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Distribution of lateral acoustic energy in Mudejar–Gothic churches

S. Girón*, M. Galindo, T. Zamarreño

Departamento de Física Aplicada II, Universidad de Sevilla, E.T.S. de Arquitectura IUCC, Avda. Reina Mercedes 2, 41012 Sevilla, Spain

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Abstract

In this work, the physical measures of spatial impression are considered in 12 Mudejar–Gothic churches in the city of Seville in the south of Spain. This study describes the spatial distribution of the early and late lateral acoustic energy, through monaural parameters derived from impulse response analysis using a maximum length sequence measurement system in each church. In the first time analysis, the two early lateral energy measures, early lateral fraction (LF) and early lateral fraction cosine (LFC) are taken in order to assess apparent source width (ASW), and the late lateral level (GLL) in the second to assess listener envelopment (LEV) are conducted. Parameters have been studied spectrally in each temple and were averaged at low- and mid-frequency values in their different naves in order to study how these two attributes of sound perception vary with source–receiver distance. Experimental results have been compared with the theoretical early lateral energy fractions and late lateral level, both of which are derived by assuming that reflected energy in these places of worship is solely dependent on source–receiver distance. This comparison is carried out in accordance with the μ-model proposed by the authors in an earlier paper in order to describe the dependence of acoustic monaural omnidirectional energy parameters on source–receiver distance. Thus, it is supposed that the directional distribution of reflections is similar to a diffuse distribution. To conclude, these spatially averaged monoaural parameters have been correlated with geometric variables by using linear regression and only weak correlations with the mean width of the churches and with the height/width ratio have been found.

1. Introduction

The first references to the significant contribution of the directional distribution of early reflections to acoustical quality were in the 1960s [1,2]. Soon after, experiments by Barron [3] took into account the importance of the proportion of early acoustic energy arriving from the lateral at one location for the perception of music. At that time, this quality was labelled "spatial impression", "spaciousness" or "spatial responsiveness" as in Marshall [4], and was universally accepted as a characteristic of good acoustic quality of rooms. Since then on the terminology used to describe the various aspects of spatial impression has been confusing and varied.

*Corresponding author. Tel.: +34 95 4557129; fax: +34 95 4557892.
E-mail addresses: sgiron@us.es (S. Girón), mgalindo@us.es (M. Galindo), teofilo@us.es (T. Zamarreño).

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Work in both Japan [5] and Canada [6] has expanded the understanding of this concept by showing that spatial impression encompasses at least two perceptual dimensions: a broadening of the actual source and diffusivity of the reverberant field or envelopment. It is well established that increased early lateral reflection energy leads to the perception of a source broadening or to an increase of apparent source width (ASW). ASW has been defined as the width of a sound image fused temporally and spatially with the direct sound image. Furthermore, later-arriving lateral sound energy leads to a sense of listener envelopment (LEV) although some work by Morimoto et al. [7] relates this aspect of perception to late energy sounds also arriving from behind the listener. LEV can be defined as the sense of being surrounded by a diffuse array of sound images that are not associated with particular source locations. The division between early- and late-arriving reflections is taken to be 80 ms. Acoustical measures have been developed that can be related to the expected amount of ASW or LEV and both these quantities are thought to be influenced by low- to mid-frequency sound [8–10].

Two types of measurements of spatial impression due to lateral reflections deduced from the impulse response in a room have emerged: the monaural lateral energy fractions related to the energy of early or late lateral reflections, and the binaural cross-correlation measure which is the interaural cross-correlation coefficient (IACC) [11].

To assess ASW, two measures of early lateral energy fractions, the early lateral fraction (LF) and early lateral fraction cosine (LFC) are accepted in the monaural measurement, and the early interaural cross-correlation coefficient IACC_E [12] (correlation calculated until 80 ms) in the binaural.

By focusing on monaural parameters that are the object of this work, LFC [13] can be expressed by

$$\mathrm{LFC} = \frac{\int_{\Omega}\int_{0.005}^{0.08} p^2(t)\cos\,\phi\,\mathrm{d}t\,\mathrm{d}\Omega}{\int_{\Omega}\int_{0}^{0.08} p^2(t)\,\mathrm{d}t\,\mathrm{d}\Omega}. \tag{1}$$

As indicated in Eq. (1), subjective experiments showed the directional sensitivity for energy to be proportional to $\cos\phi$, where the listener is assumed to be facing the source and ϕ is the angle of incident sound to the imaginary axis passing through the listener's ears.

Measurements of lateral energy are usually carried out by means of a microphone with variable directivity with both an omnidirectional and a figure-of-eight characteristic [8]. In its figure-of-eight directional configuration, the pressure is proportional to $\cos\phi$, hence, for a measured lateral energy fraction, an easy-to-evaluate modified expression of Eq. (1) becomes

$$\mathrm{LF} = \frac{\int_{\Omega}\int_{0.005}^{0.08} p^2(t)\cos^2\phi\,\mathrm{d}t\,\mathrm{d}\Omega}{\int_{\Omega}\int_{0}^{0.08} p^2(t)\,\mathrm{d}t\,\mathrm{d}\Omega} = \frac{\int_{0.005}^{0.08} p_8^2(t)\,\mathrm{d}t}{\int_{0.005}^{0.08} p_O^2(t)\,\mathrm{d}t}, \tag{2}$$

where p_O is the impulse response measured in omnidirectional configuration and p_8 that which is measured in figure-of-eight configuration.

Both LFC and LF are monoaural parameters, which try to approach the behaviour of the human ear and are defined in the ISO Standard 3382 [14].

Under an ideal diffuse field hypothesis, LFC and LF beyond the reverberant radius tend towards 0.5 and 0.33, respectively, and offer the simplest solution for conversion from one type of LF to another: $\mathrm{LFC} = 1.5\,\mathrm{LF}$.

In the same way, in order to assess for LEV, the late lateral sound level (GLL) is proposed by Bradley and Soulodre [6] as both a conceptually simple and objective predictor well correlated to the amount of LEV [9] in the monaural measurement, and the late interaural cross-correlation IACC_L (correlation calculated from 80 ms to infinity) in the binaural measurement.

Monaural GLL is defined as

$$\mathrm{GLL} = 10\,\log\left\{\frac{\int_{\Omega}\int_{0.08}^{\infty} p^2(t)\cos^2\phi\,\mathrm{d}t\,\mathrm{d}\Omega}{\int_{\Omega}\int_{0}^{\infty} p^2(t)\,\mathrm{d}t\,\mathrm{d}\Omega}\right\} = 10\,\log\left\{\frac{\int_{0.08}^{\infty} p_8^2(t)\,\mathrm{d}t}{\int_{0}^{\infty} p_A^2(t)\,\mathrm{d}t}\right\} \quad (\mathrm{d}B), \tag{3}$$

where p_A is the omnidirectional impulse response of the source measured at a distance of 10 m in a free field.

Barron [15] has also introduced the late lateral fraction parameter (LLF) to study envelopment in auditoria, defined as

$$\mathrm{LLF} = \frac{\int_\Omega \int_{0.08}^{T} p^2(t)\cos^2\phi \,\mathrm{d}t\,\mathrm{d}\Omega}{\int_\Omega \int_{0.08}^{T} p^2(t)\,\mathrm{d}t\,\mathrm{d}\Omega} = \frac{\int_{0.08}^{T} p_8^2(t)\,\mathrm{d}t}{\int_{0.08}^{T} p_O^2(t)\,\mathrm{d}t}, \tag{4}$$

where the limiting time T for integration in Eq. (4) was taken as 0.4 of reverberation time to ensure sufficient accuracy without contamination by background noise. Both parameters are related by

$$\mathrm{GLL} = G - 10\,\log(1 + 10^{C_{80}/10}) + 10\,\log(\mathrm{LLF}) = 10\,\log(l) + 10\,\log(\mathrm{LLF}) \quad (\mathrm{d}B) \tag{5}$$

with G the sound strength, C_{80} the clarity parameter, and l the late reflected energy ($t > 80$ ms). The sound strength is a measure of indoor level relative to that produced by the omnidirectional source at a distance of 10 m in free-field conditions and can be expressed as

$$G = L_P - L_{P10} = 10\,\log(d + e + l) \quad (\mathrm{d}B), \tag{6}$$

where d refers to the direct relative energy, e to the early relative energy (with a delay from the direct sound less than 80 ms), and l the late energy.

The sound field in the churches analysed can be characterized by an instantaneous normalized reflected energy density $\varepsilon'(t, r)$ proposed by the authors [16] and given by

$$\varepsilon'_\mu(t,r) = \frac{\varepsilon(t,r)}{E_{D10}} = \begin{cases} \dfrac{13.82 \cdot 31,200}{V}\mathrm{e}^{-\mu r/T}\mathrm{e}^{-13.82t/T}(\mathrm{s}^{-1}), & 0 \leqslant t \leqslant 80\,\mathrm{ms}, \\ \dfrac{13.82 \cdot 31,200}{V}\mathrm{e}^{-0.04r/T}\mathrm{e}^{-13.82t/T}(\mathrm{s}^{-1}), & 80\,\mathrm{ms} < t < \infty, \end{cases} \tag{7}$$

where $t = 0$ coincides in this expression with the arrival of direct sound at location r. This reflected energy proposal supposes that the decay traces can be modelled in two steps, the first beginning at the arrival of direct sound at that location and that stationary reflected energy is reduced by a factor $\mathrm{e}^{-\mu r/T}$ with respect to classic reflected energy, which is distance dependent and finishes in 80 ms; the second step from 80 ms onwards corresponds to the decay considered in Barron and Lee's hypothesis [17]. The μ coefficient is calculated through nonlinear regression from the C_{80} data measured for each church and these results appear in Table 1. Analyses of the results show that mean value $\overline{\mu}$ could be used to describe the behaviour of this specific type of church in order to estimate any omnidirectional parameter [16]. On proposing this mean value it was verified that the set of values (except these for San Julián church) was included in the $\overline{\mu} \pm 1.5\sigma_\mu$ interval

Table 1
Significant acoustic and geometrical data in Mudejar–Gothic churches

Church	T (s)	V (m^3)	μ (s m^{-1})	L (m)	W (m)	H (m)	S_T (m^2)	$S_C + S_L$ (m^2)	V/S_G (m^3 m^{-2})	Finish[a]
MN	3.08	10708	0.1210	34	19	15	4517	250 + 279	20.24	(v), (–), (s), (w), 3si
OM	2.71	8180	0.1400	29	16	16	3760	194 + 219	19.81	(pp), (mc), (p), (w), 2do
LO	2.28	7040	0.1392	24	24	16	3346	132 + 267	17.64	(pp), (wc), (p), (w), 2do
VI	2.47	6915	0.1571	26	18	11	3656	144 + 180	21.34	(pp), (–), (f), (w), 2do, 1si
JU	2.27	6226	0.0901	27	15	13	3321	187 + 150	18.47	(pp), (wc), (f), (w), 1do
GI	2.27	6200	0.1200	22	15	14	3249	170 + 148	19.50	(pp), (wc), (f), (w), 2do
PE	2.04	6180	0.1303	20	17	16	3035	123 + 154	22.05	(pp), (wc), (p), (t), 2do
AN	1.99	5955	0.1520	23	15	11	3380	132 + 154	20.82	(pp), (–), (f), (w), 2do, 1si
ES	1.87	4746	0.1277	20	14.5	14	2691	141 + 134	17.26	(v), (–), (p), (w), 1do, 1si
MC	3.58	4623	0.1604	26	17	10	3041	144 + 226	12.49	(d), (–), (s), (r), 2si
CA	1.60	4362	0.1072	22	15	12	2474	121 + 102	19.56	(pp), (–), (p), (w), 2do
IS	2.21	3947	0.1324	26	14.5	11	2547	133 + 144	14.25	(pp), (mc), (f), (w), 1si

Mean value $\overline{\mu} = 0.1314\,\mathrm{s\,m^{-1}}$.
Standard deviation $\sigma_\mu = 0.0205$.
[a]*Lateral wall*: v, visible brick; pp, plastered and painted; d, directly painted brick; *Baseboard*: mc, major chapel; wc, whole church; *Decoration*: s, scarce; f, fair; p, profuse; *Ceiling:* w, wooden framework in three naves; t, tiles substitute the wooden board in the laterals; r, rough ceramics substitute the wooden boards in the central nave; *Inner doors*: si, single; do, double.

(Table 1, last row). Consequently, direct sound and early and late reflected energy components are, respectively, expressed by

$$d = \frac{100}{r^2}, \tag{8}$$

$$e_\mu = \frac{31{,}200\,T}{V} e^{-\mu r/T}(1 - e^{-1.11/T}), \tag{9}$$

$$l_\mu = l_B = \frac{31{,}200\,T}{V} e^{-0.04r/T} e^{-1.11/T}. \tag{10}$$

This normalized reflected energy density enabled all omnidirectional acoustic energy parameters to be predicted with reasonable accuracy in these places [16]. This model together with the rough assumption that the directional distribution of the early and late reflections is similar to a diffuse distribution enables LF, LFC, and GLL to be obtained as a function of source–receiver distance

$$\mathrm{LF}_\mu(r) = \frac{(1/3)e_\mu}{d + e_\mu} = \frac{(1/3)(31{,}200\,T/V)e^{-\mu r/T}(1 - e^{-1.11/T})}{100/r^2 + (31{,}200\,T/V)e^{-\mu r/T}(1 - e^{-1.11/T})}. \tag{11}$$

LFC_μ is calculated through LF_μ by $\mathrm{LFC}_\mu(r) = 1.5\,\mathrm{LF}_\mu$. And GLL_μ by

$$\begin{aligned}\mathrm{GLL}_\mu(r) = \mathrm{GLL}_B(r) &= 10\,\log\left(\frac{31{,}200\,T}{V} e^{-0.04r/T}\, e^{-1.11/T}\right) - 10\,\log 3 \\ &= 10\,\log\left(\frac{T}{V}\right) - \frac{4.82}{T} - \frac{0.17r}{T} + 40.17 \quad (\mathrm{d}B).\end{aligned} \tag{12}$$

Eq. (12) shows that, in accordance to Eq. (10), both the theoretical predictions for the GLL parameter, one based on Barron's revised theory and the second on the μ model, coincide.

This paper considers monaural lateral energy fraction measurements, LF, LFC, and GLL, conducted in 12 churches of the same typology in the south of Spain, and covers the acoustical characteristics [16,18] of the sound fields in these religious places. Established work on these features of sound quality in churches is not very extensive, focusing mainly on binaural parameters with scarce possibility of comparison [19,20]. However, since these churches house musical performances of a religious or cultural nature the measurement of the spatial impression is a necessary complement of the acoustics of the churches.

2. Measurement procedure

The procedures employed are those established in the ISO-3382 standard [14] and all measures have been carried out in unoccupied churches. Temperature and relative humidity are monitored during the measurements by a precision electronic thermo-hygrometer $\pm 1\,^\circ$C, $\pm 5\%$, respectively, and a barometer determines the atmospheric pressure. The range of variation is 22.6–27.4 °C for the temperature, 35.7–65.7% for the relative humidity and 101.7–102.5 kPa for the atmospheric pressure.

Monoaural impulse responses are obtained through maximum length sequence (MLS) signals. The analysers used are the MLSSA and the WinMLS. In both cases, the obtained results are the same although GLL values cannot be obtained through the version of MLSSA available to the authors. For the measurement of the impulse response, in order to obtain the decay curves and the energy parameters, the MLS spectrum must be conditioned to that of pink noise before being fed to the amplifier, the procedure followed may be consulted in Ref. [18].

The omnidirectional source B&K 4296 is placed at the most usual point of location of the natural source: the altar at a height of 1.70 m from the floor (indicated by $S(\lhd)$ in Fig. 1). The microphone is located at the approximate height of the head of a seated person which is 1.20 m from the floor, in a predetermined number of positions distributed in the central nave and the lateral naves ranging from 12 reception points of Santa Catalina church to 23 of Santa Marina (see Fig. 1).

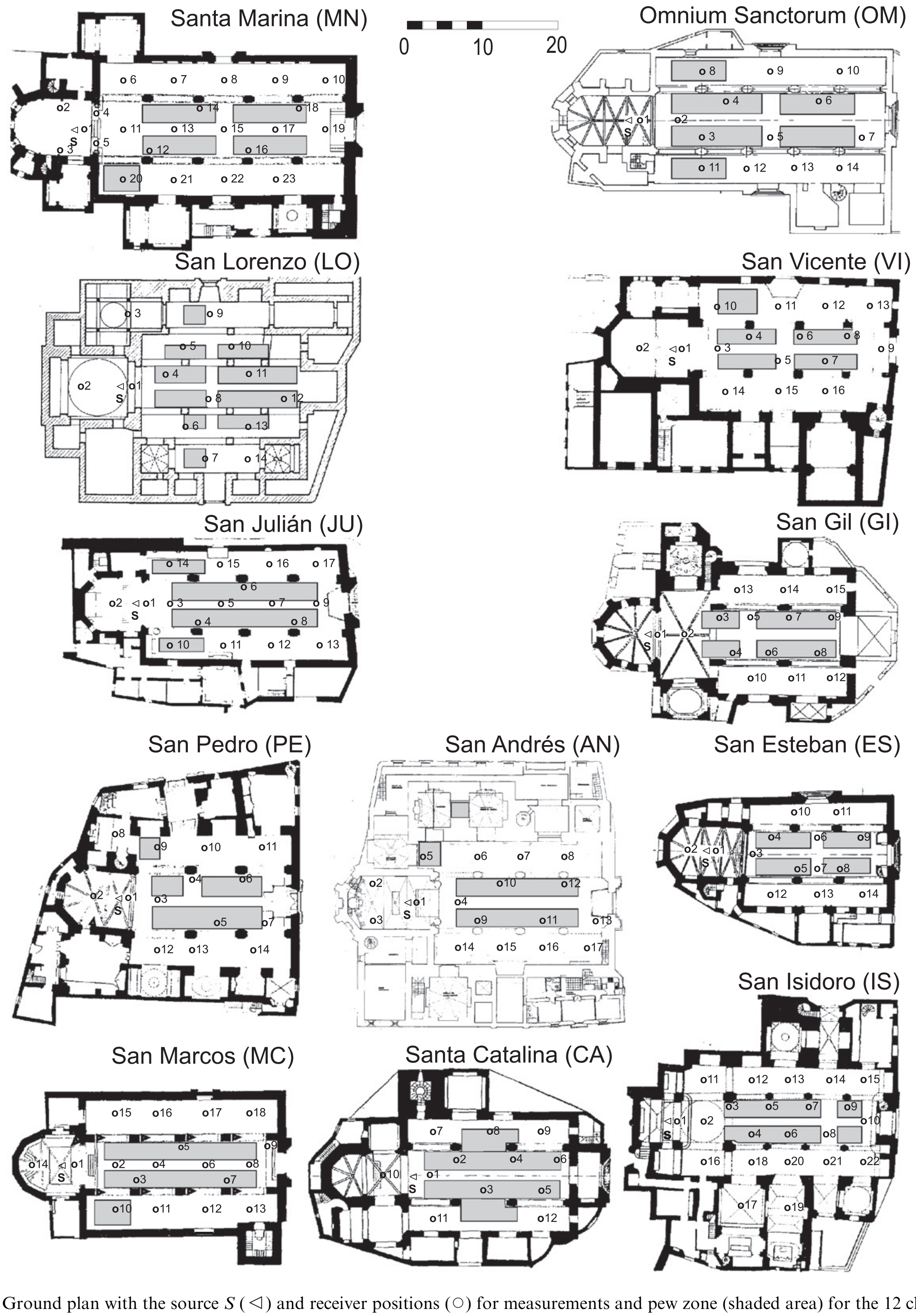

Fig. 1. Ground plan with the source S (◁) and receiver positions (○) for measurements and pew zone (shaded area) for the 12 churches (same scale for all churches and presented in order of decreasing volumes). Abbreviations are also shown.

Table 2
Standard deviations for spatial distribution of LF (upper row) and LFC (lower row) in octave bands for each church

Freq.	MN	OM	LO	VI	JU	GI	PE	AN	ES	MC	CA	IS
125 Hz	0.017	0.011	0.028	0.028	0.016	0.021	0.024	0.019	0.016	0.035	0.045	0.015
	0.015	0.016	0.028	0.029	0.019	0.021	0.025	0.023	0.024	0.019	0.036	0.019
250 Hz	0.021	0.018	0.036	0.028	0.029	0.027	0.040	0.027	0.027	0.080	0.032	0.027
	0.022	0.023	0.031	0.028	0.030	0.023	0.034	0.025	0.026	0.052	0.032	0.026
500 Hz	0.025	0.035	0.032	0.025	0.024	0.026	0.023	0.029	0.029	0.028	0.032	0.029
	0.024	0.030	0.027	0.025	0.026	0.024	0.020	0.025	0.026	0.023	0.031	0.019
1 kHz	0.023	0.019	0.042	0.024	0.027	0.016	0.029	0.031	0.021	0.020	0.028	0.025
	0.022	0.022	0.034	0.023	0.025	0.016	0.022	0.023	0.024	0.015	0.026	0.016
2 kHz	0.022	0.017	0.031	0.020	0.017	0.010	0.022	0.015	0.013	0.018	0.016	0.016
	0.019	0.021	0.032	0.021	0.021	0.017	0.018	0.015	0.020	0.015	0.020	0.020
4 kHz	0.016	0.016	0.031	0.019	0.013	0.010	0.018	0.015	0.015	0.028	0.022	0.016
	0.020	0.021	0.030	0.023	0.017	0.017	0.017	0.016	0.029	0.019	0.025	0.021

Table 3
Standard deviations for the spatial distribution of GLL in octave bands for each church

Freq.	MN	OM	LO	VI	JU	GI	PE	AN	ES	MC	CA	IS
125 Hz	–	0.83	0.57	0.38	0.77	0.67	0.64	0.35	0.12	–	0.55	0.80
250 Hz	0.47	0.76	0.95	0.71	1.24	1.07	0.99	0.70	0.66	–	0.60	0.76
500 Hz	0.48	1.09	0.85	0.84	0.91	0.95	0.56	0.97	0.55	–	1.02	0.85
1 kHz	0.35	0.44	0.72	1.51	0.58	1.01	1.09	0.71	0.60	–	0.52	0.85
2 kHz	0.67	1.14	0.87	1.14	0.72	1.33	0.98	0.77	1.11	1.50	0.68	1.44
4 kHz	0.49	1.10	0.60	1.06	0.62	1.15	0.62	0.95	2.60	0.45	0.73	1.62

The microphone used was the Audio-Technica AT4050/CM5 whose amplifier and polarization source is of Earthworks LAB1, which by means of a simple switch allows its directivity pattern to change from omnidirectional to bidirectional in a figure of eight. The reason for this selection was to keep to the ISO 3382 standard, however, a new five-microphone system for measuring the directional parameters related to spatial impression has recently been presented [21].

Monoaural impulse responses were analysed to produce results in the six octave bands of interest between 125 and 4000 Hz, and in all the receiving positions to determine reverberation times (T), the early lateral energy fraction parameters (LF and LFC) and the late lateral level (GLL). Due to the lack of a criterion of acoustical measurement in these complex places, all lateral energy measures in this work are spectrally averaged as a direct average of 125, 250, 500, and 1000 Hz octave bands in accordance with the most widely accepted method for the evaluation of the two attributes of spatial impression in concert halls [9,15,22]. Henceforward, these experimental results will be named LF_{AV}, LFC_{AV}, and GLL_{AV}, respectively.

3. Experimental results and discussion

3.1. The churches studied

All the churches were built in the Middle Ages and have suffered restorations and adaptations throughout their existence due to various reasons (including earthquakes, fires, and deterioration). Their architectural

Table 4
Minimum distances in order to take into account the mean values of the early lateral parameters. The corresponding mean values at the central nave (CN) and lateral naves (LN) for LF_{AV}, LFC_{AV}, and GLL_{AV} in each church and their corresponding standard deviations (lower row)

Church	d_{min} (m)	Mean LF_{AV} at CN	Mean LF_{AV} at LN	Mean LFC_{AV} at CN	Mean LFC_{AV} at LN	Mean GLL_{AV} at CN	Mean GLL_{AV} at LN
MN	6.39	0.14 0.02	0.25 0.02	0.21 0.02	0.31 0.01	– –	–
OM	5.96	0.14 0.02	0.21 0.01	0.20 0.02	0.28 0.09	5.4 0.4	– –
LO	6.03	0.17 0.03	0.28 0.04	0.23 0.02	0.31 0.02	4.5 0.9	6.8 0.6
VI	5.74	0.12 0.01	0.25 0.04	0.20 0.01	0.30 0.02	5.4 0.7	– –
JU	5.68	0.16 0.02	0.24 0.01	0.23 0.01	0.30 0.02	4.9 0.4	7.6 1.9
GI	5.67	0.19 0.01	0.23 0.04	0.24 0.01	0.25 0.00	6.5 0.0	– –
PE	5.97	0.15 0.00	0.24 0.04	0.21 0.01	0.29 0.02	4.6 0.3	7.6 1.0
AN	5.93	0.21 0.03	0.27 0.03	0.26 0.02	0.31 0.02	6.8 0.4	9.0 0.4
ES	5.46	0.17 0.01	0.23 0.01	0.24 0.01	0.31 0.01	6.0 0.2	– –
MC	3.89	0.11 0.02	0.41 0.06	0.18 0.02	– –	– –	– –
CA	5.66	0.20 0.02	0.25 0.04	0.26 0.01	0.30 0.04	4.4 0.3	5.6 0.8
IS	4.58	0.18 0.02	0.25 0.03	0.24 0.01	0.33 0.03	5.5 0.5	9.0 0.5

style was the result of a unique Spanish artistic movement since it was influenced by both Islamic and Gothic Christian elements.

The Mudejar–Gothic churches in Seville, all located in its historical centre, are morphologically characterized by this stylistic dualism: a vaulted Gothic apse and a body of three naves with a timber roof (collar beam in the main nave) of Moorish origin. The brick walls are complemented with portals and a stone apse. The supports are also clearly Islamic, with quadrangular or sometimes octagonal pillars and with raised brick mouldings as decoration. Pointed, round or segmental arches rest on these supports.

Fig. 1 shows the ground plan for each church with the source and receiver positions for measurements and the seating areas. These drawings are all on the same scale and presented in order of decreasing volume. The name of each church is accompanied by its abbreviation in order to fit into Tables 1–4 and Fig. 2.

Table 1 summarizes some acoustic and geometric data of the churches: mean mid-frequency reverberation time T, volume V, coefficient μ, length L, width W, average height H, total surface S_T, central nave ground surface S_C, lateral nave ground surface S_L, total ground surface S_G and a brief description of their interior finishes *Finish*, for the 12 churches. The church floors are of marble or ceramic material and the congregational seating area consists of wooden pews distributed in the main nave and also occasionally in the lateral naves (shaded area in Fig. 1). A complete description of the furnishings and other acoustical information on these temples can be found in Ref. [18].

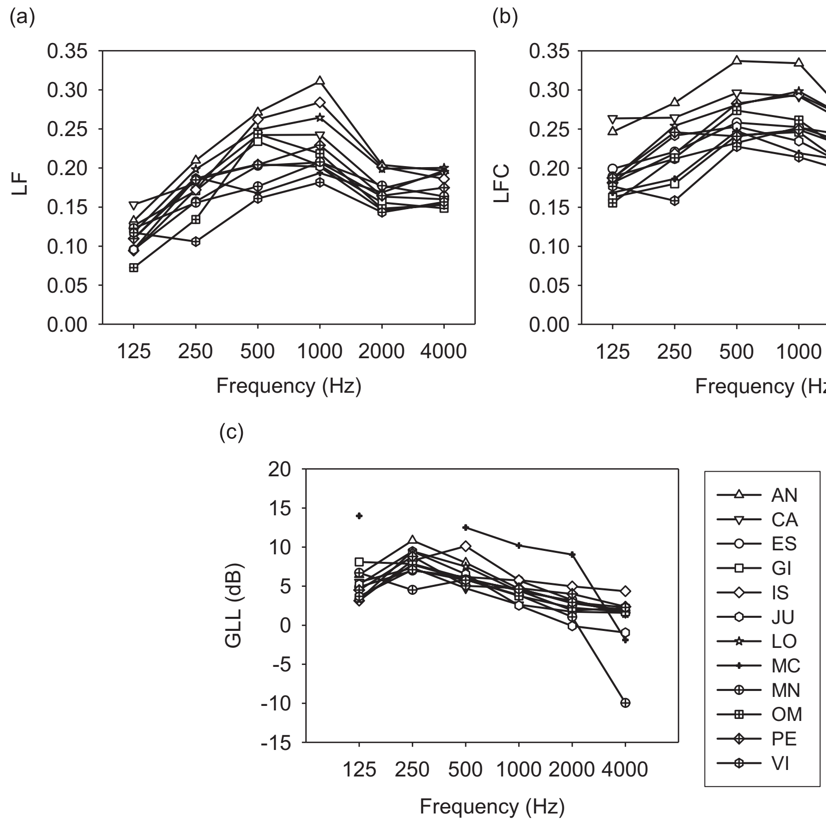

Fig. 2. Early lateral fractions: (a) LF, (b) LFC, and (c) late lateral level GLL spatially averaged for each church versus frequency.

3.2. Lateral energy measures versus frequency

Early lateral energy measures and late lateral levels are first studied spectrally. In the set of Fig. 2, the spatially averaged values of LF in Fig. 2(a), LFC in Fig. 2(b), and GLL in Fig. 2(c) versus frequency in all the churches under study are plotted. As a general comment on the first two plotted graphs of the early lateral energy fractions LF and LFC (Figs. 2(a) and (b)), similar dependence on frequency is presented, with a sharp decay at low frequencies (more marked in LF) and maximum values at mid frequencies with variable results in different churches, where San Andrés church yields the highest value and San Vicente church the lowest.

From Fig. 2(c), it should be mentioned that in some churches there have been difficulties related to finding a suitable signal-to-noise ratio to enable reliable values of GLL to be obtained. In general, this problem is exacerbated for low frequencies. Furthermore, in relation to Fig. 2(c), the highest value of GLL is found for San Marcos church which is the church of longest reverberation time due to its lack of a timber roof in its central nave, and the lowest values are given for Santa Catalina and San Julián churches, which are the deafest churches. The reason for this behaviour is that the late lateral level is affected by the overall level and later energy. In fact, the spectral trend is similar to that obtained for the measured reverberation times and G parameters in these churches, published in the previous work [18].

The standard deviations for the spatial distribution are shown in Table 2 for the early lateral energy parameters and in Table 3 for the late lateral levels. The standard deviations for LF and LFC are very similar in each church and for each frequency and the range of variation is from 0.011 to 0.08. For the GLL parameter, its standard deviations show a greater variation from one church to another and even from one frequency to another within a church.

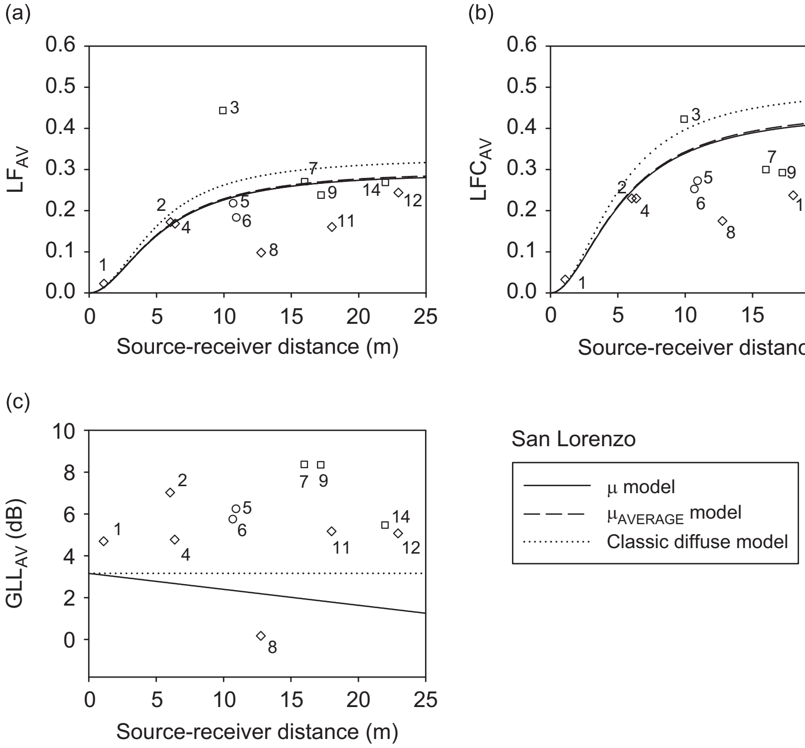

Fig. 3. San Lorenzo church, measured values at the different points of reception in the central nave (◇), in the first lateral naves (○), in the second lateral naves (□), and calculated values from the classic diffuse model (dotted line), the μ model (continuous line) and the $\overline{\mu}$ model (dashed line) versus source–receiver distance for (a) LF_{AV}, (b) LFC_{AV}, and (c) GLL_{AV}.

3.3. Lateral energy measures versus source– receiver distance

An important question is how ASW and LEV would change in a closed space according to source–receiver distance. The set of Figs. 3–8 shows the results for six churches (San Lorenzo, San Julián, San Pedro, San Andrés, Santa Catalina, and San Isidoro) of the early lateral energy fraction measures: (a) LF_{AV} parameter, (b) LFC_{AV} parameter and the late lateral level, (c) GLL_{AV} parameter, all as a function of source–receiver distance. In their plotted graphs, their different points of reception are highlighted, allowing the different naves of the churches to be distinguished (see also Fig. 1). The theoretical predictions based on a classic diffuse field and the μ model using their corresponding μ parameter or the $\overline{\mu}$ values are also shown, Eq (11). In the case of the GLL_{AV} parameter, the classic prediction is a straight horizontal line and the theoretical prediction based on the μ coefficient is independent of this coefficient and coincides with Barron's revised theory, which is solely dependent on reverberation time T and volume V variables, Eq (12).

When first considering the theoretical predictions about the parameters related to early lateral energy LF_{AV} and LFC_{AV}, it can be highlighted that classic behaviour and the μ model present the same variation with distance, where only the latter shows a greater attenuation. As for the theoretical predictions based on μ and $\overline{\mu}$ coefficients, these are very similar with only small differences due to the differences between μ and $\overline{\mu}$ ($0.1314\,\mathrm{s\,m^{-1}}$) values. At the furthest points of reception, the differences for the LF_{AV} parameter are: San Lorenzo -1.48%, $\mu = 0.1392\,\mathrm{s\,m^{-1}}$, San Pedro 0.24%, $\mu = 0.1303\,\mathrm{s\,m^{-1}}$, and San Isidoro -0.13%, $\mu = 0.1324\,\mathrm{s\,m^{-1}}$. The remaining differences never exceed 6% (San Julián = 5.24%, $\mu = 0.0901\,\mathrm{s\,m^{-1}}$, San Andrés -5.48%, $\mu = 0.1520\,\mathrm{s\,m^{-1}}$, and Santa Catalina 4.79% $\mu = 0.1072\,\mathrm{s\,m^{-1}}$).

In general, experimental data move away from the theoretical predictions and only approach them when both the results at short distances from the source are considered and at certain positions in the lateral naves.

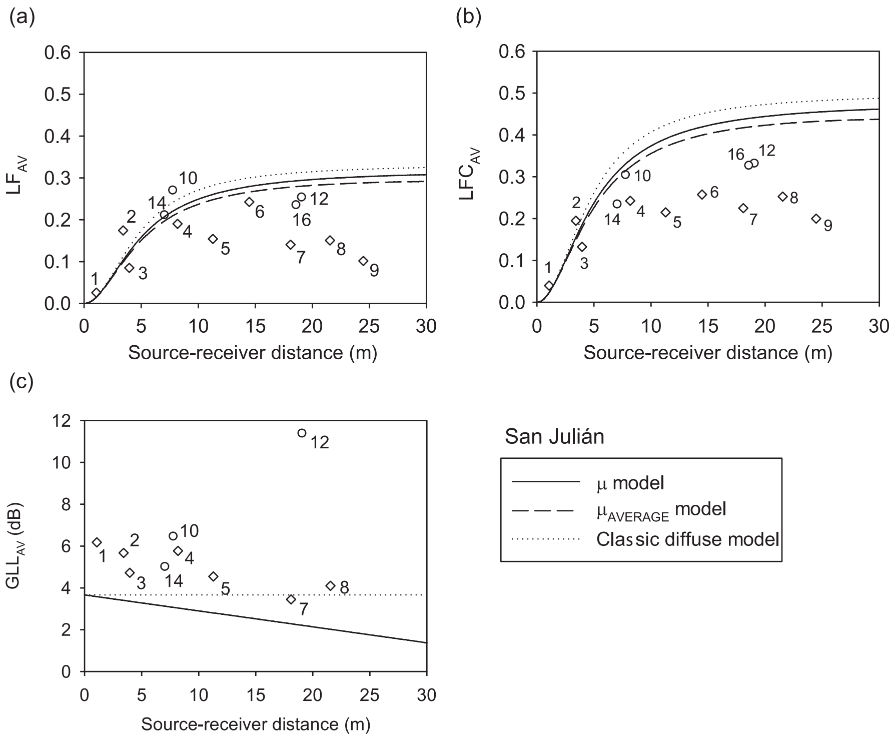

Fig. 4. San Julián church, measured values at the different points of reception in the central nave (◇), in the lateral naves (○), and calculated values from the classic diffuse model (dotted line), μ model (continuous line) and $\overline{\mu}$ model (dashed line) versus source–receiver distance for (a) LF_{AV}, (b) LFC_{AV}, and (c) GLL_{AV}.

The deviation from the μ pattern of the experimental results can be justified when it is borne in mind that the density of energy proposed by Eq. (7) supposes only one modification to the classic pattern that establishes only one dependence on source–receiver distance without adding any other directional dependence. This oversimplification of the acoustic field works appropriately when it deals with the evaluation of omnidirectional energy parameters and especially when dealing with ratios of early/late energy or early/total energy such as C_{50}, D_{50}, and T_S parameters. Things work more modestly when an adjustment of the G parameter is involved, as shown in previous work [16]. In the essence of this work, the obviated directional features are critical in weighting the lateral characteristics of energy against the omnidirectional characteristics in early energy. The acoustic field is not the same in all directions and the sound energy is diminished in relation to the classic diffuse field (attenuation introduced by coefficient μ) nor is the sound energy equal in all directions of arrival, hence LF_{AV} and LFC_{AV} are overestimated with this isotropy hypothesis.

In some churches, the experimental values are nearly constant inside each nave (for instance San Julián, San Andrés, and Santa Catalina churches) although with inferior values to those predicted by the classic diffuse field pattern, $LF_{AV} = 0.33$ and $LFC_{AV} = 0.5$, as has already been mentioned. This leads the authors to calculate their mean values in the respective naves of the 12 churches studied, which yields their corresponding standard errors (Table 4).

In the case of the LF_{AV} and LFC_{AV} parameters, the results for distances smaller than the minimum distance have been omitted (Table 4, second column), as recommended in the ISO 3382 Standard [14], so that these parameters are not affected by direct sound.

In relation to the GLL_{AV} parameter, data plotted in Figs. 3(c)–8(c) show that the experimental results are larger than the theoretical predictions in both the diffuse field and μ model cases. This can be qualitatively justified by the fact that GLL_{AV} takes into account both the overall level and the angular distribution of the late-arriving sound through the two terms of Eq. (5). However, the diffuse distribution hypothesis for the reflected energy proposed in Eq. (7) through the μ model overestimates the subtrahend of this equation.

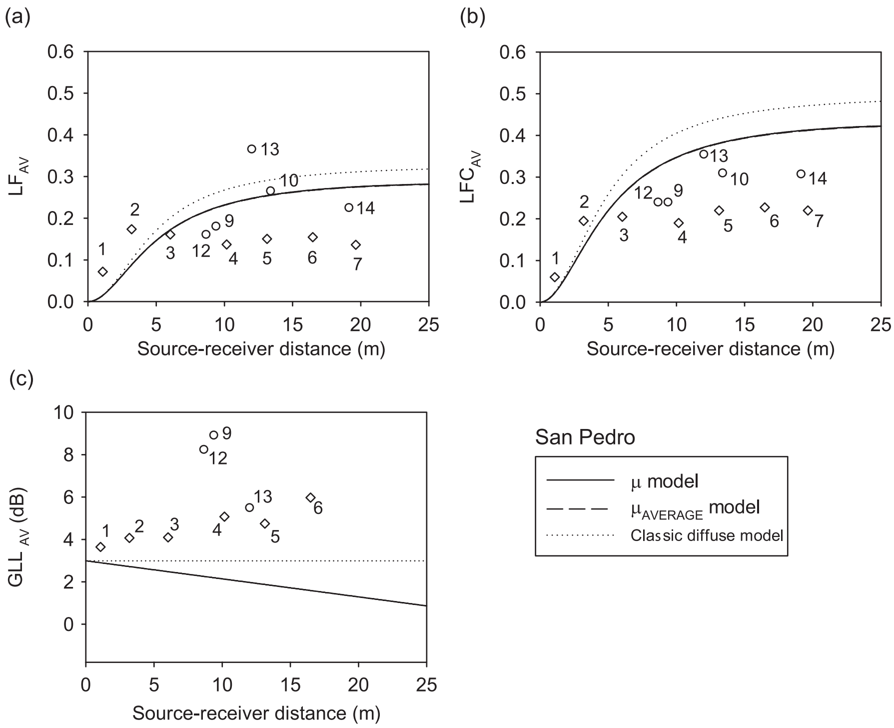

Fig. 5. San Pedro church, measured values at the different points of reception in the central nave (◇), in the lateral naves (○), and calculated values from the classic diffuse model (dotted line), μ model (continuous line) and $\overline{\mu}$ model (dashed line) versus source–receiver distance for (a) LF_{AV}, (b) LFC_{AV}, and (c) GLL_{AV}.

The deviation of experimental results of the three parameters analysed which assess the two attributes of spatial impression in rooms, indicates that there is a certain dispersion in these parameters in relation to source–receiver distance (especially between the different naves) and that the assumption of a diffuse directional distribution of the sound field (acoustic energy density dependent only on distance) is an oversimplification of the features of the sound field in the churches.

Another feature worth mentioning is that both parameters LF_{AV} and LFC_{AV} associated to the amount of ASW have higher values in the lateral naves of the temples than in the central naves (see the set of Figs. 3(a)–8(b) and Table 4). For LEV, apparently a similar conclusion can be drawn in spite of the minor quantity of measurement positions (Table 4). As a general trend, these figures show greater asymmetrical behaviour at certain positions of lateral naves than in central naves. The distance to the lateral wall and decoration (statuettes, pictures, and altarpieces in some lateral walls) may produce these variations, especially in San Pedro, San Andres, and San Isidoro churches.

To illustrate these comments, the nature of the directional pattern of early energy can be shown by ray-tracing simulation, using Catt-Acoustic. Fig. 9(a) shows the early directional simulated echogram for position 11 (lateral nave) in the 500 Hz octave band in San Esteban church. The contributions of energy coming from the different directions (forward–behind, overhead–below and left–right) are shown, and the weighting is obtained through a square cosine.

This echogram shows that in the first milliseconds after direct sound arrival the contribution to energy coming from the vertical direction is smaller than the rest. However, in position 6 (central nave) Fig. 9(b), the lateral contribution is similar or inferior to the vertical contribution.

In all the simulations, the lateral walls are the surfaces that receive a great deal of impact and these generate lateral reflections over the receivers located in the naves, with major energy in the positions of lateral naves. All these facts corroborate the features highlighted in the set of experimental results of Figs. 3–8 where values of LF_{AV} and LFC_{AV} in the lateral naves of the churches are higher than those in their central naves.

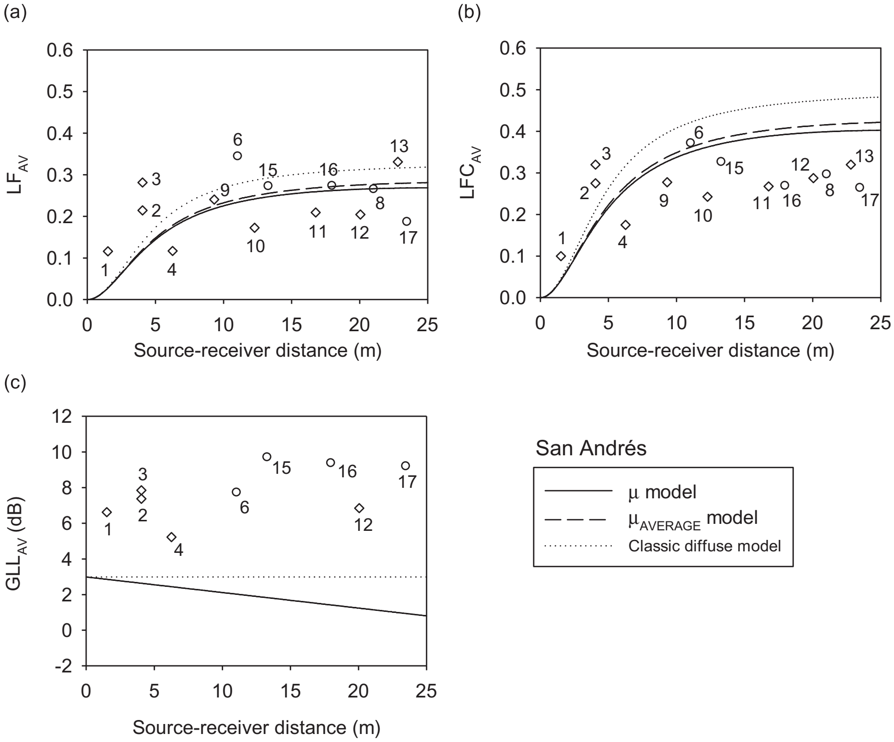

Fig. 6. San Andrés church, measured values at the different points of reception in the central nave (◇), in the lateral naves (○), and calculated values from the classic diffuse model (dotted line), μ model (continuous line) and $\overline{\mu}$ model (dashed line) versus source–receiver distance for (a) LF_{AV}, (b) LFC_{AV}, and (c) GLL_{AV}.

3.4. Lateral energy measures for all churches

In the set of Fig. 10, the corresponding values of LF_{AV} Fig. 10(a), LFC_{AV} Fig. 10(b), and GLL_{AV} Fig. 10(c) as a function of source–receiver distance for all the churches are shown. Points belonging to the different naves have been highlighted and again it can be emphasized that, both individually and as a whole, there is a net increase of all parameters studied for positions in the lateral naves against the central naves. Their corresponding mean values are shown in the graphs plotted with their standard deviations. In Fig. 10(a), the two points which are the farthest from the mean value correspond to San Lorenzo church (position 3 in the second lateral nave without direct sound), and to San Marcos church in its lateral nave (position 11, behind a column). Both represent anomalous characteristics: San Lorenzo church because it presents four lateral naves and San Marcos church due to the fact that it lacks a timber roof, thereby yielding special acoustic characteristics, as have been mentioned in the previous work [16,18]. The scarcity of data of GLL available at low and mid frequencies in the different churches has repercussions on the experimental results of GLL_{AV} in Fig. 10(c). The standard deviation for LF_{AV} and LFC_{AV} have similar values for the measured positions of the central naves and lateral naves, while for GLL_{AV} the dispersion of lateral nave measures is greater than that for central naves.

These results show that the best option for the perception of the two spatial attributes of music in these churches is in the lateral naves as opposed to the results obtained for the assessment of speech intelligibility where better results are encountered in the central nave [23].

According to these results, the averaged values of the parameters and their corresponding standard deviations at the different naves are as follows: for LF_{AV} in the central naves 0.16 and standard deviation 0.05; for LF_{AV} in the lateral naves 0.25 and standard deviation 0.07 (these values are 0.24 and 0.05, respectively, if the two named points in Fig. 10(a) are eliminated). For LFC_{AV} the mean value in the central naves is 0.23 with its standard deviation 0.04; for LFC_{AV} at the lateral naves the mean value is 0.30 with its standard deviation

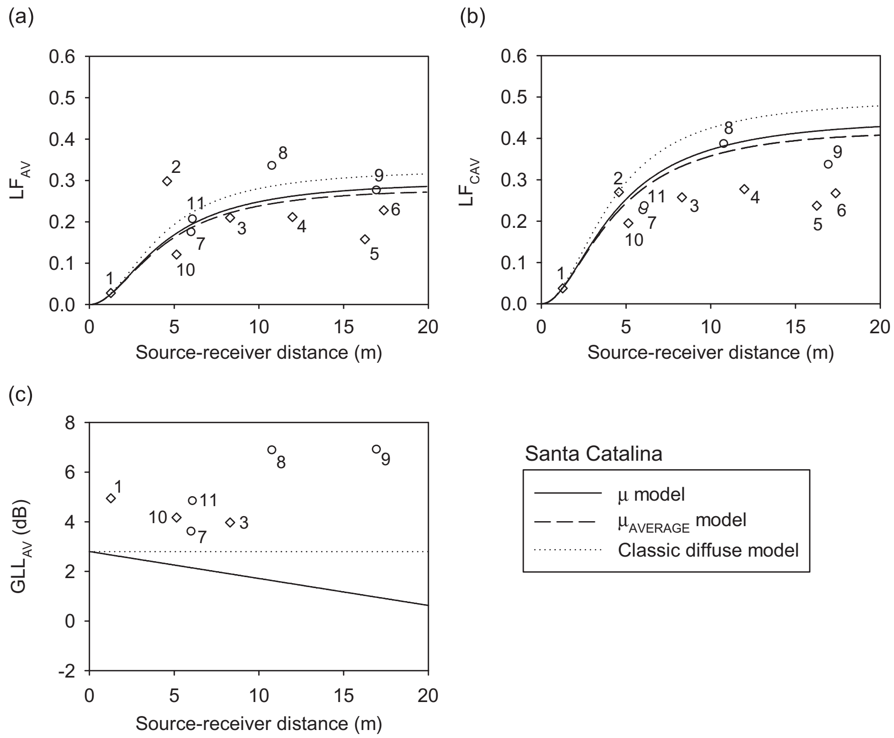

Fig. 7. Santa Catalina church, measured values at the different points of reception in the central nave (◇), in the lateral naves (○), and calculated values from the classic diffuse model (dotted line), the μ model (continuous line) and the $\overline{\mu}$ model (dashed line) versus source–receiver distance for (a) LF_{AV}, (b) LFC_{AV}, and (c) GLL_{AV}.

0.05. For GLL_{AV} parameter the mean values are 5.27 dB at the central naves and 7.58 dB at the lateral naves with their respective standard deviations 1.39 and 1.97, respectively.

Recommended values for auditoria are $LF_{AV} > 0.20$ which is exceeded in the lateral naves of the churches. It should be pointed out that these values are found in the best range of the results obtained in a survey [22] of 17 British auditoria whose mean value is 0.19 and 13 American auditoria whose mean value is 0.15. In the churches, the global mean value is 0.20 for LF_{AV} in all churches and positions and 0.25 for LFC_{AV}. For the GLL_{AV} parameter, the results are also notably superior to the results obtained in the aforementioned survey of auditoria which presents a mean value of −4.8 dB [15], while for the churches the global mean in all churches and positions is 6.42 dB. The LF_{AV} standard deviation presented for the experimental data is even less than the just noticeable difference (JND = 0.05) reported by Cox et al. [24] for this parameter. In this sense, the change can be perceived when the receiver moves from central nave to lateral naves, since the mean values differ by about 0.09 which is approximately twice the JND value. Likewise, it should be mentioned that there is a considerable overlap between measured values of LF_{AV}, LFC_{AV}, and GLL_{AV} in the different churches. Hence, the relevance of describing source broadening or envelopment in these religious enclosures by their mean early energy fractions or mean late lateral level respectively is questionable, as also happens in concert halls and opera houses [22].

A comparison of the experimental values of LFC_{AV} versus LF_{AV} measures has been carried out in Fig. 11 (omitting positions for $r < d_{min}$) which shows that the relationship between these two parameters is linear $LFC_{AV} = 0.73\ LF_{AV} + 0.11$, $R^2 = 0.78$. However, the slope of the regression is substantially different (about half) to that predicted by a classic diffuse field hypothesis, which once again confirms the oversimplification which assumes that early reflected energy is independent of direction of precedence and only dependent on source–receiver distance.

Finally with the intention of associating lateral energy fractions values to architectural variables, the spatially averaged values of LF_{AV}, LFC_{AV}, and GLL_{AV} parameters in each church have been compared with

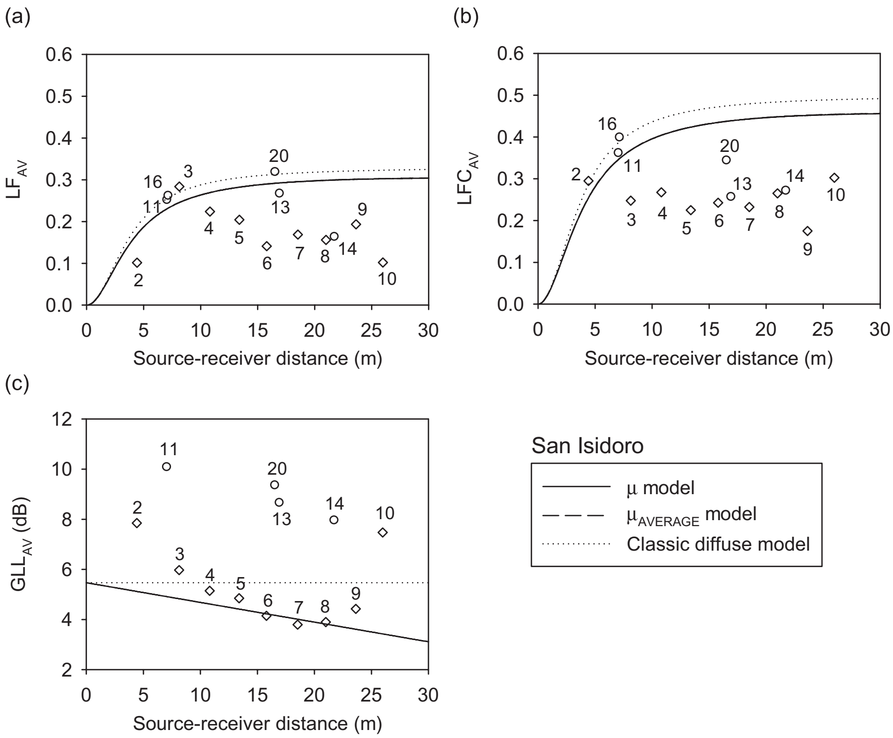

Fig. 8. San Isidoro church, measured values at the different points of reception in the central nave (◇), in the lateral naves (○), and the calculated values from the classic diffuse model (dotted line), the μ model (continuous line) and the $\overline{\mu}$ model (dashed line) versus source–receiver distance for (a) LF_{AV}, (b) LFC_{AV}, and (c) GLL_{AV}.

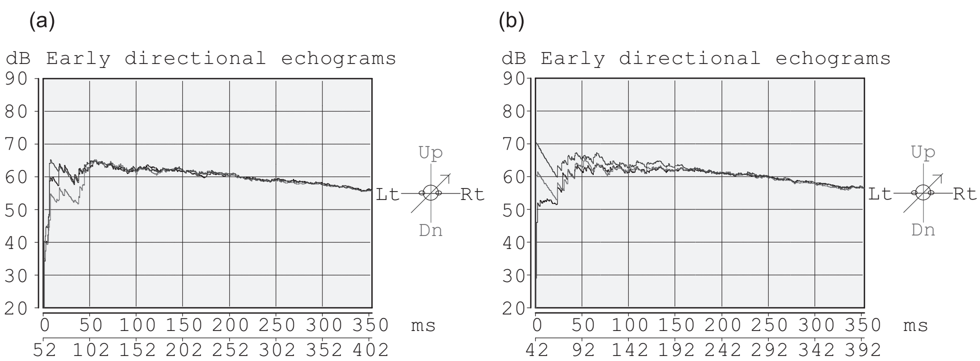

Fig. 9. Early directional simulated echogram at 500 Hz band in San Esteban church: (a) for position 11 (lateral nave) and (b) for position 6 (central nave).

various geometrical parameters by regression analysis. The comparison has been carried out using all the geometrical and acoustical parameters that appear in the heading of Table 1. In the case of the GLL_{AV} parameter, correlations with the mean absorption coefficient or the total absorption of the churches have also been tested, and show that they are uncorrelated.

As the simple image model indicates in concert halls and opera houses, the mean hall early lateral energy fractions are, on average, influenced by the hall width. In Fig. 12, a plotted graph of these two quantities, LF_{AV} versus mean width, is shown. Experimental results indicate a low correlation between these two quantities due to the fact that there are only small variations in mean width W in the different churches studied

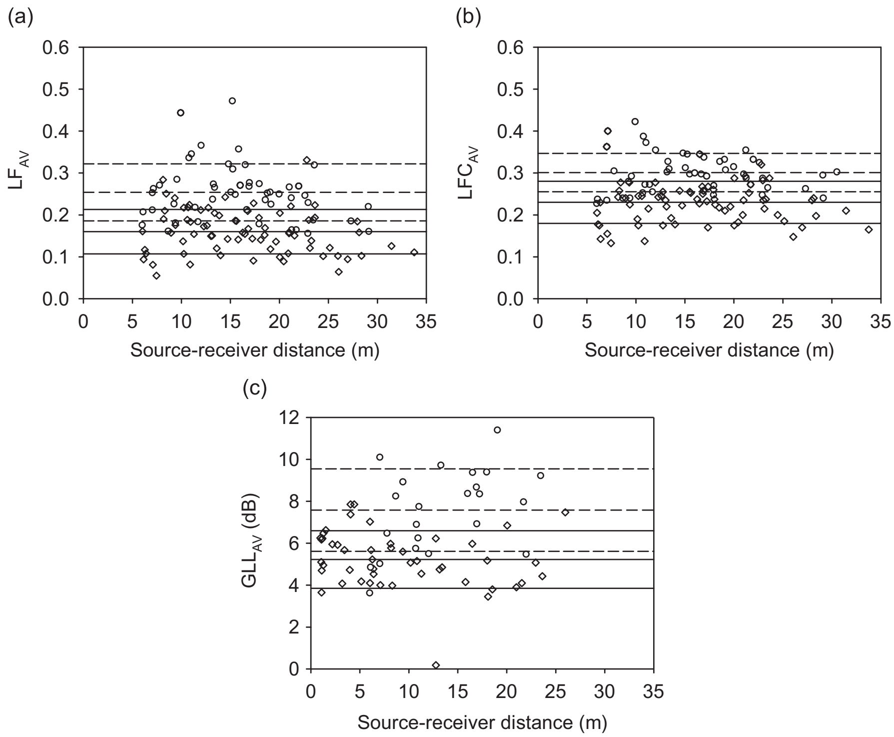

Fig. 10. Early lateral fractions (a) LF_{AV}, (b) LFC_{AV} (omitting the points at $r<d_{min}$), and (c) late lateral level GLL_{AV} for all churches versus source–receiver distance. The points of reception of the different naves are shown: (◇) central nave and (○) lateral naves. The range of standard deviation is shown for the different parameters.

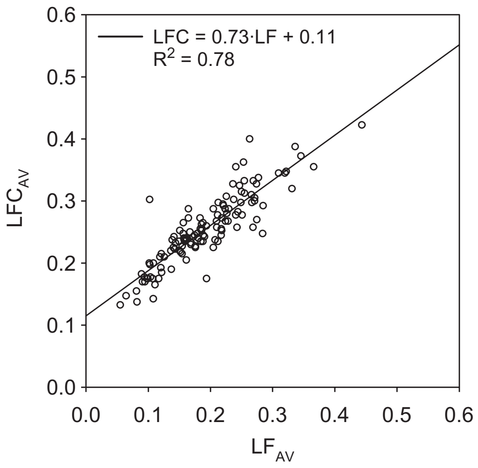

Fig. 11. LFC_{AV} versus LF_{AV} for all churches at all the points of reception (omitting the points at $r<d_{min}$).

with the same parallel-sided walls. In Fig. 13, the LF_{AV} parameter is plotted versus the ratio $2H/W$ that determines the relative arrival time of early lateral and vertical reflections, as West [25] suggested for concert halls. In this case the regression line is also nearly horizontal although the correlation coefficient is slightly better.

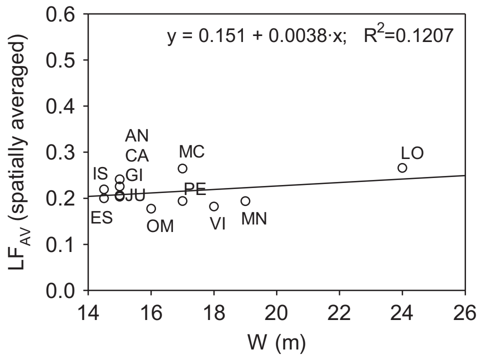

Fig. 12. Comparison of LF_{AV} values spatially averaged in the churches (omitting the points at $r<d_{min}$) as a function of mean width W.

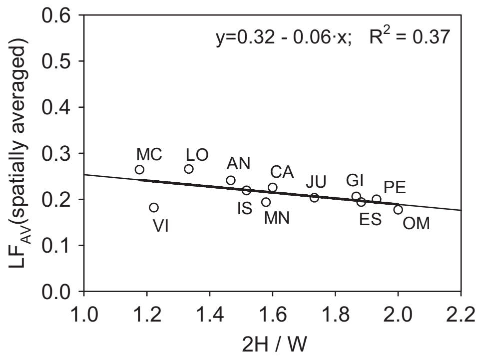

Fig. 13. Comparison of LF_{AV} values spatially averaged in the churches (omitting the points at $r<d_{min}$) as a function of $2H/W$.

4. Conclusions

Spatial impression measurements have been analysed in 12 Mudejar–Gothic churches of the city of Seville in southern Spain through monaural parameters derived from impulse response analysis. The perceived ASW has been assessed through the influence of early lateral energy fractions through two objective monaural measures LF and LFC. A measure of the sense of LEV has been carried out through the objective late lateral level GLL.

The behaviour of these parameters at different frequencies has been studied in all churches using their spatially averaged values. It has been shown that LF and LFC behave similarly for all churches by presenting a decay at low frequencies and a maximum at mid frequencies. For GLL the behaviour is quite different to the early lateral energy parameters and shows a dependence on octave band frequencies similar to that obtained in previous work for the reverberation time and the sound strength in the churches.

The spatial distribution of the parameters has been analysed where these parameter have been spectrally averaged at low and mid frequencies, the most widely accepted way in order to describe sound quality in concert halls and auditoria. Experimental results have been compared with theoretical predictions based on the analytical model obtained to interpret the sound field in these religious places: the μ model. This model assumes that early normalized reflected energy suffers an attenuation with respect to classic diffuse theory which is source–receiver dependent through a coefficient μ obtained by nonlinear regression from the experimental data of clarity index in the churches. In this comparison experimental results behave differently for the two types of parameters studied. For the early lateral energy parameters, LF_{AV}, and LFC_{AV}, experimental results are smaller than the theoretical predictions due to the fact that the directional distribution of the reflected energy in a diffuse model overestimates the early lateral energy. Conversely, in the case of late lateral level GLL_{AV}, the experimental results are greater than the theoretical predictions due to the fact that the overestimation of the late lateral energy, as a consequence of the isotropy of the sound field hypothesis, mainly affects the subtrahend of a difference. The oversimplification that supposes a diffuse field is also shown through the comparison of LFC_{AV} versus LF_{AV} with the whole set of data in all churches.

Another feature that deserves mention is that the experimental results present greater values in the lateral naves of the churches than in the central naves. These results are in accordance with the simulated results derived by ray-tracing whose directional echograms show both the preponderance of early acoustic reflections coming from the lateral in these areas, and the greater number of ray impacts on the lateral walls. These results indicate that in spite of the visual difficulties involved in observing the sound source in the lateral naves of the churches, these areas are the most suitable positions for the perception of these two attributes of spatial impression for music (in contrast to what happens for the intelligibility of speech and singing).

Finally, in order to draw conclusions in relation to design variables LF_{AV}, LFC_{AV}, and GLL_{AV}, spatially averaged values within each church have been compared with geometrical parameters by using regression. The results of the GLL_{AV} parameter show no correlation. However, for the early lateral energy fractions, the best correlation appeared with the mean width and with the ratio height/width, which determines the relative arrival time of early lateral and vertical reflections. In the former case, the correlation is practically constant due to the small range of variation of width in all churches with the same parallel-sided walls, while the latter case presents a smooth linear dependence with a negative slope.

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