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# ACOUSTICALLY COUPLED VOLUMES IN THE CATHEDRALS OF MURCIA AND SEVILLE

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## ABSTRACT

Cathedrals are complex monuments built through the repetition of volumes separated by arches, vaults, and columns, in addition to a great variety of lateral chapels. In the so-called "Spanish mode" the choir is situated in the centre of the main nave and generally constitutes a more absorbent volume connected by an acoustically transparent opening with the rest of the cathedral. This space, together with the lateral chapels, can present the phenomenon of acoustic coupling. In this work, as a manifestation of this coupling, an analysis is performed, by means of standardised parameters and through the application of Bayesian methods, on the non-linearity of the energy decay curves of the impulse responses registered in situ in the Vélez Chapel of the Cathedral of Murcia, the Royal Chapel of the Cathedral of Seville, and in their respective choirs.

## RESUMEN

Las catedrales son monumentos complejos construidos mediante la repetición de volúmenes separados por arcos, bóvedas, columnas…, así como gran variedad de capillas laterales. En el denominado “modo español” el coro se sitúa en el centro de la nave principal y constituye generalmente un volumen más absorbente conectado mediante una apertura acústicamente transparente con el resto de la catedral. Este espacio, así como las capillas laterales, pueden presentar el fenómeno de acoplamiento acústico. En este trabajo, como manifestación de este acoplamiento, se analiza la no linealidad de las curvas de decaimiento energético mediante parámetros estandarizados y utilizando métodos bayesianos, de las respuestas al impulso registradas in situ en la Capilla de los Vélez de la Catedral de Murcia, la Capilla Real de la Catedral de Sevilla y en sus respectivos coros.

## INTRODUCTION

Among the different enclosures within which research into sound propagation has been carried out, cathedrals constitute one of the most complex: not only do they present a great volume but also major geometric complexity due to the various architectural styles, and to modifications resulting from additions and adaptations to the historical periods and liturgical practice.

One of the most complex conditions that can be found in these places of worship is that of acoustic coupling between their different sub-volumes. This coupling not only takes place between two clearly distinct parts of the temple, such as a chapel and a nave, but often involves sections that are normally considered as a unique architectural element. In this context, the original statistical model corresponding to the coupling of two volumes [1] has been generalised through matrix notation to a greater number of subspaces. Such is the case of the numerical model of the St. Paul's cathedral in London, created by Anderson and Bratos-Anderson [2], which divides the cathedral into 70 acoustic subspaces that are united by the exchange of sound energy. Taking advantage of the use of Bayesian analysis [3] and the correction introduced by Summers et al. [4] in the statistical model, Martellotta [5], with a similar methodology and with experimental measures, analyses the effects of surface absorption and acoustic coupling over reverberation in the Basilica of St. Peter. Subsequently this author extends the study to cover all the Papal Basilicas in Rome [6]. Likewise, the hypothesis by Chu and Mak [7] corresponding to a church model composed of a set of coupled spaces instead of one single diffuse space, presents good agreement with the experimental results of two Christian churches of Hong Kong.

An important consequence of this phenomenon is that, within the same church, different acoustic conditions can be experienced, depending on the relative position of the sound source and receiver. In particular, when source and receivers are in the same subspace and this subspace is less reverberant than the whole church, then a double slope can be observed in the energy decay, with a steeper initial decay and a late part that reverberates according to the coupled volume. Under these conditions, shorter early decay time (EDT) and greater clarity and speech intelligibility are observed. In cathedrals arranged in the Spanish mode, an area that shows significant differences is that of the choir, since the presence of large quantities of absorbent material and the isolation of that portion of space due to the presence of high stalls propitiates the conditions for a non-uniform energy distribution within such spaces [9].

In the literature, several quantifiers of the double-slope effect can be found as can ratios between different energy decay intervals to describe the slope variation as a function of time [10, 11]. However, the introduction of Bayesian probability theory into the evaluation of decay time in acoustically coupled spaces has proved to be very useful in the analysis of the decay curve [3].

In this work, the specific cases of acoustic coupling in various subspaces of two cathedrals in the south of Spain are studied: the Vélez Chapel and the choir of the Cathedral of Murcia, and the Royal Chapel and the choir of the Cathedral of Seville. The characteristics of the energy decay are studied and discussed using standardised parameters and Bayesian analysis.

## METHODS: MEASUREMENTS AND ANALYSES

Impulsive responses (IR) have been obtained in the unoccupied cathedrals, at night, following the recommendations of the ISO 3382-1:2009 [12] and other guidelines specific to churches [13]. As a general procedure in all cathedrals, 5 source positions have been considered: high altar, transept, pulpit, choir, retrochoir; and other specific positions in the most relevant lateral chapels (the Vélez Chapel in the case of the cathedral of Murcia and the Royal Chapel in the case of the cathedral of Seville) [14]. At each source position, the microphone positions for the set of reception points, in which direct sound is received, have been studied. This is reflected in the coloured areas of Figure 1 for each of the subspaces of the cathedrals.

The process of generation, acquisition, and analysis of the acoustic signal was performed by using the EASERA v1.2 programme, through an AUBION x8 multichannel sound card in the case of Murcia cathedral, and with the WinMLS2004 programme through an EDIROL UA-101 sound card in the case of Seville cathedral. At each reception point, located at 1.20 m from the floor, the IR were registered exciting the enclosure with sine-swept signals, in which the scanning frequency increases exponentially with time. The frequency range, the level, and the duration of the excitation signal were adjusted so that the frequency range would cover the octave bands from

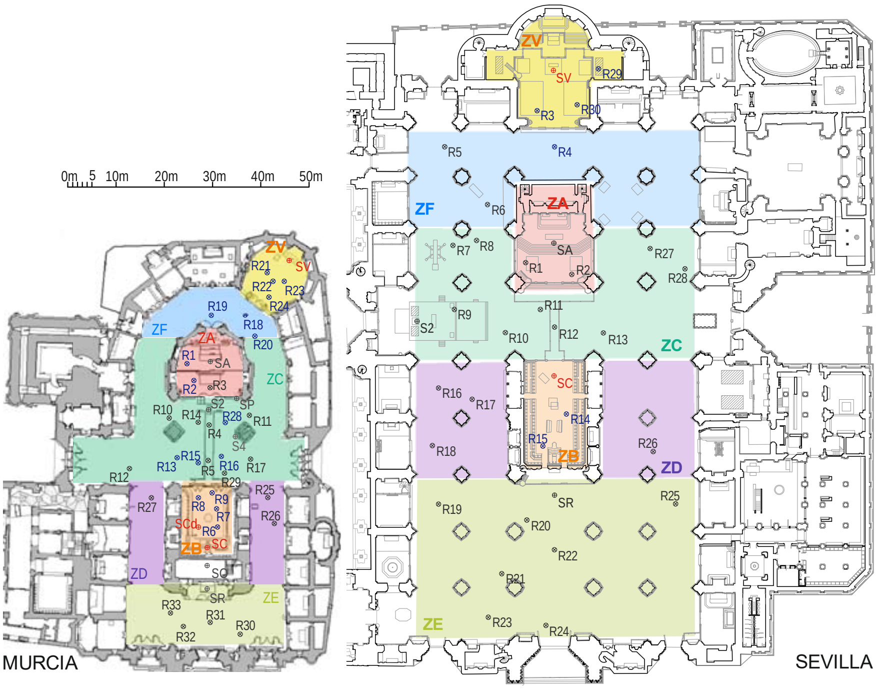



**Figura 1.** Ground plans of the cathedrals of Murcia and Seville with source and receiver locations indicated. Sources involved in this work are highlighted in red. Coloured areas correspond to the different acoustic zones of each space.

63 to 16000 Hz, and the impulse response to noise ratio (INR) would be at least 45 dB in each octave band to guarantee accuracy of certain parameters, such as $T_{30}$. The generated signal was emitted through an AVM DO-12 dodecahedral sound source with a B&K 2734 power amplifier. For Murcia cathedral, a self-amplified Beringher Eurolive B1800D-Pro subwoofer was incorporated in order to improve the low-frequency results. At each reception point, IR were captured by means of an Audio-Technica AT4050/CM5 microphone in its omnidirectional and figure-of-eight configurations connected to Earthworks-LAB 1 or Sound Field SMP200 polarisation source and preamplifier.

In order to study acoustic coupling, those spaces in which a priori this phenomenon is more clearly manifested have been selected: the lateral chapels, choir, presbytery, and transept. In each of the selected spaces, the energy decay curves for a representative source-receiver configuration were analysed in order to study their degree of linearity in accordance with the parameters defined in Annex B of the ISO 3382-2: 2008 standard [15]: $C$ and $\xi$. This procedure has also been used by Fernández et al. [16] in the study of acoustic coupling in the cathedral of Toledo.

The curvature parameter, $C$, expresses the percentage deviation between the reverberation times $T_{20}$ and $T_{30}$.

$$C = 100\left(\frac{T_{30}}{T_{20}} - 1\right) \quad (\%) \tag{1}$$

$C$ values between 0% and 5% denote linearity in the decay, while values above 10% indicate a decay curve that digresses far from a straight line. The non-linearity parameter, $\xi$, is expressed as:

$$\xi = 1000\left(1 - r^2\right) \quad (‰) \tag{2}$$

where $r$ is the coefficient of linear correlation between the line of best fit and the curve of energy decay. Values of $\xi$ between 0‰ and 5‰ denote linearity in the decay, while values above 10‰ indicate a decay curve that cannot resemble a straight line.

The results obtained from parameters $C$ and $\xi$ allow the determination of whether the decay curve has a degree of elevated linearity, that is to say, either it can be associated to a single straight line, or there are sections with different slopes. Obtaining a non-linear decay curve can be indicative of acoustic coupling, since in this case it approaches several straight lines, associated to the decay curves characteristic of each of the sub-volumes.

In order to investigate the non-linear behaviour of the decay curves, Bayesian analysis [3, 17] represents the most powerful and reliable tool for the detection and quantification of multiple slopes in the IR. In fact, Bayesian analysis allows the exact determination of both the decay constant and the relative amplitude of each of the exponential decays that characterise the space.

In order to ensure the greatest accuracy in the identification of the different slopes, the fully parameterised approach proposed by Xiang et al. [3, 17] was implemented in a MATLAB GUI which facilitates data entry and output of both numerical and graphical results. Although the procedure can be applied to an unlimited number of slopes, only double and triple slopes were investigated for the IR analysed (in the latter case, only in limited circumstances due to the heavy computational load). The Bayesian information criterion (BIC) was used to evaluate the most appropriate model (selection of energy decay orders). This parameter expresses in a first term the degree of the model adjusted to the data minus a second term that represents the penalty for the over-parameterised models, since the over-parameterised models result in a greater value associated with the first term. In order to select the best decay model, that yielding the highest BIC value can be considered as the most concise, since it ensure a good fit to the decay function data without the use of over-parameterised solutions.

## RESULTS AND DISCUSSION

The results are now compiled of each analysis of the enclosures studied. In accordance with the typological and architectural similarity, those of the respective choirs are grouped on one side while on the other side are those of the two chapels. In the case of the non-linearity parameter, $\xi$, the corresponding values for $T_{10}$, $T_{20}$, and $T_{30}$ have been calculated for different sections of the decay curves. The results corresponding to the range between -5 and -15 dB ($T_{10}$) are not presented here because they are not significant: their derived non-linearity is better related to the variations of the pattern of first reflections from one receiver to another more than with the possibility of coupling spaces. Since the values are very similar for $T_{20}$ and $T_{30}$ intervals, results corresponding to $T_{30}$ have been selected for presentation. The bands of 0.5 and 1 kHz have been chosen since, for the lower octaves curves, irregularities can appear that are attributable to their isolated eigen-modes rather than to the phenomenon of coupling. Table 1 summarises the results of the non-linearity analysis for the two chapels, and Table 2 presents those corresponding to both choirs.

It can be observed that, in the two chapels, the values of $C$ remain within the interval [0%, 5%] and those of $\xi_{T30}$ within the interval [0‰, 5‰], which denotes linearity in the decays. In both cases, the openings connecting the chapels to the volume of the cathedrals are small and therefore although the energy emitted through these openings excites the reverberant field of the cathedrals, the energy returned from the cathedrals towards the chapels is very limited (about 20 dB below the field of each chapel [8]).

In the case of the choirs, the situations differ. In the case of Seville, all values are higher than 5% (alternatively 5‰), many of which even exceed 10% (or 10‰), which clearly shows the non-linearity of the decays and therefore the clear possibility of acoustic coupling between the choir and the space of the cathedral [9]. In the case of Murcia, for the initial position of the source (SC in Figure 1), only the values corresponding to R6 (the closest receiver to the source) are greater than 5% (5‰) showing, in principle, a possible slight coupling. Things change substantially when the source is moved within the choir to the SCd position. In such a case, the values for R6 rise above 10% (10‰) and for R7 and R9 some values exceed the limit of 5% (5‰). This might suggest acoustic coupling between the subspace of the choir and the volume of the cathedral. Both in the case of chapels and choirs, the analysis of parameter values for receivers located outside the source space, but in the vicinity of the aperture, reveals no signs of non-linearity in the decays (see Tables 1 and 2).

**Table 1.** Values of *C* and $\xi_{T30}$ for the receivers selected in the chapels of the two cathedrals when the source is located inside the chapel (SV). The identifiers of the receivers placed in the same sub-volume as the source are in bold. Results in bold display values greater than 5% and 5‰ for each parameter, respectively.

| | | Royal Chapel | | | | Vélez Chapel | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Freq- | **R3** | R4 | **R29** | **R30** | R18 | R19 | R20 | **R21** | **R22** | **R23** | **R24** |
| *C* | 500 Hz | 3.2 | 3.5 | 1.4 | 0.0 | 0.8 | 1.7 | 0.5 | 0.0 | 4.7 | 3.1 | 4.1 |
| | 1 kHz | 1.7 | 0.1 | 0.1 | 0.7 | 5.0 | 1.8 | 3.5 | 0.6 | 3.7 | 1.0 | 0.0 |
| $\xi_{T30}$ | 500 Hz | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 0.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| | 1 kHz | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

**Table 2.** Values of *C* and $\xi_{T30}$ for the receivers selected in the choir of the two cathedrals when the source is located inside the choir (SC and SCd). The identifiers of the receivers placed in the same sub-volume as the source are in bold. Results in bold display values greater than 5% and 5‰ for each parameter, respectively.

| | | Seville choir | | Murcia choir (SC) | | | | | | | | | | Murcia choir (SCd) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Freq. | **R14** | **R15** | R1 | R2 | **R6** | **R7** | **R8** | **R9** | R13 | R15 | R16 | | **R6** | **R7** | **R8** | **R9** |
| *C* | 500 Hz | **10.2** | **8.9** | **5.2** | 2.0 | **5.2** | 2.7 | 1.8 | 1.8 | 1.0 | 1.3 | 2.2 | 0.5 | **11.5** | 4.1 | 2.7 | **5.1** |
| | 1 kHz | **22.5** | **14.0** | 1.7 | 2.7 | **7.8** | 3.5 | 4.9 | 2.6 | 1.9 | 1.5 | 1.3 | 2.0 | **12.8** | **6.6** | 4.8 | **6.0** |
| $\xi_{T30}$ | 500 Hz | **8.0** | **6.0** | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | **10.0** | 2.0 | 2.0 | 2.0 |
| | 1 kHz | **19.9** | **10.0** | 0.0 | 0.0 | **6.0** | 2.0 | 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **6.0** | 4.0 | 2.0 | 2.0 |

Using a tool implemented in MATLAB in order to attain information of a more detailed nature, we have analysed the decay curves by applying Bayesian methods in order to identify both the various decay constants, if any, and their respective amplitudes. The BIC allows the identification of the best approach to describe each of the decays with the lowest computational cost. Although we have attempted descriptions with three slopes, in all these cases the results have revealed that the application of two slopes provides sufficient approximation [9].

**Table 3.** Summary of decay constants, BIC, and ratios of amplitudes resulting from the application of Bayesian analysis to the combination SC-R15 in the choir of Seville cathedral.

| | Octave band central frequency [Hz] | | | | | |
|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | 4000 |
| T1 | 5.54 | 5.43 | 4.61 | 3.73 | 2.72 | 1.85 |
| T2,1 | 6.29 | 5.94 | 5.56 | 4.86 | 4.02 | 3.11 |
| T2,2 | 3.11 | 2.61 | 1.81 | 1.53 | 1.41 | 1.23 |
| BIC2-BIC1 | 6.75 | -0.70 | 25.95 | 44.41 | 40.68 | 35.86 |
| 10*log(A2/A1) | 1.97 | -0.49 | 2.50 | 3.88 | 5.43 | 8.11 |

In Table 3, the results of the Bayesian analysis are synthesized for the SC-R15 combination of the Seville choir, while in Figure 2, the measured decay curves are compared with those calculated using different models with the tool implemented in MATLAB, for the various octave bands. As can also be observed in the work by Martellotta et al. [9], values of T2,1 are similar to $T_{30}$ averaged over all source-receiver positions of the cathedral, while T2,2 is of the order of EDT measured in the choir.

In Table 4, the same comparison is carried out for SC-R6 and SCd-R6 combinations of the Murcia choir, while in Figure 3, the measured decay curves are compared with those calculated using different models for the same octave bands.

It can be observed that, in this case, the two-slope model provides a good description of the decay curves for all octave bands. In an attempt to identify the significance of the values of T2,1 and T2,2, the situation differs slightly from that which occurred in the choir of the cathedral of Seville.

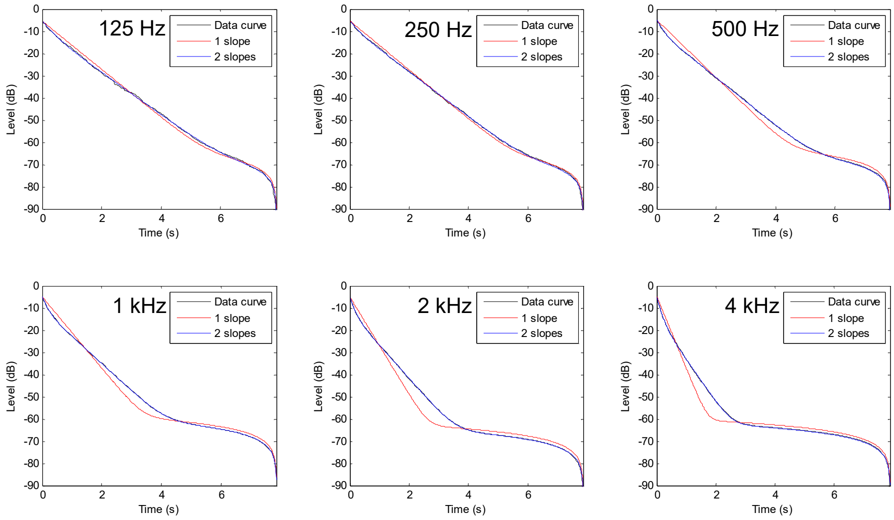



**Figure 2.** Comparison of measured decay curves and those calculated using the different models of decay for the octave bands ranging between 125 and 4000 Hz for source-receiver combination SC-R15 in Seville cathedral.

In fact, the reverberation times measured in the cathedral and in the choir are shown in Figure 4(a) and compared with T2,1 and T2,2. The values of T2,1 are also very similar to the values of $T_{30}$ averaged for all source-receiver positions of the cathedral. However, those of T2,2 are almost half of those corresponding to the EDT of the choir. Figure 4(b) shows the decay curves measured in the Murcia choir for the SC-R6 combination. It can be seen that their curvature appears in the first part of the decay, which suggests that the non-linearity detected in this case probably has to do with the preponderance of direct sound and first reflections given the smaller dimensions of the choir, more than with a phenomenon of coupling with the volume of the cathedral.

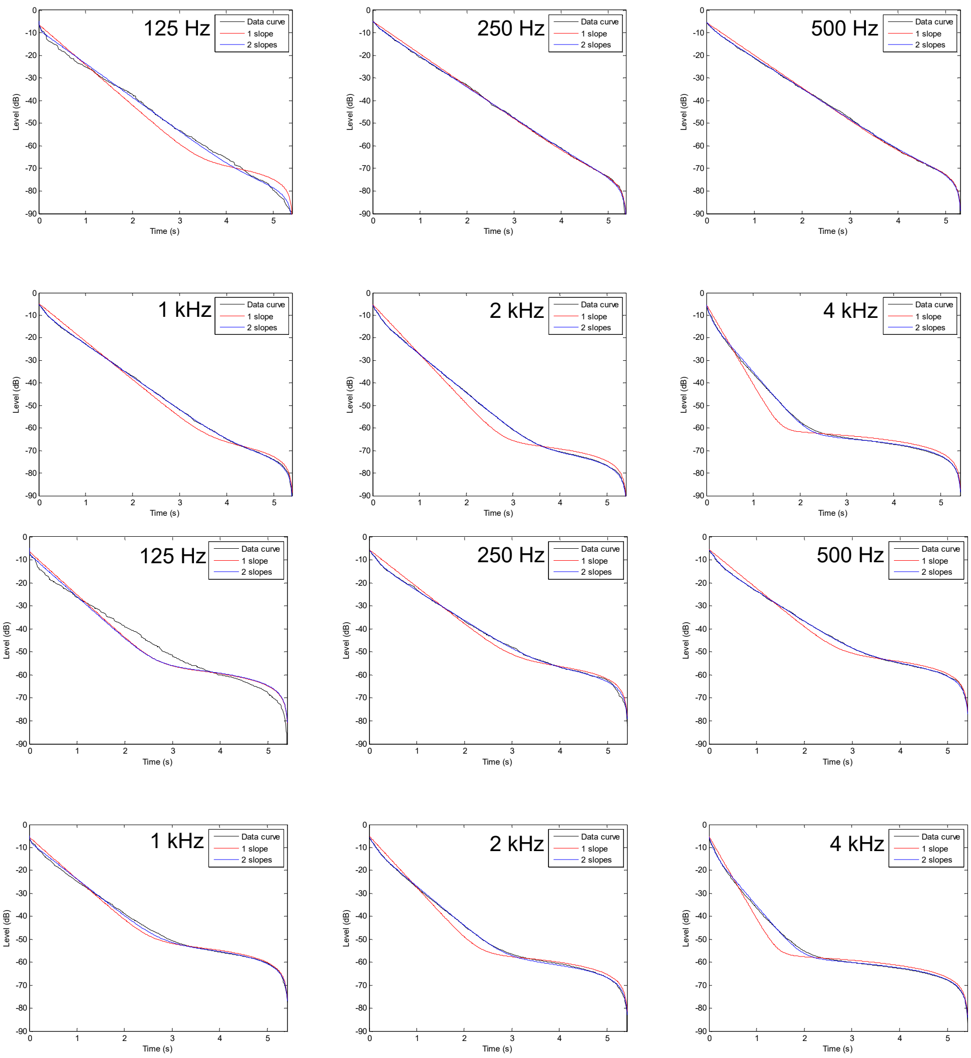
**Table 4**. Summary of decay constants, BIC and ratios of amplitudes resulting from the application of Bayesian analysis to the combination SC-R6 and SCd-R6 in the choir of Murcia cathedral.

| | Octave band central frequency [Hz] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 125 | | 250 | | 500 | | 1000 | | 2000 | | 4000 | |
| | SC | SCd | SC | SCd | SC | SCd | SC | SCd | SC | SCd | SC | SCd |
| T1 | 3.35 | 3.19 | 4.17 | 3.71 | 4.14 | 3.53 | 3.54 | 3.30 | 2.72 | 2.68 | 1.70 | 1.67 |
| T2,1 | 4.01 | 3.26 | 4.37 | 4.6 | 4.37 | 4.35 | 4.12 | 3.70 | 3.52 | 3.47 | 2.49 | 2.45 |
| T2,2 | 0.25 | 0.06 | 1.29 | 1.51 | 1.22 | 1.45 | 1.34 | 0.24 | 1.29 | 1.16 | 0.76 | 0.81 |
| BIC2-BIC1 | 11.10 | -12.63 | -3.15 | 15.19 | 2.42 | 28.05 | 19.77 | 1.94 | 42.69 | 15.05 | 26.82 | 19.58 |
| 10*log($A_2$/$A_1$) | 1.58 | -0.56 | -2.65 | 3.02 | -2.13 | 3.12 | 0.65 | -0.82 | 3.11 | 2.42 | 4.33 | 4.22 |

## CONCLUSIONS

Various techniques of analysis have been applied to evaluate the non-linearity of the decay curves in several volumes of the cathedrals of Seville and Murcia in order to ascertain whether this non-linearity is due to acoustic coupling phenomena. The normalised analysis of the ISO [15] shows that there is no non-linearity in the case of the two chapels that connect with the cathedral space through openings of reduced size in relation to their surfaces. This same conclusion is reached when applying Bayesian techniques for the analysis of decay curves.

In the case of choirs things are very different: in Seville, the coupling is clear, whereby a model with two slopes sufficiently describes the measured curves: the first decay is characterised by a similar value of T2,1 to the $T_{30}$ of the cathedral and the second by another, T2,2, similar to the value of EDT measured in the choir. The amplitude ratio is approximately 3 dB (see Table 3). In the case of the choir of Murcia, the situation is less clear: the parameters of the cited ISO suggest




(a)

(b)

**Figure 3.** Comparison of measured decay curves and those calculated using the different models of extinction for the octave bands ranging between 125 and 4000 Hz for source-receiver combination SC-R6 (a) and SCd-R6 (b) in Murcia cathedral.

non-linearity, and when applying the Bayesian analysis to describe the phenomenon, the two slope models are also more suitable. The first decay is characterised, as in the case of Seville, by the time of reverberation of the cathedral. However, unlike that which occurred in Seville, the second decay in the case of Murcia is not identified with the value of EDT measured in the choir. Rather it suggests a relationship with the prevalence of direct sound and pattern of early reflections caused by the relatively small dimensions of the choir. The acoustic simulation of this cathedral and an appropriate model of the choir could elucidate the influence of direct sound and the pattern of first reflections in this double slope.

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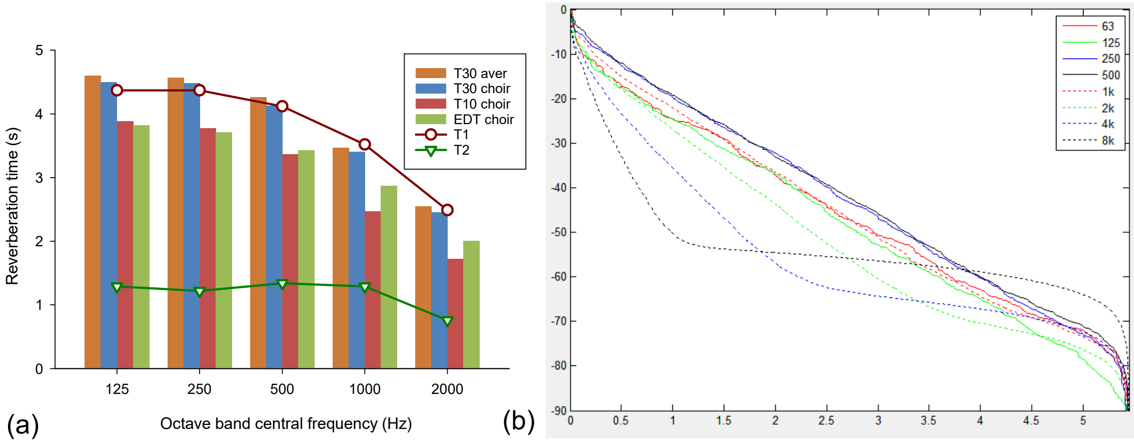


**Figure 4.** (a) Acoustic parameters measured in R6 of the choir of Murcia ("choir") and the average calculated over all source-receiver combinations in the cathedral ("aver"). T1 and T2 are the reverberation times of decays resulting from Bayesian analysis. (b) Decay curves for the various octave bands at the source-receiver combination SC-R6.

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