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AN ARCHAEOACOUSTIC ANALYSIS OF THE LATE MEDIEVAL ST. MARY'S CHURCH OF SASTAMALA

Pyry-Herkko Sadeaho[1*] **Mikko Kylliäinen**[1] **Jesse Lietzén**[1]
[1] AINS Group, Department of Acoustical Engineering, Finland

ABSTRACT

This paper describes the historical changes in acoustics of the late medieval St. Mary's church of Sastamala located in western Finland. The church has been the main venue of an annual early music festival since 1996, and its acoustics have garnered attention also internationally. From the 1500s to date, the church has gone through several renovations. This study aimed to determine how the current acoustic conditions have been shaped. This was achieved by modelling the church and its acoustics at different points in time. The room acoustic model of the present-day church was validated with in-situ measurements. The validated model was then altered to account for the state of the church in 1777 and 1870. Information necessary for modelling the historical states of the church was acquired from literature, archives, and interviews. According to the simulations, the reverberation time has become shorter in every major renovation. The changes to the interior have affected other room acoustic parameters as well. The results also note that due to the earthen floor made at the end of the 1970s, the acoustics have become more independent from the occupation of the church.

Keywords: *acoustics, room acoustics, archaeoacoustics, room acoustic modelling*

1. INTRODUCTION

Stone churches concern most of the surviving medieval architecture in Finland, being around 100 in total. Most of these churches are located in the provinces of Western and Southern Finland. [1] Some of the churches built in the Middle Ages were left partly unfinished. One of which is the St. Mary's' church of Sastamala located in Pirkanmaa region in Western Finland.

The St. Mary's church of Sastamala is a rectangular, single-aisle long church built at the turn of the 15th and 16th centuries. It consists of approx. 15,5 x 33,5 m nave with a chancel at the eastern end, and a sacristy on the northern side of the nave next to the chancel. Like most of the Finnish medieval stone churches, the St. Mary's church of Sastamala does not have a smaller chancel projecting from the nave but the chancel is defined as the east part of the body. [1] The walls of the nave are mainly built of natural stone, except the upper part of the western end, which is built with logs. The ceiling is a wooden barrel vault whose vertex is approx. 12 m above the floor level. Formerly, the floor has been covered with wooden planks. However, the former floor was demolished at the end of the 1970s and was replaced with an earthen floor[1].

During the past 500 years, the church has gone through many different phases from renovation to nearly destruction. Despite the colourful past, the church continues its journey, even though nowadays mainly as a road church and a concert hall in summer. The church is generally considered a great performance space, especially for early music[2]. During the past decades, the church has gathered attention and praise for its acoustics. The reason for a growing interest in the acoustics of St. Mary's church is largely due Sastamala Gregoriana, which is one of the oldest and largest early music events in Finland, held annually in July. Since 1996, the church has served as the

*__Corresponding author__: pyry-herkko.sadeaho@ains.fi.

[1] Generally, a floor made of dirt, straw, and clay. In this case, a floor made of compressed sand on top of a thick layer of compressed gravel.

[2] Early music consists of European classical music from the Middle Ages (500–1400), the Renaissance (1400–1600) and the Baroque (1600–1750).

main venue for the festival during which numerous musicians from around Europe have performed there as well. The musical director of Sastamala Gregoriana, Michael Fields, considers the church one of the best performance spaces for early music in the world. As for spoken presentations, the acoustic conditions are not considered as favourable.
Although the church is nowadays mostly known for its acoustic excellence, the room acoustics of the church has not been examined before. Due the many phases of construction raise the question, of whether the acoustics have been always the same as now or if not, what is the main reason that has contributed to the present-day acoustics? This study aimed to conduct an archaeoacoustic survey concerning the acoustics of different states of the church during history. The acoustics of medieval buildings in Finland haven't been studied previously but similar kinds of studies regarding the acoustics of vanished spaces have been done. However, these studies consider theatres and concert halls built in the 19th century. [2]–[4]
This paper is based on the study carried out by Pyry-Herkko Sadeaho in his master's thesis which discusses more precisely the process of measuring and modelling the room acoustics as well as the history and background of the church itself. The information regarding the building history of the church necessary for modelling the former states has been acquired through literary and archival research, and from interviews. [5]

2. BUILDING HISTORY OF THE CHURCH

It is estimated that the St. Mary's church of Sastamala was built at the turn of the 15th and 16th centuries. The sacristy was built before the nave of the church, in 1497 at the earliest. The nave was then finished in the following few years by the year 1505. Shortly after the completion of the nave, a second sacristy was built probably due to an error on the disposition of the first sacristy. The first sacristy was, eventually, torn down in 1703, but its south wall is yet part of the north wall of the nave. [1],[5]
The church was originally intended to be a twin-aisled with four bays. This can be seen from still existing vaulting supports and concluded from the configuration of the two windows of the chancel (see Fig. 1 and 2). However, the intended masonry vault structure was never implemented, which was, in fact, not very exceptional. In Finland, then part of the Swedish kingdom, masonry vaults in several late medieval churches were never built because of the transition from Catholicism to Lutheranism due to the Reformation. [1] There is no reference to a ceiling structure earlier than the year 1777 when, as far as is known, the first wooden barrel vault ceiling was built. Nevertheless, it is probable, that a former ceiling structure still existed. [5]

Figure 1. The St. Mary's church of Sastamala in its current state. The view to the chancel.

Figure 2. The St. Mary's church of Sastamala in its current state. The view from the chancel to the nave.

The amount of information remaining on the church before the 18th century is minor. In 1735, some of the interiors were renewed, and in 1749, a new altar was received as a donation. Apparently, in the late 18th century, the condition of the church was noticeably deteriorating. It is noted that in 1797, the bearing structures were supported from the southwestern and south-eastern corners. In the process, the westernmost window of the south wall was covered. [5]
In the 19th century, the condition of the church kept getting worse, and in 1847, the church was decided to be demolished and replaced with a new one. However, due to some disagreement between the parishioners, the church was, after all, chosen to be renovated until the new church was built. Between the years 1866–1870, the interior was almost entirely updated, the height of the roof was lowered several meters, the wooden barrel vault ceiling was renewed

and the eastmost window aperture of the north wall was opened. [5]

In 1913, the new church of the parish was completed, and the St. Mary's church was abandoned. As unused, the church started to come apart once again. In the 1950s, several inspections concerning the condition of the church were conducted. Therefore, several propositions for actions were made to save the remaining structure and interior from coming apart. In 1959, the Regional Council of Pirkanmaa implemented the restoration of the church to its more original form. The renovation was then carried out between the years 1960–1962. At the time, the roof was restored to its original height, the wooden floor was lowered down 0,6 m, the interior walls were replastered and painted, and the pews were repaired. [5] The former interior is seen in Fig. 3 in which the surface of the floor was higher than it was after the renovation (see Fig. 4).

Figure 3. The nave of the church before the renovation carried out in 1960–1962. (The Aalto University archives)

Figure 4. The nave of the church after the renovation was completed in 1962. (E. Lahtinen, Vapriikin kuva-arkisto, 1962)

During the 1970s, some goat moths were found eating away the wooden structures and the interior. At first, the floor was meant to be replaced with a new wooden structure. Eventually, the idea of the wooden floor was dismissed and in 1978, an earthen floor was made.

Due to the lack of essential information from the ceiling structure, modelling the room acoustics of the church in its states earlier than 1777 is not reliable enough. Therefore, the earliest states to be studied through room acoustic modelling in a trustworthy way are the states after 1777, when the wooden barrel vault was built.

3. MATERIALS AND METHODS

3.1 Present-day church

3.1.1 Room acoustic measurements

The present-day room acoustics of the St. Mary's church were investigated by in-situ measurements. To study the room acoustic conditions comprehensively, it was decided to measure both the auditorium parameters and stage parameters as well as the speech intelligibility. The measurements were conducted, and the measurement positions were chosen by following the standards ISO 3382-1 [6], ISO 3382-2 [7] and IEC 60268-16 [8]. In addition to the standards, the recommendations by Martellotta et al. [9] were observed when choosing the source locations.

The measurements were carried out using a tetrahedral ambisonic microphone as a receiver, and a dodecahedron loudspeaker as a sound source, fulfilling the requirements of omnidirectionality for all parts of ISO-3382. Impulse responses were made for three source positions (A–C) and six receiver positions (1–6) which are presented in Fig. 5.

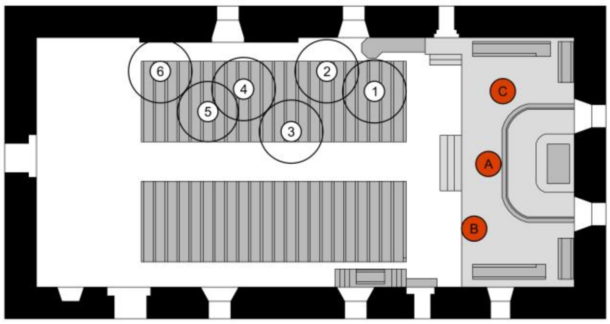


Figure 5. The sound source positions (A–C) and receiver positions (1–6) for auditorium parameters.

Source positions approximate the location of the performers in a situation the space is mainly used for nowadays. The receiver positions were chosen from the other side of the centre aisle since the space is estimated to be generally symmetrical. Additionally, impulse responses were made for three receiver positions around every source position (A–C) to derive the stage parameters ST_{Early} and ST_{Late} as well. The receiver positions were chosen in agreement with ISO 3382-1 Annex C and are shown in Fig. 6.

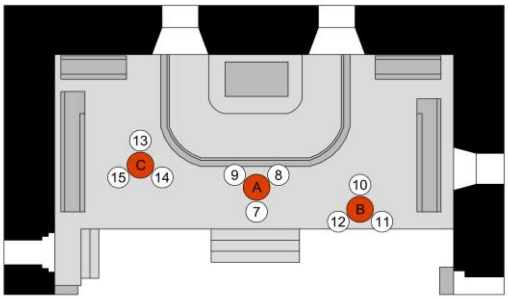


Figure 6. The sound source positions (A–C) and receiver positions (7–15) for stage parameters.

Impulse responses were measured using an exponential sine sweep signal with a length of 30 seconds. Also, background noise levels were measured in receiver positions 1–6 with a sound analyser to derive the speech transmission index *STI*. For the recommendation of ISO 3382-1, the temperature *T* (20 °C) and the relative humidity of the air *RH* (54 %) were measured as well.
From the impulse responses of the receiver positions 1–6, room acoustic parameters T_{30}, *EDT*, C_{80}, *G* and speech transmission index *STI* were derived. The stage parameters ST_{Early} and ST_{Late} were also derived for each source position from the source-specific impulse responses measured in receiver positions 7–15. The auditorium and stage parameters were computed for octave bands from 125 to 4000 Hz.

3.1.2 Room acoustic modelling

The geometry of the church was discovered by producing a 3D model of the interior using an AI-powered 3D capturing system. The system was using SLAM[3] technology based on RGB-D images which is a combination of RGB image and depth image. Briefly, the algorithm of the system then uses elements from the picture including RGB values and spatial data to align adjoining scans to reconstruct the geometry of the space. Additionally, a point cloud[4] was obtained from the captured data, which is presented in Fig. 7. To ensure the accuracy of the produced data, some in-situ verification measurements of the internal dimensions were also made.

Figure 7. The point cloud of the present-day church.

The geometrical model of the present-day church was modelled in accordance with a point cloud and in-situ verification measurements. The room acoustic modelling was carried out with the room acoustic software Odeon 16 and by following the specific instructions of the software itself [10]. Since modelling geometrical details hasn't been discovered affecting significantly the simulated room acoustic parameters [11]–[14], some simplifications were made while modelling the geometry. The foremost action was simplifying the geometry of the stone-made walls, which were rough and irregular. Therefore, the wall surfaces were chosen to be modelled flat and considered when defining the scattering coefficients.
For the surfaces, the absorption coefficient values were chosen from the literature [15]–[16] and comparable studies conducted earlier [11],[17]. The absorption coefficient of the earthen floor was approximated from the generally used absorption values for sand and according to research related to the absorption properties of fibrous materials [18]–[19].
The scattering coefficients for different surfaces were estimated from the 3D model in accordance with the recommendations [10],[13],[15]. For mainly smooth surfaces, the scattering coefficient was set to have values between 0,05–0,1. More irregular surfaces were assessed to have a scattering value of 0,2. Additionally, for stone walls, values between 0,25–0,3 were set. The measured and simulated room acoustic parameters and speech

[3] Simultaneous Localization and Mapping.

[4] A set of data points in a 3D coordinate system which can also include e.g., RGB colour values.

transmission index are shown in Tab. 1. During the conducted measurements, the average of A-weighted background noise level $L_{p,A,B,Eq}$ was 18 dB.

3.1.3 Fully occupied situation

Apart from investigating the church in an empty situation, which was possible to be measured, the situation while fully occupied is also essential to be considered. Therefore, the validated model was also altered to correspond to the fully occupied situation by modelling the areas of the pews as boxes. The absorption coefficients were assessed to respond to the measured values of an audience on wooden chairs with a density of 2 per m^2 [15]. As for the scattering coefficient, a value of 0,7 was used.

3.2 Models of the church in 1777 and 1870

The earlier states of the church were chosen by evaluating the occasions, which are both trustworthy as good as possible and with maximum disparities in room acoustics. Additionally, the era of the state was also considered in the selection. The states earlier than 1777 were ignored due to the lack of information on the ceiling structure. On this basis, the church was chosen to be modelled in the states that existed in 1777 and 1870.

Between the years 1866–1870, the church was comprehensively renovated, and the interior was renewed. Compared to the present-day church, the structures of the interior in 1870 were mostly the same as it is now. However, some major differences affecting the room acoustics still appear. The main differences between the present-day church and the church in 1870 are as follows:

- The floor was made of wood and the surface of the floor was approx. 0,6 m higher than the current earthen floor.
- There were four rows of pews at the back of the nave and one row more in the front part of the nave on both sides which increases the seating capacity by approx. 80 persons.

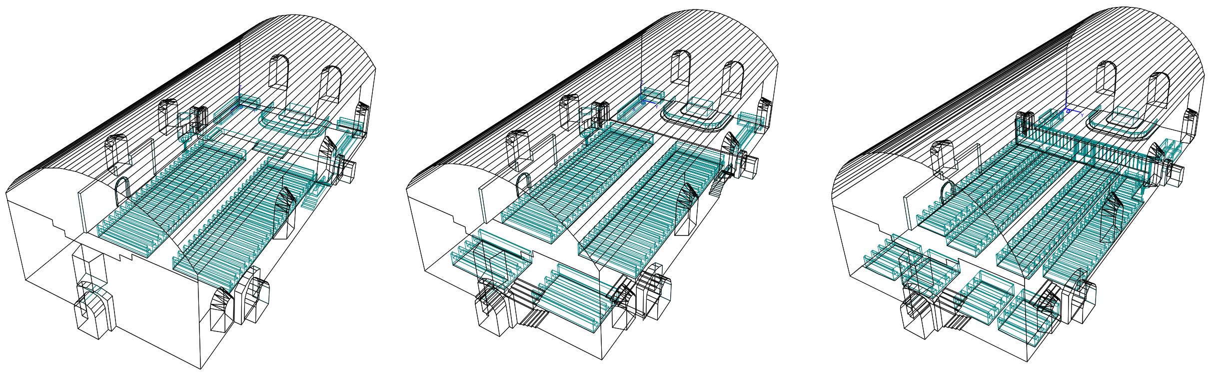
In 1777, the church was still reminiscent of the original, as for the interior. The main disparities compared to the church in 1870 are as follows:

- The wooden barrel vault ceiling was higher, and the profile of the ceiling was rounder.
- The interior had more characteristics of Catholicism: The chancel and the nave were separated with a wooden choir screen, and the pews were in four rows divided with a centre aisle and two side aisles on both sides of the nave.
- The pulpit was on the other side of the chancel.
- The eastmost window aperture of the north wall was still closed.

The geometric model of the present-day church was at first altered to account for the church's layout in 1870 and 1777. After this, the room acoustic models were created using the same principles as in the present-day model. The room acoustic models of the church in 1870 and 1777 as well as the model of the present-day church are presented in Fig. 8. From the figure, the influence of the change in height of the wooden floor as well as the barrel vault ceiling can be seen. Also, the change in the arrangement and configuration of the pews can be observed.

Table 1. The spatially averaged measured and simulated parameters in an empty present-day church for source positions A–C.

Parameter		125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	Average
T_{30} [s]	Measured	2,3	2,4	2,6	2,8	2,4	1,9	2,7
	Simulated	2,3	2,4	2,6	2,7	2,3	1,8	2,7
EDT [s]	Measured	2,2	2,5	2,7	2,8	2,4	1,7	2,7
	Simulated	2,3	2,4	2,6	2,8	2,4	1,8	2,7
C_{80} [dB]	Measured	-3,4	-4,0	-4,3	-4,2	-2,5	0,6	-4,2
	Simulated	-2,8	-3,2	-3,8	-4,1	-3,4	-1,9	-4,0
G [dB]	Measured	12,3	10,5	10,9	11,7	10,6	8,7	11,3
	Simulated	9,2	9,7	10,1	10,2	9,3	7,8	10,2
ST_{Early} [dB]	Measured	-11,3	-12,5	-12,6	-12,1	-11,7	-13,0	-12,2
	Simulated	-12,4	-12,2	-12,3	-12,5	-12,9	-13,3	-12,5
ST_{Late} [dB]	Measured	-12,8	-10,5	-10,1	-9,7	-10,2	-13,9	-10,1
	Simulated	-12,8	-11,9	-11,6	-11,2	-12,0	-13,8	-11,7
STI	Measured	-	-	-	-	-	-	0,43
	Simulated	-	-	-	-	-	-	0,41



Present-day church
$V \approx 5700$ m^3, capacity ≈ 340 pers.

The church in 1870
$V \approx 5500$ m^3, capacity ≈ 420 pers.

The church in 1777
$V \approx 6300$ m^3, capacity ≈ 450 pers.

Figure 8. The geometrical models of the church in different eras with respective volume and seating capacity. The seating capacity is estimated from the area of the pews with a density of 2 persons / m^2.

4. RESULTS AND DISCUSSION

The averages of the simulated room acoustic parameters in different eras are shown in Tab. 2. In addition to the measured parameters, late lateral sound energy LF_{80} was also simulated. For more detailed analysis, the spatially averaged results in octave bands 125–4000 Hz of parameters T_{30}, EDT, C_{80} and G are shown in Fig. 9.
According to the results, the early decay time *EDT,* and the reverberation time T_{30} are the longest in the 1777 version and shortest in the present-day version. From the figures, it is seen that T_{30} and *EDT* in the empty church are noticeably longer in the 1870 and 1777 churches than in the present-day, especially at frequencies 1000–4000 Hz. In the present-day version, the decay time seems to be more independent from the occupation since the variation between empty and fully occupied situations is smaller than in other eras at every octave band. Furthermore, the effect of the volume of the space on the reverberation is detected when comparing the 1870 and 1777 versions in both empty and fully occupied situations. In the 1777 version, T_{30} and *EDT* are longer at all frequencies.
The variation of clarity C_{80} between empty and fully occupied churches is smallest in the 1777 version and greatest in the 1870 version. With full occupation, C_{80} receives corresponding values in 1870 and the present-day versions at all frequencies. In the 1777 version, C_{80} varies noticeably from the values of 1870 and present-day versions in fully occupied situation. This can be seen especially at frequencies 1000–4000 Hz. As for the strength *G*, no significant differences between observed eras can be seen. This becomes even more obvious with full occupation. The variation between empty and fully occupied churches seems to be greatest in the 1870 version. Along with the late lateral sound energy LF_{80}, the perceived width of the space is corresponding in 1870 and present-day versions. In 1777, LF_{80} receives smaller values probably due to different configuration of the pews.
Stage acoustics have remained the same throughout the centuries since no remarkable difference in the results is seen between different eras. Particularly with the early support ST_{Early}, no significant variation can be seen. Hence, the ease of hearing other musicians on the stage remains the same despite the occupation of the church in all observed eras. However, for the late support ST_{Late}, the influence of the occupation is greater since it affects the reverberation time of the space. Therefore, the variation is smallest in the present-day version, in which the influence of the occupation on the reverberation time is also smallest.
The spatially averaged speech transmission index *STI* is less than 0,45 in every observed era and situation. Based on this, speech intelligibility is perceived as “poor” in all eras regardless of the amount of occupation. Though, in the 1777 version, the room acoustics for spoken presentations are the poorest. This may be due to the choir screen as well as the longer reverberation time.

Table 2. The spatially averaged simulated parameters for all eras in empty and fully occupied situations.

Occupation	Version	T_{30} [s]	*EDT* [s]	C_{80} [dB]	*G* [dB]	LF_{80} [-]	ST_{Early} [dB]	ST_{Late} [dB]	*STI* [-]
Empty	Present day	2,7	2,7	-4,0	11,3	0,27	-12,5	-11,7	0,41
	1870	3,2	3,2	-4,6	11,4	0,27	-12,4	-10,9	0,39
	1777	3,3	3,4	-5,6	10,3	0,24	-12,1	-11,5	0,35
Full	Present day	1,9	1,8	-0,9	7,5	0,24	-12,5	-12,6	0,45
	1870	1,9	1,8	-0,5	7,7	0,24	-12,4	-12,4	0,46
	1777	2,3	2,3	-3,0	7,5	0,22	-12,1	-11,6	0,39

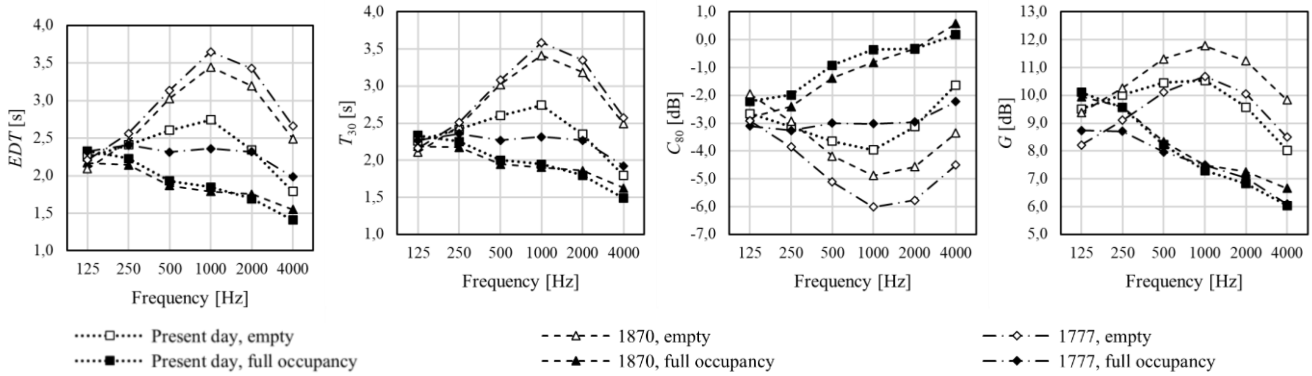


Figure 9. Comparison of the simulated room acoustic parameters T_{30}, *EDT*, C_{80} and *G* in octave bands 125–4000 Hz for all eras in empty and fully occupied situations.

5. CONCLUSIONS

St. Mary's church of Sastamala is one of the surviving late medieval stone churches in Finland. Due to its rather eventful building history, the interior, as well as the architectural image of the church, has varied throughout the past 500 years. Till 1913, the church was used merely for ecclesiastical activity. After several decades of being generally abandoned, today, the church serves as a road church and a main venue for the early music festival Sastamala Gregoriana. Along with the early music performed annually in the church since 1996, the St. Mary's church of Sastamala has received praise concerning its room acoustic conditions. However, since the church hasn't been always identical, a question raises, how have the room acoustics varied during the centuries, and which changes have had the most effect on the formation of the present-day conditions?

The room acoustics of the present day as well as the earlier stages of the church were investigated through room acoustic modelling. To discover the current room acoustics, some in-situ measurements were conducted. In addition, a 3D model of the interior of the church was captured to discover the geometry for modelling. According to the measurements and the information of the geometry, a present-day room acoustic model of the church was generated. The model was then validated and adapted to the layouts of the church that occurred in 1870 and 1777. The room acoustics were investigated in both empty and fully occupied situations in all eras observed.

The results showed that the room acoustics have not been similar for all parts throughout history. It can be noted that the current room acoustics have been formed as a consequence of several renovations and by accident. The major factor is the earthen floor, along which the variation of the reverberation between empty and fully occupied churches remains noticeably less than in the former stages. Since the earthen floor absorbs the sound more efficiently than the wooden floor structures of the former stages, the room acoustic conditions of the nave are less dependent on the amount of occupation. The acoustics in the nave have changed along with the alteration of the church because of the change in volume of the space as well as in the interior and the configuration of the pews. Despite the variation in

the room acoustics between the observed eras, the speech conditions in the church have always been poor due to the long reverberation time. However, in the present day, the church is somewhat more suitable for spoken presentations than in the 18th century.
When it comes to the stage acoustics, the conditions haven't varied as much even though the reverberation time has changed noticeably. This may be because the floor structure of the chancel has remained mainly the same. Additionally, there have been no remarkable changes on the interior surfaces of the chancel between the observed eras. Nevertheless, it must be noted that the altar may have been different in the Catholic days.

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