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Effects of sound source direction on acoustical parameters in a church

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ABSTRACT

After the Second Vatican Council, the Catholic liturgy has changed: a priest is facing the congregations and not with his back to the congregation. However, the acoustical change has not been examined yet. To discuss the desirable acoustical conditions of a church, it is necessary to know acoustical characteristics in accordance with such Catholic liturgy. In this study, acoustic measurements were conducted with various sound source positions and directions following the old and new Catholic liturgy in four churches in Nagasaki, Japan. The source was directional loudspeaker. Binaural impulse responses were measured using a dummy-head microphone. Acoustical parameters such as listening levels, initial time-delay gap, reverberation time, and interaural cross correlation coefficient (IACC) were analyzed. The values of IACC at frontal seats in the new Catholic liturgy condition were higher. This suggests that the change of the Catholic liturgy may lessen an acoustical characteristic.

INTRODUCTION

Acoustical characteristics in churches are complex because geometrical patterns are of great variety and various kinds of sound message, such as spoken word, organ music, and congregational singing, are used. Some researches have clarified the effects of geometrical patterns, such as dimensions and styles, and intelligibility of speech and singing (e.g. Sendra et al., 1999; Magrini and Ricciardi, 2003; Cirillo and Martellotta, 2003; Galindo et al., 2005; Zamarreño et al., 2008).

After the Second Vatican Council, the Catholic liturgy has modified. A priest is facing the congregations and not with his back to the congregation. It is expected that acoustical characteristics in church also change. However, the acoustical change has not been examined yet. That is to say, the effects of direction of a priest has not been clarified yet since an omni-directional loudspeaker has been used as a sound source in most of previous studies.

To discuss the desirable acoustical conditions of a church, it is necessary to know acoustical characteristics in accordance with such Catholic liturgy. In this study, acoustic measurements were conducted with various sound source positions and directions following the old and new Catholic liturgy in four churches in Nagasaki, Japan.

THE CHURCHES OF NAGASAKI IN JAPAN

There are more than 100 Catholic churches in Nagasaki, most of which were built in the late 19th and early 20th centuries. Acoustic measurements were conducted in four churches. Figure 1 shows the ground plan and pictures for each church (These plans are on the same scale). Church A was built of brick in 1882 and made extensions to the church in 1891 and 1902. The ceiling of the central nave is plastered and bowed. Church B was built of ferroconcrete in 1915. The ceiling of the central nave is timber structure and bended up. Church C was built of steel-reinforced concrete in 1959. The ceiling of the central nave is vaulted. Church D was built of ferroconcrete in 2008. The shape is like a fan.

EXPERIMENTAL METHODS

The binaural impulse responses were measured in each church. The sound source was a directional loudspeaker (1029A, Genelec) and located at the approximate height of the mouth of a standing person, which is 1.5 m from the floor. The receiver was a dummy head with binaural microphones (KU-100, Neumann). The microphone was located at the approximate height of the head of a seated person, which is 1.2 m from the floor. A sinusoidal signal with an exponentially-varying frequency sweeping from 40 Hz to 20 kHz over a period of 18 s was radiated from the loudspeaker and recorded by the PC at a sampling rate of 48 kHz and a sampling resolution of 32 bits through the microphone and an AD/DA converter (AudioFire8, Echo Digital Audio).

The source and receiver positions for measurements are shown in Fig. 1. The position of source 1 (S1) was in the centre of the chancel. The position of source 2 (S2) was in front of the pulpit. The position of source 3 (S3) was also in front of the other pulpit, it only exists in Church C. Regarding the S1, the directions of the loudspeaker were taken in accordance with Catholic liturgy before and after the Second

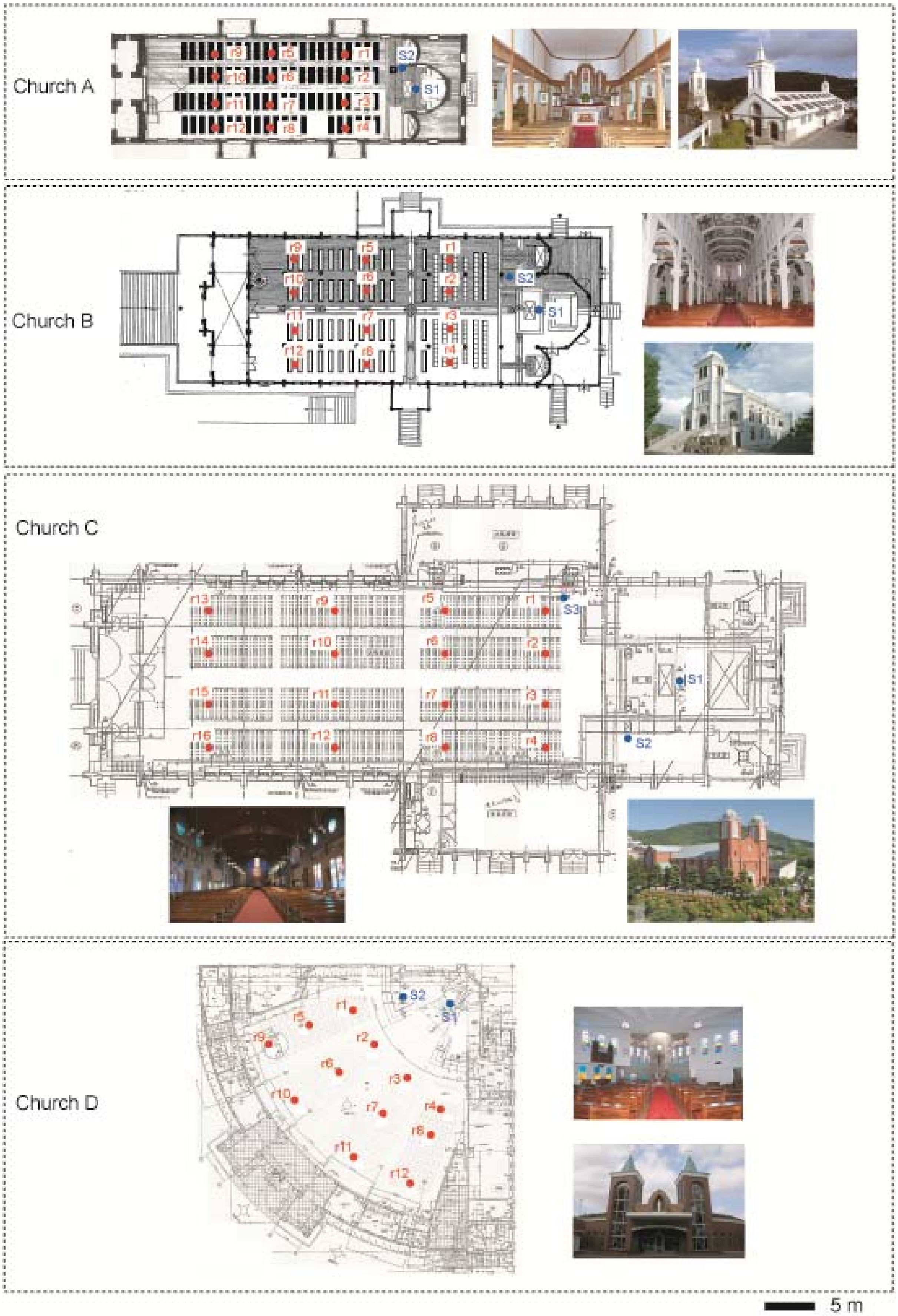

Figure 1. Ground plan with the source (S) and receiver positions (r1-r16) and pictures for four churches (same scale for all churches).

Vatican Council: the loudspeaker (priest) was facing the alter and with his back to the congregation (D1) and the loudspeaker (priest) was facing the congregation and not with his back to the congregation (D2). The loudspeaker at the S2 and S3 was always facing the congregation. The receiver was placed in a grid pattern and the number was from 12 to 16. It was num-bered in order from left to right and front to back. The re-ceiver was always aimed at the sound source.

Four acoustical parameters, listening level (LL), initial time delay gap between the direct sound and the first reflection (ITDG), reverberation time (RT), and magnitude of the interaural cross-correlation function (IACC) were calculated from the binaural impulse response. Relative LL was calculated with reference to the sound pressure that would be measured at a distance of 10 m from the same sound source in a free sound field, which is corresponding to an acoustical parameters, strength (G) (ISO 3382). The ITDG was defined as the time interval between the direct sound and the first reflection with the maximum amplitude arriving at the ears excluding reflections from the floor (Sakai et al., 2004). RT was obtained by the regression of the decay curve from a level 5 dB below the initial level to 35 dB below. IACC is defined as the maximum absolute value of the interaural cross-correlation function of the binaural impulse responses within the possible maximum interaural delay range (1 ms). LL, RT, and IACC are values obtained as values at 1/1 octave band centre frequency between 125 Hz and 4 kHz. A-weighted LL is also obtained.

RESULTS

LL

Figure 2 shows relative LL as a function of frequency in each church. The results clearly indicated LL for S1D1 (the sound source is located in the centre of chancel and facing toward the alter) was smaller than that for S1D2 (the sound source is located in the centre of chancel and facing toward the congregations) in the frequency of more than 500 Hz. LL for S2 and S3 (the sound source is located in front of the pulpit) was nearly identical to that for S1D2.

Figure 3 shows A-weighted relative LL as a function of the source-receiver distance. The results indicated the values of LL for S1D1 were smaller than those for S1D2 regardless of the source-receiver distance. The values of LL for S2 and S3 were intermediate between those for S1D1 and S1D2.

ITDG

Figure 4 shows ITDG at each receiver position for each source in each church. The values of ITDG for S1D1 were more than 30 ms and the values of ITDG for S1D2 and S2 were approximately between 5 and 30 ms in church A, B and C. In church D, the values for ITDG were approximately 20 ms at the most of the receiver positions However, the values for ITDG decreased with increasing source-receiver distance at some receiver positions for S1D2 and S2.

RT

The differences of RT values between receiver positions were small. Figure 5 shows averaged RT values for all receiver positions in each church. The frequency characteristics were different among churches. In church A, the differences between frequency bands were relatively small. In church B, RT in the frequency of 4000 Hz was shorter than that in other frequencies. In church C, RT in the middle frequencies (500 and 1000 Hz) was longer than that in lower and higher frequencies. In church D, RT in the frequency of 4000 Hz was the shortest and that in the frequency of 250 and 500 Hz was shorter than that in other frequencies.

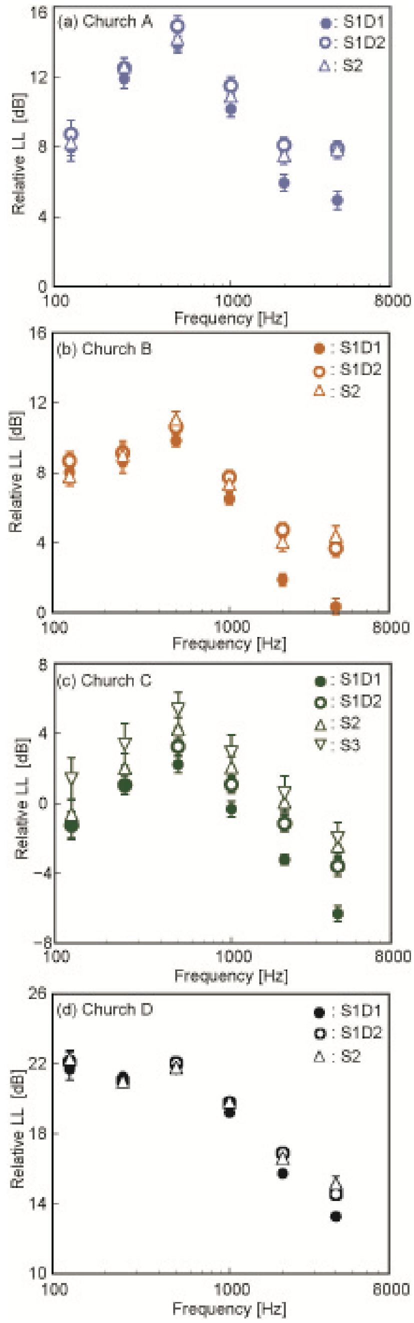

Figure 2. Measured relative LL as a function of frequency in each church.

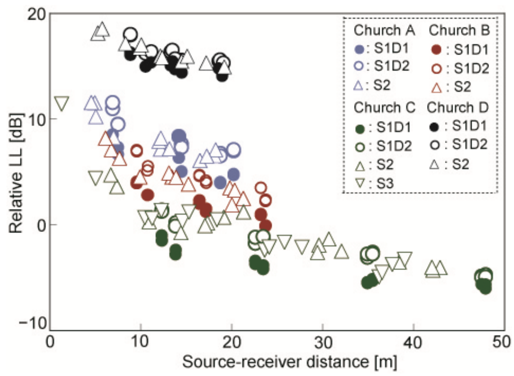

Figure 3. Measured relative LL (A-weighted) as a function the source-receiver distances.

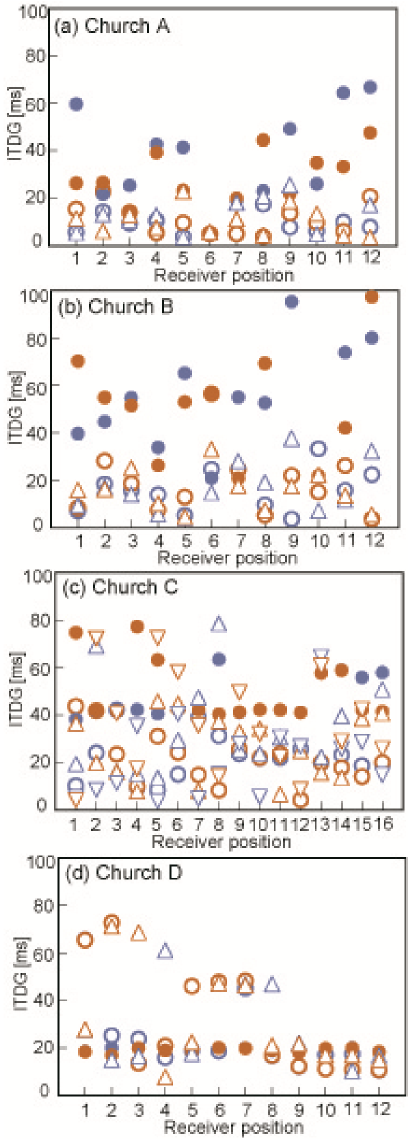

Figure 4. Measured ITDG at each receiver position for S1D1 at left (●) and right ear (●), S1D2 at left (○) and right ear (○), S2 at left (△) and right ear (△), and S3 at left (▽) and right ear (▽) in each church at each.

IACC

The direction of the sound source has clear effect on IACC. Figure 6 shows IACC values for receiver positions of r2 (frontal position) and r8 (middle position) in each church. The values of IACC for S1D1 were lower than those for S1D2, S2, and S3 in higher frequencies (2000 and 4000 Hz) especially at frontal positions.

Each church has the pulpit in own position. Then, the values of IACC for S2 showed different tendencies among churches.

DISCUSSION

The LL values for the old style of the Catholic liturgy (S1D1: priest is facing the alter) is 1-3 dB smaller than those for the new style of the Catholic liturgy (S1D2: a priest is facing the congregations). This might mean that new style of the Catholic liturgy is beneficial for the congregations who seated at the back. When the sound source faces the congregation, the effects of the location of the source on LL are small. The LL values for S1D2 are nearly identical to those for S2 and S3 (a priest is in front of the pulpit).

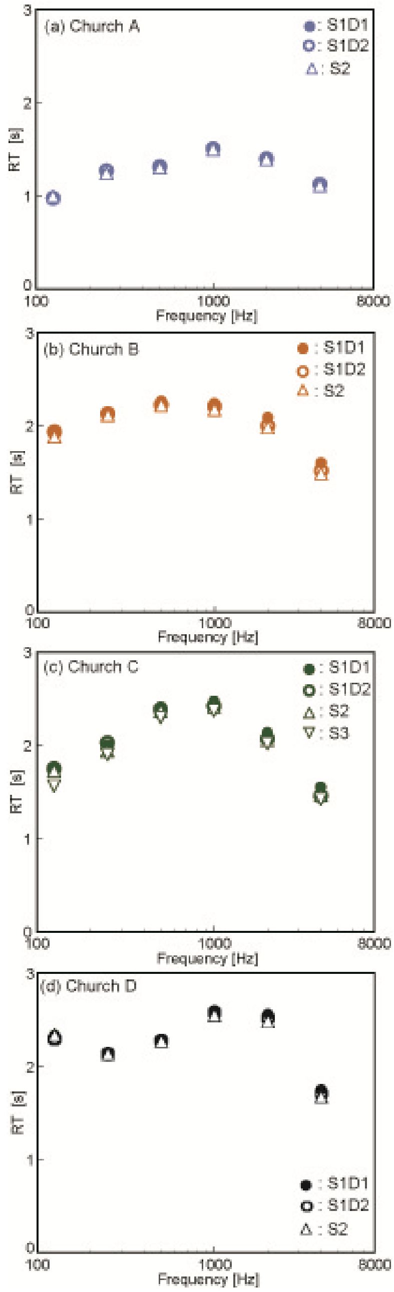

Figure 5. Averaged RT values for all receiver positions in each church.

The largest LL values are observed in Church D and the smallest values are observed in Church C. The measured LL values correspond to the G (ISO 3382), although we used the directional loudspeaker not the omni-directional loudspeaker. Then, our results can compare with those of other churches. LL in Apulian-Romanesque (Cirillo and Martellotta, 2002) and Mudejar-Gothic churches (Galindo et al., 2005) are smaller than LL in Church D and is nearly equal to LL in Church A and B. In addition, LL in Church A is almost equal to LL in Japanese small temple (Ito et al., 2009). LL in Church C is much smaller than LL in other churches because of the interior materials.

The ITDG values for the old style of the Catholic liturgy (S1D1) are longer than those for the new style of the Catholic liturgy (S1D2) except for Church D. The values of ITDG for the new style of the Catholic liturgy are approximately between 5 and 30 ms in church A, B and C. The most preferred ITDG, $[\text{ITDG}]_p$, can be predicted by the effective duration of the autocorrelation function of the sound source, τ_e, and the amplitude of reflection, A_1 ($[ITDG]_p \approx (1 - \log_{10} A_1)\,\tau_e$). The τ_e values for speech are approximately 5-30 ms (Ando, 2007). These suggest that new style of the Catholic liturgy improves the ITDG in terms of subjective preference for speech.

There is little effect of source position and direction on RT. The frequency characteristic of RT is different in each church. The averaged values of RT over 500 and 1000 Hz are about 2.2 s in Church B, C, and D. In Mudejar-Gothic churches (Galindo et al., 2005), there are two groups of RT. One has longer RT, which is longer than 3.0 s. The RT of another one is approximately 2 s, which is close to that in Church B, C, and D. In most of the Apulian-Romanesque churches (Cirillo and Martellotta, 2002), the RT is longer than 3.0 s, which is quite longer than that in Church B, C, and D.

The IACC values for the old style of the Catholic liturgy are lower than those for the new style of the Catholic liturgy at frontal seats. Lower IACC is preferred (Ando, 1998) and induces more diffused sound image (Ando and Kurihara, 1985) or larger apparent source width (Ando et al., 1999; Sato and Ando, 2002). These suggest that new style of the Catholic liturgy lessens subjective preference for a sound field in the church.

CONCLUSIONS

The effects of location and direction of sound source on acoustical parameters in churches were investigated. It is noteworthy that IACC at frontal seats increases when the sound source faces the congregation, that is, in the new style of the Catholic liturgy. This suggests that the change of the Catholic liturgy made worse the acoustical characteristics, so that acoustic improvements, particularly in the frontal part of the church, are recommended.

REFERENCES

Y. Ando and Y. Kurihara, "Nonlinear response in evaluating the subjective diffuseness of sound field" *J. Acoust. Soc. Am*. **80**, 833–836 (1985).

Y. Ando, *Architectural Acoustics*, (Springer, New York, 1998) pp. 105–108.

Y. Ando, S. Sato and H. Sakai, "Fundamental subjective attributes of sound fields based on the model of auditory-brain system." in *Computational acoustics in architecture*. ed. J.J. Sendra, (WIT Press, Southampton, 1999) pp. 63–99.

Y. Ando, "Concert hall acoustics based on subjective preference theory" in *Springer Handbook of Acoustics*. ed. T.D. Rossing, (Springer, New York, 2007) pp. 351–385.

E. Cirillo and F. Martellotta, "Acoustics of Apulian-Romanesque churches: an experimental survey" *Build. Acoust.* **9**, 271–288 (2002).

M. Galindo, T. Zamarreño and S. Girón S, "Acoustic analysis in Mudejar-Gothic churches: experimental results" *J. Acoust. Soc. Am*. **117**, 2873–2888 (2005).

K. Ito, R. Shimokura, Y. Soeta, T. Ohsawa, S. Sato and Y. Ando, "Broken symmetry of spatial and temporal design in Japanese temple" *J. Temporal Des. Arch. Environ.* **9**, 47-50 (2009).

International Organization for Standardization ISO 3382, Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters, 1997.

A. Magrini and P. Ricciardi P, "Churches as auditoria: analysis of acoustical parameters for a better understanding of sound quality" *Build. Acoust.* **10**, 135–158 (2003).

H. Sakai, S. Sato and N. Prodi, "Orthogonal factors for the stage and pit inside a historical opera house" *Acustaica/Acta Acustica* **90**, 319–334 (2004).

J.J. Sendra, T. Zamarreno and J. Navarro, "Acoustics in churches" in *Computational acoustics in architecture*. ed. J.J. Sendra, (WIT Press, Southampton, 1999) pp. 133–165.

S. Sato and Y. Ando, "Apparent source width (ASW) of complex noises in relation to the interaural cross-correlation function" *J. Temporal Des. Arch. Environ.* **2**, 29-32 (2002).

T. Zamarreño, S. Giróna and M. Galindoa, "Assessing the intelligibility of speech and singing in Mudejar-Gothic churches" *Appl. Acoust.* 69, 242-254, 2008.

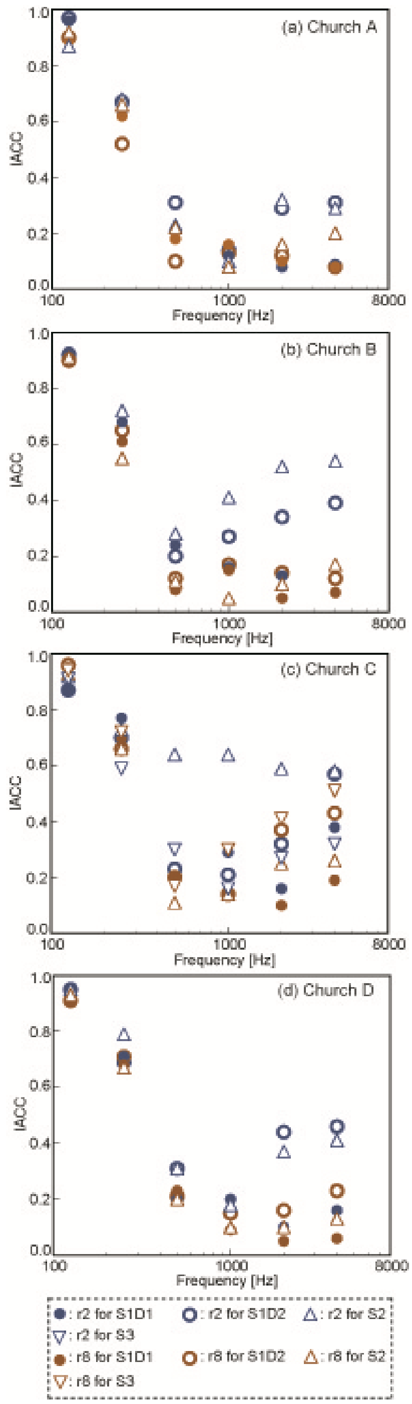

Figure 6. Measured IACC values at receiver positions of r2 and r8 in each church.