

## **Auralization as a tool of historic reconstruction of Vadstena Abbey church**

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### **ABSTRACT**

Throughout human history, there have been locations used for performance of speech and music. Many of these locations are considered part of our common cultural heritage, and more and more of them can be visited virtually as technology advances to produce better and better reconstructions. However, the technological capabilities are not the only limitations when it comes to historical reconstruction, and one of the most important research questions is often to determine the actual historical configuration of a space. This is the case for a project regarding Vadstena Abbey church in Sweden. As a step in producing the virtual reconstruction, a number of different configurations for one of the major performance locations will be examined using acoustic simulations and auralizations. As the acoustic properties of a space affects the performances within it, there should be a correspondence between the musical and oral traditions of this location in particular and its acoustics. Historical records of the performance traditions within the space, as well as records of the acoustic experiences of visitors, will be used as an evaluation tool to distinguish between the models.

**Keywords:** Historical Acoustics, Virtual heritage, Vadstena Abbey  
**I-INCE Classification of Subject Number:** 06

### **1. INTRODUCTION**

There are some locations that have played an important role in history, or in the personal stories of many people's lives. These locations can be considered part of our common cultural heritage, and there is undoubtedly value in ensuring they are preserved for posterity, as well as available for visitors today. However, these two goals are sometimes in conflict as visitors can cause wear and tear, and other damage. Another possible complication is if the locations are already lost to time, so that it may be too

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late to employ preservation strategies and no longer possible to visit. One way to tackle these issues is by producing virtual reconstructions of these sites. Developing a virtual reconstruction does not require as much resources, and digital copies can be distributed and shared without the risk of degradation of the material. As such, these efforts are becoming more and more common.

One piece of cultural heritage of the nordic countries, and Sweden in particular, is Vadstena Abbey church. It is located by the lake Vättern in southern Sweden, and is the mother church of The Order of the Most Holy Saviour, more commonly known as the Birgittines. The church was inaugurated in 1430, and played an important role in the politic, religious and cultural societies of the Nordic Union for more than a hundred years. After the dissolution of the union in 1523, the reformation lead to the destruction of many of the riches in the church and finally the dissolution of the abbey in 1595. The church fell into disrepair for many years, until it was reinstated as a parish church for the town Vadstena in the 19th century. The many years of neglect mean that the physical grandeur of the church during the 15th century is probably lost forever. A project is in place with the goal of creating a **historically accurate virtual reconstruction** of the interior of Vadstena Abbey church during a service in the 15th century.

Although this is a historically important and rather well-documented location, a lot of questions exist about what it looked like in the 15th century. Due to the renovations and the neglect, the information that exists is scattered and ambiguous. This poses one of the biggest challenges, if not the biggest, in creating a historically accurate reconstruction; exactly what historically correct means is not clear. In order to deal with this issue, it is important to take into account as much as possible of the available information. While this, obviously, includes descriptions of the visual qualities of the church, the acoustical properties should not be neglected. This includes accounts of the auditive experiences of visitors to the church, but can also be extended to accounts of the liturgy commonly used for services in the church. Using the fragmented information from various sources and regarding different aspects, an holistic image should be formed, paying attention to as many pieces of information as possible. This paper focuses on how the **acoustic information** should be used to evaluate and aid in the reconstruction of the Vadstena Abbey church.

This method of including the acoustics as a central part of a virtual construction and a virtual reality experience is somewhat innovative. Classically, most of the focus in virtual reality and virtual environments such as games, has been on the visual aspects. While vision is, in many contexts, the dominant modality through which humans perceive the world, a truly realistic experience can not happen unless the acoustics matches reality and the visual experience [1].

## **2. A BRIEF HISTORY OF VADSTENA ABBEY**

Before the construction of the church, one of the largest stone estates of the region was situated there. This estate was granted to St Birgitta by king Magnus and queen Blanka in the 14th century, with the express purpose of establishing a abbey there. It was to be founded according to rules described in her revelations in the 1340s, and in 1349 she travelled to Rome to receive Papal recognition for the institution. In 1370, the Pope granted the abbey rights for the foundation of the double abbey, and by that time the construction work on the abbey had already begun. In 1384, nuns and monks entered the enclosure and the abbey was formally founded. The construction of the church continued

for many years, and the church was not inaugurated until 1430. By that time, there was already significant interest in the abbey, both due to the political and religious influence of St Birgitta and the indulgences granted by the abbey. The abbey remained a centre of political, religious and cultural power in the Nordic countries until and beyond the dissolution of the Kalmar Union in 1523 [2].

During its more than one hundred years of fame, the abbey was frequented by both royalty and pilgrims. One event which gathered a particularly large following was the great feast for the enshrinement St Katarina in 1489, the daughter of St Birgitta who was herself beatified. Surprisingly, there is a written account of that particular feast, which describes much of what we know about the church today. The account was written about ten years after the occasion, by a monk named Nils Ragvaldsson [3].

In 1527, the reformation reached Sweden and the Swedish king was granted the mandate to confiscate clerical assets. Subsequently, much of the material wealth was removed from Vadstena abbey church in repeated interventions from the king. The abbey library was also removed from the abbey during this time. In the 1540s the congregation of monks was dissolved, and in 1595 the nunnery.

Vadstena Abbey church was, to a large extent, left to disrepair for some 200 years, during which it was only used intermittently and during the summer. In 1829 century, it was again employed as the parish church of the town Vadstena, despite objections from the populace. Among the disadvantages stressed by the inhabitants of the town were the poor acoustics of the church [2].

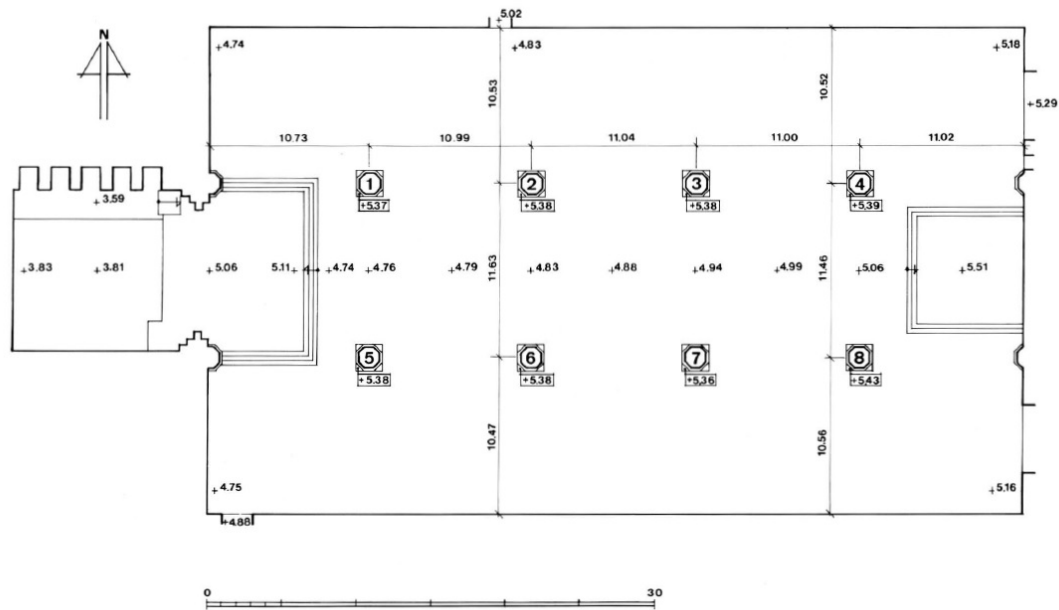
In the late 19th century, the church underwent significant renovations. These are thought to have increased the rate of deterioration in the church, as well as have caused significant changes to the interior [2, 4], and it is likely that the renovations themselves destroyed a significant amount of indications of the historical configuration of the church. In the 20th century to the modern day, more research regarding the history of the church has been performed, some of which is presented in this paper.

### **2.2.1. What is known about the historic interior of the church**

The tenets of the abbey was based on St Birgittas revelations, and this holds also for the construction of the church. Quite clear and explicit instructions exist of how the church should be constructed, but it is not clear how closely these instructions were followed. There are also inconsistencies between different accounts of St Birgittas revelations. In all, the provided instructions are very valuable in providing a general idea of how the church was constructed, but it can not be taken as a truth [2].

While it is not entirely known how much the actual construction of the church deviated from St Birgittas revelations, at least one deviation is known of. The ideals presented by St Birgitta are strict and somber, and she prescribes a simple interior. There were to be no paintings only for decoration, and yet there are decorations in the ceilings that are from a time close to the construction. Additionally, the prescription was that the church be constructed of stone and not of brick, but the ceiling arches are constructed in brick [2]. While this choice can be explained by structural requirements, it still shows that the instructions were not followed to the letter.

From an acoustic point of view, a few of the unanswered questions are of particular interest. Firstly, this regards the interior wall surfaces. The walls themselves are constructed by limestone, and the ceiling arches are constructed from brick. The ceiling is also plastered, but the historical situation for the walls is not known. During the renovations in the late 19th century, the plaster covering the interior walls was removed.

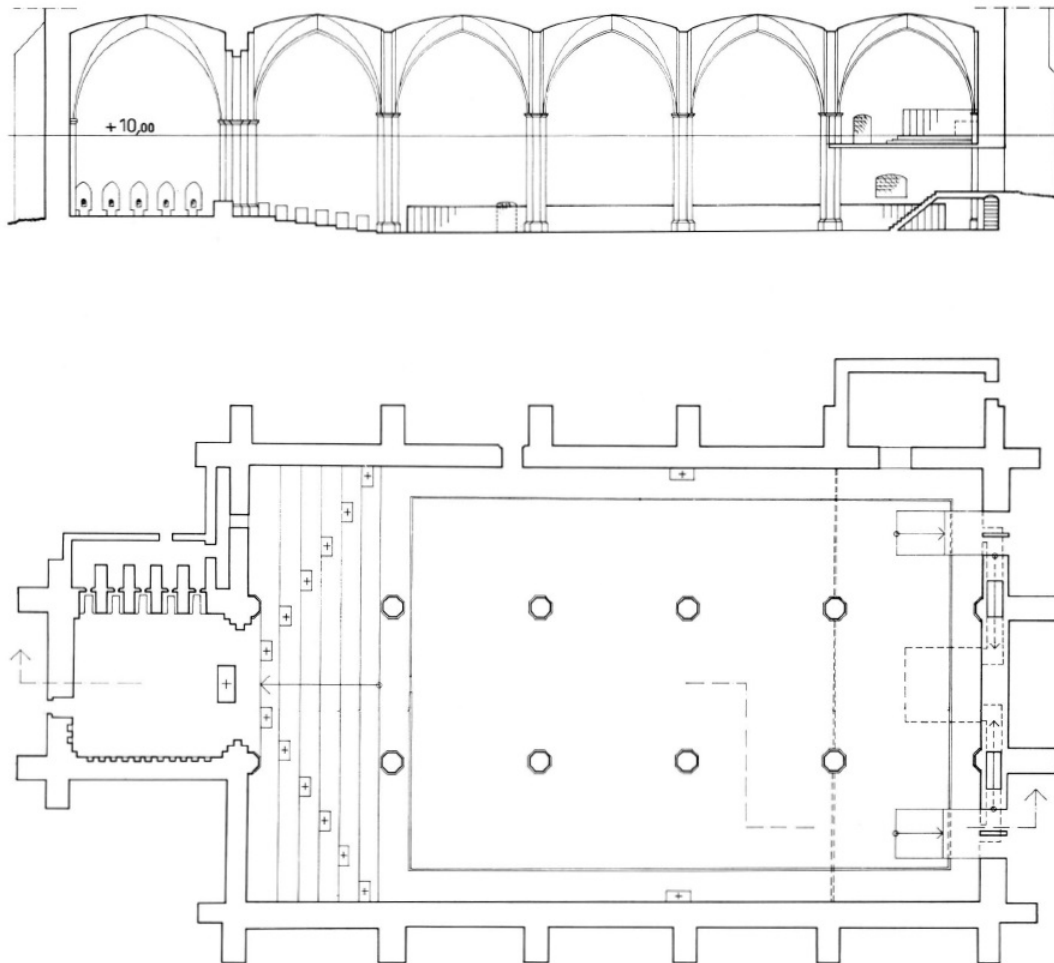


*Figure 1: Floorplan of Vadstena Abbey today. The absolute floor elevation is noted in the figure. The high altar is located to the far west in the nave, while the altar dedicated to the virgin Mary was originally located to the far east. Note that the floor in the far west (the monks' chancel) is significantly lower than the rest. [2]*

The choice to do so was based on an assumption that the plaster was added during an earlier renovation. However, there are indications that the plaster was there before this earlier renovation. Furthermore, the surface of the stones along the interior are rougher in structure, something that often is done in order to easier cover them with plaster [2]. The practices regarding medieval churches in Sweden also suggest that the walls were covered, as anything else would be unheard of. In conclusion, there are signs that the walls were plastered rather early in the history of the church, but it is not entirely certain.

The other main question, from an acoustical standpoint, regards the location of the singers, in this case the monks and the nuns. Unfortunately, there are uncertainties regarding both of these. According to the instructions provided by St Birgitta, the nuns should be located on a gallery above the eastern part of the church, right next to the altar dedicated to the Virgin Mary. This gallery was to be located 11 ells above the floor, and constructed of wood and brick with a copper covering on the bottom [2]. While there are no traces of such a construction, it is assumed to have existed. There is a door in the northern wall of the church on a height roughly matching this description, which would lead from the abbey buildings straight to the gallery. An account from 1579, of a royal wedding in Vadstena, mentions an accident wherein a platform in the eastern part of the church fell down and injured and killed several people, and it is often assumed that this platform is the lost gallery [2]. This, however, still does not determine the location or the structure of the gallery, which is likely to have affected the acoustic field in the church, in the main hall as well as on the gallery itself.

When it comes to the location of the monks, the situation is only slightly more clear. The location of their chancel is in the far west of the church, beyond the high altar. This is as prescribed by the revelations, but the floor level is more than a meter below what is implied in the instructions. With the current configuration, the acoustical communication



*Figure 2: Drawing of the church seen from the south and from above, based on the plans presented by St Birgitta. Note that the monks' chancel in the west is at a higher elevation than the nave. Also note the nuns' gallery in the east, with a dedicated entry in the northern wall. This drawing is based on an interpretation by Anderson in 1972 [2].*

channel from the monks' choir to the main hall is virtually non-existent. It seems unlikely that any sort of services could have occurred, where the voices of the monks in their chancel could be heard in the church, with the current configuration. Rather, it seems likely that the west-most part of the church was constructed in two levels, where the second floor was a wooden construction on a suitable elevation. Again, however, physical traces supporting this theory are not readily apparent.

Besides the construction of the actual church, the acoustical properties would have been affected by furniture and decorations. It is known that upwards of 60 altars existed in the church at its peak. All of these are likely to have been decorated with sculptures, altarpieces and textiles. This would increase the surface area significantly, and the absorption potentially even more so. Besides the altars themselves, there were wax sculptures, coats-of-arms, decorative textiles, carpets and decorated graves. All of this will have affected the acoustical properties significantly, most likely by reducing reverberation, as described in the case of St Mark's by Howard [5]. While most of the physical objects described have been destroyed or removed, it is possible to estimate their effects on the sound field partially based on measurements of the remaining pieces.

During services in the church, another important absorbent should be considered: people. While it seems plausible that the number of individuals in the church varied significantly depending on the time of week, as well as on whether a particular event was occurring, it seems likely that at least a significant portion of the abbey members were present. By the instructions of St Birgitta, there should be 60 nuns and 25 monks in the abbey, which depending on the clothing could provide significant absorption especially in their respective performance areas. Thankfully, quite detailed information regarding the prescribed clothing for the monks and nuns during various seasons and for various purposes has been preserved.

### **2.2.2. What is known about the liturgical and acoustical practices in Vadstena**

The Birgittine order was founded primarily for women, and it is the source of the only known monastical office exclusive for women [6]. Its focus on the female aspects can be seen in the establishment of the Cantus Sororum (the office previously mentioned), in the administrative configuration of the abbey where the abbess was the highest-ranking member of the abbey, and in the geographical plan for the mother church where the traditionally most important side in the east was dedicated to the nuns and the Virgin Mary [2]. Even in the first revelation of St Birgitta, it was mentioned that the women should be the focus of the order [6].

While there are no liturgical sources preserved from Vadstena itself, its position as the mother church of an order, which gained significant popularity in the 15th century, means that there are several other sources that can be examined. For example, a version of the Cantus Sororum mentioned above is available in the abbey in Mariënwater, in an edition from around 1500. While a lot of work still remains to determine what, if anything, can be said to be distinctive for the Birgittine acoustical practices, and therefore the Vadstena acoustical practices, there is some promise. An interesting aspect is that Strinnholm-Lagergren, in her examination of the invitatories in the Cantus Sororum, found that there were rather few melisma [6]. While this is not in itself indicative of any particular acoustic qualities, the lack of melisma could theoretically be explained by a long reverberation time affecting such musical movements negatively. It is also possible that the reason for the scarcity of these movements relate to the ideals of St Birgitta, which shows a strong inclination towards more simple and humble as opposed to the quite difficult melismatic sections mentioned above.

As previously mentioned, the ideal pursued by St Birgitta were quite somber, and in her instructions for the abbey she prohibited the use of polyphony in the services. Based on the account of the enshrinement of her daughter [3], however, these instructions were not followed, at least not at all times. It seems likely that her instructions that no instruments were to be present were observed, however, as there are no contradictory accounts.

## **3. BACKGROUND ON RAYTRACING SIMULATIONS AND HISTORICAL ACOUSTICS**

In this section, the acoustic simulation strategy employed in this project is briefly explained, and the use of it is motivated. In addition, the usage of acoustics as a tool in historic research is discussed.

### **3.3.1. The Auralization algorithm to be used**

The auralization algorithm to be used in this project is based on the raytracing framework introduced by Krokstad et al in 1968 [7]. This simulation technique is based on assumption that geometrical acoustics provide a valid approximation of the behaviour of the sound field in the relevant frequency range. As the primary sound sources in the church are historically human voices, the relevant frequency range should start at approximately 125Hz [8]. The Schroeder frequency for the space is estimated to be below 50Hz, based on a floor surface area of  $54.77 \times 32.54 \text{m}^2$ , a ceiling height of about 15m to the arches [2], and a reverberation time of 8s [9]. This supports the usage of statistical or geometrical acoustics, as human vocalizations generally are well above this range.

Raytracing simulations give an estimate of the energetic directional impulse response for a certain source-receiver configuration. As the frequency range of interest is well above the estimated Schroeder frequency, the energetic impulse response should be sufficient to describe the behaviour of the sound field under the given configuration. With sufficiently many samples, or rays, the obtained impulse response can be used for auralizations. In addition, energetic measures as the  $T_{60}$ ,  $C_{50}$  or the definition can be obtained trivially, allowing for objective comparisons between configurations of the Vadstena abbey, but also to other locations.

The comparison between different possible configurations of the Vadstena abbey is a vital part of this project, and this further suggests the raytracing algorithm as the most suitable one. The current configuration of the church consists of mostly flat, acoustically hard surfaces, but as previously mentioned this has most likely not always been the case. Introducing the large amounts of decorations and furniture that historically have been present in the church is likely to introduce large amounts of scattering. Currently, there are very few, if any, algorithms that are as capable of dealing with scattering as the raytracing method. While the current configuration could plausibly be simulated using an image source method, it seems unlikely that this method would work for all historical cases. As such, using a method that can be applied for all cases must be preferred, when the goal is comparison between configuration results.

Raytracing algorithms have some shortcomings, but there are several methods of mitigating these weaknesses. At its core, raytracing uses a Monte Carlo simulation strategy to take many samples of the paths between source and listener, which is then used to approximate the full, statistical distribution of sound particles in time and space. By virtue of being a Monte Carlo strategy, however, the level of accuracy depend strongly on the number of samples, and so the number of rays used in the simulation is critical in order to obtain stable and accurate estimates. The chosen implementation of the raytracing algorithm uses a diffuse-rain method, which can reduce the number of rays needed [10].

For the auralization itself, it will be rendered binaurally using headphones.

### **3.3.2. Acoustics as a tool of historical research**

The acoustics of historical spaces can be and has been used as a tool for historical research. The connection between European christian traditions and acoustics of the worship spaces has been more thoroughly discussed by, for example, Lubman and Kiser [11]. Another example of acoustics and historical research coming together is a project by Kolar et al, where acoustic measurements were used as a way of examining whether a type

of Incan platforms were used as a communication platform [12]. Another, more obvious use is regarding musical history, where evaluations based on acoustical impressions can be used to make assumptions regarding performance traditions, including what types of performances were supported. This has been done, for example, with regards to St. Mark's in Venice [5].

The suggested method in this paper, however, is to exploit the connection between practical use and acoustic properties in the other direction. For Vadstena abbey, it is more or less known how the space was used, and there are some sources regarding the musical and liturgical traditions. Based on this knowledge, it is possible to construct a model for the necessary requirements for the space to be used in this way. This model should be based both on what is known of this specific location, regarding acoustic impressions and liturgical traditions, but also information from other and similar locations.

The use of acoustic simulations are invaluable in this context, as it would be impossible, or at least extremely impractical, to physically recreate all the possible configurations that should be tested.

It is important to note that while the acoustics can be used as a valuable tool, it should not be expected that the single modality of sound can be used to make any definitive statements regarding the historical truth. While some possibilities might be discounted as not fulfilling the demands posed by the model defined, it is more likely than not that more than one possible configuration could be sufficient. In that case, other aspects such as visual qualities or structural concerns should obviously not be neglected.

#### **4. THE ROLE OF ACOUSTICS IN THE VADSTENA PROJECT**

The goal of constructing a historically correct virtual reconstruction of Vadstena abbey is ambitious, and it will require skillful and creative research in many different fields. As the project is formulated, the acoustic aspects are a priority, and ensuring their accuracy will be a primary focus. However, if the project is to produce satisfactory results in any of the important areas, all the available information must be considered every step of the way. This section of the paper will discuss how the acoustic research will be used to benefit the whole reconstruction, including but not limited to the acoustic reconstruction itself.

One of the ways that the acoustic simulations should be used in the current project is as an evaluation tool for various possible configurations. It is suggested that a few alternatives for what the church looked like, based on what is known and what is plausible, are formulated and computer models are constructed. The digital models should then be examined using acoustic simulations, considering especially the aspects presented below. The digital models should be evaluated based on visuals, structural soundness and the results of the acoustic simulations. This method is expected to be especially relevant for questions regarding the two major performance locations, e.g. the monks' chancel and the nuns' gallery.

##### **4.4.1. The role of acoustics so far**

In 2017, reverberation time measurements were performed in Vadstena Abbey. The results were presented in 2018 [9]. The reverberation time for the current configuration of the space varies between 10 – 7s in the range 100 – 1000Hz. These values are inappropriately large for most applications, but corresponds well with historical



statements on the poor acoustics, as well as the discussion presented in this paper on the current state of the church. Given the information regarding the interior of the church during the 15th and 16th century, it seems plausible that the reverberation time was lower then. This is also congruent with the documented popularity of the church, as it is more likely that an acoustically satisfactory environment will attract visitors and donations. The measurements themselves can be considered the first step in developing a more complete picture of the acoustics in Vadstena Abbey.

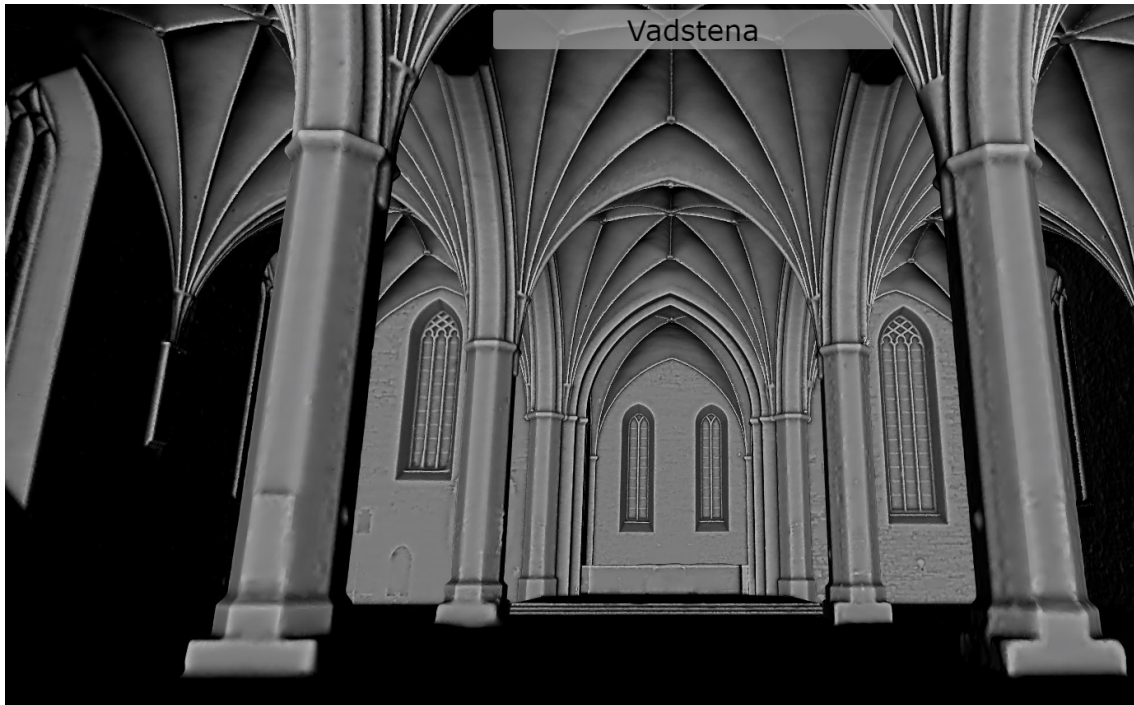
The reverberation measurements also offered some insights regarding the acoustic properties of the monks' chancel in the west, see fig. 1. It was treated as a location for the sound source during the measurements, as it historically has been used as a performance location. In general, however, the measurements with the source located in the chancel did not produce the SPL required for the measurements in the nave. This problem was specific to this location, and illustrates poor acoustic transmission between the chancel and the nave. This is, in itself, strong evidence that the current configuration with the lower floor surface is not historically accurate.

In addition to physical measurements, some acoustic simulations of the space have already been made. The Humanities Lab at Lund university has performed a scan of the interior of the church, and used this information to construct a digital 3-dimensional model of it, see fig. 3. Although digital models constructed this way are generally much more complex than those constructed with other methods, the model can be studied on regular desktops, and has been used for acoustic simulations. As the model is based entirely on scans of the actual church, it is very geometrically accurate. However, the scanning method can not provide values of the acoustical parameters of the surfaces in the space. Instead, the measured values of the reverberation time are used to tune the scattering and absorption coefficients of the digital model. This is done by iteratively performing simulations, comparing the calculated reverberation time to the measured, and updating the relevant coefficients. This method provides estimates of the acoustic coefficients of the surfaces present in the current church. For some of these surfaces, such as the ceiling arches, not much is thought to have changed over the centuries and the estimates should be valid also for the historical model.

#### **4.4.2. Important considerations for the future acoustic simulations**

The properties of the sound transmission channel between the performance locations and the nave should be examined. The songs chosen for services, and even more so for special events, likely sounded good in the nave when performed in either of the performance locations. On a fundamental level, this implies that the music could be heard in the nave. For these simulations, the energetic impulse responses between the performance locations and various positions in the nave should be considered, and it should be determined whether the results are adequate for the chants and songs performed. Research by Martellotta has found that EDT is closely connected to the listening experience in churches [14], and it is suggested that this is used as a tool for evaluating the different alternatives. It should be noted that this research is comparatively recent, and it is not certain that the preferences of the historical listener coincides with the preferences of a trained musician today. All the same, it is suggested as a starting point.

While the transmission of songs to the populace are an important aspect, sound would have been transmitted in the other direction as well. In particular, services performed at



*Figure 3: Rendering of Vadstena Abbey, model constructed based on a scan of the interior of Vadstena Abbey. Model and scanning performed by Lindgren at the Humanities Lab from Lund University. [13]*

the main altar should be heard by both the nuns and the monks. Simulations for a given configuration should also aim at providing an estimate of how well this need was fulfilled.

While it is important to consider whether sufficient acoustic information could be transmitted over some paths, it is also important to examine whether sufficient acoustic information could be *blocked* over other paths. It is known that there were around 60 altars present in the church at one time. With this number, it is likely that at any given time, some service or ritual was conducted somewhere in the church. In addition to the large number of altars, the abbey was frequented by pilgrims. With this amount of visitors and activity, the acoustical properties in the nave itself are an important consideration. Especially the gallery is likely to have affected the sound field in the nave, even when no performances took place there. This effect should not be disregarded.

Besides considering the sound field in the nave, as generated by singers and visitors, the sound field within the performance spaces should also be considered. After all, the members of the abbey are likely the ones that most frequently and regularly participated in services, and who had the most influence on the sound field and on what practices were established. This implies that the sound field in the gallery and the chancel might be the most important for the choice of liturgy. The chancel and gallery should be considered not only from a listeners point of view, but from a performers. This means that properties such as support and the ability to hear the rest of the ensemble should be evaluated. While the preferences regarding these properties can be highly subjective [15], they are relevant to the comfort of the singers and should thus be considered. In order to obtain adequate results from these tests, musicians trained for this particular performance style should be involved in the listening tests. In traditional, non-digital settings, the musicians would be able to perform in these spaces to evaluate the quality, but that may not be possible in this context. With the current technological solutions it would be impossible for an ensemble

to perform together in virtual reality, for instance. If the performer is a single individual, the situation might be different and this opportunity should be examined.

## 5. CONCLUSIONS

The usage of acoustic measurements in historical research is becoming more and more common, and there is still much to be explored within the field. In this paper, a method is suggested for using acoustic simulations as a way of gaining more information regarding historical locations which are now lost. The theory is developed with respect to a specific location in southern Sweden, and some of the available information regarding this location is discussed. In particular, the information is considered from an acoustic point of view rather than a visual, aesthetic or historic.

Some examples of questions where the suggested method could be useful are presented, and it is also discussed what aspects should be considered when using this method. In general, it is important to examine values that have relevance to the historic context and the historical documents. Only this way can the acoustic simulations be related to the historical information, and used to support or discard theories of what might have been.

While it is suggested that acoustic simulations can be used as a tool for evaluating, and making plausible, various historical circumstances, it is important to note that the acoustic or auditory aspect can not be more than just one aspect. The visual and structural aspects must be considered, within the cultural and historical context of the time. With that in mind, the acoustic aspect should not be forgotten, especially not for locations which depend so heavily on auditory communication as a church.

However, as this paper shows, the tools developed for the auralization of Vadstena can and should be an integrated part of the development of the full model. They are not only an end goal, but also a valuable tool for the historical research.

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