



Virtual reconstruction of Spanish Cathedrals: the sound of choir and other weakly coupled volumes in Seville Cathedral

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Abstract

The paper takes advantage of a recent detailed survey of Spanish Cathedrals to investigate the acoustic differences between choir and other weakly coupled volumes in very large spaces. Experimental measurements carried out in a limited number of source-receiver combinations confirmed the existence of double slope behaviour, which markedly influences such spaces. The analysis of the impulse responses was carried out by means of Bayesian parameter estimation, in order to correctly identify the individual decay times. The subjective effect of such coupling was first discussed, showing that having steeper initial decay may significantly contribute to clarity and intelligibility without affecting reverberation. Then, in order to better clarify the role of the architectural features defining such spaces, a geometrical acoustic model of the Cathedral of Seville was performed and a more refined analysis was carried out by analysing a tightly spaced grid of receivers inside the sub space and investigating point by point variations. Results showed that further variations appeared inside the sub-volume, depending on source receiver distance, but the double slope behaviour was clearly visible and characterised the listening experience inside the choir.

Keywords: Acoustics of churches, coupled volumes, virtual acoustics

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1 Introduction

Among the different spaces in which sound propagation has been investigated, churches represent one of the most complex to understand. In fact, churches are often very large (if not huge), having room volumes that may span from tens to hundreds of thousands cubic metres, combined with a geometrical complexity due to different architectural styles, and with modifications resulting from additions and adaptations to different historical periods and liturgical practice. Literature now offers a rich scenario of researches involving different countries, different problems, and different investigation methods [1-8]. From this point of view, acoustical simulations, mostly carried out using geometrical acoustic methods but, more recently, including also other numerical approaches such as FDTD, represent a convenient instrument to investigate spaces that no longer exist [9,10], or that have been modified, or, more simply, to take into account the variations induced by the additions of elements that would be too difficult to measure [11,12].

One of the most complex conditions which may be encountered in churches is that of acoustical coupling between different sub-volumes. This not only takes place between two clearly distinct parts of a church, such as a chapel and a nave, but more frequently than one could imagine involves parts that normally are considered as a unique architectural element. Investigations carried out in St. Paul Cathedral in London [13] and in St. Peter's Basilica in Rome [14], together with the proposal by Chu and Mak [15], support this hypothesis. One important consequence of this is that inside the same church different acoustic conditions can be experienced, depending on the relative position of sound source and receiver. In particular, when source and receivers are in the same sub-space and this is less reverberant than the whole church, double slope decays can be observed, with an initial part characterized by a steeper decay and a late part which reverberates according to the "coupled-volume" decay. Under these conditions, shorter early decay time (EDT) and improved clarity and speech intelligibility can be observed.

Taking advantage of a recent survey of Spanish Cathedrals the presence of such anomalies was investigated. In general, one area showing significant differences was the choir, as the presence of large amounts of sound absorbing materials and the isolation of that portion of space due to high wooden stalls, reduced the amount of acoustical coupling (which is directly proportional to the opening area and inversely proportional to the sound absorbing area), thus creating the conditions for non-uniform energy distribution inside such spaces. In the present paper, the specific case of Seville Cathedral is discussed. First the results of on-site measurements are discussed, also identifying decay characteristics by means of Bayesian analysis and considering the consequences from the listener point of view. Then, a geometrical acoustic model of the Cathedral of Seville was performed and a more refined analysis was carried out by analysing a tightly spaced grid of receivers inside the sub-space and investigating point by point variations in order to clarify whether the double slope behaviour actually depends on a difference in energy distribution or rather on a "local" effect of early reflections.

2 Methods

The Catholic Gothic cathedral of Seville, also known as "Santa María de la Sede", is located at the south of the historical centre of the Andalusian city. The plot of the building was occupied by an ancient mosque, in the same rectangular area 116 metres long and 76 m wide [16]. Some historians date the start of the construction in 1401, however, there is no written record until 1433 [17]. The construction process started from the retrochoir to the head, and it was directed by different architects over the years.

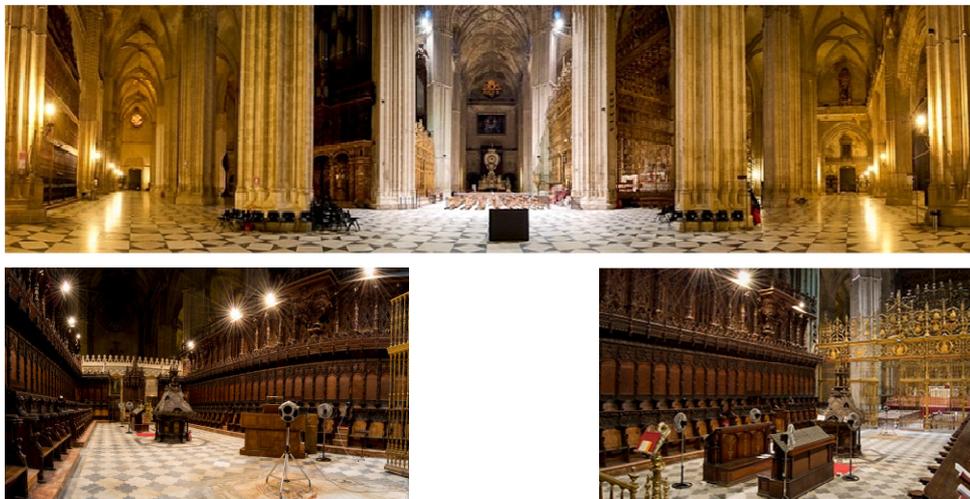


Figure 1 –Photographs of the interior of the Cathedral and detailed view of the choir.

The interior of the Gothic church (Figures 1 and 2) is divided into five naves facing east. The transept nave and the central nave are the highest naves, in which domes raise nearly 40 metres from the floor. Its structure has 60 masonry pillars which are covered by stone, 32 of them are exempt. This entire framework supports the 68 ribbed vaults that cover the various naves. The choir is situated in the central nave, furnished with wooden stalls carved by various artists. Its entrance is delimited by a Renaissance fence, and the three remaining sides are enclosed by stone walls, where four alabaster chapels that open to the aisles are located in. The organ is composed by two large boxes located on the walls on both sides of the choir. At the head of the temple stands the Royal Chapel. It forms a large enclosure, closed by a semicircular apse and covered by a solemn dome. A large fence covered by thick curtains defines the entrance to this space.

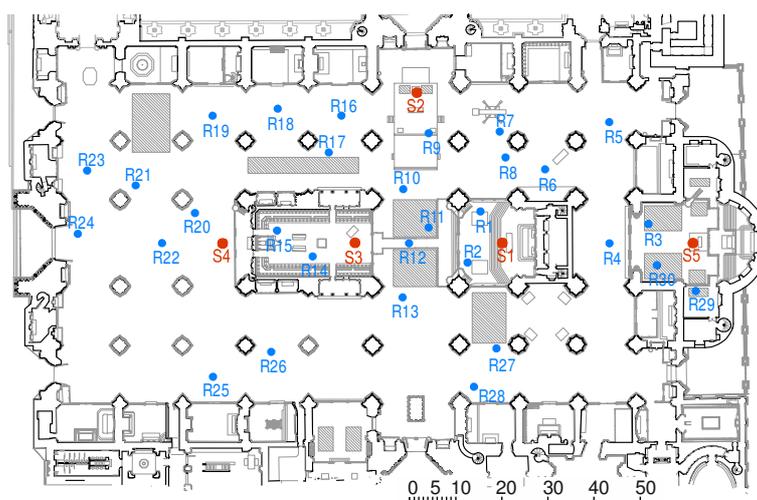


Figure 2 – Ground plan of the Cathedral with indication of sound source positions (S1-S5) and receivers (R1-R30).

2.1 Measurements

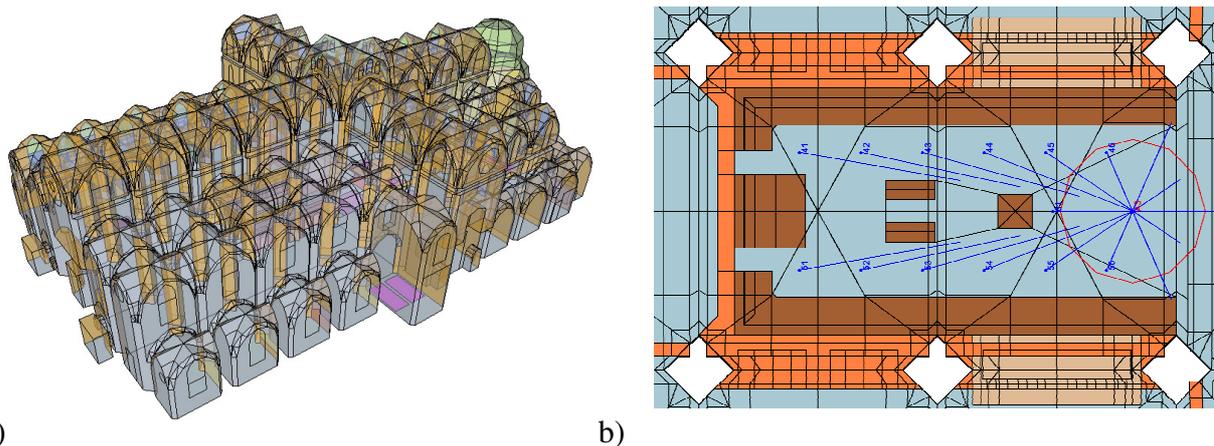
Impulse responses (IRs) are obtained following the recommendations of the standard ISO 3382-1:2009 [18]. Five different source positions have been considered which correspond to the usual locations of the main sound sources in the various celebrations that take place in the temple and located 1.50 metres above the floor. A total of 30 microphone positions were distributed throughout the congregation/audience area, using the symmetry of the enclosure (Figure 2).

For each source position the microphone positions, from the all set of reception points, that receive the direct sound have been studied. At each point of reception, located at 1.20 metres from the floor, impulse responses were recorded through sine swept signal in which frequency increases exponentially with time. The frequency range was adjusted to cover the octave bands between 63 and 16,000 Hz, and the sweep duration in order to get a signal-to-noise ratio greater than 45 dB for the octave bands of interest. All experimental tests were performed under unoccupied conditions at night time. Temperature and relative humidity ranged between 25 and 25.5 °C, and 55 and 58%, respectively.

The process of generation, acquisition and signal analysis was performed with the WinMLS2004 software through an EDIROL UA-101 sound card. The frequency sweep signal is reproduced on the church using the AVM DO-12 omnidirectional source, with the pre-amplified with the B&K type 2734 power amplifier. The impulse response is captured with the Audio-Technica Multi AT4050/CM5 microphone, in the omnidirectional and bidirectional configurations (figure-of-eight) connected to the Earthworks LAB 1 polarization source.

2.2 Analysis of coupling phenomena

In order to investigate the non-linear behaviour of decay curves, several proposals are encountered in the literature to measure the non-linearity of the decay. Thus T60/T15 [19], early-to-late decay ratios [20], and other metrics have been proposed. However, Bayesian analysis [21,22] represents the most powerful and reliable tool to detect and quantify multiple slopes in IRs. In fact, Bayesian analysis allows the accurate determination of both the decay constant and the relative amplitude of each of the exponential decays that characterise the room. Consequently, it is the most rigorous instrument for detecting multiple slopes in measured IRs and, hence, for investigating coupled-volume problems. In order to ensure the highest accuracy in the identification of the different slopes, the fully parametrized approach proposed by Xiang *et al.* [22] was implemented in a MATLAB GUI. Even though the procedure may be applied to a virtually unlimited number of decays, for the IR under test only double and triple slopes were investigated (the latter, only in limited circumstances due to the computational burden). To evaluate the most appropriate model (decay order selection) the Bayesian information criterion (BIC) was employed. This parameter is given by the degree of the model fit to the data minus a second term representing the penalty for over-parameterized models, since over-parameterized models will result in a larger value associated with the first term. In order to select the best decay model, the one yielding the largest BIC value may be considered as the most concise, ensuring a good fit to the decay function data without using over-parametrized solutions.



a) b)
Figure 3 – (a) 3D geometrical model of the Cathedral of Seville. (b) Positions of receivers in the choir.

2.3 Simulations

The computer simulation of the acoustic behaviour of the churches was carried out by using the software CATT Acoustic v.9.0.c [23], which is based on geometric acoustic algorithms. The simulations undertaken use TUCT v1.0h engine to obtain the acoustic parameters through processing energy-based echograms (E) and/or pressure-based impulse responses (h). In particular, considering the mixing geometry of the church, the so called “Algorithm 1” was used. According to this algorithm, the diffuse part of each reflection is treated deterministically for reflections up to a certain order that can be chosen by the user. Above that limit, diffuse reflections are simply randomized speeding up the calculations. As a compromise between detailed results and computational burden the 1st order reflection was selected.

A simplified 3D geometrical model of the cathedral (4495 planes and 203,161 m³ volume) was created (Figure 3a) in order to perform the simulations by representing the actual geometrical characteristics of the church while surfaces having rich decorative patterns were simulated as flat planes with a proper modification of the absorption and scattering coefficients. In fact, modifying absorption and

scattering coefficients of richly decorated surfaces that are modelled as flat planes is a common practice, useful to take into account the larger exposed area as well as the scattering effects that cannot be handled by ray tracing software, even increasing the level of detail.

The absorption coefficients were first assigned considering usual literature values [24,25], possibly combining them with those resulting from documented simulations of similar buildings [11,14]. To this end, an iterative adjustment process was carried out starting from the absorption coefficients of the most unusual or uncertain surfaces, possibly covering large areas so that small variations from the originally assigned values could lead to a better agreement between simulated and measured parameters.

In particular, during this step, only reverberation times were considered and the iterative calibration process was concluded when simulated values differed from measured by no more than one just noticeable difference (JND). According to ISO 3382-1 [18], the JND for reverberation time corresponds to 5% of the reference value. The assessment was carried out at each octave band and averaging the JND over all source-receiver combinations. After that, the agreement between measured and simulated values of the other acoustical parameters defined in ISO 3382-1, at each receiver and also at each frequency octave band, was checked. Again prediction errors were compared to JND, assuming as a reference the values given in ISO standard 3382-1 [18] and in Martellotta [26].

3 Results

3.1 Measurement results

Among the different source receiver-combinations S3-R14 was first chosen to investigate how the choir modified the acoustic response compared to other locations in the church. As shown in Figure 4, T30 values measured inside the choir differ from those measured in the remaining part of the church by a percentage varying between 4% and 22%, the latter at higher frequencies. However, when T10 and EDT are considered, the measured values get significantly shorter, with the mid frequency value dropping to 1.7 s for EDT, well below the 4.6 s observed for T30. Analysis of the decay curves confirms the observation, pointing out the existence of clearly non-linear behaviour (Table 1). This much shorter initial decay also has important consequences on the other acoustic parameters. In fact, $C80_{500-2k}$ is 5.4 dB, $T_{S500-1k}$ is 64 ms, and Speech Transmission Index (STI) is 0.66, while typical values found in the other parts of the church were: $C80_{500-2k}=-2.52$ dB; $T_{S500-1k}=275.6$ ms; $STI=0.34$; $EDT_{500-1k}=4.4$ s.

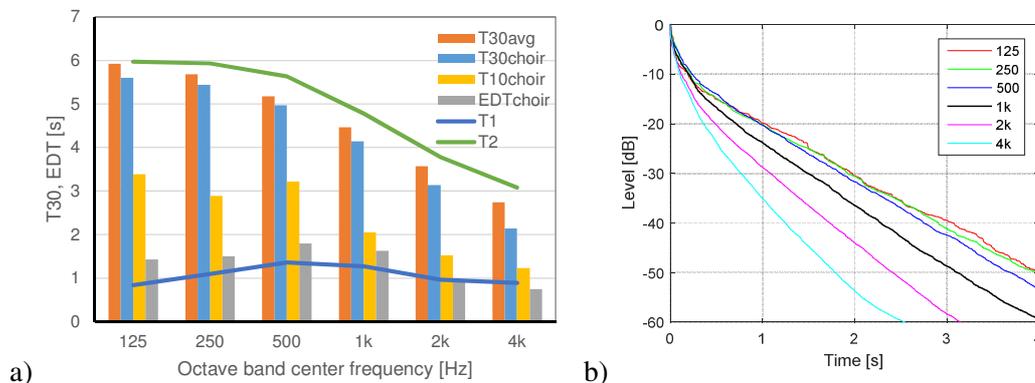


Figure 4 – (a) Plot of acoustical parameters measured at R14 (subscript “choir”) and the average calculated over all the receivers. T1 and T2 are the decay times resulting from Bayesian analysis. (b) Decay curves at different frequencies.

Table 1 – Summary of the decay constants, amplitudes and BIC resulting from application of Bayesian analysis to combination S3-R14.

	Octave band centre frequency [Hz]					
	125	250	500	1000	2000	4000
T1 (s)	4.93	4.39	4.00	3.03	2.14	1.39
T2,1 (s)	5.97	5.93	5.63	4.78	3.78	3.08
T2,2 (s)	0.84	1.10	1.36	1.27	0.96	0.89
BIC2-BIC1	14.8	15.11	24.7	37.1	28.7	34.5
A2/A1	2.42	2.99	2.82	3.81	4.56	11.69

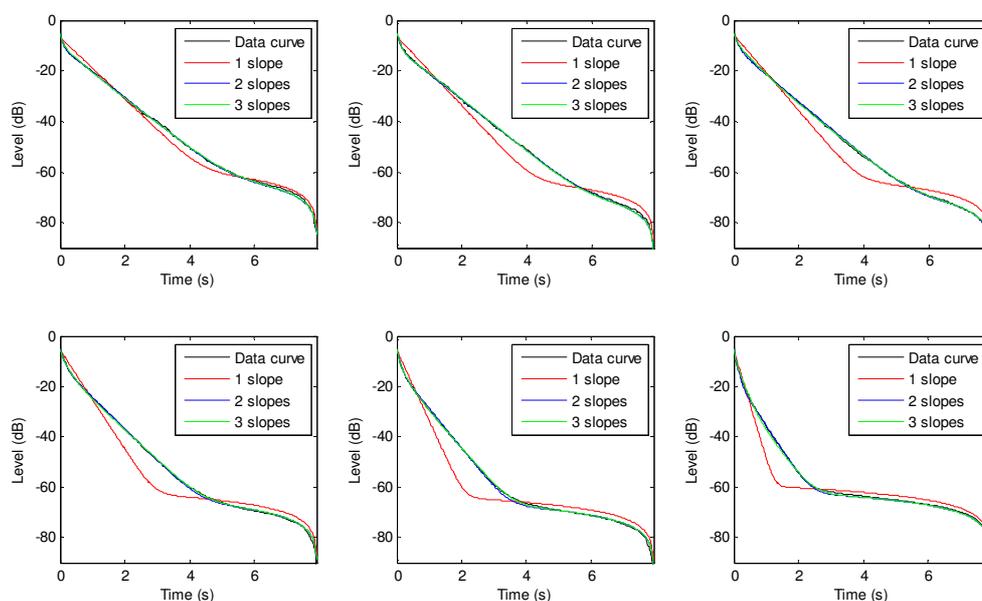


Figure 5 – Comparison of decay curves and different decay models with 1 to 3 slopes for S3-R14 at the six octave bands.

Considering the above results, it was important to apply Bayesian analysis in order to clarify whether the observed behaviour was simply a consequence of the strong direct sound and early reflections or not (Figure 5). For this purpose, the first 5 dB of each decay curve were neglected and only the remaining part was considered. The very good signal to noise ratio, allowed a detailed analysis over all the frequency range. The BIC confirmed that the 2 slopes model was better than the 1 slope model in fitting the actual decay curve. Addition of a 3rd slope actually did not improve the accuracy very much, hence two slopes appeared definitely as the best choice. The longest decay is characterised by a lower level compared to the initial decay. In fact, the A2/A1 ratio varies between a minimum value of 2.5 at 125 Hz (corresponding to 7 dB difference) and a maximum of about 12 at 4 kHz (corresponding to a 21 dB difference), signifying a weaker coupling between the choir and the remaining volumes. From the architectural point of view this may be explained by the taller stalls and by the majestic organ that completely closes two spans, thus creating a slightly more “isolated” sub-space. Another explanation for the lower level of the coupled-volume reverberation might be the much larger dimensions of the church, which, combined with the increased absorption, causes late reflections to be significantly attenuated before they come back to the choir.

3.2 Simulations results

3.2.1 Simulation calibration

Calibration of the acoustical model was carried out in two steps. First the global T30 was optimized by small adjustments of the absorption coefficients of the stone. Then, a refinement procedure was applied in order to match EDT and other acoustic parameters inside the choir. At this stage absorption and scattering coefficients of wooden choir were modified (Figure 6a). In order to test the accuracy the classical assessment of the variations expressed in terms of JND was carried out together with the application of Bayesian analysis. In the first case results were somewhat contradictory, as for R14 most of the parameters were correctly simulated (Table 2), except for EDT which was overestimated and T30 which was underestimated. At R15 the parameters showed a more uniform error, spanning between 0.4 s for T20 and 2.8 for D₅₀. Bayesian analysis applied to R14 (Figure 6b) showed that the initial and late decay times were predicted with good accuracy, while the A2/A1 ratio were slightly different, thus explaining the larger differences observed between measured and predicted EDT. Similarly, at R15 at 1 kHz the analysis of the simulated IR returned T1=4.81 s, T2=2.25 s, A2/A1=1.63, while measured values were T1=4.93 s, T2=1.67 s, A2/A1=2.25. Therefore, despite the larger differences, the calibration was considered satisfactory because the dependence on the fine structure of the early reflections made it rather difficult to obtain better results.

Table 2 – Summary of the JND variations between measured and predicted values inside the choir.

	C50 _{500-1k} [dB]	C80 _{500-2k} [dB]	D50 _{500-1k} [%]	Ts _{500-1k} [ms]	EDT _{500-1k} [s]	T10 _{500-1k} [s]	T20 _{500-1k} [s]	T30 _{500-1k} [s]
S3-R14	0.3	0.7	0.5	0.0	4.2	0.1	0.9	1.8
S3-R15	1.7	1.0	2.8	1.2	1.7	2.3	0.4	0.7

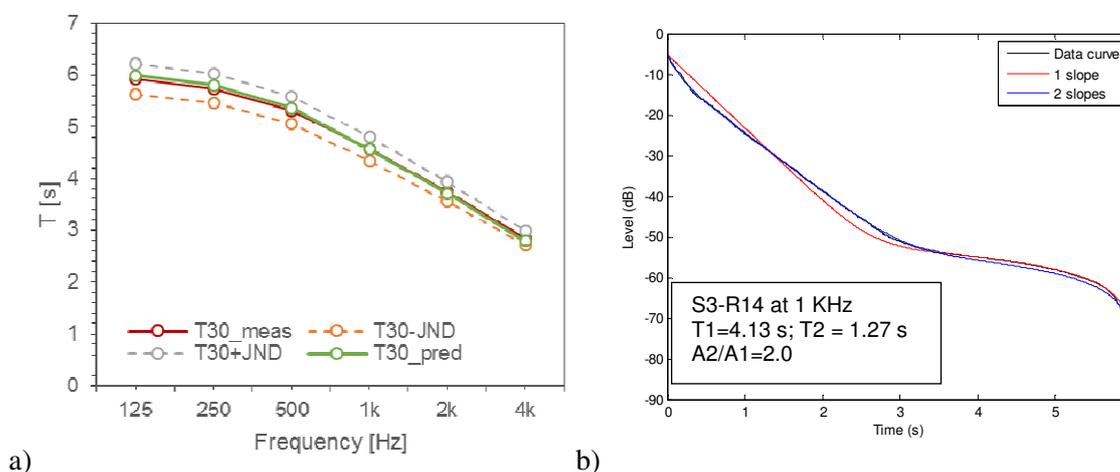


Figure 6 – (a) Plot of the average T30 versus frequency, resulting after model calibration. (b) Bayesian analysis of simulated decay curve at S3-R14.

3.2.2 Results

Once the calibrated model was obtained, in order to better understand the acoustic behaviour of the choir, a detailed grid of receivers was used (Figure 3b) to investigate how acoustic parameters varied. Results showed (Figure 7a-7c) a clear dependence on the source receiver distance, which was

expected in consequence of the role of direct sound. However, it was Bayesian analysis which returned the most interesting results as the late decay showed a mild increase with an asymptotic trend, while the initial decay showed a steeper increase as the distance grew. The ratio of the amplitudes decreased steeply as the distance grew, showing some stabilization beyond 10 m. Now it is good to remind that the sound source was located very close to the sub-volume opening, so that the farthest receivers were actually located in a position where the influence of direct sound was likely to be negligible compared to early and late reflections. In fact, Figure 7d shows that for receivers close to the source variations up to 10 dB appeared in the direct sound, while late sound (due to the coupled-volume system) appeared to be weaker, in relative terms. In fact, as the plot is normalized, the late sound only appears as weaker, but it is just direct sound and early reflections that are stronger. Conversely, at the farthest receivers the double slope is visible, but the transition is smoother (with no strange steps in the decay, corresponding to strong individual reflections).

In this way, the above observations may actually be considered as an evidence that the double slopes appearing in the measured results actually depend on acoustical coupling effects taking place between the choir and the rest of the church. From the subjective point of view, markedly hearable differences appeared within a 10 m distance from the source, while at greater distances variations tended to be closer to 1 JND. When compared to values measured in the remaining parts of the church, even the values predicted at the farthest locations in the choir show large variations, spanning from about 5 JNDs for $C80_{500-2k}$, to about 10 JNDs for EDT_{500-1k} , thus suggesting that a listener would hear a clear difference while being in the choir. Even without occupancy the sound is much clearer and intelligible, as demonstrated by STI that never goes below 0.60.

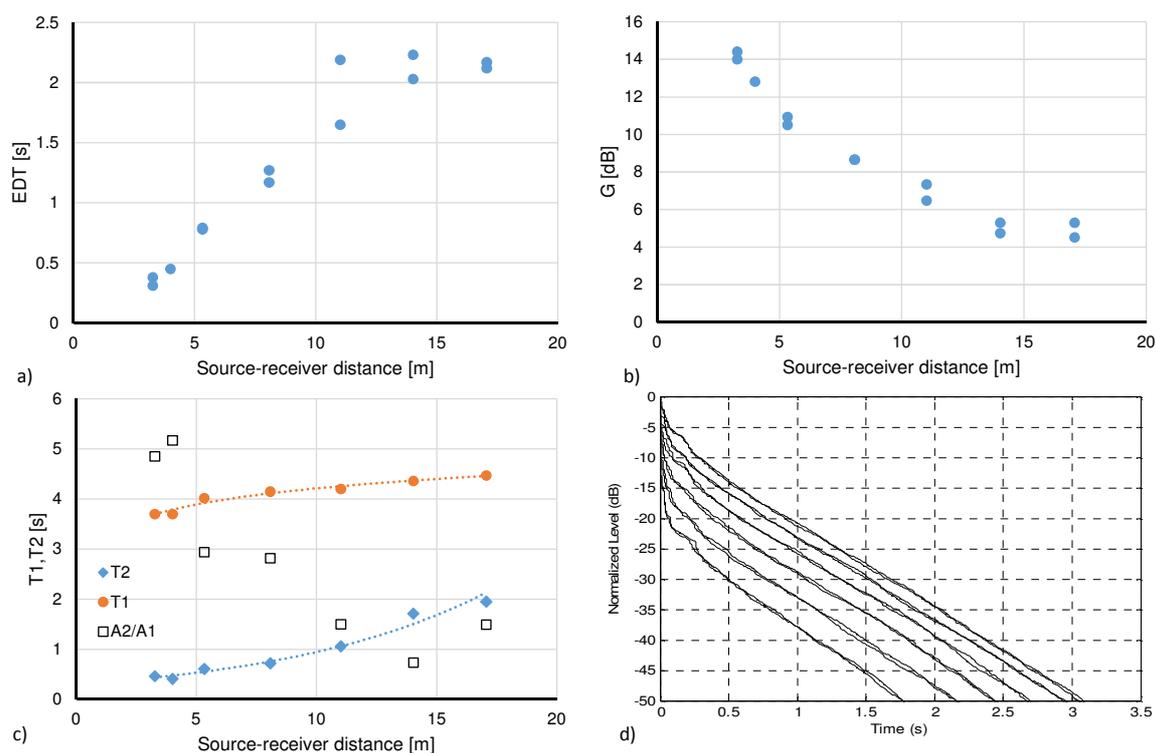


Figure 7 – (a) Plot of the average EDT_{500-1k} , (b) G_{500-1k} , and (c) 1st and 2nd slope decay constants as a function of source-receiver distance. (d) Normalized decay curves at increasing distances from the source (lower curves correspond to closer receivers).



4 Conclusions

The paper discussed the acoustics of the choir of Seville Cathedral by first showing that measured IRs are characterised by double slopes, with an initial decay that at 1 kHz is about 1.5 s, while the coupled-volume decay (late part) is about 4.4 s. Similar differences were found at other frequencies. To better understand the nature of such variations a geometrical acoustic model was made and properly calibrated. Obtaining a satisfactory result in the choir required a careful control of both absorption and scattering coefficients and, in any case, only provided approximate results because of the fine structure of the early reflections. Once the model was finalized, results simulated inside the choir showed that beyond a certain distance the influence of direct sound becomes negligible but the double slope behaviour still appears, confirming that acoustic coupling between volumes may be the cause. From the point of view of the listener, the choir offered significantly improved acoustic conditions, with JNDs as big as 10 when compared to values in the remaining part of the church.

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