15	0.15	0.15	
Wood	0.04	0.05	0.06	0.08	0.10	0.10	992
	0.20	0.20	0.20	0.20	0.20	0.20	
Sheet metal	0.05	0.04	0.03	0.02	0.01	0.01	251
	0.15	0.15	0.15	0.15	0.15	0.15	
Wooden pews	0.09	0.14	0.16	0.18	0.22	0.22	637
	0.30	0.40	0.50	0.60	0.70	0.80	
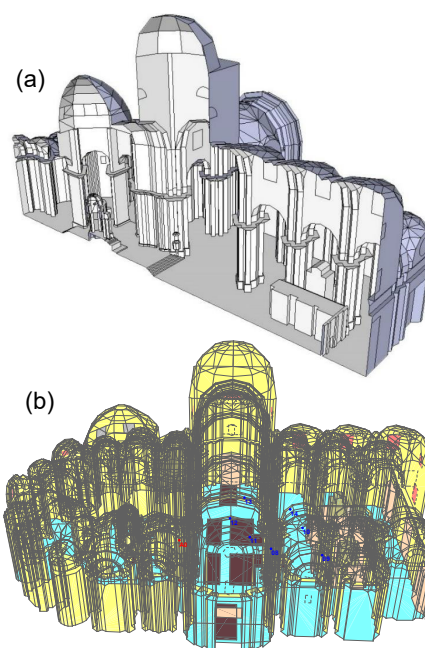
Figure 8. (a) Model in SketchUp (without applying simmetry), (d) completed model in CATT.

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SIMULATION RESULTS

The results are herein presented and analysed by comparing the values of the simulated acoustic parameters and those measured in situ, from three points of view:
- Spectral behaviour, spatially averaged for each octave band, through the evaluation of the spatial dispersion in each band by means of the standard deviation.
- Valuation of the absolute differences, point by point and for each octave band, between the measured and simulated values, expressed in terms of JND values of each parameter.
- Analysis of the spectrally averaged values in each receiver, in accordance with the proposal of the 3382-1 standard [9] versus source-receiver distance.

Table 2 shows the acoustic parameters that are to be analysed, grouped by subjective aspects of perception, frequencies for the spectral average, differential threshold values, and typical range of concert halls and multifunctional rooms with a volume less than 25,000 m^3 [9]. The JND values for very reverberant spaces are given in parentheses and in bold [10].

Figure 11 compares the spectral behaviour of the various parameters (measured and simulated), spatially averaged over all receivers. *G* values have not been included because the differences are more significant, due to the calibration of the measurement system. The EDT values are very similar to those of T_{30} (see Fig. 10), whereby the simulated values are very similar to those measured (differences less than 7%), with lower values at high frequencies due to the absorption of air. Its spatial dispersion (less than 8%) is, however, somewhat greater than that of T_{30} (3%). For T_S, the greatest differences appear in the bands of 250 and 500 Hz, at less than 8% in all cases, and the spatial dispersion is very similar for the measured and simulated values, and somewhat greater at high frequencies. The clarity indices (C_{50} and C_{80}) show the most pronounced differences in the bands of 250 and 500 Hz (although less than 2 dB) with somewhat less spatial dispersion for the simulated values. In the definition, the differences remain below 17% for all the octave bands, the spatial dispersion is lower in the simulation, and the greatest dispersions appear for the extreme frequencies. The simulated parameter of early lateral energy J_{LF} shows very similar behaviour to that measured (differences less than 29%), with a greater spatial dispersion in the case of the simulated values.

In order to assess the differences between simulated and measured values, it is interesting to carry it out in relation to the discrimination capacity of our auditory system. In this respect, the differential threshold characteristic of each parameter is used (Table 2). When comparing measured and simulated values for concert halls and similar rooms, it is common to admit differences of up to 2 JND; however, when analysing complex premis-
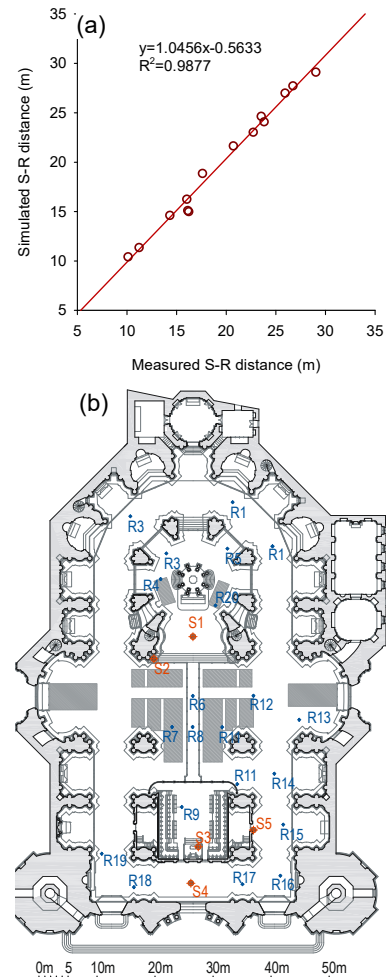
Figure 9. (a) Source-receiver distance in the model versus in the measurement. (b) Location of the source (S) and receptors (R).
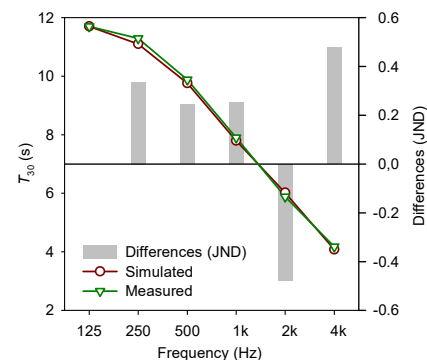
Figure 10. Results of the adjustement process of the model by using T_{30}.

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Table 2. Acoustic parameters grouped by subjective listener aspects according to 3382-1:2009 [9]. In bold and in parenthesis the JND according to [10].

Subjective aspect to evaluate	Acoustic parameter	Spectral average	Difference threshold (JND)	Typical range
Subjective sound level	Sound strength G (dB)	500-1k Hz	1 dB	-2; +10
Perceived reverberation	Early decay time, EDT (s)	500-1k Hz	5%	1; 3
Perceived clarity of sound	Clarity, C_{80} (dB)	500-1k Hz	1 (**1.5**) dB	-5; +5
	Definition, D_{50} (%)	500-1k Hz	5%	0.3; 0.7
	Centre time, T_S (ms)	500-1k Hz	10 ms (**8,5%**)	60; 260
Apparent source width, ASW	Early lateral energy fraction, J_{LF}	125-1k Hz	0.05	0.05; 0.35
*Spectral average values, individual positions, in non-occupied concert and multifunctional halls with V < 25000 m³				

es, such as cathedrals, it is possible to increase these differences up to 3 JND [2]. Therefore, in this section, this limit of 3 JND is used as the admissible limit value for the evaluation of the differences between simulated and measured values after expressing them in terms of the JND of each parameter. Furthermore, its application is extended to each and every one of the octave bands of interest. This has the additional advantage of allowing these differences to be assessed globally for all the parameters.

Figure 12 shows the differences in absolute values, in terms of the corresponding JND, between measured and simulated values for all the parameters. In the case of T_{30}, it can be observed that, except for receiver R6 at 125 Hz, in all cases these differences are lower than 1 JND, which is much lower than the limit we set (this is the parameter used to adjust the model and this result was therefore expected). For EDT, the differences are somewhat greater but most of the values remain below 3 JND, with a high concentration below 1 JND (69%) and only 3% higher than 3 JND. For T_S, most of the values are lower than the 3 JND limit (only 4.8% above 3 JND). For C_{50}, although values below the limit predominate, more values appear outside it (23.9% higher than 3 JND). In the case of C_{80}, most of the values are below the limit (only 10.7% is greater than 3 JND). In the case of D_{50}, most comply with the limit (only 7.2% is greater than 3 JND). Due to the difficulty in calibrating the measurement system to obtain G, this is the parameter that presents the most differences (48.8% of the values exceed 3 JND). Finally, for the early lateral energy fraction (J_{LF}), most of the values are lower than the fixed limit (only 17.85% exceed the limit).

In order to evaluate globally the generated model, in Fig. 14 the deviations for all the parame-
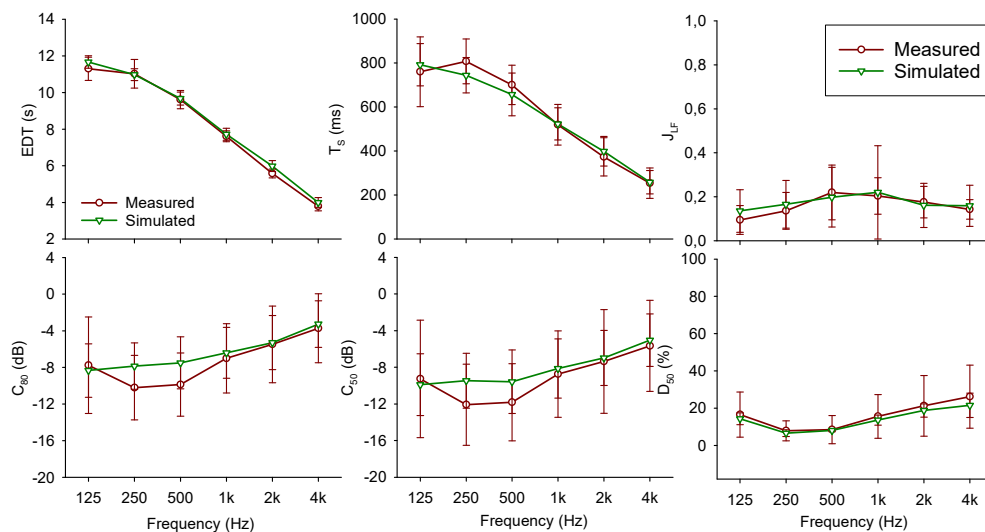

Figure 11. Spectral behaviour spatially averaged of the measured and simulated acoustic parameters.

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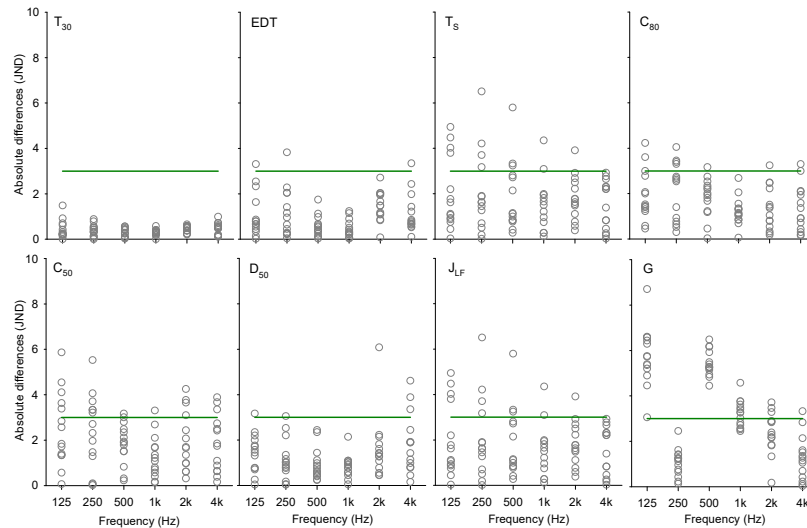
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Figure 12. Differences (in absolute value) between measured and simulated values of the parameters indicated, for all octave bands in each receptors in terms of the respective JND (○). The limit of 3 JND has been shown as an acceptable limit for these differences (—).

ters, all the receivers, and all the octave bands are displayed. Since we have qualified the problems inherent to the measured values of parameter G, these combinations have been represented with and without the values of G. Specifically, in this global calculation, more than half (51.5%) of the values (46.9% with G) lie between 0 and 1 JND, 25.7% (24.9% with G) between 1 and 2 JND, 13.6% (14.1% with G) between 2 and 3 JND, and only 9.2% (14.1% with G) has deviations greater than 3 JND. This means that 90.8% (85.9%) of the combinations remain within the range of 3 JND, which shows that the model is suitable for the simulation of values of the acoustic parameters of the cathedral, both spatially and spectrally.

Finally, the behaviour of the acoustic parameters versus source-receiver distance is analysed. To this end, we chose to use the spectral average suggested in the standard (Table 2), which is the value commonly employed to rate the perceived sensation in each receiver. Figure 15 shows the behaviour of the spectral average versus source-receiver distance, both measured in situ and simulated. The behaviour of EDT, with very high values, presents no predefined pattern, although differences (up to 1 s) appear between certain receivers. T_S is very similar for the simulated values and those measured in situ, with a pattern that implies growth as we move away from the source (about 400 ms in the nearest receiver to about 700 ms for receivers furthest from the source). The behaviour of C_{50}, C_{80}, and D_{50} shows that simulated and measured values are very similar, with a marked attenuation in terms of distance. The values of G have not been included due to the difficulties in the calibration process and to the corresponding uncertainty in the measured values. The measured and simulated J_{LF} values, except for certain exceptions, remain very similar and no clear pattern can be observed. Figure 16 shows the behaviour of the STI (Speech Transmission Index), which qualifies the intelligibility as *poor* in the closest receptor to the source and *bad* for the furthest. These deficient values are due to the high reverberation since the background noise, which was measured in situ, is not significant (NCB 25).
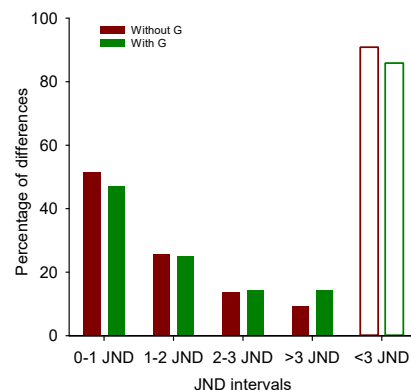

Figure 13. Distribution of the differences (in absolute value) between measured and simulated values on each interval indicated.

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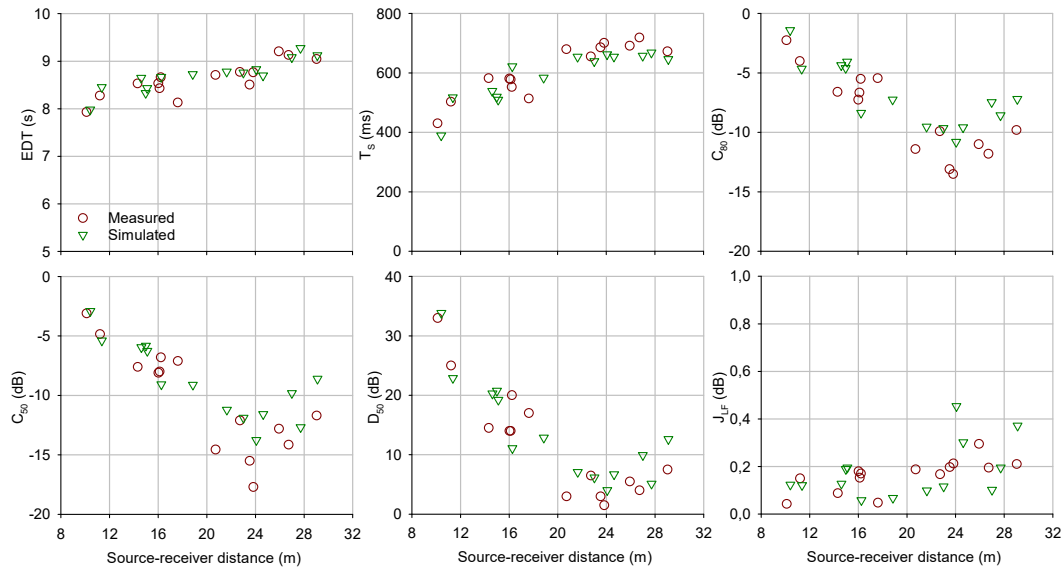**24 al 26 de octubre**

Figure 14. Behaviour of the spectral average of acoustic parameters versus source-receiver distance.

CONCLUSIONS

The main objective of this work involves the acoustic characterisation of the cathedral of Cadiz by using simulation techniques and its contrast with the measurements obtained in situ, based on standard acoustic parameters to describe the interior sound field of enclosures. To this end, starting from the measurements of the acoustic parameters carried out in situ, and from previous documentation, a 3D model of the cathedral has been built, whereby the complexity that this architectural typology entails is fully taken into account. The geometrical model has been implemented through the Sketchup programme due to its intuitive nature and the ease of exporting to the acoustic simulation programme through the SU^{2}CATT plugin.

The comparative analysis of the values of the parameters obtained in the simulation with the experimental values has shown the model to be consistent and that it provides enough accuracy to simulate the sound field inside the cathedral of Cadiz, since, both in the spatially averaged spectral behaviour and in the spectral average versus distance, the simulated values are similar to those of the measured values. Especially convincing in this respect is the result of the analysis of point-by-point and band-by-band differences between measured and simulated results.

ACKNOWLEDGEMENTS

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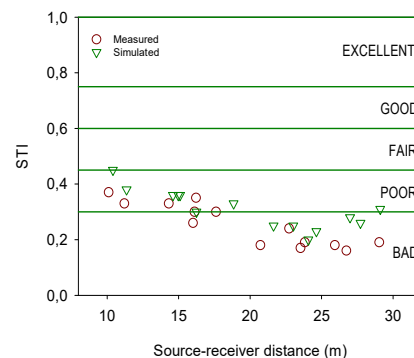[2] Álvarez-Morales L., Zamarreño T., Girón S., Galindo M. A methodology for the study of the acoustic environment of

Figure 15. Behaviour of STI paramater versus source-receiver distance.

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