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Evaluation of Acoustic Parameters of Churches

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The purpose of this paper is to give an evaluation of subjective and objective acoustic parameters in two architecturally different churches in Zagreb, Croatia. These churches have completely different architectural parameters due to different style, shape and volume. The influence of high vaulted ceiling in one church is compared to the lower flat ceiling of the other. The influence of large high ceiling lateral chapels to both binaural and monaural parameters is examined. Subjective parameters such as Intimacy, Clarity, Reverberation, Spatial and Overall Impression are compared to measured objective parameters. A comparison of obtained values of objective parameters has been made in order to examine the influence of different sound source positions.

1 Introduction

The interest in church acoustics has increased in recent years and many studies have been carried out in different countries, although many questions are still unanswered and we still have a lot to do to reach the level of analysis, results and conclusions that were achieved and published for concert and opera halls [3-8]. Many decades of study of concert and opera halls are a great legacy that enables us to continue the research of churches, as the specific area of architectural acoustics. Large volume as the architectural parameter and very long reverberation time as the principal acoustic parameter are the most common, easily recognizable and measurable parameters that we encounter in churches. Certain studies have tried to find a novel way of describing properties of sound in huge volumes of churches or have proposed new parameters in order to give us a clearer picture of how a church sounds and how the listeners perceive that sound [5,8]. Up to this moment most of the studies on church acoustics have been based on generally accepted and recognized acoustic descriptors, defined and formally recommended in ISO 3382 [2]. This is why we have tried in this paper to present and define acoustic properties of examined churches using objective parameters as defined in ISO 3382, following the recent recommendations on measurement setup [1], and to compare them with subjective quality descriptors obtained through listeners' evaluation tests.

The principal idea was to compare acoustic properties of two Jesuit churches in Zagreb that differ in style, shape and other architectural properties: The Basilica of the Sacred Heart of Jesus (SHJ) and the Church of the Immaculate Heart of Mary (IHM). The former was built in 1902 in neobaroque style and resembles a Roman basilica shape with 8 lateral chapels, while the latter is a typical modern church, hall type, built in 1995. The research consisted of measuring both objective and subjective parameters, followed by their evaluation. The measurements were carried out using an omnidirectional speaker dodecahedron as a sound source and the omnidirectional microphone Behringer ECM8000 for monaural and a dummy head for binaural parameters measurements at the listener's end. The test signal was sine sweep for monaural and MLS for binaural measurements and all the data acquisition and processing was done using TASCAM US-144 soundcard, IBM T61 notebook with ARTA - Audio Measurement and Analysis Software as software tool.

2 The comparative description of the selected churches

The examined churches have almost the same floor surface of around 800 m^2 and the most noticeable difference is the ceiling shape and height.

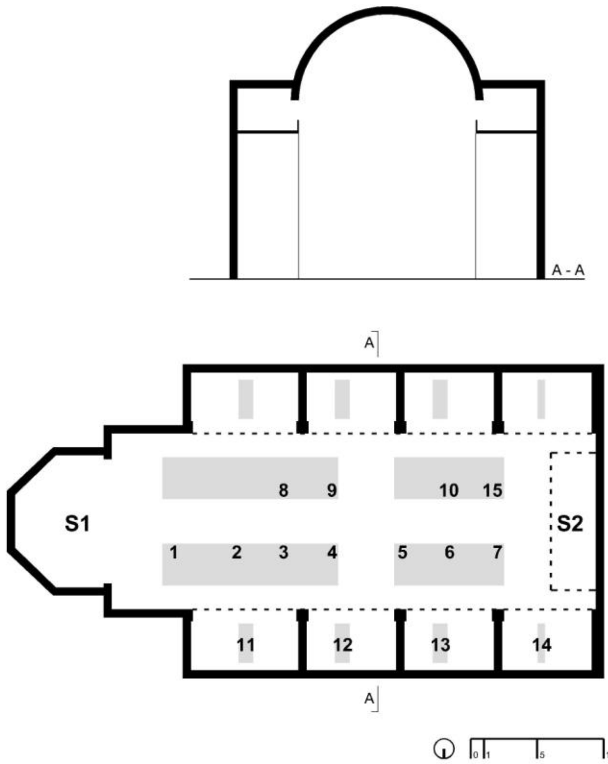

Figure 1: The plan and a section of the Basilica of the Sacred Heart of Jesus

Figure 1 shows the plan and the A-A section of the basilica. Shaded gray areas represent main listening areas where thick wooden pews are situated. S1 and S2 represent source positions, one at the altar and the other situated in front of the organ to simulate the listening conditions for music. It is important to notice that the altar position S1 is elevated 60 cm above the main listening area level, while S2 and the organ are situated at the balcony above the doors at the height of approximately 11 m. The numbers in shaded areas represent the positions where the measurements were taken, both objective and subjective. Altogether there are 15 positions, 4 in lateral chapels and 11 in the main nave, 4 of these 11 were positioned symmetrically on the other side to ensure control measuring points [1]. Complete architectural parameters are given in Table 1.

Total Length L = 43,1 m	Total Width W = 22,5 m	Height H = 20,0 m
Total Volume V = 13000 m^3	Floor Surface S = 803,1 m^2	V/S = 16,2 m
L_{chapel} = 6,75 m	W_{chapel} = 4,6 m	H_{chapel} = 11,0 m
V_{chapel} = 341,6 m^3	S_{chapel} = 31 m^2	

Table 1: Architectural parameters of the Basilica of the Sacred Heart of Jesus

The first lateral chapel is longer than the following three and its length is 8,1 m, surface 37,3 m^2 and volume 410 m^3. The connecting area to the nave of this largest chapel is 89 m^2, while this area for the other chapel equals 74,3 m^2. These measures are given because coupling effects between lateral chapels and the nave will also be examined. The ceiling is vaulted and its highest point reaches 20m. Though the church is built in neobaroque style it does not have rich ornamentation and most diffusive surfaces result from lateral altars, confession booths and pews, all made of wood. The floor is made of polished stone plates which are highly reflective. Side walls and ceiling are finished in plaster, and each chapel has a central thick glass window covering 9,2 m^2.

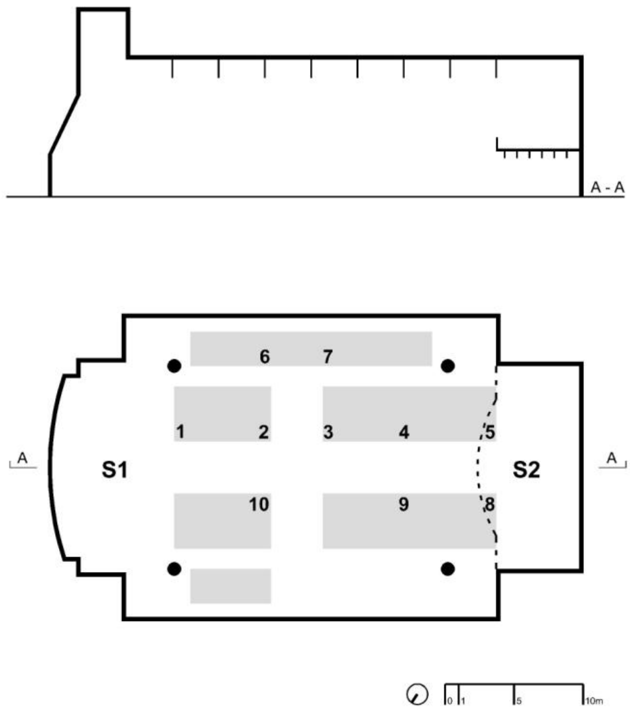

Figure 2: The plan and a section of the church of the Immaculate Heart of Mary

In Figure 2 we present the plan and A-A section of the church of the Immaculate Heart of Mary. It is quite obvious that the ceiling plan is completely different in comparison to the previously described church. The height is twice as low, and what is more important is that the ceiling is flat and coffered, made of concrete. Only recently the central part of the ceiling has been slightly modified by inserting wooden plates with light reflectors into coffers. The floor is made of polished stone plates, similarly to the previous church, while the whole structure is made of concrete with sharp edges and almost no diffusive elements at all. Side walls are covered in flat wooden plates up to the height of 2,5 m. Wooden pews, wooden plates at the ceiling and the recently built organ represent the only absorbing and diffusing elements. The architectural parameters are given in Table 2.

Total Length L = 37,8 m	Total Width W = 24,0 m	Height H = 10,1 m
Total Volume V = 7500 m^3	Floor Surface S = 792,4 m^2	V/S = 9,5 m

Table 2: Architectural parameters of the church of the Immaculate Heart of Mary

Shaded areas represent main listening areas with wooden pews, and numbers refer to the measuring point similarly as in the previous church. Two source positions, S1 and S2, were used, one at the altar and the other in front of the organ at the back western wall. The S1 position was approximately 70cm above the main floor level, and the S2 position is about 5m above the floor level.

3 The results of the measurements

3.1 Evaluation of subjective parameters

The subjective quality scores were obtained by listeners' evaluation tests. The test rating scale had 5 grades, from 1 to 5, with 1 corresponding to bad or poor and 5 to excellent or optimal. The following subjective parameters were evaluated:

- Reverberation: from 1 (totally dry, too reverberant) to 5 (optimal reverberation)
- Loudness: from 1 (too weak, too strong) to 5 (optimal loudness)
- Intimacy: from 1 (very far) to 5 (completely intimate)
- Clarity: from 1 (bad) to 5 (excellent)
- Envelopment: from 1 (too weak, too strong) to 5 (optimal surrounding)
- Directionality: from 1 (bad) to 5 (excellent)
- Impression of higher frequency sounds: from 1 (bad) to 5 (excellent)
- Impression of lower frequency sounds: from 1 (bad) to 5 (excellent)
- Echoes: from 1 (strong, disturbing) to 5 (not audible)
- Background noise: from 1 (strong, disturbing) to 5 (not audible)
- Overall impression: from 1 (bad) to 5 (excellent)

Organ music was played during all the tests, because the idea was to get the subjective scores for music. Two independent evaluation tests were taken in each church, with altogether 46 listeners who were seated at the measuring positions or their symmetrical positions inside the church. No subjective tests were taken from the altar position and the quality of speech intelligibility was not examined, because both churches have a Public Address system installed and all speech involved services use the PA system. Thus, measuring speech intelligibility would in fact present more of a test for the quality of the installed PA system than the physical acoustic quality of the church.

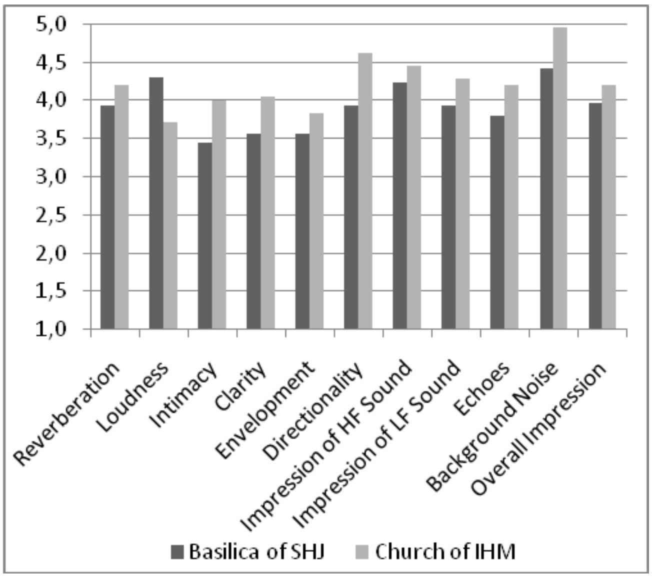

Figure 3: Comparative subjective scores of acoustic parameters

Figure 3 shows subjective scores of evaluated subjective parameters for the examined churches. The values of all parameters except Loudness are higher for the Church of IHM than the Basilica of SHJ.

	Basilica of SHJ		Church of IHM	
Subjective	**Value**	**st.dev.**	**Value**	**st.dev.**
Reverberation	3,92	0,83	4,21	0,98
Loudness	4,30	0,72	3,71	0,91
Intimacy	3,44	0,81	4,00	0,66
Clarity	3,56	1,02	4,04	0,69
Envelopment	3,56	0,86	3,83	0,76
Directionality	3,94	1,09	4,63	0,58
Impression of HF Sound	4,23	0,84	4,46	0,51
Impression of LF Sound	3,92	0,92	4,29	0,81
Echoes	3,80	0,88	4,21	0,78
Background Noise	4,42	0,80	4,96	0,20
Overall Impression	3,97	0,86	4,21	0,66

Table 3: Subjective parameters values and standard deviation

The subjective impression of loudness is stronger in the Basilica because of the larger volume and consequently longer reverberation time values. The exact subjective scores and their standard deviation values are presented in Table 3. Intimacy, Clarity and Directionality were evaluated substantially higher in the Church of IHM.

3.2 Objective parameters of the Basilica of Sacred Heart of Jesus

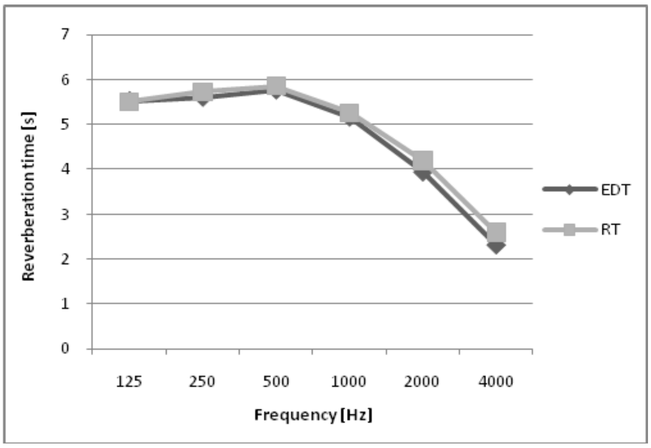

Figure 4: Average Octave Band Reverberation time of the Basilica of the Sacred Heart of Jesus

Both EDT and RT follow the same pattern and we can see that values are a little bit lower at the frequencies of 125 and 250 Hz which is due to low-frequency absorption effect of wooden structures (pews, altars, confession booths). Generally the reverberation frequency function follows the expected curvature, with values getting lower at high frequencies due to the sound absorption in the air. Exact RT and EDT values and their standard deviation are given in Table 4.

Freq.[Hz]	125	250	500	1000	2000	4000
EDT [s]	5,52	5,60	5,76	5,16	3,94	2,32
st.dev.	0,38	0,33	0,30	0,27	0,23	0,21
RT [s]	5,50	5,72	5,86	5,25	4,19	2,59
st.dev.	0,13	0,11	0,13	0,11	0,07	0,08

Table 4: Average Octave Band EDT and RT values

The differences in average RT and EDT values and their values in the lateral chapels have been examined for six octave bands, but the coupled room effect with the differences of at least 0,4s is found only at low and mid frequencies for EDT. These differences in EDT values are given in Table 5.

Difference: Average EDT [s] - Receiver pos. EDT [s]					
Source	**Receiver p.**	**125**	**250**	**500**	**1000**
S1	11	0,3	0,4	0,1	-0,1
S1	12	0,0	0,2	-0,1	-0,1
S1	13	-0,1	0,3	-0,4	-0,3
S1	14	0,1	-0,4	0,0	-0,1
S2	11	0,1	0,0	-0,4	-0,2
S2	12	0,7	0,0	0,2	-0,2
S2	13	-0,8	-0,6	0,0	0,1
S2	14	0,4	0,6	0,5	0,5

Table 5: Coupling effect: difference between Average Octave Band EDT and Octave Band EDT in lateral chapels

In our case this effect occurs at certain octave band frequencies in each chapel depending on the position of the source. The changes in EDT are higher when the source is at the S2 position at the organ.

The next examined parameter is clarity C80, presented graphically in Figures 5 and 6. The numbers on the X axis represent the receiver position number and they are sorted starting from the closest position to the farthest position from the sources S1 (the altar position) and S2 (the organ position).

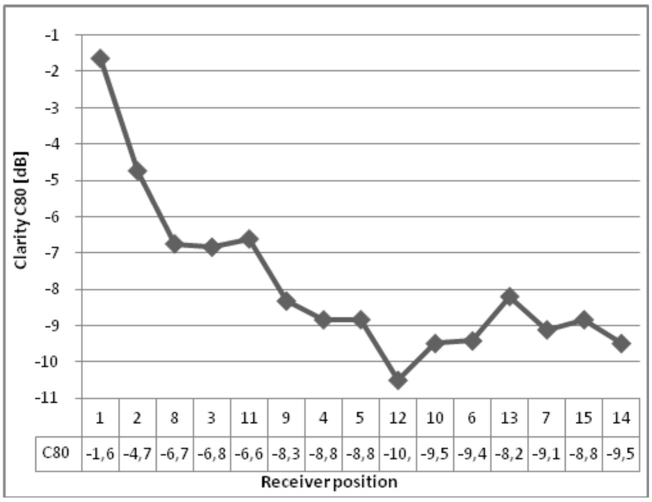

Figure 5: C80 vs. Source S1 – receiver position distance

In Figure 5 are the measured C80 values when the source was situated at the altar (S1). The C80 decreases with the distance from the source. The height of S1 is approximately 2m above the main listening area floor. In this case the sound reflecting from the ceiling has to travel longer to reach the listeners, thus resulting in an averagely lower C80 = -7,8 dB, compared to S2 (the organ position) when the average C80 = -5,9 dB.

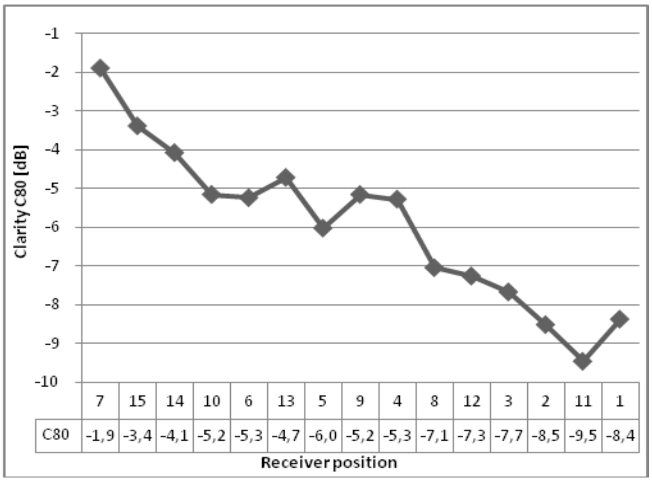

Figure 6: C80 vs. source S2 – receiver position distance

Figure 6 shows the second case when the sound source was in front of the organ. Again, the clarity decreases with distance, but the overall values are higher when compared to the values when the source is at the altar. The central positions in the nave show almost no difference in clarity compared to the positions in the lateral chapels, as the two closer lateral chapels have a higher C80 than the farther two and the source-receiver distance seems to be the leading factor influencing the clarity. The source S2 at the organ position is situated at the height of approximately 11 meters above the floor (8m height of the balcony + stairs + 1,5m height of the speaker stand), so it is just a little closer to the ceiling than to the floor. Still, we can say that this sound source is well centered with regard to floor-ceiling distance and by looking at the values of parameters at different positions we can observe more uniformity and smaller differences in values of adjacent receiver positions than in the first case. Objective parameters Definition D50 and Center Time TS were also measured and their values correlate to a large extent with the pattern of C80, so they are not presented in graphical form.

Receiver p.	C80 [dB]	D50 [%]	TS [ms]
1	-1,6	35,4	273
2	-4,7	20,0	352
3	-6,8	11,6	393
4	-8,8	8,6	419
5	-8,8	6,3	451
6	-9,4	3,8	471
7	-9,1	4,3	484
8	-6,7	11,1	414
9	-8,3	7,2	414
10	-9,5	3,7	488
11	-6,6	11,0	379
12	-10,5	2,3	466
13	-8,2	5,2	455
14	-9,5	2,7	487
15	-8,8	4,2	473
Average	**-7,8**	**9,1**	**427,9**

Table 5: Source S1; measured values of C80, D50 and TS at different receiver positions

Complete measurement results of objective parameters from the altar position (S1) are given in Table 5. In the second case, with the source at the organ position (S2), we have obtained the parameter values presented in Table 6.

Receiver p.	C80 [dB]	D50 [%]	TS [ms]
1	-8,4	5,8	453
2	-8,5	6,3	461
3	-7,7	6,6	445
4	-5,3	10,1	394
5	-6,0	10,4	384
6	-5,3	15,7	347
7	-1,9	25,5	287
8	-7,1	6,9	435
9	-5,2	10,4	400
10	-5,2	14,5	357
11	-9,2	5,8	484
12	-7,3	9,5	424
13	-4,7	12,7	353
14	-4,2	18,4	315
15	-3,4	19,8	298
Average	**-5,9**	**11,9**	**389,0**

Table 6: Source S2; measured values of C80, D50 and TS at different receiver positions

Binaural quality index was measured when the source was S2. The parameter $IACC_E$ was measured at all receiver positions. It is presented in the form 1-$IACC_E$ and is averaged over three octave bands (500 Hz, 1000 Hz, 2000 Hz). The results are given graphically in Figure 7. The receiver positions are sorted in the same way as before to show that the 1-$IACC_E$ has almost no dependence on source-receiver distance. The values inside the nave are very similar with average value 0,52 while the position in the lateral chapels have significantly higher values averaging 0,69.

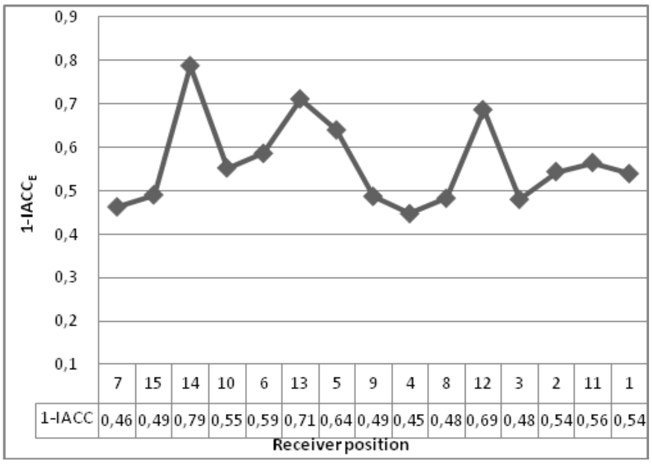

Figure 7: 1-$IACC_E$ vs. Source S2 – receiver distance

The positions in lateral chapels are closer to the side walls and are also surrounded by front and back wall of the chapel, which all contribute to a higher difference in the sound coming to the left and the right ear, thus resulting in higher and better IACC values.

3.3 Objective parameters of the Church of Immaculate Heart of Mary

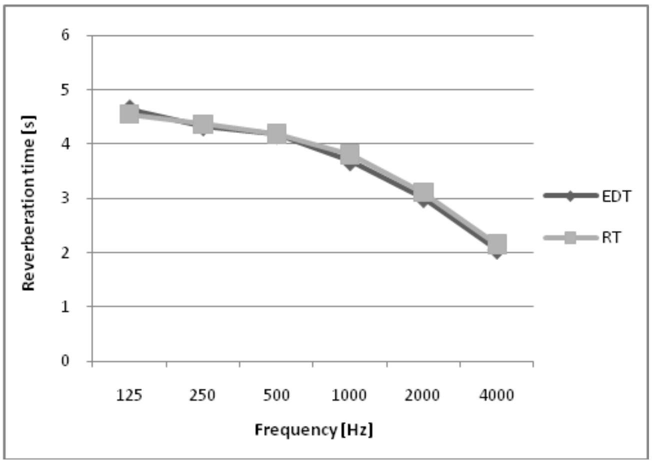

Figure 8: Average Octave Band Reverberation time of the church of the Immaculate Heart of Mary

Figure 8 shows EDT and RT as a function of frequency. Both parameters follow the same pattern, with highest values at 125 Hz and then decreasing as the central octave frequencies get higher. The balanced absorption at low frequencies results in better Bass Ratio BR = 1,12 than in the previously examined basilica where BR = 1,01.

Freq.[Hz]	125	250	500	1000	2000	4000
EDT [s]	4,64	4,33	4,18	3,69	3,01	2,06
st.dev.	0,38	0,22	0,20	0,11	0,14	0,10
RT [s]	4,55	4,36	4,18	3,81	3,11	2,16
st.dev.	0,14	0,08	0,10	0,09	0,06	0,03

Table 7: Average Octave Band EDT and RT values

In Table 7 are given exact values of EDT and RT and their respective standard deviation. Figure 9 shows C80 values as a function of receiver positions sorted from the closest to the farthest from the source, in this case S1 at the altar position.

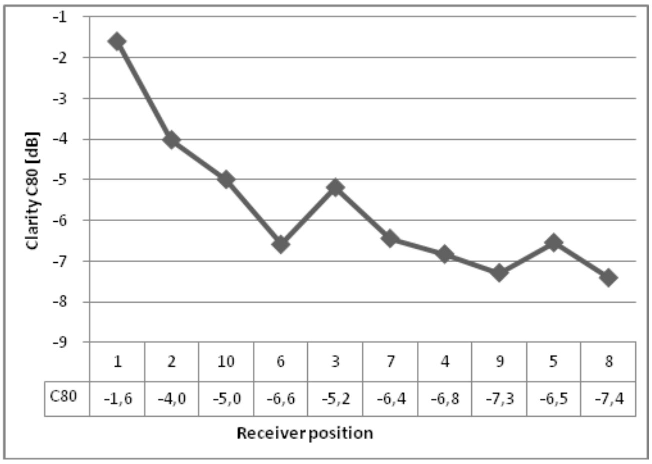

Figure 9: C80 vs. Source S1 – receiver position distance

C80 follows the expected pattern for the simple hall plan as is the case in this church, decreasing with the distance from the source S1 and shows no specific fluctuations. Quite in contrast, in Figure 10 we see C80 when the source is at the organ position S2.

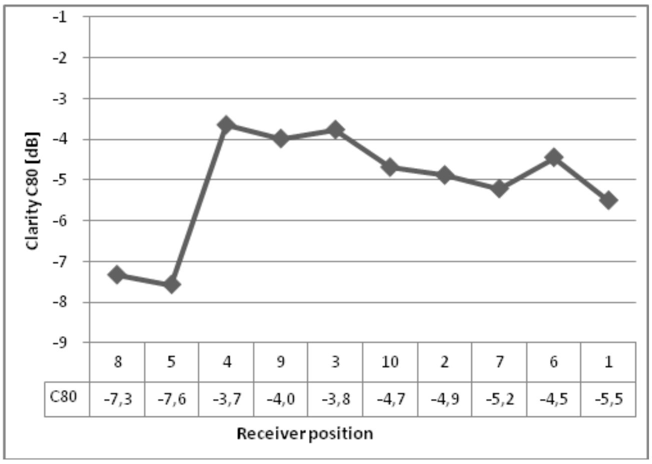

Figure 10: C80 vs. Source S1 – receiver position distance

The closest positions, 8 and 5, have the lowest C80 of all the positions in the church and the difference is significant. The reason for this unusual and unexpected behavior is that these two positions are only geometrically closest to the source when looking at the church plan. But they are in fact under the balcony and they have no direct line of sight with the source S2 or the organ. When carefully observing the church plan in Figure 2, one can see the dashed line that shows the position of the balcony. The height of the balcony is approximately 3m, so in fact we have the lower part of the balcony as the ceiling plan, coffered in concrete, above those two positions. This specific situation explains such low values of C80. The values decrease with the distance from the source. The complete measurement results are presented in Table 8. Comparing the values from Tables 8 and 9 we can see there is no significant difference in regard to the source positions S1 and S2, although the clarity values are a little higher for S2, which can be explained in the same manner as for the previous church.

Receiver p.	C80 [dB]	D50 [%]	TS [ms]
1	-1,6	26,5	234
2	-4,0	16,3	314
3	-5,2	13,8	316
4	-6,8	8,3	343
5	-6,5	9,5	339
6	-6,6	12,5	313
7	-6,5	13,6	313
8	-7,4	9,2	345
9	-7,3	8,6	333
10	-5,0	14,3	289
Average	**-5,7**	**13,2**	**313,9**

Table 8: Source S1; C80, D50 and TS

Receiver p.	C80 [dB]	D50 [%]	TS [ms]
1	-5,5	12,4	309
2	-4,9	12,7	295
3	-3,8	22,8	273
4	-3,7	16,0	281
5	-7,6	5,3	360
6	-4,5	17,2	298
7	-5,2	12,4	299
8	-7,3	8,4	349
9	-4,0	16,7	285
10	-4,7	14,3	305
Average	**-5,1**	**13,8**	**305,4**

Table 9: Source S2; C80, D50 and TS

The source that is situated closer to the half of the church height or the imaginary central line of floor-ceiling distance contributes to a better and more equal distribution of reflections from the ceiling and the floor which eventually results in better clarity. Definition D50 and Center Time TS are very similar in both cases.

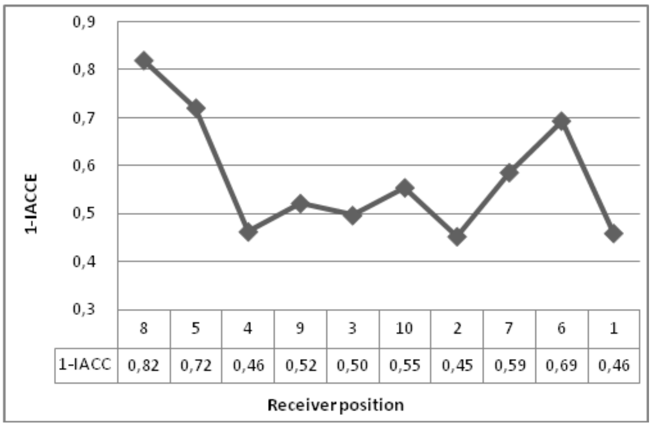

Figure 11: 1-IACC$_E$ vs. receiver positions

Figure 11 shows 1-IACC$_E$ values in the church. The positions that are closer to the side walls have higher values than the central positions. Again, there is interesting behavior at the positions 5 and 8 that have the highest values overall. These positions are also very close to a reflecting surface, the low coffered ceiling at the height of 3m, and that gives the explanation for high 1-IACC. Furthermore these positions generally receive only the reflected sound. The average 1-IACC$_E$ in the church is 0,58.

4 Conclusion

The results of subjective evaluation of acoustic quality suggest that the Church of IHM is better appreciated, with generally higher scores than the Basilica of SHJ. The Church of IHM has substantially smaller volume, due to the lower ceiling, thus resulting in shorter reverberation time which also contributes to a better impression of acoustic properties. Objective measurements were taken in an unoccupied church, so the reverberation times and related parameters are even better when the church is eventually occupied. The simple shape of this sacral building allows more balanced spatial distribution of C80, D50 and TS. The Basilica of SHJ has very long RT and the parameters have low values when the sound source is at the altar, but when the source is at the organ position the objective parameters look better. The meaning of attributes “better” or “worse” that we have been using throughout this paper refers to known and recognized quality levels that were mostly determined for concert halls, specifically because the sound of music in churches was in the focus of our interest.

Further research will continue focusing on the importance of the height of the source position in regard to floor level and ceiling and the position of the source in general. The churches are unique in the way that they usually have two or three completely different sound source positions and almost no acoustical treatment on any large surface.

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