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Article

An Acoustic Survey of the Cathédrale Notre-Dame de Paris before and after the Fire of 2019

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Abstract: The Cathédrale Notre-Dame de Paris is amongst the most well-known worship spaces in the world. Its large volume, in combination with a relatively bare stone construction and marble floor, leads to rather long reverberation times. The cathedral suffered from a significant fire in 2019, resulting in damage primarily to the roof and vaulted ceiling. Despite the notoriety of this space, there are few examples of published data on the acoustical parameters of this space, and these data do not agree. Archived measurement recordings from 1987 were recovered and found to include several balloon bursts. In 2015, a measurement session was carried out for a virtual reality project. Comparisons between results from these two sessions show a slight but significant decrease in reverberation time (8%) in the pre-fire state. Measurements were recently carried out on the construction site, 1 year since the fire. Compared to 2015 data, the reverberation time significantly decreased (20%). This paper presents the preliminary results of these measurements, providing a documentation of the acoustics of this historic worship space both prior to and since the 2019 fire.

Keywords: room-acoustic measurement; Notre-Dame de Paris; reverberation time; cultural heritage

1. Introduction

The acoustics of worship spaces have been a topic of research for many decades. Due to their significant dimensions, these spaces have been used over the centuries for cultural as well as religious activities. Such spaces often exhibit acoustic anomalies (e.g., whispering galleries and coupled volumes). An overview of a significant portion of this research has been reviewed in Girón et al. [1], discussing different experimental procedures, results, and their theoretical interpretations. A number of notable studies have been carried out in spaces of significant historical importance: St. Peter's Basilica [2], Hagia Sofia and Süleymaniye Mosque [3], St. John's Baptistery [4], Saint-Germain-des-Prés Abbey [5], and St. Paul's Cathedral [6].

The Cathédrale Notre-Dame de Paris is amongst the most well-known worship spaces in the world. This medieval cathedral is widely considered to be one of the finest examples of French Gothic architecture. The large volume in combination with its vast exposed limestone and marble surfaces lead to long reverberation times. Despite the notoriety of this space, there are few examples of published data on the acoustical parameters of this space.

Built at the end of the 12th century, the Gothic Cathédrale Notre-Dame de Paris became the emblematic place of musical creation in Europe, which historians call the "Ecole Notre Dame". Documents testify to the musical activity during this period and it is possible to think that the spectacular development of this Parisian polyphony coincided with the organization of the liturgy in the new choir inaugurated in 1182. The decrees of Cathédrale Notre-Dame de Paris, promulgated in 1198 and 1199 by Bishop Eudes de Sully, attest to a practice of two, three, and four voices for the responsorial chants of the mass and offices as well as for the *Benedicamus Domino* of Vespers [7,8].

We are fortunate to have a historic text written by an English schoolmaster [9], which describes the musical practices around 1275 in the choir of this Cathedral where the sound of the organum and semi-improvised conductus could rise, towards the apse, before being noted in various manuscripts which testify to the richness of the *Magnus liber organi* [10] (Latin for “Great Book of Organum” in use by the Parisian School of Notre-Dame around the turn of the 12th & 13th centuries). Over the centuries, the methods evolved and with the Gregorian melodies, which escape the closed choir or circulate with the processions, the sounds of the organ, the bells, and the complex polyphonic works of the Franco-Flemish counterpoint were mixed together. “The appointment of Antoine Brumel in 1498 brought a breath of fresh air: the future choirmaster of the Duke of Ferrara brought with him the best and latest in Franco-Flemish polyphony” [11]. The history of music will remember the names of great masters and composers such as André Campra, Jean-François Lalouette, or Jean-François Lesueur, who, after the revolutionary period, composed the famous March of the Coronation, for Napoleon’s entry into the cathedral in 1804, and various pieces for the Coronation Mass. (Edited excerpt from <http://acoustic-task-force-notre-dame.dalembert.upmc.fr/doku.php?id=lavierge2020>)

On 15 April 2019 a fire broke out in the attic of the Cathédrale Notre-Dame de Paris. The resulting damage destroyed the roof and left three large holes in the vaulted ceiling when the spire and other debris fell. As the restoration work continues, with significant documentation efforts being carried out on the structural and material aspects of the cathedral, this work presents recent efforts to document the room acoustic conditions of the cathedral, providing analysis of data acquired both before the fire and during the reconstruction process. Certain elements of this work have been presented previously in a scientific conference [12].

2. Published Acoustic Data

Despite the notoriety of this space, there are few examples of published data on the acoustical parameters of this space. Hamayon [13] presented reverberation time estimations as a function of octave bands [125 to 4000 Hz: 8.5, 8.0, 7.5, 6.0, 4.5, 2.7 s]. Mercier [14] presented slightly different reverberation time values [125 to 4000 Hz: 8.5, 8.2, 6.5, 6.2, 4.7, 2.5 s]. Both studies presented simply the reverberation times without any reference or measurement protocol information.

3. Materials and Methods: Measurements in the 20th & 21st Centuries

3.1. Historical Data from 1987

Archival recordings (1987) were recovered from an acoustic study relating to a new organ [15] which included several balloon bursts.

Measurement protocol—Figure 1a shows the measurement plan for the 1987 measurements with source-receiver (S–R) positions. While a variety of techniques using different stimuli were employed, only balloon burst sources were exploitable due to lack of excitation stimuli details (e.g., anechoic signals, sweep stimuli parameters). Three balloon bursts from source position 1 were recorded as well as 1 balloon burst from source position 2. These positions corresponded to “relavent” source positions [16] for the cathedral, with S2 being near the center of the altar area in the transept and S1 being near the pulpit, which is closer to the center of the public area.

Measurement equipment input—The sound was recorded with 13 omnidirectional microphones which were connected to a multitrack reel-to-reel recorder (Tascam). While not an ideal omnidirectional source, balloon bursts are a useful tool in certain situations, offering a portable impulsive source [17]. Recordings were digitized from the analog tape.

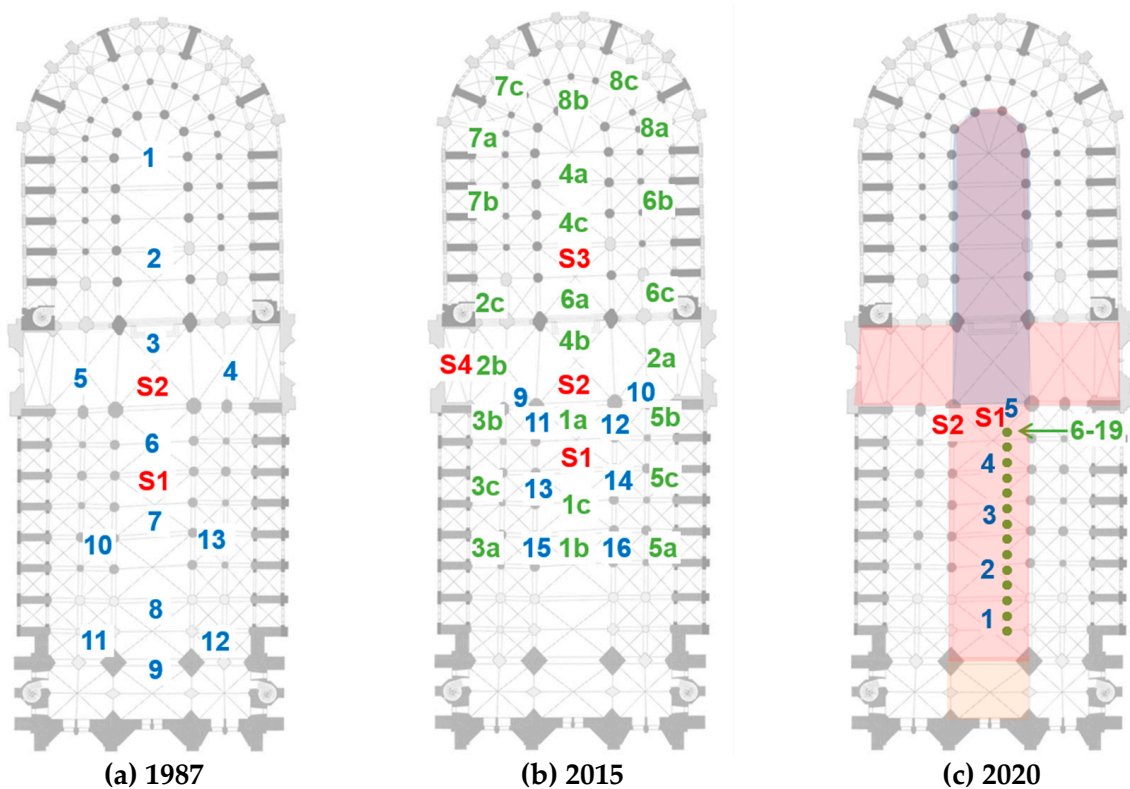


Figure 1. Measurement plans for the (a) 1987, (b) 2015, and (c) 2020 sessions at the Cathédrale Notre-Dame de Paris. Positions are centered under numbered source (S# (red)) and microphone (# (blue and green)) labels or at points when the measured grid too dense. The 2020 plan (c) also indicates in shaded regions the scaffolding (yellow), exclusion zone to people (red), and encumbered/damaged ground of the exclusion zone (blue) where it was not possible to place measurement equipment.

3.2. Detailed Measurements in 2015

On the evening of 13 April 2015, almost 4 years to the day before the 2019 fire, a series of acoustic measurements were carried out following a small concert performance.

Measurement protocol—Figure 1b shows the measurement plan highlighting S-R positions for the 2015 measurement (see photos in Figure 2a). Source positions reflected those from the 1987 measurements as well as S3 representing the choir and S4 as this was tested in 1987, though without balloon burst as was discovered after the measurements were carried out. Three measurement sets of 2 sine-sweeps during which microphones 1–8 changed positions were carried out (height of 1.5 m, the changing positions of these microphones are represented by the letters behind the measurement position). Due to excessive exterior noise, the first measurement repetition was carried out twice, resulting in 4 measurement sets. Microphones 9–16 hung from the ceiling (7 m above floor 88 level, to capture the reverberant field for use by the recording engineers for the concert recording), 89 thus remained at the same position and consequently recorded eight similar RIRs. These repeated 90 measurements allowed for an investigation into the stability of the acoustic response over time, 91 addressing subtle effects of temperature change [18]. After the last sweep measurement, a balloon burst at every source position was recorded with the receivers at the final position.

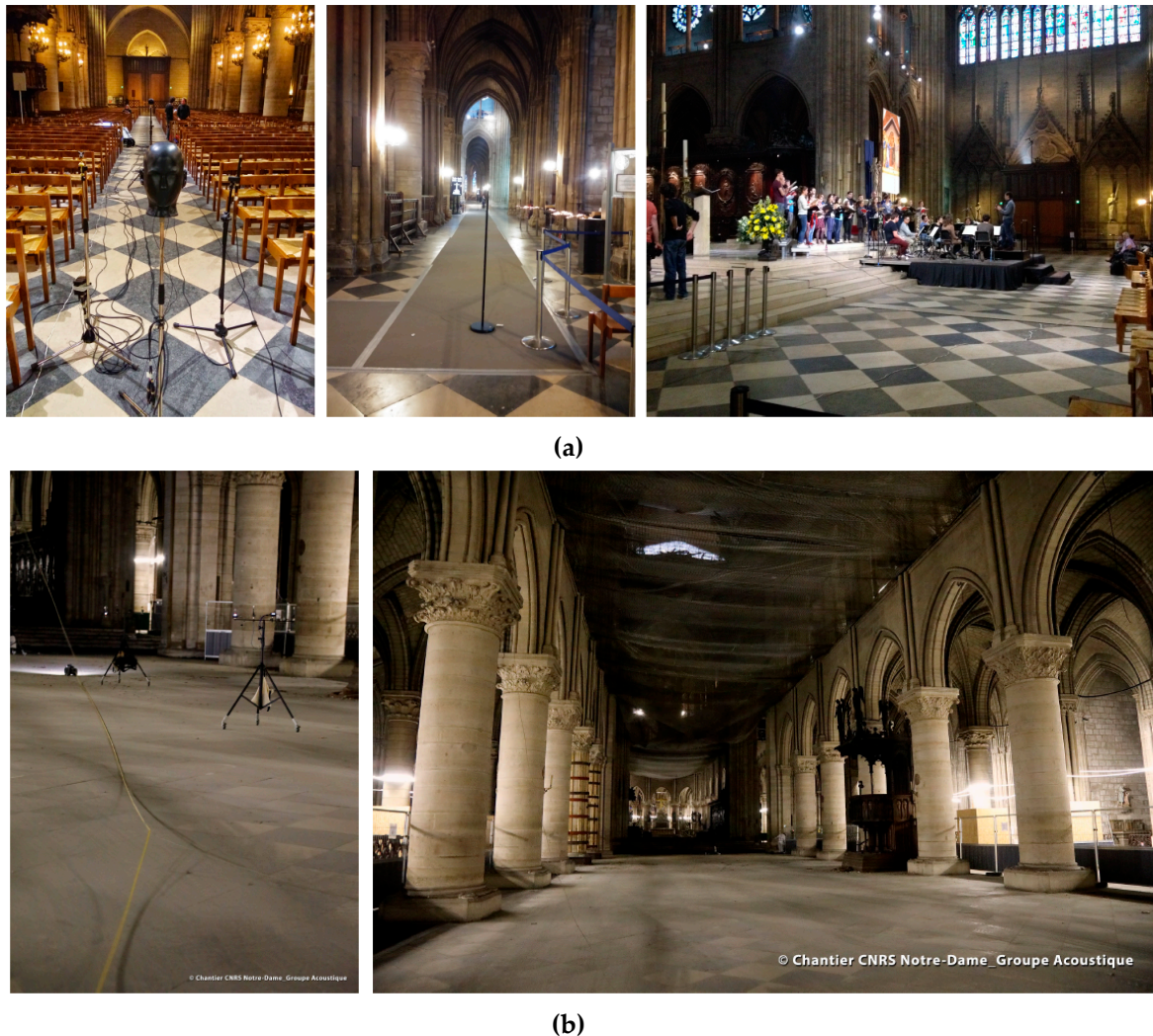


Figure 2. Photos of conditions for the (a) 2015, highlighting measurement equipment, carpet runner, and small concert risers in place during the measurement session; (b) 2020, highlighting microphone tripods pulled by remote controlled robot, barrier, and general empty state of the nave during the measurements.

Measurement equipment output—The audio output was sent to an amplifier (SAMSOM, model Servo 120a, Hicksville, USA) and sequentially to four miniature dodecahedral sound sources (Dr-Three, model 3D-032, Tokyo, Japan). **Signal**—The excitation signal was based on the Swept Sine method. The sweep frequency rose exponentially over 20 s from 20 to 20,000 Hz. However, due to the frequency response of these specific speakers, there was insufficient energy below the 250 Hz octave band for analysis. The sweep was played at a sample rate of 44.1 kHz using the DAW software Reaper and sound card (RME, Fireface 800, Haimhausen, Germany).

Measurement equipment input—The reverberated signal was recorded by two measurement chains as the measured session was carried out in conjunction with a concert recording installation. (I) The sweep was recorded at a sample rate of 44.1 kHz by 5 omni-directional microphones (4 DPA (Alleroed, Denmark), model 4006 (1–4) and 1 Schoeps (Karlsruhe, Germany) model MK5 omni (5), 1 dummy-head (KU-80, equipped with DPA 4060) and a 1st-order Ambisonic microphone (Core Audio, Tetramic, Teaneck, NJ, USA), all recorded using a sound card (RME, Fireface 800). (II) The sweep was recorded at a sample rate of 48 kHz by the other 11 omni-directional microphones (6 DPA model 4006 (11–16), 5 Schoeps model MK5 omni, (6–10)) and using a sound card (RME, Micstasy).

3.3. Measurements Post-Fire during Reconstruction, 2020

Access was granted to the reconstruction site and acoustic measurements were carried on the 30 June 2020. Due to the restrictions on the work site, only certain areas were accessible. Due to the risk of falling debris, the central nave and transept was off-limits to people, as detailed in Figure 1c. The central part of the transept/altar marble floor was damaged by the falling spire. The choir area was cluttered with debris, sorted by the recovery team, and therefore totally inaccessible. Many of the side altars have been used to store objects. There was also scaffolding installed for the removal of the organ and a protection barrier (construction fencing and waist-height perforated metal panels) surrounding the central nave. See photos in Figure 2b; a short video documenting the measurement session is available online (<https://youtu.be/YLi7ASosKvw>).

Measurement protocol—Figure 1c shows the measurement plan highlighting S-R positions for the 2020 measurement. Source position S1 was chosen for the loudspeaker, so as to be as close as possible to positions used in previous measurements, given the access constraints. Source position S2 was used for hand-held impulse sources, as this was the closest position to S1 achievable. A remote controlled robot (used for tunnel inspections) was employed to pull microphones installed on wheeled tripods. Microphone positions 1–5 represented the first measurement trajectory. Due to the time remaining, the return trajectory by the robot (positions 6–19) allowed for a denser distribution. Sweeps were played from position S1.

Measurement equipment output—The source was a battery powered dodecahedron acoustic source (Look Line, S103 ACDC, Massa Finalese, Italy), equipped with its own internal amplifier and sweep generator, remote controlled, positioned at source position S1. The excitation signal was the internal 20 s Swept Sine. Several supplemental impulsive stimuli, starter pistol gun shots and balloon bursts, were made from source position S2, at the limits of the exclusion zone.

Measurement equipment input—The reverberated signal was recorded on a variety of portable recording devices, in order to limit cabling and clutter due to the robot manipulations. Recordings were made using two omni-directional microphones (Bedrock, BAMT1 1/2", Delft, The Netherlands) connected to a portable recorder (Zoom, H6, Tokyo, Japan) in addition to one MS pair (Zoom, H6). Two 3D microphones (Core Audio, Tetramic and Octomic) were recorded onto portable recorders (Zoom, F8). Finally, two autonomous 3D microphones (Zoom, H3-VR) were used, one in conjunction with a 360° camera (Samsung, Gear360, Seoul, South Korea). Source/receiver heights were 1.7 m, limited by the wheeled-tripod apparatus used to place the equipment.

3.4. Post-Processing

Subsequent deconvolution for swept sine stimuli, sample rate conversion, and post-processing steps were performed in MATLAB. RIRs were analyzed using our in-house MATLAB IR analysis (IRA) toolkit in accordance with the ISO 3382 standard [19].

3.5. Architectural Details

The Cathédrale Notre-Dame de Paris is approximately 130 m long, 48 m wide, and 35 m high.

In a telephone conversation with the office of the Cathédrale Notre-Dame de Paris, it was confirmed that a carpet runner was installed in several areas and two confirmation booths were added in the two chapels (side alcoves or bays) adjacent to the first two bays of the south naves during this time period. As such, the difference between 1987 and 2015 is principally the installation of a carpet runner (see Figures 2a and 3a). From the 2015 to 2020, the principal differences following the fire are the removal of the carpet runner, the removal of the pews, and the holes in the vaulted ceiling. Figure 3b shows the principal reported holes in the ceiling from the restoration team. The size of the holes in the architectural drawing was estimated at 263 m², using a 2D projection (ignoring elevation topology). This equates to about 1% of the bounding box's surface area, based on the above dimensions.

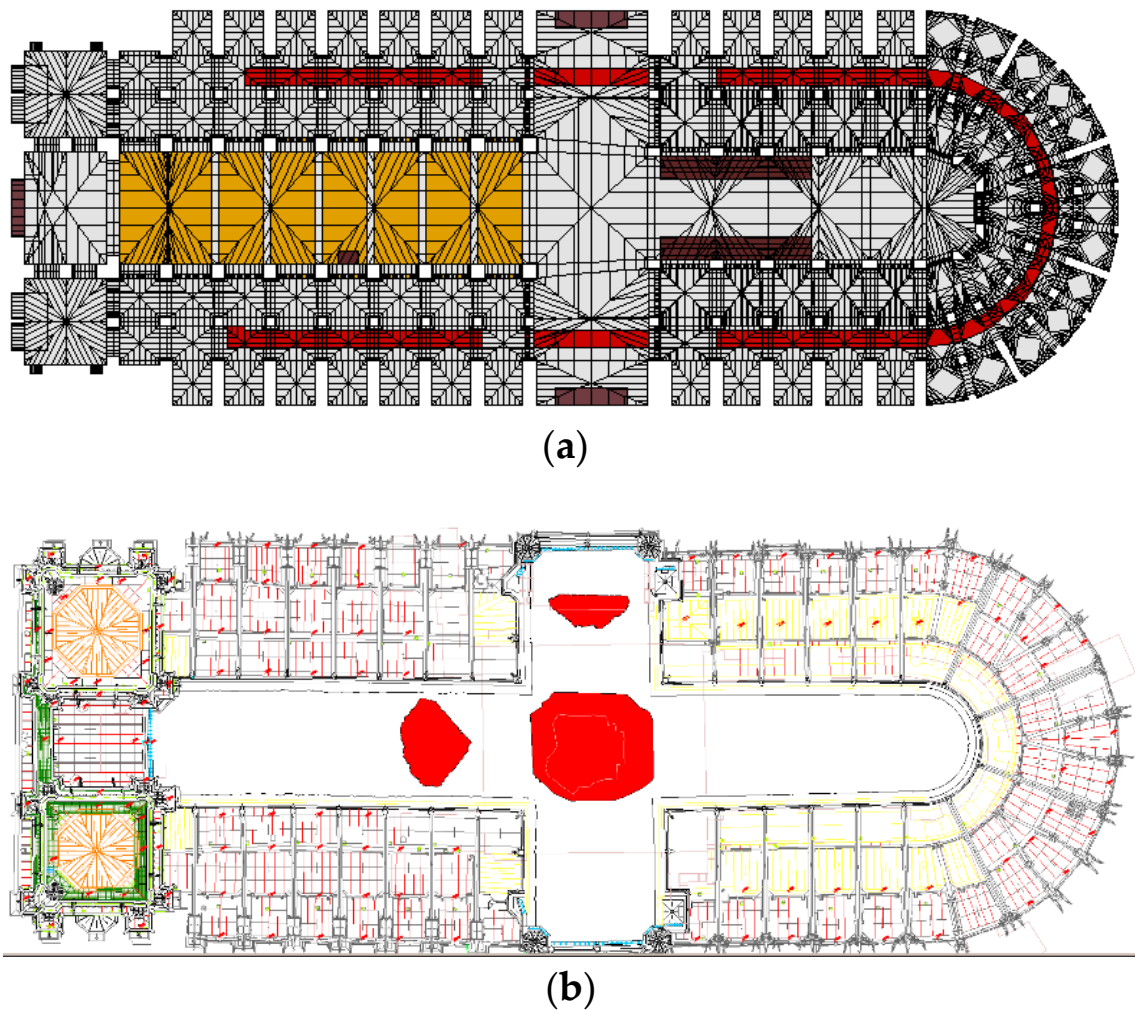


Figure 3. Schematics of the Cathédrale Notre-Dame de Paris highlighting specific surfaces. (a) Computer model highlighting pew locations (yellow) and carpet runner addition (red); (b) Architectural plans indicating the principal holes (red) in the vaulted ceiling (2020).

4. Measurement Results

4.1. Acoustic Parameters

Due to the variations in source/receiver positions over the three measurement sessions, and the drastic differences in conditions for the 2020 measurements, preliminary analysis presented here focuses on reverberation time measurements, rather than parameters which are more sensitive to local architectural features. Mean reverberation times (T_{20}) were calculated over omnidirectional microphones in all three measurement conditions, shown in Figure 4a.

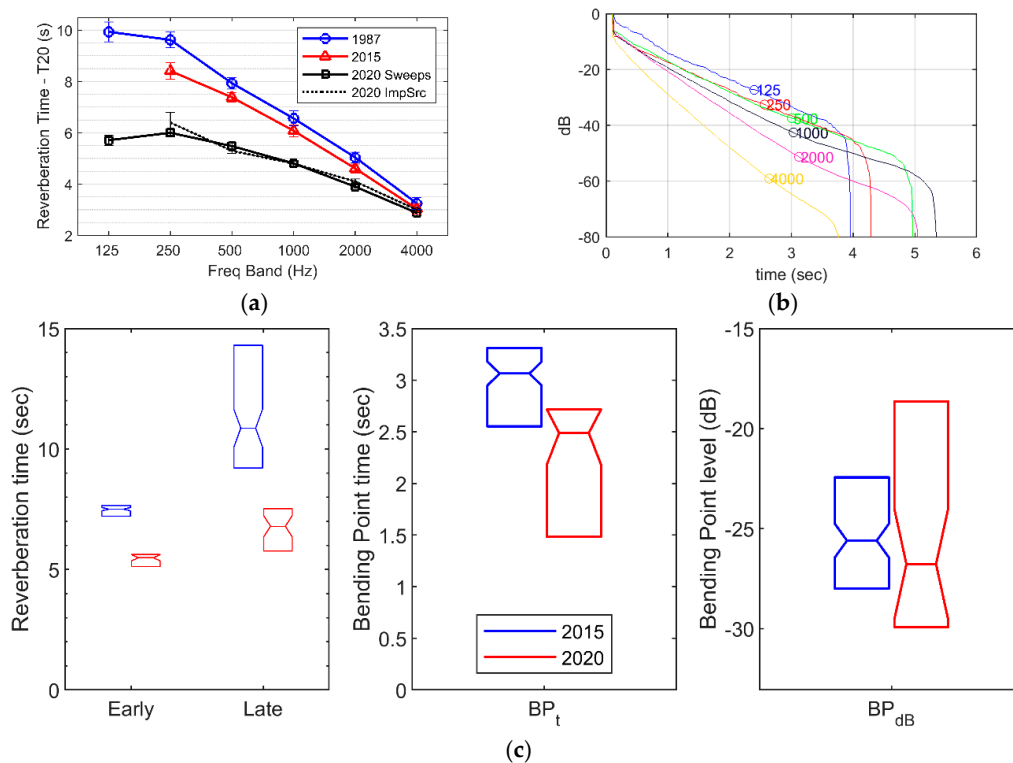


Figure 4. Summary of mean reverberation time over receivers, example decay curve, and coupled volume analysis, (a) Mean reverberation time (T20) over omnidirectional microphones with standard error bars. 2020 results show those for sweep stimuli (S1) and impulse source gun-shots (S2, Rec positions 1–5); (b) Example of octave band filtered RIC decays, normalized, optimized SNR truncation, 2020 sweep stimuli data-set; (c) double-slope decay 500 Hz-octave band analysis distributions showing **Early** and **Late** reverberation times and the relative time (BP_t) and level (BP_{dB}) of the identified bending point in the RIC decay curves ([20] for parameter details). Notched boxplots show the median, 95% confidence interval, 25th and 75th percentiles of the data spread.

The 2020 measurement protocol employed non-synchronized audio input/output devices. While differences in exact clock rates between devices could result in temporal distortions of the deconvolved signal, Hak and Hak [21] have shown that such errors are less significant for sweep stimuli when compared to MLS signals. In addition, typical clock errors were found in that study to be sufficiently small, such that expected deviations in reverberation time would be less than a few percent. To verify the asynchronous measures, reverberation times were also calculated for the 2020 impulsive source gun shots, made from source position S2. Results show differences between the two measurement methods varied within standard error across positions and frequencies, except for the 250 Hz band which showed slightly higher values (by 7%) and the 125 Hz band which lacked sufficient energy for analysis.

Examining reverberation time across measurement sessions, a mean reduction of 8% is observed from 1987 to 2015. Comparison between 2015 and 2020 shows a markedly more significant reduction, mean decrease in T20 of 20%, across frequency bands.

Closer inspection of the RIR can provide additional information. An example of the RIC, used to calculate the above room acoustic parameters, is shown in Figure 4b. Decay curves show a sharp step, or “cliff” response, as has been observed in open-air theatres [22]. This is reasonable, considering the lack of proximal reflecting surfaces, other than the smooth empty floor. Some slight change in decay rate is apparent between the earlier and later part of the response, indicating a lightly coupled volume behavior.

Further analysis of this has been carried out, using the **marching line** multiple slope analysis method [23,24]. For brevity, this analysis has been limited to the 500 Hz octave band filtered RIRs,

and compares the 2020 measurements with the subset of 2015 measurements using comparable source and receiver positions to the reduced measurement zone in 2020. This method estimates the early and late decay rates in the RIC, in addition to characterizing the bending point in both time and level relative to the RIR onset. As the behavior of coupled volume decays varies with respect to source and receiver position within the complex architecture [25], the distribution of results are presented for each parameter, comparing the 2015 and 2020 RIRs, for source and receiver positions in the lower part of the nave (the common measurement area in the two datasets).

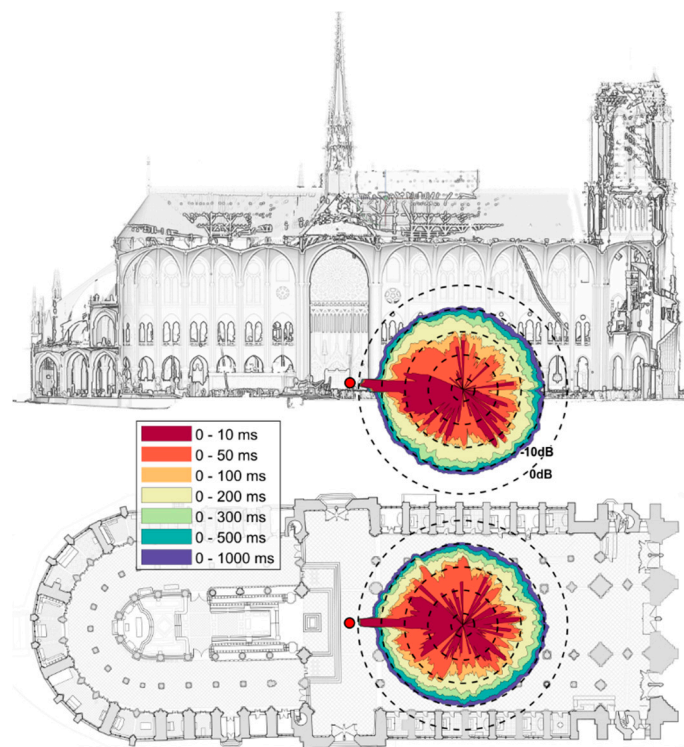
Results of the non-linear decay analysis, shown in Figure 4c, reflect the general decrease in reverberation times indicated in Figure 4a, while also highlighting the problem of using the ISO parameters when non-linear decays are present. Results show a decrease in both **Early** and **Late** decay rates, indicating reductions in both the primary and secondary “volumes”. In the case of Notre-Dame, the delimitation of the different acoustic volumes is not as stark and evident as in coupled reverberation concert hall designs. However, the transept could be considered as rather different from other spaces, due to its high ceiling, while side areas (except for the transept) have multiple levels. As the holes in the vaulted ceiling are in the region of the transept (Figure 3b), but one of the holes is over the source/receiver region, the damage could be imagined to affect multiple acoustic “volumes”. The reduction in decay rates in these volumes also results in a decrease in the bending point time and, to a lesser extent, level, and it is noted that all of these parameters are linked to the acoustic coupling conditions. The variability in **Late** reverberation times for the 2015 condition could be attributed to the complexity of the space, and the various acoustic zones, leading to more than a simple double-slope decay, and rather higher order coupling. Further analysis and measurements would need to be carried out to examine this supposition further.

Finally, considering perceptual detectability, following Luizard et al. [20], the mean just-noticeable-difference (JND) for **Early** decay rates in coupled conditions can be on the order of 7% to 10%, and twice that for **Late** decays. Similarly, the JND for BPT is on the order 15% to 30%, which covers the differences observed here. As such, it can be confidently stated that the differences in the acoustic conditions are clearly audible.

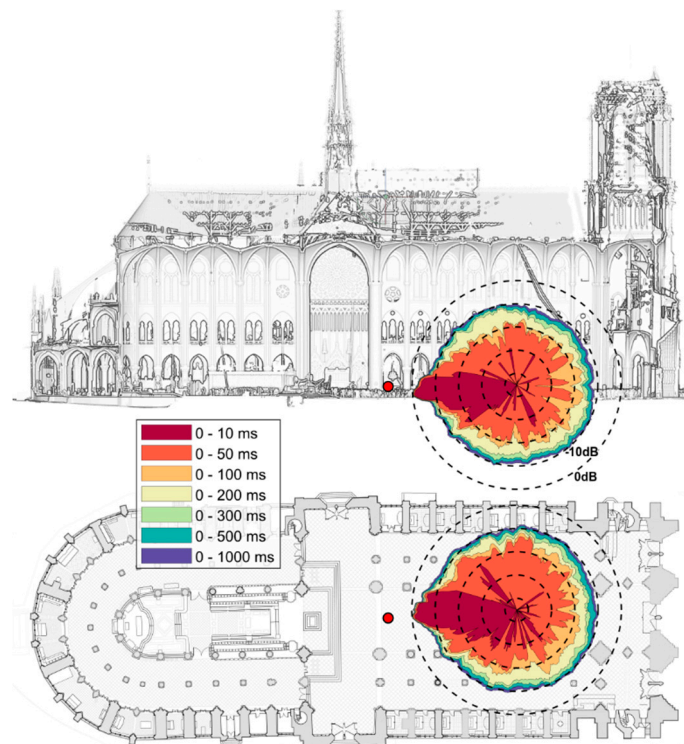
4.2. Spatial Analysis

Spatial room impulse responses (SRIR) can be used for a comparative directional analysis of room acoustics. The method chosen here is a parametric approach, the Spatial Decomposition Method (SDM) [26]. It is based on the assumption that the sound field can be described as a succession of plane waves and thus a SRIR can be decomposed into a set of discrete pressure values and their corresponding direction of arrival (DOA), i.e., an image-source is attributed at each time sample. For this, a small time window centered on the sample of interest is applied to the SRIR and the DOA is estimated by least squares solution for the time difference of arrival (TDOA) estimates. The pressure value is assigned using ideally an omnidirectional impulse response at the center of the array. This method has been used for analysis and auralization of concert hall SRIR [27], and also for their graphical representation [28]. These tools are implemented in a MATLAB package, the SDM Toolbox [29].

SDM analysis was applied to the 2015 and 2020 measurements made with the same 3D tetrahedral microphone array. DOA were estimated using the A-format signals (representing a tetrahedral array of near-coincident cardioid microphones). The analysis window was set to the minimal allowed size defined by twice the time it takes for an impulse to travel through the array, for the microphone used, representing approximately 0.4 ms. To obtain the pressure value at the center of the microphone, necessary for graphical representation of SRIR, the post-processed B-format omnidirectional W-channel signal was used, as such assignment should be applied to a direction independent RIR. Results in the median and lateral planes for a similar source-receiver pair position are shown in Figure 5. It is important to note that in 2020, there were no pews, with the floor being empty. In contrast, in 2015 there were both pews and some stage risers and, chairs, and music stands for the music performance (see Figure 2a). In comparing these results, several observations can be made.



(a)



(b)

Figure 5. SDM analysis showing cumulative energy polar distribution curves from 0 ms to [10, 50, 100, 200, 300, 500, 1000] ms, band pass filtered 100 Hz to 5000 Hz, 5° sliding average. Source position indicated (red dot). (a) SDM analysis: state 2015, Src S2–Rec 1c; (b) SDM analysis: state 2020, Src S1, Rec 16. Longitudinal cross-sections obtained from the digital platform of the CNRS/MC scientific action for the restoration of Notre-Dame de Paris, source: 3D laser-scanning by Andrew Tallon (2016).

Concerning the direct sound, 2015 shows this as well localised and sharp (slightly elevated, which corresponds to its position and the fact that the source was raised at the time). The floor reflection is not visible, likely due to the presence of chairs and pews. In 2020, the direct sound “lobe” is broader, less sharp. Examining the side-view plot, the direct sound (actually the initial 0 ms to 10 ms window of the response) exhibits a slightly negative elevation. This is likely due to the empty flat floor, where the strong floor reflection is counted within the 10 ms analysis window, thereby lowering and broadening the early part of the response.

Concerning the cumulative energy, in 2015 this increases rather smoothly and uniformly from all directions, as represented by the regular radial spacing between subsequent energy contour curves, with the largest increase from 100 to 200 ms, thus reflections arriving with path differences of 35 to 70 m after the direct sound, mainly attributed to the vaulted ceiling. The first increase in lateral energy occurs from 10 to 50 ms after the arrival of direct sound, coinciding with reflections from the rows of columns in the nave as well as the side balconies. The final analysis window comprising 0 to 1000 ms is quite round at a relative level of -10 dB, both in plane and section. In contrast, 2020 results show a more step-function decrease in energy after the initial time window, as mentioned in the earlier analysis, indicating a lack of progressive reflection accumulation over time, especially in the vertical direction. The relative cumulative level between 200 and 1000 ms, averaged over all directions, is 2 dB, which is 2 dB lower than the 2015 results.

5. Discussion and Future Work

As data from [13,14] were comparable to the 2015 measurements, it can be concluded that changes leading to the shorter reverberation time estimations were carried out between 1987 and 1996. As the volume of the Cathédrale Notre-Dame de Paris is rather large, the reverberation time difference has to be the result of substantial changes. The possibility of the atmospheric conditions influencing the reverberation time results can also be considered. However, as temperature and relative humidity mainly effect reverberation estimations above 1000 Hz [30], this can be excluded as the cause for the decrease in reverberation time. The carpet runner is therefore a likely candidate.

The decrease in reverberation time since the destructive fire of 2019 is clearly evident. The same differences were observed using both swept-sine and impulsive sources and relatively proximal positions. The architectural elements inducing the drastic reduction in T20 of 20% remain to be verified. Non-linear decay rates, or coupled acoustic volume analysis, highlight the fact that the changes are large in scale, affecting different areas of the cathedral, for which the holes in the vaulted ceiling are likely candidates for at least a significant contribution. Subsequent work will require identifying the acoustic effects of the fire damage relative to the effects of the temporary installations in place and remaining debris.

As a geometrical acoustic model of the Cathédrale Notre-Dame de Paris was created and calibrated from the 2015 measurements for the production of a virtual concert reconstruction based on a concert performance recording on 24 April 2013 [31], future work on the cathedral’s acoustics can employ this computer model, the recent measurements, and simulations to adapt the model to the evolving state of the building. As recent studies have shown the reliability of numerical simulations for studying complex and coupled acoustic conditions [24], as well as perceptual viability [32], such geometrical acoustic analysis efforts can be expected to be reliable in the cathedral. Initial efforts will focus on the 2020 post-fire state, in order to attribute the acoustic impact of the various changes. These results will be made available to the reconstruction team and the model can then be further employed to evaluate the acoustic impact of architectural reconstruction proposals during the project.

In the same manner that the acoustic model can be used to study possible evolutions during the reconstruction, it can also be used to explore the evolution of the acoustics of the Cathédrale Notre-Dame de Paris since its construction over 850 years ago. As many elements of the cathedral have changed over the centuries, from the various architectural renovations and damage which occurred during the French revolution, to the varied decorations employed for different events, both religious

and political, and across the seasons, the acoustics of the Cathédrale Notre-Dame de Paris was not a constant throughout history but an evolving intangible product of its environment and human occupation. Combined with historical research efforts, the acoustic model and associated virtual simulations can be used to explore and experience these previous states [33].

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