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Opening the Lateral Chapels and the Acoustics of Notre-Dame de Paris: 1225–1320

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ABSTRACT

Significant architectural modifications were made to Notre-Dame de Paris between the 1230s and the middle of the 14th century despite the completion of the central volume in the 1220s. These changes include the restructuring of the windows and attics along the clerestory and the gradual outward expansion of the building. Mainly, the transept arms were widened and side chapels were constructed between the buttresses along the perimeter of the cathedral. This study explores the acoustic effect the modifications to the transept and side chapels may have had on sound produced in the cathedral.
Keywords: room acoustics, cultural heritage acoustics, Notre-Dame de Paris

1. INTRODUCTION

Notre-Dame, the emblematic cathedral of the city of Paris, is an extraordinary monument of Gothic architecture with a storied history. Though the 2019 fire and plans around its restoration brought Notre-Dame de Paris back into the public eye, it is important to realize that large cathedrals such as Notre-Dame are "living" buildings, constructed and modified through centuries of development. Many multi-disciplinary projects are currently invested in detailing and preserving "intangible" cultural heritage [1, 2]. The present study focuses on the changes in the acoustics of Notre-Dame between the late 1220s and 1320s as the building was enlarged by expanding the transept and the construction of 35 chapels around the periphery of the cathedral.

Construction on the Cathédrale Notre-Dame de Paris began in the middle of the 12th century under the auspices of the bishop Maurice de Sully [3, 4]. By the year 1182, the apse-end of the cathedral was sufficiently completed such that the religious community began using the *chancel* (the holy eastern end of a church used by clergy) for religious ceremonies [5]. At this time, the vaulting above the chancel was not completed, and a temporary dividing wall would have separated the chancel from the yet-incomplete transept and nave. Around 1220, the body of the nave was completed, though nearly immediately, the cathedral underwent several significant changes. The clerestory windows and attics along the triforium level were restructured, the transept was enlarged and adorned with large, stained-glass rose windows, and 35 lateral chapels were added along the perimeter of the building between the buttresses [5, 6]. The acoustics of the earliest states of Notre-Dame (1160–1225) are discussed in [7], while the expansion of the transept and chapels (1225–1320) is the main subject of this study.

2. CHANTRY CHAPELS

In the 13th century, many cathedrals built *chantry* chapels that were funded and used by private foundations

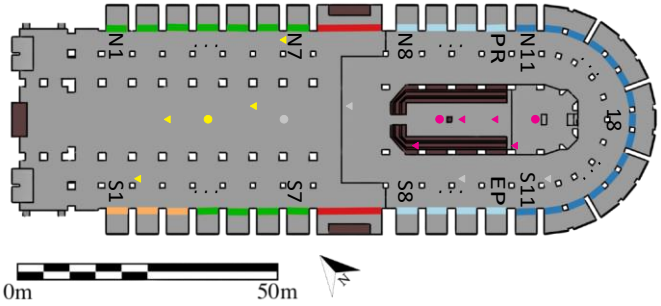

Figure 1 – Plan view of Notre-Dame between 1225–1320, showing the expansions in 1230 (red), 1240 (orange), 1250 (green), 1295 (cyan), and 1320 (blue). Source (●) and receiver (◂) locations used to calculate Figs. 2 and 3 are shown in magenta (apse), yellow (nave), and gray (not plotted).

[8, 9, 10]. These chapels served several purposes, including providing a locations for divine services, commemorating the dead, and displaying statues, stained-glass, and artwork for wealthy laypeople of the community. In Notre-Dame, the chapels were appended to the building in between the existing buttresses. While this structural limitation meant the chapels of Notre-Dame were relatively small and uniform in size (each about $5.2 \times 3.3 \times 10.3$ m with an entrance approximately 30 m^2), many other French churches copied their style. Doquang [10] argues that the lateral chapels of Notre-Dame had a large effect on the use of the cathedral as there were many (sometimes simultaneous) daily masses held within them.

There is textual evidence that there were chantry altars in the aisles of Notre-Dame before the chapels were built [3, 9, 10]. In 1209, the clergy in Notre-Dame passed an ordinance regulating the schedule and timings of private masses inside the cathedral due to their disruptive noise [11]. Over the course of $\approx$ 95 years, 35 chapels were appended (see Fig. 1). Their construction were overseen by several distinct craftsmen across multiple construction campaigns. The first several chapels were built in the nave on the south

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side (S). Following this, the seven chapels were completed on the north side (N) and first 4 chapels on the south side were complete. All the nave chapels were likely finished by 1250. Following the construction of the nave chapels, the first three straight chapels along the apse were completed by the end of the 13th century. Finally, the remaining chapels, including the double and tripled bays curving around the end of the cathedral, were completed by 1320 [12].

3. MATERIALS AND METHODS

Reverberation time (T_{30}), early decay time (EDT_{15}), and sound pressure (L_p) were calculated from simulations using a geometric acoustic (GA) model of Notre-Dame at different points during its construction. T_{30} provides a general impression of the reverberant conditions while EDT relates more to the perceived reverberance while sound is being produced.

A calibrated model of modern Notre-Dame (ca. 2015) [13, 14] was used as a starting point. Modifications were then made to the model to reflect the state of its construction between 1225–1320, as was done in [7, 15]. Acoustic simulations were run using CATT-Acoustic (v9.1f, TUCT v2.0e) [16] using algorithm 1 (split order $N = 1$) with 350,000 first-order rays to compute 10 s impulse responses for the sources and receivers shown in Fig. 1. Acoustic parameter results were averaged across 5 runs to account for variation due to stochastic processes. Mapping simulations were also produced using 150,000 rays to compute 4 s of data on a 0.5 m grid across the main floor of the cathedral.

Six model states were selected spanning approximately 1225 to 1320. These states, summarized in Table 1, include the "finished" state of the building when the nave was completed in 1220, a version with the expanded transept, several intermediate states as the chapels were built, and the state in 1320 after all the side chapels were completed.

It is important to note that these dates, and the associated models, are speculative. By consulting primary sources and through forensic inspection, historians can still only hypothesize—and disagree—about the timeline of the construction of Notre-Dame [3, 4]. Construction is a slow, physical process, and only important dates, such as when an altar was dedicated, funds received/allocated, or construction commenced or ended, are typically recorded. Even with a wealth of documentation, there are many aspects to the history of Notre-Dame that historians and archaeologists simply do not know. Especially in the early phases of construction, it is also likely that multiple sections of the cathedral were built simultaneously, so choosing "stable" milestones is likely anachronistic.

In order to understand the influence of the expansion of the perimeter of the cathedral, decor and material properties in the cathedral were kept constant across versions of the model. The geometry of Notre-Dame in 1320 is substantially similar to that of the base 2015 model. The main differences are that the modern choir stalls and altar have been replaced with ones modeled after depictions such as Jean Marot's painting of the *Te Deum* and the work of historians such as [5]. Additionally, the modern pews and carpeting have been removed from the nave. Finally, the building was simulated in an unoccupied state.

Table 1 – Approximate model dates with volume (V) and sur-face area (S) for Notre-Dame simulated in this study.

Year	V (m^3)	S (m^2)	Notes
1225	79,345	28,800	Nave completed
1230	82,380	29,710	Transept widened
1240	83,815	30,125	S1–3
1250	86,605	31,635	All nave chapels
1295	87,540	32,690	N8–10 and S8–10
1320	90,795	34,425	All chapels

4. RESULTS AND DISCUSSION

4.1 Chapels and Reverberation

Fig. 2 shows mean octave band T_{30} and EDT calculated from simulations of two omnidirectional sources and four receivers distributed throughout the choir. These sources (in the center of the choir and at the altar) and receivers (along the central line and in the choir stalls) were selected to give a general impression of the acoustic behavior in the space inhabited by the clergy of Notre-Dame. As the perimeter of the building was expanded, it seems likely that the reverberation time actually decreased. In all but the lowest 2 frequency bands, T_{30} and EDT drop by less than 5 % across the total time period considered.[1] In the 125–250 Hz bands, T_{30} decreases by less than 10 % and EDT decreases about 11 %. The choir stalls provide a substantial amount of early reflections, creating an acoustic subspace and leading EDT to be considerably lower than T_{30}. In the rest of the cathedral, EDT approaches T_{30} (see Fig. 3).

Between 1225 and 1320, the volume of the cathedral increased nearly 15 %, and the surface area by nearly 20 %. The fact that the surface area increased at a faster rate than the volume is one possible explanation for why the reverberation time decreased as the cathedral was expanded. That said, the expansion of the cathedral progressed at a gradual rate. Considering that 1 JND is the perceptual limit where a change is barely noticeable, it is reasonable to conclude that the opening of the chapels would have had a relatively minor effect on the perceived reverberation in the cathedral year by year due to the slow rate of construction.

In the current model, all side chapels have been modeled identically, however that does not truly conform to the

[1] 5 % is typically considered the JND for T_{30} and EDT [17], Though recent work [18] suggests that these limits for EDT may be too conservative.

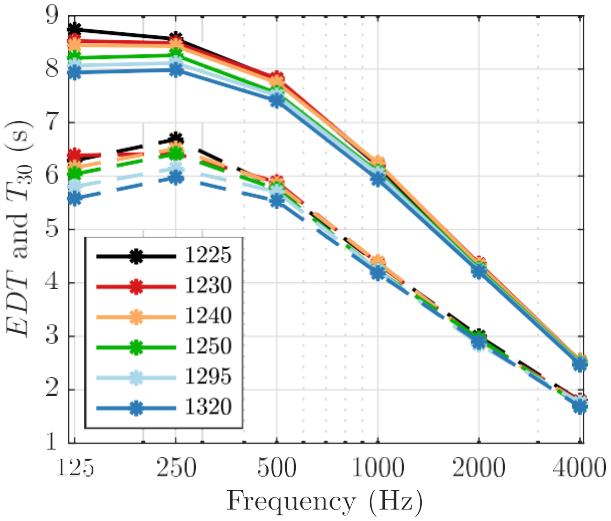

Figure 2 – Spatial average of Notre-Dame T_{30} (—) and *EDT* (- -) for source and receiver positions in the choir as a functionof building state.

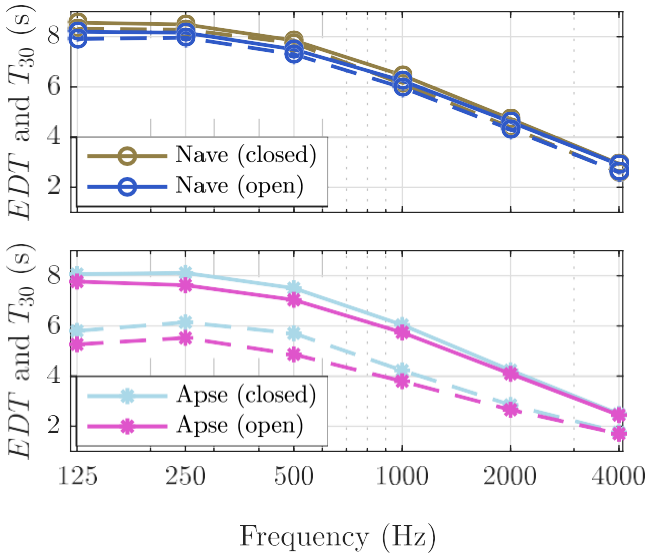

Figure 3 – Comparison of 1295 state T_{30} (—) and *EDT* (--)with open vs closed exterior walls in chapels S8–10 and N8–10. Source/receiver positions in the nave (top) and apse (bottom).

real cathedral. Since the chapels were sponsored by private foundations, each was ornately decorated by their benefactors. When the chapels were first constructed, they would likely have had plain windows that were gradually replaced with more ornate stained-glass over time [8]. Since so little is known about the early state of the chapels, it is interesting to consider the influence of the construction process on the reverberation time. Fig. 3 shows a comparison of mean T_{30} and *EDT* of the 1295 state with the outer wall of the chapels removed (i.e., 6 chapels open to the outside, modeled as fully absorbing). Here, it is possible to observe a 3–6 % reduction in T_{30} and a 10–15 % reduction in *EDT* from within the chancel. In the nave, further away from the holes in the building, the *EDT* and T_{30} change by 3–5 %, a much more modest amount. From within the chancel, this change in reverberation might be considered significant. Considering the rose windows in the transept took years to complete [5], the overall process of construction may have had a more significant effect on the reverberation in the cathedral than the end result of the expansion of the building.

4.2 Chapel activity and noise

It is also worthwhile to consider the effect of the use of the lateral chapels by chaplaincies. In the Middle Ages, there is evidence of a significant number of masses taking place at altars in the side aisles, and later at those of the lateral chapels [10, 11]. Fig. 4 shows a sound pressure level map across the cathedral in the 1225 and 1320 states for a single source at either an altar in the side of the cathedral in the apse or nave. Considering the sound of a chaplain saying a private mass, a vocal directivity pattern [19] and speech spectrum of a male voice speaking at a normal level [20] were used. For the 1225 model, the altar is assumed to be facing the external wall of the cathedral (north), while for the 1320 model, the altar is positioned on the wall facing liturgical east. As the differences can be challenging to see, Fig. 4 also shows the difference between the two conditions.

Beyond the longer reverberation time in the 1225 model, the mapping results demonstrate a slightly elevated background noise level (2–5 dB; L_p JND ≈ 1dB) in the ambulatory when a source is in the aisle in contrast to a side chapel. When considering a sound source in the nave, this effect is surprising given the large distance between the source in the nave and the receivers in the ambulatory. In light of the documented concern of the clergy with the noise level produced by the chaplaincies [10], it seems like the construction of side chapels may have helped mitigate noise issues, even if by a small amount.

5. CONCLUSION

This study explored the relatively minor change in reverberation time seen in Cathédrale Notre-Dame de Paris between the years of 1225 and 1320 as 35 lateral chapels were constructed around the perimeter of the building. T_{30} and *EDT* likely decreased throughout this time period, but by a relatively small amount (5–11 % in total). When the exterior walls of 6 chapels were removed entirely, as could have been the case during construction, the *EDT* for source/receivers in the chancel decreased by a more significant amount (10–15 %) while the T_{30} only decreased by 3–6 %. In the nave, further away from the open walls, both T_{30} and *EDT* for source/receivers there decreased by less than 5 %. Other factors likely had a more significant effect on the acoustics of the cathedral, such as tapestries and other adornments that would be displayed during holiday celebrations, and the occupation of the space during daily activities in the Middle Ages. These questions are the subject of future studies currently in preparation. Finally, a sound source within

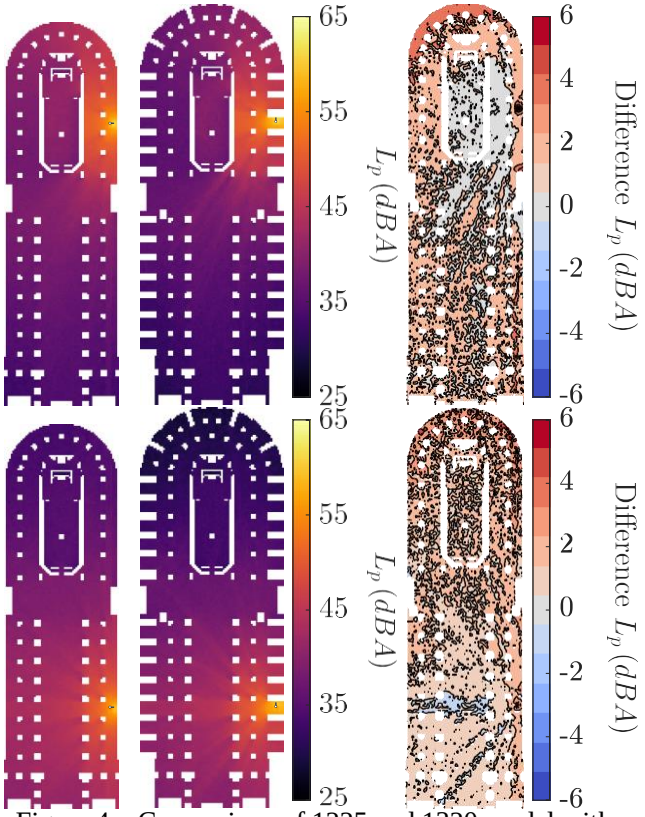

Figure 4 – Comparison of 1225 and 1320 model with source located in the aisle vs side chapel, and their difference (the level of the 1225 state minus the level of the 1320 state). Source in the apse (top) and nave (bottom).

a side chapel radiates differently throughout the cathedral compared to a source located in the aisle.

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REFERENCES

[1] UNESCO, "The importance of sound in today's world: promoting best practices," UNESCO, Tech. Rep. Resolution 39 C/49, 2017. [Online]. Available: https://unesdoc.unesco.org/ark:/48223/pf0000259172

[2] ——, "Convention for the safeguarding of the intangible cultural heritage," UNESCO, Tech. Rep., 2018. [Online]. Available: https://ich.unesco.org/en/convention

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

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

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

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

[7] S. Mullins, E. K. Canfield-Dafilou, and B. F. G. Katz, "The development of the early acoustics of the chancel in Notre-Dame de Paris: 1160–1230," in *Proc. Symp. Acoust. of Ancient Theatres*, 2022.

[8] H. Kraus, "Notre-Dame's vanished medieval glass," *Gazette des beaux-arts*, vol. 68, pp. 131–148, 1966.

[9] ——, "New documents for Notre-Dame's early chapels," *Gazette des beaux-arts*, vol. 74, pp. 121–134, 1969.

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

[11] C. Freigang, "Chapelles latérales privées. origines, fonctions, financement: le cas de Notre Dame de Paris," in *Art, cérémonial et liturgie au Moyen Âge*, N. Bock, Ed. Études lausannoises d'histoire de l'art, 2002.

[12] M. T. Davis, "Splendor and peril: The cathedral of Paris, 1290–1350," *Art Bulletin*, vol. 80, no. 1, pp. 34–66, 1998.

[13] B. N. J. Postma and B. F. G. Katz, "Creation and calibration method of virtual acoustic models for historic auralizations," *Virtual Reality*, vol. 19, pp. 161–180, 2015.

[14] ——, "Perceptive and objective evaluation of calibrated room acoustic simulation auralizations," *J. Acoust. Soc. Am.*, vol. 140, no. 6, pp. 4326–4337, Dec. 2016.

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

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

[17] ISO 3382-1, "Acoustics – measurement of room acoustic parameters – part 1: Performance spaces," Int. Organization for Standardization, pp. 1–26, 2009.

[18] F. del Solar Dorrego and M. C. Vigeant, "A study of the just noticeable difference of early decay time for symphonic halls," *J. Acoust. Soc. Am.*, vol. 151, no. 1, pp. 80–94, 2022.

[19] A. Marshall and J. Meyer, "The directivity and auditory impressions of singers," *Acta Acustica united with Acustica*, vol. 58, no. 3, pp. 130–140, 1985.

[20] ANSI/ASA S3.5-1997, "Methods for calculation of the speech intelligibility index," 1997.