PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6–8 July 2022 Verona, Italy

The Development of the Early Acoustics of the Chancel in Notre-Dame de Paris: 1160–1230

Sarabeth Mullins[1]; Elliot K. Canfield-Dafilou[1]; Brian F.G. Katz[1]

[1] Institut Jean le Rond ∂'Alembert, Sorbonne Université/CNRS, France
sarabeth.mullins@dalembert.upmc.fr; elliot.canfield-dafilou@dalembert.upmc.fr; brian.katz@sorbonne-universite.fr

ABSTRACT

The primary construction of the Cathédrale Notre-Dame de Paris began in the spring of 1163 CE and continued into the mid-14th century. Two decades after construction efforts commenced, the pre-existing liturgical community in Paris began its occupancy inside the incomplete building. To better understand the interrelationship between the occupants and the cathedral, the acoustical characteristics of key moments in the cathedral's early development in the 12th and 13th centuries are examined using geometric acoustic modeling. Room acoustic parameters of the sacred regions of the cathedral are examined with attention to the experiences of active participants within the chancel of the cathedral.

Keywords: room acoustics, cultural heritage acoustics, Notre-Dame de Paris

1. INTRODUCTION

The Cathédrale Notre-Dame de Paris is a building of great cultural significance with a rich heritage that began in its earliest years of existence. Since construction began in 1163 CE, the cathedral has hosted over 850 years of religious, musical, and French national history. While it is easy to conceptualize the heritage of the cathedral as a single and undivided abstraction, the continuous occupancy of the cathedral has led to structural and decorative modifications over time. As a part of the ongoing study of the acoustical heritage of Notre-Dame, this study focuses on the acoustic conditions of Notre-Dame's earliest decades.

2. ARCHITECTURAL DEVELOPMENT

Notre-Dame de Paris was among the first new constructions in France to fully realize a Gothic architectural sensibility, which began to emerge around the Île-de-France region in the preceding decades [1]. Development began in the spring of 1163 under the aegis of bishop Maurice de Sully when construction began on the eastern termination of the cathedral's ambulatory [2]. At this time, demolition began on extant church buildings to clear the site for the growing cathedral, including a small chapel dedicated to Mary under the present-day transept and a large basilica located underneath the present-day *parvis* of Notre-Dame [3][4, §*Cathédrale*]. In 1182, the first phase of construction (the full completion of the chancel) concluded with the consecration of the grand altar in the apse [5].

In this period, a large retaining wall was built to separate the consecrated chancel from the rest of the work-site. This wall allowed the liturgical community to begin religious activities within the completed structure after 1182, uninhibited by the ongoing construction. At this time, work continued west across the transept crossing, reaching the western rose window and grand facade by the 1230s [6]. From then, the cathedral was expanded, first at the transept, and later as chantry chapels granted to patrons of the chapter were built between the foundations of the flying buttresses [7]. Construction of lateral chapels concluded by the 1330s, and the external structure remained largely unchanged until the renovations of Viollet-le-Duc in the 19th century.

During his excavations and renovations, Viollet-le-Duc found evidence of an early design change in the clerestory of the cathedral (the location of the modern stained glass windows). In an effort to reduce the weight of the monumental walls, circular voids (termed here *oculi*, $\varnothing \approx 2$ m) were built into the walls below smaller versions of the windows we see today. If these oculi had been filled with glass, they would have resembled miniature rose windows, but since they were left open, they coupled the main acoustic volume with attics located above the triforium arcades. According to Viollet-le-Duc, the oculi were present from the beginning of construction until around 1230, when the windows above the oculi were extended down to create the longer windows seen today [4, §*Rose*]. Visual representations of the oculi can be found in [6, 8], which were used to inform the creation of the acoustic models containing the attics and oculi.

This study examines the effect of the retaining wall and oculi on the acoustics of Notre-Dame's early decades and compares the impact of these features to the acoustic behavior of a speculative model of the early basilica replaced by Notre-Dame. In this study, the cathedral has been modeled at points of partial architectural completion in the time period from ca. 1160 to ca. 1225, and the models have been been named after the years roughly corresponding to these architectural way-points. Historians and archaeologists, however, agree that construction on the structure was continuous and likely simultaneous [9, 10]. Consequently, the dates assigned to these models should be considered as temporal approximations rather than prescriptive claims re-

peer reviewed

10.58874/SAAT.2022.183

garding the cathedral's state in that year. This approach is necessitated by continuous construction onsite and the contemporaneous documentation available, but more significantly reflects a desire on the authors' part to examine and quantify the acoustic effect of certain architectural changes in isolation from others.

3. MATERIALS AND METHODS

This study follows the methodology set out in [11], where a geometric acoustic (GA) model is calibrated to room impulse responses of the existing building. Four total GA models were created (see Table 1), with the speculative ca. 1163 model based on an extant building and the ca. 1182, ca. 1220, and ca. 1225 models based on the GA model reported in [12], subsequently modified to match the historical states as discussed in [13].

3.1 Geometric Acoustic Models

The oldest building modeled is the largest of the church buildings associated with the religious community on Île de la Cité in 1163. It is likely that this large building fulfilled a similar role for high feasts and holy days as Notre-Dame eventually would, and it is generally accepted that the building was built in the basilica-style [3, 8, 5, 14]. Traces of its foundation have been discovered underneath the parvis in front of Notre-Dame, outlining a rectilinear building ≈ 35 m wide, ≈ 70 m long [3, 5], with two sets of side aisles flanking the main aisle. Based on similar basilica-style churches, it is likely that a semicircular apse was appended in the liturgical east, framing the altar and providing a focal point for ceremonies held within the church. There is no record of the height of the ancient structure.

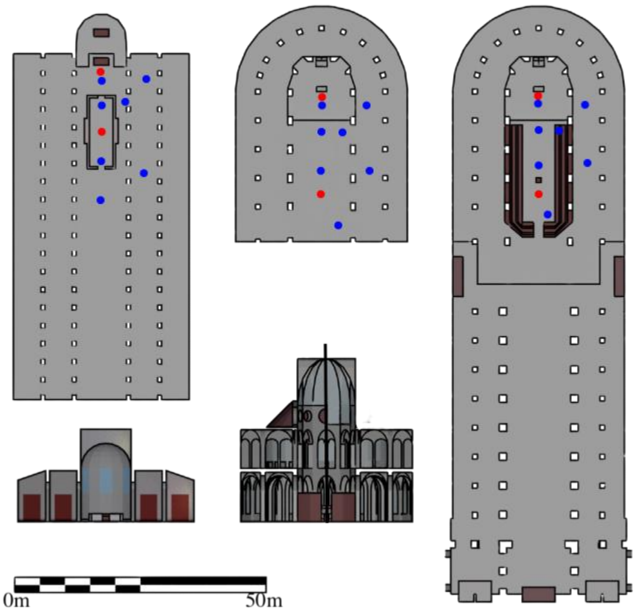

Figure 1 – Plans and elevations of ca. 1163, ca. 1182, andca. 1220, with sources (red) and receivers (blue) under con- sideration indicated.

To aid in the development of a speculative model of the early building, a well-preserved, contemporaneous basilica-style church was identified and selected to stand-in as a possible representation of the building. The Basilica of *Santa Sabina all'Aventino* is a basilica-style church located on Aventine Hill in Rome. Originally built in the 5th century, the interior of the basilica has survived largely unmodified to the modern era, maintaining the characteristic semicircular apse and flat, wood-paneled ceiling common to basilicas of the early Middle Ages. The acoustics of Santa Sabina were measured and reported in [15], and the base model was created and calibrated to the measurements following the procedures outlined in Section 3. Since materials from the demolished buildings were reused for the construction of Notre-Dame, the same acoustical material properties were used to ensure continuity between the models. After verifying the Santa Sabina model calibration with measurements, the model was morphed to match the dimensions of the pre-Gothic building, maintaining the calibrated material properties as well as key design elements from Santa Sabina. Without knowing the height of the historic basilica, surviving contemporaneous basilicas of similar or larger size were consulted to maintain a consistent proportion of width and height for the center and side-aisles. In addition to Santa Sabina, these include the basilicas of *San Paolo fuori le Mura* (Rome), *Sant'Apollinare in Classe* (Ravenna), and the *Church of the Nativity* (Bethlehem).

The ca. 1182, ca. 1220, and ca. 1225 models were based on the 2015 calibrated model of Notre-Dame [16]. Oculi were modeled as circular voids in the clerestory walls and the windows were shortened. The materials of the attics were chosen to represent the masonry, dust, and wooden bracing likely found in such a space. The interior geometry was altered to reflect the commonly-held view of the construction timeline, with attention paid to changes in furnishings and decorations. Changes from the 2015 model [11] include the closing of the lateral chapels, the inclusion of the clôture, reshaping the choir stalls, altering the ground floor of the chancel, positioning of the grand altar, and other local adornments.

3.2 Simulation Settings

All models were generated using CATT-Acoustic (v9.1e, TUCT v2.0e) [17]. As the goal of these simulations was an exploration of the acoustics of the buildings under consideration, simulations were generated using algorithm 1 (split order $N = 1$), with a 350,000 rays. The length of the impulse response duration was determined by an initial test run and then rounded up to the next integer second. For the ca. 1163 and ca. 1182 models, this procedure resulted in a 7 s impulse response, and for all other models a 10 s impulse response. Impulse responses were calculated for the

Table 1 – Approximate dates modeled in this study with volume (V) and surface area (S).

Year	V (m^3)	S (m^2)	Notes
ca. 1163	29,640	11,785	basilica
ca. 1182	27,935	12,900	apse only, + attics
ca. 1220	82,365	32,235	full length, + attics
ca. 1225	79,430	28,805	full length, - attics

sources and receivers noted in Fig. 1. For the purposes of addressing run-to-run variation, reported acoustic parameters are averaged over five repetitions.

Source and receiver positions were chosen to reflect the liturgical use of the space, with omnidirectional sources located where priests and lay members would speak or sing as a part of mass. Receivers were positioned to examine local variations in the acoustics in and around the consecrated portions of the chancel.

4. RESULTS

The change from the basilica to the Gothic style was a significant change in the architectural massing of the two buildings. Although the internal volumes were likely similar in magnitude (see Table 1), the Gothic building rearranges the internal volume vertically, creating a large ceremonial space, reinforced in later years by the inclusion of the clôture and the high-backed choir stalls. This reordering of the massing within the cathedral can be seen in the elevations of Fig. 1, and the effect of this rearrangement can be seen in Fig. 2, which compares the center time (T_S)[1] within the ca. 1163, ca. 1182 models and ca. 1120 models. Fig. 2 showcases the effect of the Gothic chancel on the temporal energy balance. Notably, while T_S clearly increases as a function of distance within the basilica model, the chancel maintains a steady and low T_S value for a larger area within the Gothic models. Furthermore, the lower ceilings and the corridors of the ambulatory maintain a relatively even energy balance after the installation of choir stalls and clôture in the ca. 1220 model. These mappings hint at the existence of acoustic sub-spaces from the earliest of the Gothic cathedrals (reported in the 21st century cathedral in [18, 19]), coupled by the volume overhead. Fig. 3 reports the global average of reverberation time (T_{30}) using the sources in the chancel as indicated in Fig. 1 and the receivers distributed throughout the apse. The reduction in T_{30} between ca. 1163 and ca. 1182 is significant, with a maximum difference of −0.8 s at 1000 Hz. While the removal of the attics between ca. 1220 and ca. 1225 represents a change of only 3% of the internal volume of the model, the closing of this coupled volume represents an increase of 7–13 % in T_{30}. For all octave bands, this increase of reverberation time falls outside

[1] T_S is measured in ms and is the balance point of early and late energy within the IR. Higher values of T_S indicate an IR with a large amount of late energy, correlating with low intelligibility and clarity.

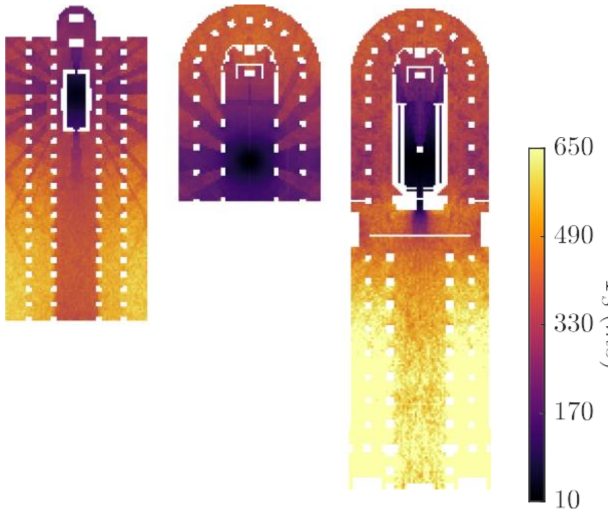

Figure 2 – Comparison of T_S in the ca. 1163, ca. 1182, and ca. 1220 models for a source in the center of the choir.

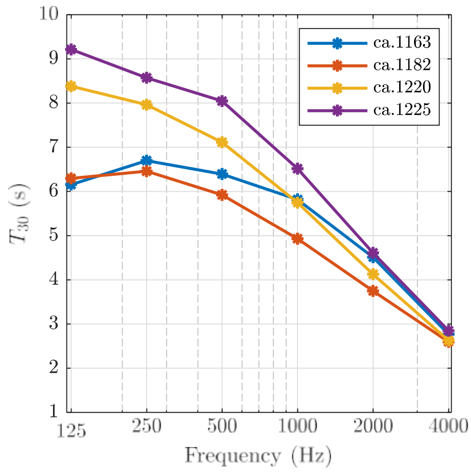

Figure 3 – Global average T_{30} values in the four modeled statesfor two chancel sources.

both computational run-to-run variation and the just noticeable difference for T_{30}. In general, the changes in T_s and T_{30} between these modeled states surpass the minimum requirements of the just noticeable difference(±40 ms for T_s [20] and ±5% for T_{30} [21]).

5. DISCUSSION AND CONCLUSIONS

These results demonstrate the acoustical evolution that occurred over the course of a few generations. The rearrangement of reflective structures and increased height of the new cathedral exaggerated the acoustical behavior of the basilica style model from ca. 1163. As can be observed in Fig. 2, T_s within the basilica increases linearly with distance from the choir source. In the Gothic buildings, this behavior does not occur at the same scale, with T_s remaining relatively stable in the apse. However, the T_s increases dramatically and to a greater extreme in the nave, creating a clear distinction between sacred and profane sections of the cathedral. In general, the acoustical changes between ca. 1163 to ca. 1182 and ca. 1182 to ca. 1220 pass the threshold of perception and likely would not have gone unnoticed by the community. Furthermore, the decrease in volume from ca. 1220 to ca. 1225 and the subsequent increase in reverberation time indicates that the high, flat walls of the clerestory play a significant role in the acoustic behavior of the cathedral.

Future work will deal with the acoustic sub-spaces and coupled volumes revealed in this preliminary examination and will expand to cover the entirety of the cathedral's 850-year history, including connecting the present work to recent contributions [22].

ACKNOWLEDGEMENTS

Many thanks to Prof. Francesco Martellotta for his measurements of Santa Sabina all'Aventino. Funding has been provided by the European Union's Joint Programming Initiative on Cultural Heritage project PHE (The Past Has Ears, phe.pasthasears.eu), the French project PHEND (The Past Has Ears at Notre-Dame, Grant No. ANR-20-CE38-0014, phend.pasthasears.eu), and the Chantier Scientifique CNRS/MC Notre-Dame.

6. REFERENCES

[1] C. Hourihane, "Gothic architecture," in *The Grove Encyclopedia of Medieval Art and Architecture*, New York: Oxford University Press, 2012, doi:10.1093/acref/9780195395365.013.1007.

[2] S. Berger and D. Sandron, "La maîtrise d'ouvrage: XIIe-XIVe siècle," in *Notre Dame de Paris*, La Grâce d'une Cathédrale, pp. 29–39, Strasbourg: La Nuée Bleue, 2019.

[3] J. Barbier, D. Busson, and V. Soulay, "Avant la cathédrale gothique: IVe-XIIe siècle," in *Notre Dame de Paris*, La Grâce d'une Cathédrale, pp. 17–27, Strasbourg: La Nuée Bleue, 2019.

[4] E.-E. Viollet-le Duc, *Dictionnaire raisonné de l'architecture française du XIème au XVIème siècle*, vol. 1-10. Paris: B. Bance, 1866.

[5] D. Sandron, *Notre-Dame de Paris: histoire et archéologie d'une cathédrale, XIIe-XIVe siècle*. L'esprit des lieux, Paris: CNRS éditions, 2021.

[6] D. Sandron and A. Tallon, *Notre Dame Cathedral: Nine Centuries of History*. University Park, Pennsylvania: The Pennsylvania State University Press, 2020.

[7] S. Berger and D. Sandron, "Des transformations radicales: XIIIe-XIVe siècles," in *Notre Dame de Paris*, La Grâce d'une Cathédrale, pp. 29–39, Strasbourg: La Nuée Bleue, 2019.

[8] M. Aubert, *Notre-Dame de Paris: sa place dans l'histoire de l'architecture du XIIe au XIVe siècle*. H. Laurens, 1920.

[9] C. Bruzelius, "The construction of Notre-Dame in Paris," *The Art Bulletin*, vol. 69, no. 4, pp. 540–569, 1987.

[10] M. S. Doquang, "The lateral chapels of Notre-Dame in context," *Gesta*, vol. 50, no. 2, pp. 137–161, 2011.

[11] B. Postma and B. F. Katz, "Creation and calibration method of virtual acoustic models for historic auralizations," *Virtual Reality*, vol. 19, pp. 161–180, 2015, doi:10.1007/s10055-015-0275-3. SI: Spatial Sound.

[12] B. Postma and B. F. Katz, "Acoustics of Notre-Dame Cathedral de Paris," in *Intl. Cong. Acoust.*, pp. 0269:1–10, sep 2016.

[13] S. Mullins, V. Le Page, J. De Muynke, E. K. Canfield-Dafilou, F. Billiet, and B. F. Katz, "Preliminary report on the effect of room acoustics on choral performance in Notre-Dame and its pre-Gothic predecessor," *J. Acoust. Am.*, vol. 150, no. 4, p. A258, 2021, doi:https://doi.org/10.1121/10.0008212.

[14] J. Hubert, "Les origines de Notre-Dame de Paris," *Revue d'histoire de l'Église de France, tome 50, n°147, 1964.*, 1964, doi:10.3406/rhef.1964.1726.

[15] E. Cirillo and F. Martellotta, "Sound propagation and energy relations in churches," *J Acoust Soc Am*, vol. 118, July 2005, doi:10.1121/1.1929231.

[16] B. Postma and B. F. Katz, "Perceptive and objective evaluation of calibrated room acoustic simulation auralizations," *J. Acoust. Soc. Am.*, vol. 140, pp. 4326–4337, Dec. 2016, doi:10.1121/1.4971422.

[17] B.-I. Dalenbäck, "CATT-A v9.1e:1 user's manual," 2019.

[18] B. F. Katz and A. Weber, "An Acoustic Survey of the Cathédrale Notre-Dame de Paris before and after the Fire of 2019," *Acoustics*, vol. 2, pp. 791–802, Nov. 2020, doi:10.3390/acoustics2040044.

[19] J. De Muynke, M. Baltazar, M. Monferran, C. Voisenat, and B. F. Katz, "Ears of the Past, an inquiry into the sonic memory of the acoustics of Notre-Dame before the fire of 2019," *J. of Cultural Heritage*, pp. 1–18, [submitted].

[20] F. Martellotta, "The just noticeable difference of center time and clarity index in large reverberant spaces," *J. Acoust. Soc. Am.*, vol. 128, pp. 654–663, Aug. 2010, doi:10.1121/1.3455837.

[21] ISO 3382-1, "Acoustics – measurement of room acoustic parameters – part 1: Performance spaces." Int. Organization for Standardization, 2009.

[22] E. K. Canfield-Dafilou, S. Mullins, and B. F. Katz, "Opening the lateral chapels and the acoustics of Notre-Dame de Paris: 1225–1320," in *Proc. Symp. Acoust. of Ancient Theatres*, 2022.