A preliminary investigation on the sound field properties in the Sagrada Familia Basilica

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ABSTRACT

This paper reports on a preliminary investigation of the sound field properties inside a large Roman Catholic Church in Barcelona, the Sagrada Familia Basilica, which is a World Heritage Site although its construction has not been completed. The impulse responses were measured at 5 sound source positions combined with 14 measurement locations inside the Sagrada Familia Basilica, and the Impulse response to Noise Ratios (INR) were examined to check the reliability of the measured impulse responses. The room acoustic parameters were calculated and the following 5 sound field properties in the Sagrada Familia Basilica were analysed: reverberation, spaciousness, loudness, warmth and clarity. No optimal values of room acoustic parameters for such large volume churches have been found in the literature; thus, the preferred values of the reverberation time (T20) and the Early Decay Time (EDT) for small volume churches, and the preferred values of the middle frequency strength of sound (G_{mid}), the low frequency strength of sound (G_{125}), the clarity (C_{80}) and the binaural quality index ($1 - \mathrm{IACC}_E$) for concert halls were compared with the measurement results to illustrate a primary impression of the listening experience in the Sagrada Familia Basilica. The reverberation time (T20) and the EDT in the Sagrada Familia Basilica are much higher than the preferred values, while the middle frequency strength of sound (G_{mid}), the low frequency strength of sound (G_{125}) and the clarity (C_{80}) are less than the preferred values. The binaural quality index ($1 - \mathrm{IACC}_E$) is just above the typical satisfactory value.

1. INTRODUCTION

Scientific studies on the acoustics of churches were not conducted until the mid-1900s, and a general goal of church acoustics is to design an enclosed environment with good or suitable acoustical qualities for the functions that are expected in that particular space (Carvalho, 1994). However, a question arises with the characterization of good acoustical quality inside churches, because church acoustics generally represent a compromise between music and speech.

To evaluate the acoustical quality inside enclosed spaces, many objective acoustic parameters have been adopted, primarily classified into three categories. The first category is the monaural energy based parameters such as Reverberation Time (RT), Early Decay Time (EDT), Clarity (C_{80}), Definition (D_{50}), Center Time (T_s), etc. (ISO, 2009). The second category is the Inter-Aural Cross Correlation (IACC) coefficients, which are usually used to measure the spaciousness or the apparent source width (ISO, 2009; Lee, 2003). The last category of objective acoustic parameters describes speech intelligibility such as the Articulation Loss of Consonants ($\mathrm{ALC}_{\mathrm{ons}}$), and the Speech Transmission Index (STI) (Gonzalez, 2009; IEC, 2011). Lokki suggested that the current parameters are inadequate since they are averaged over listener positions and use only mid frequencies, and proposed a loudspeaker array with 34 loudspeakers placed on the stage to simulate the orchestra (Lokki, 2013). This approach can give more information than the traditional approach that uses only one omnidirectional loudspeaker as the sound source. However, it is expensive and inconvenient to perform such measurements with so many loudspeakers. Thus the measurement procedure of ISO 3382-1 is followed in this paper. The typical range of the monaural energy based parameters has been recommended in the ISO standard for concert and multi-purpose halls (ISO 3382-1, 2009). However, there is still great disagreement on the optimal value for churches, which generally represent a compromise between music that requires longer reverberation time and speech that requires shorter reverberation time (Everest and Pohlmann, 2009).

Each of the objective acoustic parameters can describe only one aspect of the acoustic conditions in a church: a global index is desired to assess the overall acoustical quality of churches. The weighted average of several individual indices has been proposed based on the aforementioned acoustic parameters (Engel and Kosala, 2007). Unfortunately, the same value for the global index can be obtained for churches with acoustical conditions optimal for music and negative for speech, or vice versa (Berardi, 2012). Hence, a double index that can be adapted to the musical perception and speech intelligibility has been formulated and shown to adhere well with subjective preferences (Berardi, 2012). The double synthetic index was calculated from seven room acoustic parameters; however, the method used to choose the optimal value is still not clear because some of the optimal values are from concert hall studies rather than from studies for churches (Berardi, 2012). To date, the optimal values of these parameters are still not known for churches because of little subjective research compared to concert halls.

Although the objective parameters have shown reasonable performance in assessing the acoustical quality of churches, subjective tests are the final assessment criteria and should be used to improve the knowledge of the complex relationships between geometry, acoustics, and perception preferences (Carvlho & Silva, 2010). The difficulty in performing subjective tests is that a statistically significant number of participants need to be involved in the tests.

To investigate the sound quality inside churches, Carvalho et al. (1996) employed 15 participants to listen to live music and complete a subjective survey in 36 Roman Catholic churches in Portugal, whose volumes range from 299 m^3 to 18,674 m^3. An acoustical evaluation questionnaire was used to measure listeners' overall impression of room acoustical qualities and factors that can contribute to perception such as loudness, reverberance, intimacy, envelopment, directionality, balance, clarity, echoes and background noise (Carvalho et al., 1996). It has been found that for the Roman Catholic churches with EDT ranging from 2 s to 8 s, the overall impression of the sound quality inside the churches primarily depends on the EDT (averaging 500 and 1000 Hz) and the overall impression decreases with increasing EDT (Carvalho et al., 1997). It is noteworthy that the volumes of the investigated churches in this research were between 299 m^3 and 18674 m^3, and whether the conclusions can be applied for the churches with larger or smaller volume remains unclear.

A more recent subjective test was conducted by Martellotta (2008), who convolved five anechoic motifs with binaural impulse responses measured in over 10 Italian Catholic churches with volumes that ranged from 5,500 m^3 to 39,000 m^3. The convolved signal was reproduced in a listening room and 143 participants performed the listening tests, using the paired comparison method between for every signal pair. From the factor analysis results, the subjective preference was found to mostly depend on the average EDT from 125 Hz to 4000 Hz (Martellotta, 2008). The subjective rating of the choral music and organ music decayed with increased EDT, in accordance with the conclusions by Carvalho et al. (1997). The subjective rating of the Gregorian chant also decreased with EDT, except at 2 s, which was lower than the subjective rating at 3 s. Although Carvalho (1994) and Martellotta (2008) utilized different experimental schemes and obtained different regression analysis results, similar overall trends of the subjective rating varying with EDT were observed. It is noteworthy that the EDT used by Carvalho (1994) is averaged from 500 Hz to 1000 Hz while the EDT used by Martellotta is averaged from 125 Hz to 4000 Hz.

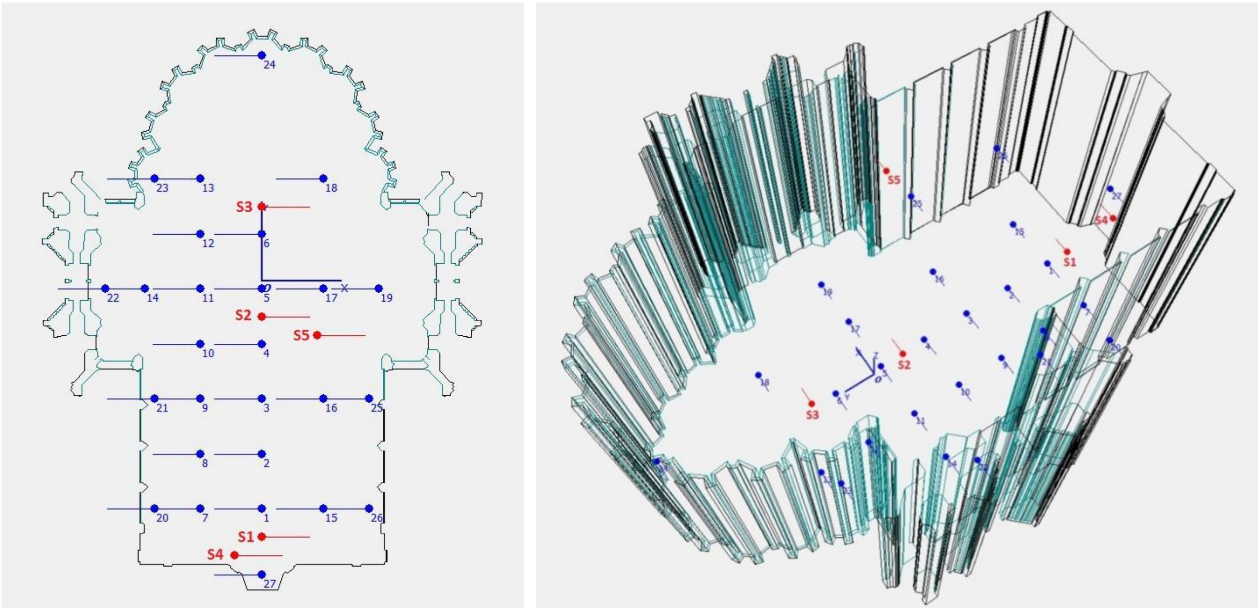
In summary, the acoustical quality inside churches should be evaluated with a single acoustic parameter for each aspect of the sound field and with a synthetic parameter for the overall impression of the acoustical quality. The recommended reverberation time for churches with volumes from approximately 270 m^3 (10,000 ft^3) to 27,000 m^3 (1,000,000 ft^3) is between 0.9 s and 3.5 s (Everest & Pohlmann, 2009). The subjective research shows the overall impression of the acoustical quality inside churches to depend mainly on the EDT, and the optimal EDT for churches with volumes from 5,500 m^3 to 39,000 m^3 is from 2.1 s to 4.2 s (Martellotta, 2008). The Sagrada Familia Basilica investigated in this paper is a large Roman Catholic Church in Barcelona, Spain, with a size of approximately 95 m × 62 m × 45 m and a volume of approximately 200,000 m^3, which is much larger than the churches in previous studies. This paper reports on a preliminary investigation of the sound field properties inside the Sagrada Familia Basilica. The impulse responses were measured at five sound source positions combined with 14 measurement locations, and the room acoustic parameters were calculated and the following five sound field properties in the Sagrada Familia Basilica were analysed: reverberation, spaciousness, loudness, warmth and clarity. The preferred values of objective room acoustic parameters for small volume churches and concert halls in the literature are presented together with the measurement results to illustrate a primary listening experience in the Sagrada Familia Basilica.

2. MEASUREMENT SETUP AND PROCEDURES

The exponential sweep signal was generated by a B&K DIRAC Room Acoustic Software Type 7841 installed on a Personal Computer (PC). A B&K USB Audio Interface ZE-0948 was used to transfer the signal to a B&K OmniPower™ Sound Source Type 4292-L via a B&K Power Amplifier Type 2734B, which was remotely controlled by an AKG WMS 470 wireless Transmitter and Receiver. The two-channel signal was measured with a G.R.A.S Kemar Manikin Type 45BA. The left ear signal was recorded by a G.R.A.S. ½'' Pressure Microphone Type 40AG with a G.R.A.S. ¼'' Pre-amplifier Type 26AC, and transmitted to the USB interface through the first channel of a G.R.A.S. Power Module Type

12AA. The right ear signal was recorded by a G.R.A.S. ½'' Pressure Microphone Type 40AG with a G.R.A.S. ¼'' Pre-amplifier Type 26AC, and transmitted to the USB interface through the second channel of the G.R.A.S. Power Module Type 12AA. The system for the left ear was calibrated at 94.0 dB at 1000 Hz with a B&K Sound Calibrator Type 4231, and the right ear was examined after the calibration with the B&K Sound Calibrator Type 4231. The deviation between the left ear and the right ear was within 1.0 dB.

The impulse responses were measured at five sound source positions. The sound source positions and measurement positions are shown in Figure 1 as red and blue points, respectively. The sound source positions S1 ~ S3 and measurement locations M1 ~ M19 were at ground level, S4 and M20 ~ M27 were on the Cantonia level which is about 17 m above the ground level, and S5 was on the top of one column which is about 45 m above the ground level. For the measurements at ground level (M1 ~ M19), the Kemar Manikin was oriented to face the front direction of the Sagrada Familia Basilica, whereas for the measurements on the Cantonia level, the Kemar Manikin was placed on a seat and oriented to face the front direction of the audience area. For the sound source positions S1 ~ S3, the impulse responses were measured only on the left side of the church (M1 ~ M14), using the symmetrical geometry of the Sagrada Familia Basilica. For the sound source positions S4 and S5, the impulse responses were measured both at ground level and on the Cantonia level. The specific measurement locations for each sound source position are summarized in Table 1.



(a) (b)

Figure 1: (a) Top view and (b) full view of the sound source positions (red points) and the measurement locations (blue points). The measurement locations M1 to M19 are at ground level and M20 to M27 are on the Cantonia level, which are about 17 m above the ground level.

Table 1: Measurement locations corresponding to each sound source position

Sound Source Positions	Measurement Locations
S1	M1 ~ M14
S2	M1 ~ M14
S3	M1 ~ M14
S4	M5, M7, M9, M11, M13, M15 ~ M18, M20 ~ M24
S5	M5, M7, M9, M11, M13 ~ M27

The sound source positions and the measurement locations were marked with labels before the measurements were conducted. For the measurements, the Kemar Manikin was placed on a trolley at the measurement location. The impulse response was measured with a 23.8 s exponential sweep signal and pre-averaged three times for each measurement, and stored as .wav files annotated with information specific information to the DIRAC software. After each measurement, the Kemar Manikin was moved to the next measurement location on the trolley, and the procedures were repeated at each location. The impulse responses for sound source positions S1 ~ S4 were measured on the 3rd December 2015, and for sound source position S5 the impulse responses were measured on the 4th December 2015.

3. RESULTS AND DISCUSSIONS

3.1 Impulse responses

Two typical impulse responses, measured at the measurement location M1 and M13 corresponding to the sound source positions S1 (S1M1 and S1M13), are shown in Figure 2. The measurement locations M1 were close to the sound source positions S1; thus, the impulse response S1M1 shown in Figure 2(a) consists of the direct sound, strong reflection and reverberation sound. In contrast, the measurement location M13 was distant to the sound source position, so the impulse response S1M13 shown in Figure 2(b) is dominated by the reverberation sound. It is noteworthy that the vertical axis in Figure 2(b) has been magnified for clarity.

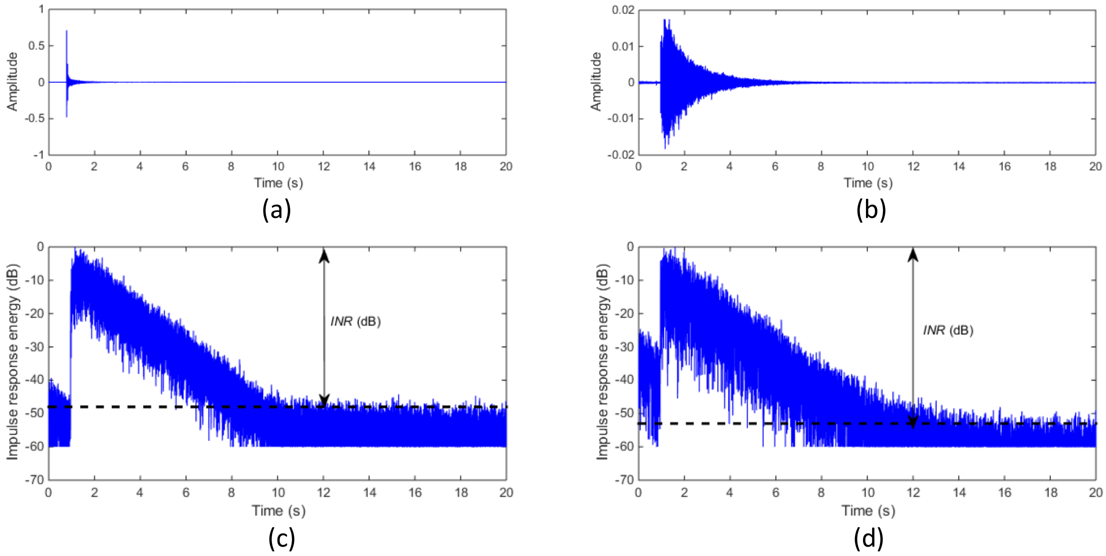


Figure 2: The impulse responses measured in the left ear at (a) M1 and (b) M13 corresponding to the sound source position S1, and the illustration of the Energy Time Curve (ETC) and Impulse response to Noise Ratio (INR) for the impulse responses at (c) M1 and (d) M13.

According to ISO 3382-1 (2009), if the impulse response is measured directly using an impulse source such as a pistol shot, the impulse source shall be able to produce a peak sound pressure level sufficient to ensure a decay curve starting at least 35 dB above the background noise in the corresponding frequency band to derive T20. However, if special sound signals such as an exponential sine signal are used to yield the impulse response after special processing of the recorded microphone signal according to ISO 18233, the signal-to-noise ratio can be improved. Because of the improvement in signal-to-noise ratio, the dynamic requirements on the source can be considerably lower than 35 dB for the measurement of T20 (ISO, 2009).

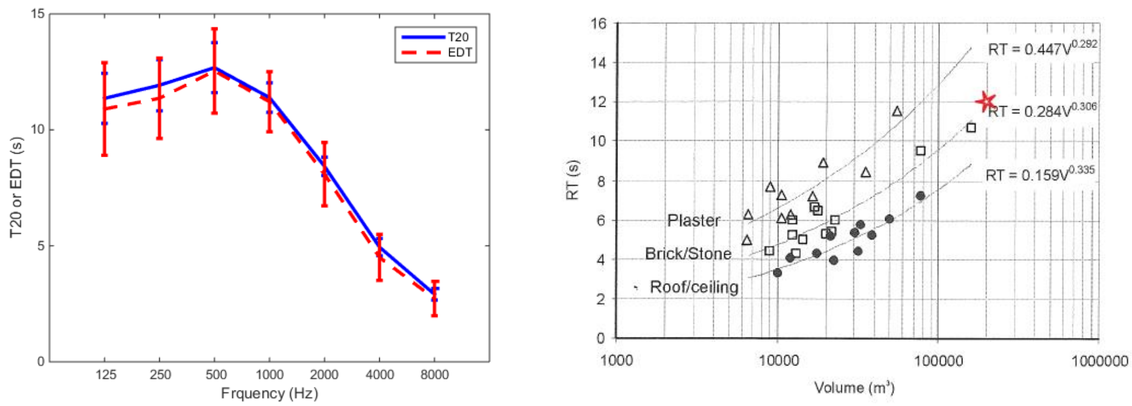
The B&K DIRAC Room Acoustic Software Type 7841 is compliant with both ISO 3382 and ISO 18233. Therefore, the dynamic range can be lower than 35 dB to obtain the reverberation time T20. However, ISO 3382-1 does not provide any specific dynamic range requirements for this kind of measurement. In addition, no definition of the “decay range” is given in ISO 3382. Therefore, Hak et al. (2008) proposed the use of the Impulse response to Noise Ratio (INR) as an estimator for the decay range of the room acoustic impulse response. The INR is defined as INR = (L_{IR} – L_N), where L_{IR} is the maximum RMS level in dB of the impulse response and L_N is the noise level in dB. Figures 2(c) and (d) show the INRs for the corresponding impulse responses in Figures 2(a) and (b), respectively. To estimate the decay range at different frequencies, the impulse responses can be filtered with a band pass filter that is compliant with ISO 61260 (2014). The impulse responses and the ETC in octave frequency bands were exported from the B&K DIRAC Room Acoustic Software Type 7841, which is compliant with ISO 61260 (2014).

The INR in each octave frequency band for the impulse responses measured in the Sagrada Familia Basilica are calculated by the B&K DIRAC Room Acoustic Software Type 7841. The results showed that in octave frequency bands above 125 Hz, the INRs are higher than 35 dB at all the measurement locations corresponding to the sound source positions S1, S3, and S4. For the sound source position S2, most of the INRs are above 35 dB except those measured at the M4 measurement location at 125 Hz and 250 Hz. For the sound source position S5, at 125 Hz the INRs are below 35 dB at four of the 19 measurement locations, i.e., 33 dB at M20 and M21, 34 dB at M25, and 32 dB at M26; at 250 Hz, the INRs are lower than 35 dB at five of the 19 measurement locations, i.e., 34 dB at M5, M9, M15 and M25, and 33 dB at M7; from 500 Hz to 2000 Hz, the INRs are above 35 dB at all the measurement locations except at M20, which is 31 dB at 500 Hz and 1000 Hz, and 32 dB at 2000 Hz; at 4000 Hz, the INRs are higher than 35 dB at all the measurement locations; at 8000 Hz, the INRs are below 35 dB at two of the 19 measurement locations, i.e., 33 dB at M20 and 34 dB at M26.

Most of the measurement locations where the INR is lower than 35 dB correspond to the S5 sound source position, probably because the sound source position S5 was located at the top of the Sagrada Familia Basilica and far away from the measurement locations. However, it can also be seen that the smallest INR at all the measurement locations at all octave frequency bands above 125 Hz is 31 dB, which is just below the threshold 35 dB specified by ISO 3382-1 (2009). Considering that the impulse responses were measured with the exponential sweep signal by the DIRAC software in compliance with ISO 18233 (2008), and that the dynamic requirements can be "considerably lower" than 35 dB to obtain T20, the INRs above 31 dB are considered acceptable. The following room acoustic parameters calculated from the measured impulse responses should therefore be reliable.

3.2 Reverberation

The average Reverberation Time (T20) in the Sagrada Familia Basilica is shown in Figure 3(a), where it can be seen that T20 is the longest at 500 Hz and decreases dramatically with frequency above 500 Hz, and the variation of T20 at lower frequencies (< 1000 Hz) is much larger than for higher frequencies (> 2000 Hz). The vertical bars in Figure 3(a) indicate the standard deviation of the measurement results at different measurement locations. The middle frequency reverberation time averaged from 500 Hz to 1000 Hz is 12.0 s, which is in good agreement with previous studies of the reverberation time in churches built from brick and stone and of a similar size to the Sagrada Familia Basilica; this is shown in Figure 3(b), where the red star indicates T20 as measured in the Sagrada Familia Basilica (Cirillo and Martellotta, 2006).



(a) (b)

Figure 3: (a) The average Reverberation Time (T20) and Early Decay Time (EDT) in the Sagrada Familia Basilica, and (b) the middle frequency reverberation time as a function of the room volume (Cirillo and Martellotta, 2006). The vertical bars in Figure 3(a) indicate the standard deviation of the measurement results at different measurement locations.

The reverberation time (T20) averaged from 125 Hz to 8000 Hz is 9.1 s; there is no optimal reverberation time for such a large volume church as the Sagrada Familica Basilica (approximately 200,000 m^3) in the literature at present. For liturgical churches and cathedrals with a volume of approximately 270 m^3 to 27,000 m^3, Everest and Pohlmann (2009) recommends the reverberation time between 2 s and 3.5 s, which is already quite reverberant. It is noteworthy that the preferred reverberation time should increase with the volume (Everest and Pohlmann, 2009), so these preferred values of reverberation time for small volume churches should not be directly used to assess the sound quality in the Sagrada Familica Basilica.

Recent research on the subjective evaluation of church acoustics showed that the subjective perception of the reverberance and the overall impression of the acoustical quality in churches to be more related to EDT (Martellota, 2008). The average EDT in the Sagrada Familia Basilica is also shown in Figure 3(a), which illustrates that the average EDT exhibits a similar trend to T20. However, the variations of EDT are larger than for T20 across all the frequency bands. The EDT averaged from 500 Hz to 1000 Hz and from 125 Hz to 4000 Hz are 12.6 s and 11.9 s respectively. The preferred value of EDT for churches with volumes from 5,500 m^3 to 39,000 m^3 is about 4.2 s from subjective test (Martellotta, 2008). It remains unclear whether these preferred values for small churches can be applied to evaluate churches of such large a volume as the Sagrada Familia Basilica, and whether the subjectively preferred listening conditions in churches are relevant to the volume.

3.3 Spaciousness

Spaciousness is one of the key characteristics perceived in a listening space. The possible subjective importance of early lateral reflections on the spaciousness was first proposed by Keet (1968) and it was shown that the early Inter-Aural Cross Correlation coefficient ($IACC_E$) is particularly effective in rating the spaciousness of a concert hall (Beranek, 2004). Therefore, the $IACC_E$ was chosen to assess the spaciousness in this paper. The $IACC_E$ are often averaged in the three octave frequency bands from 500 Hz to 2000 Hz, where the wavelengths are comparable or smaller than the acoustical distance between the two sides of a head (Okano et al., 1998). However, the index (1 – $IACC_E$) is more frequently used in the literature such that the index is zero for the case of no lateral reflections, namely, only the direct sound exists. Beranek (2004) demonstrated that in a typical satisfactory concert hall, the value (1 – $IACC_E$) was above 0.5 and in the highest-rated concert halls the value was above 0.6, indicating that in very good halls the similarity of the sounds at the two ears is surprisingly low. No optimal values for churches have been found in the literature.

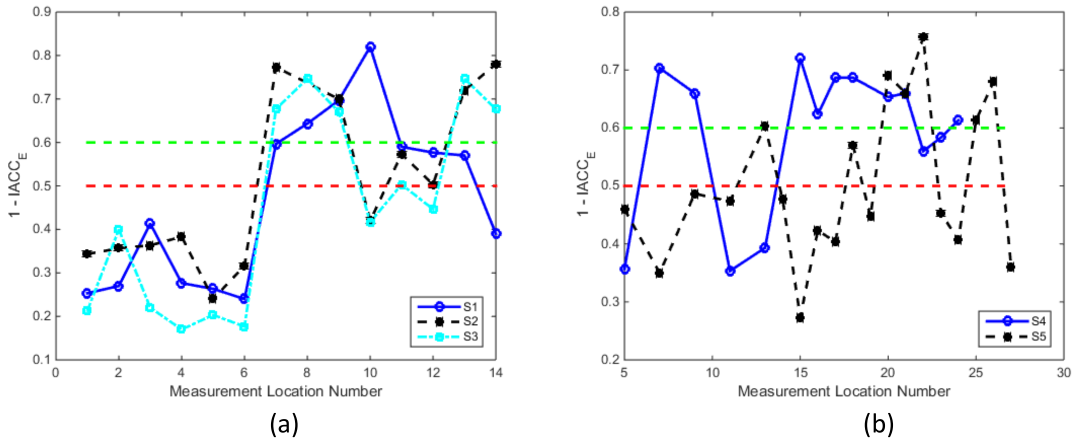


Figure 4: The middle frequency (500 Hz to 2000 Hz) index (1 – $IACC_E$) at the measurement locations corresponding to the sound source positions (a) S1, S2 and S3, and (b) S4 and S5. The red and green dashed lines indicate the values for typical satisfactory and the highest-rated concert halls.

The measurement results of (1 – $IACC_E$) in the Sagrada Familica Basilica are shown in Figure 4, from which It can be seen that all the values at the measurement locations M1 to M6 corresponding to the sound source positions S1 to S3 are lower than that at the measurement locations M7 to M14. This may potentially be due to these measurement locations and the sound source positions being all on the center line of the Sagrada Familia Basilica, thus leading to the high similarity of the sounds at the two ears. In terms of the sound source position S4, the values at most of the measurement locations are quite large, except at M5, M11, and M12, which are 0.35, 0.36 and 0.39, respectively. The preferred values of (1 – $IACC_E$) for the typical satisfactory and highest-rated concert halls are denoted by red and green dashed lines in Figure 4 for reference. The average value over all the measurement locations corresponding to all the sound source positions is 0.51, just above the typical satisfactory value, indicating a satisfactory spaciousness quality.

3.4 Loudness

Loudness refers to the subjective perception of the volume or force of a sound at one's ear (Beranek, 2004). Loudness is closely related to the parameter "Strength of Sound" *G,* which is defined as the ratio of the sound energy that emanates from a non-directive source measured at a seat, relative to the sound energy from the same sourced measured in a free field at 10 m (Beranek, 2011). If the strength of sound increases or decreases by approximately 10 dB, the loudness heard is doubled or halved, respectively (Beranek, 2004). No optimal values have been found for the strength of sound in churches.

The measured middle frequency strength of sound is shown in Figure 5, where the preferred range (4 dB ~ 7.5 dB, Beranek, 2011) for concert halls is denoted by the red and green dashed lines for reference. It is clear that the sound source positions have an impact on the sound strength at the same measurement location. In addition, the strength of sound fluctuates dramatically with the measurement locations, and values at the measurement locations near the sound source are much higher than those far from the sound source. For the sound source positions S1 and S4, the strength of sound at three of the 14 measurement locations is within the preferred range. For the sound source position S2, the strength of sound at only one of the 13 measurement locations is within the preferred range. For the sound source position S3, the strength of sound at seven of the 14 measurement locations are within the preferred range. For the sound source position S5, the strength of sound at all 19 measurement locations are much lower than the preferred range. This may be because the sound source position S5 is located on the roof; therefore, there is no direct sound to the measurement location. The average strength of sound over all the measurement locations corresponding to all the sound source positions is 2.4 dB, which is less than the lower limit of the preferred range. It is noteworthy that the comparison with preferred values of *G* for concert halls is to show a primary listening experience in the Sagrada Familia Basilica, rather than to judge the sound quality which will need subjective tests in the future.

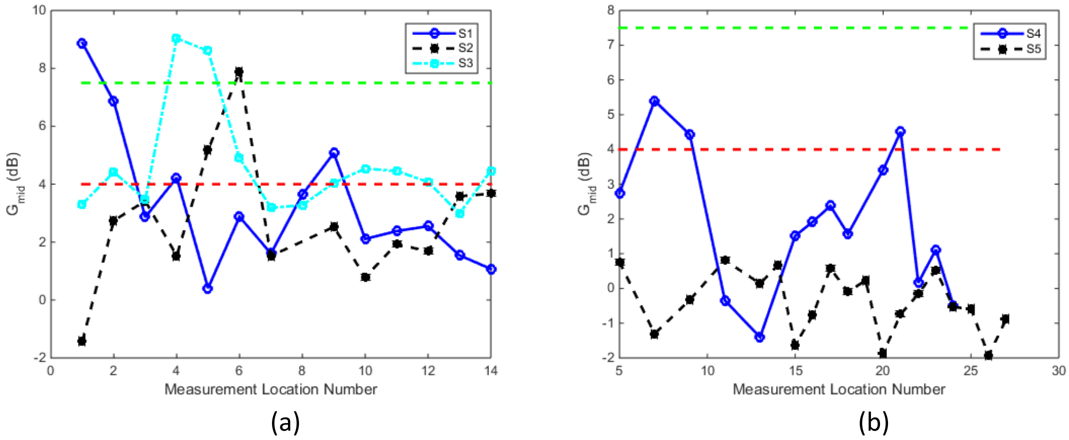
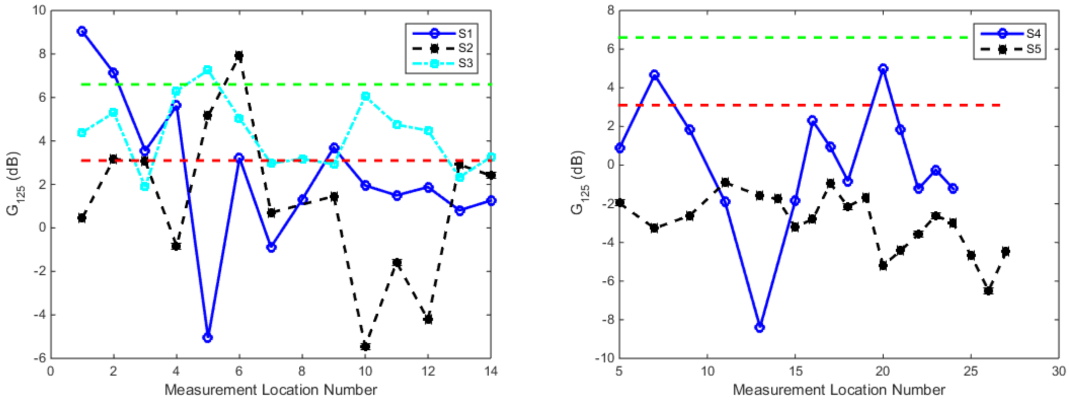


Figure 5: The measured middle frequency (500 Hz to 1000 Hz) Strength of Sound (G_{mid}) at each measurement location corresponding to sound source positions (a) S1, S2, and S3, and (b) S4 and S5. The red and green dashed lines indicate the optimal range for the concert halls.

3.5 Warmth

Warmth is the subjective description of the fullness of bass tones, which is generally considered a hallmark of good concert hall acoustics (Beranek, 2004). Beranek (2004) demonstrated that the bass strength G_{125} indicates a correlation with the rank-orderings of concert halls. There is no optimal value for G_{125} in the literature; however, it was shown that G_{mid} and G_{125} increase with hall quality by approximately the same amount for the same hall, with an average difference of -0.9 dB (Beranek, 2004). Therefore, it might be appropriate to set the preferred values for G_{125} at 0.9 dB lower than that for G_{mid}, namely between 3.1 dB and 6.6 dB.

The measured bass strength G_{125} is shown in Figure 6, from which it can be observed that the sound source positions have an impact on the bass strength at the same measurement location. Figure 6 also shows that the bass strength fluctuates dramatically with the measurement locations, and the values at the measurement locations that are close to the sound source are much higher than those far from the sound source. The preferred values of G_{125} for concert halls are denoted by red and blue dashed lines in Figure 6 for reference. Similar to the Strength of Sound *G* in previous section, the bass strength G_{125} at most of the measurement locations is lower than the preferred values. The average bass strength over all the measurement locations corresponding to all the sound source positions is 1.0 dB, which is less than the lower limit of the preferred range.

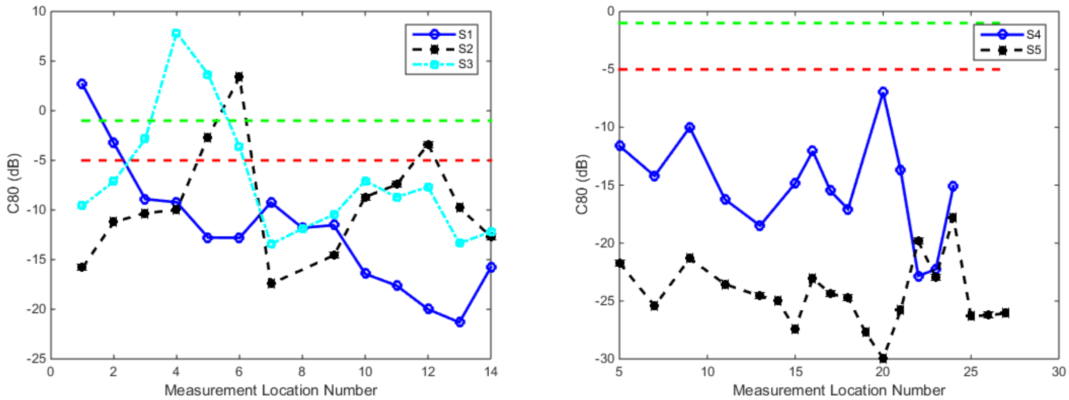


(a) (b)

Figure 6: The measured low frequency (125 Hz) Strength of Sound G125 at each measurement locations corresponding to the sound source positions (a) S1, S2, and S3, and (b) S4 and S5. The red and green dashed lines indicate the optimal range for concert halls

3.6 Clarity

The typical physical measurement of clarity is the ratio of the energy in the early sound to the reverberant sound, a ratio that is expressed in decibels (dB) by C_{80} (Beranek, 2004). Published C_{80} are usually the averaged values in the 500 Hz, 1000 Hz and 2000 Hz octave bands and at a number of seats in a hall. Different amounts of clarity are desirable in different situations. During rehearsals, a conductor will often express satisfaction with a rehearsal hall that has a C_{80} of 1 dB to 5 dB, such that the details of the music can be heard. But at a concert, whether conducting or listening in the audience, the same person will usually prefer a more reverberant space, i.e., with C_{80} equal to –4 dB to –1 dB. Regarding the subjective evaluation of the acoustical quality in concert halls, venues with clarities between –5 dB and –1 dB are judged as the best (Beranek, 2004). There are no optimal values of clarity for churches in the literature.



(a) (b)

Figure 7: The measured middle frequency (500 Hz to 2000 Hz) clarity (C80) at each measurement location corresponding to the sound source positions (a) S1, S2, and S3, and (b) S4 and S5. The red and green dashed lines indicate the optimal range for concert halls.

The measured clarity in the Sagrada Familia Basilica is shown in Figure 7, where the red and green dashed lines indicate the optimal range for concert halls. It can be seen that C_{80} at most of the measurement locations are below the preferred range for the concert halls, leading to low speech intelligibility which is consistent with the primary listening experience by the authors. This is because the volume of the Sagrada Familia Basilica is so large that there are few early reflections in the first 80 ms after the direct sound. In practice, the 80 ms timeframe corresponds to a

27.2 m distance with the sound speed 340 m/s, which is smaller than the size of the Sagrada Familia Basilica. Therefore, the sound energy of the early reflections is quite low, leading to relatively lower values of C_{80}.

3.7 Summary

In summary, the sound field properties in the Sagrada Familia Basilica are analysed in terms of the reverberation, spaciousness, loudness, warmth and clarity. The room acoustic parameters measured in the Sagrada Familia Basilica are summarized in Table 2, where the preferred values for small volume churches and concert halls are also shown for reference. It is noteworthy that the preferred values of T20 and EDT are for small volume churches and the preferred values for (1 – $IACC_E$), G_{mid}, G_{125} and C_{80} are for concert halls. It is not known whether these values can be used to assess the sound field properties in churches, especially in a church of such large volume as the Sagrada Familia Basilica, and further research is necessary.

Table 2: Average values of the acoustic parameters measured in the Sagrada Familica Basilica

	Reverberation		Spaciousness	Loudness	Warmth	Clarity
Frequency range (Hz)	125~8000	125~4000	500~2000	500~1000	125	500~2000
Parameter	T_{20}	EDT	(1 - $IACC_E$)	G_{mid}	G_{125}	C_{80}
Measured value	9.1 s	11.9 s	0.51	2.4 dB	1.0 dB	-13.6 dB
Preferred value	1.5~3.5 s	2.1~4.2 s	0.5	4~7.5 dB	3.1~6.6 dB	-5~-1 dB

*Note: The preferred values of T_{20} and EDT are for small volume churches and the preferred values for (1 – $IACC_E$), G_{mid}, G_{125} and C_{80} are for concert halls.

4. CONCLUSIONS

The impulse responses were measured at 5 sound source positions combined with 14 measurement locations in the Sagrada Familia Basilica, from which the room acoustic parameters are calculated and the following sound field properties analysed: reverberation, spaciousness, loudness, warmth and clarity. The reverberation time (T20) and the EDT in the Sagrada Familia Basilica are much higher than the preferred values, while the middle frequency strength of sound (G_{mid}), the low frequency strength of sound (G_{125}) and the clarity (C_{80}) are less than the preferred values. The binaural quality index (1 – $IACC_E$) is just above the typical satisfactory value. The preferred values of T20 and EDT are for small volume churches whilst the preferred values for (1 – $IACC_E$), G_{mid}, G_{125} and C_{80} are for concert halls. It is unclear whether these values can be used to assess the sound field properties in churches, especially in a church of such a large volume as the Sagrada Familia Basilica, and further research is necessary for a more thorough understanding. Future work includes conducting subjective tests to investigate the subjective preferences in large volume churches such as the Sagrada Familia Basilica.

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