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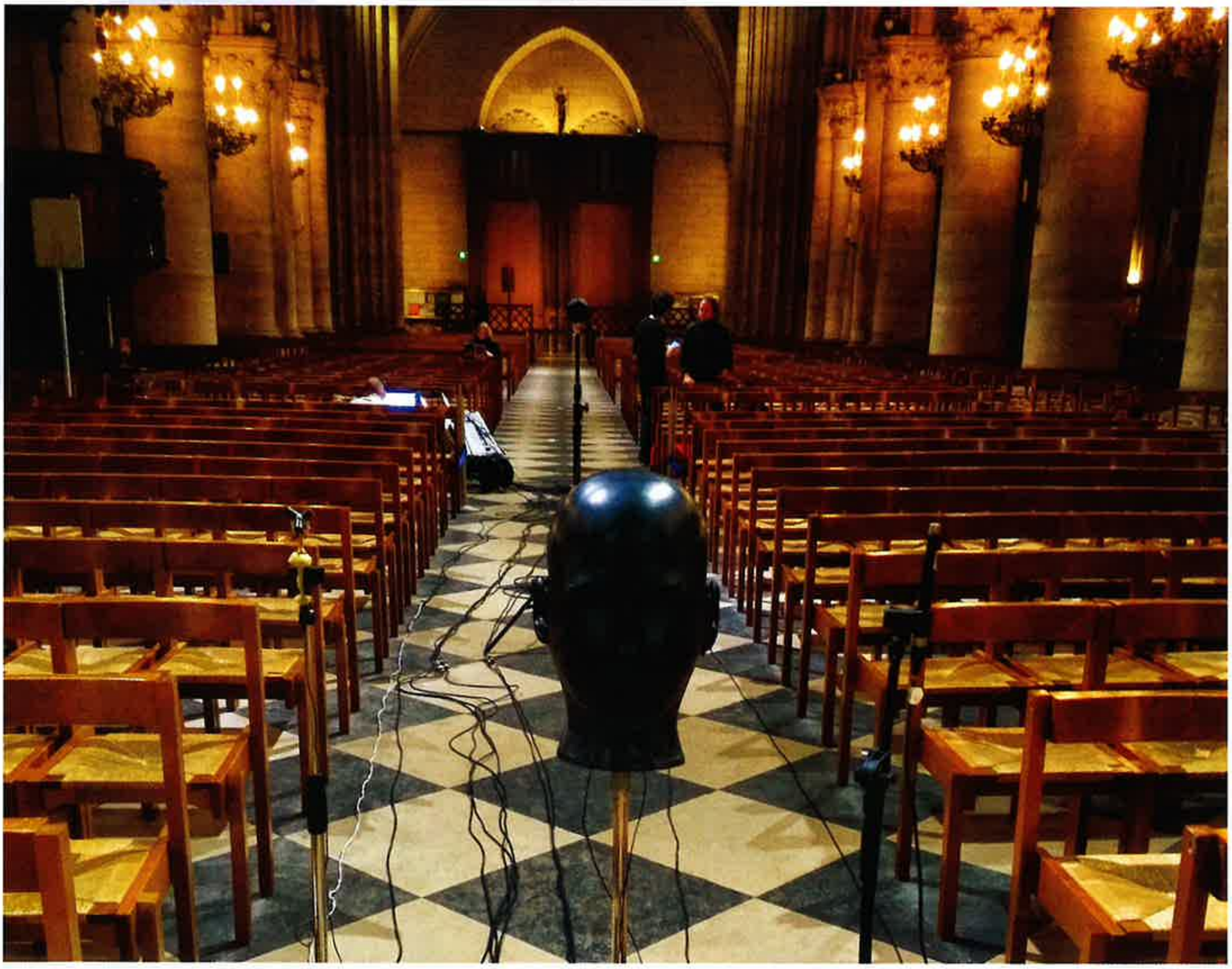
ACOUSTICS BULLETIN



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Exploring the cultural heritage and restoration of Notre-Dame Cathedral through acoustic digital reconstructions

The acoustics of a place are ephemeral, but they are intrinsically connected to the physical environment. With acoustic measurements, acoustic models, and extensive archival research, acousticians are reconstructing the sounds of Notre-Dame through the ages after it was damaged by fire on 15 April 2019.

By Sarabeth S. Mullins, Elliot K. Canfield-Dafilou and Brian F.G. Katz

The modern experience of profound historical architectural achievements such as Etruscan tombs or Gothic cathedrals is strongly linked to each site's acoustic environment. The acoustics of an ephemeral heritage site are an intangible consequence of the tangible construction and furnishing of the space.

The echo of the cathedral

With the recent adoption of the UNESCO resolution on the importance of sound, in addition to the Convention for the Safeguarding of the Intangible Cultural Heritage, awareness is now growing of the importance of preserving, studying, and recreating the soundscapes and acoustics of historical sites. At the same time, the rapid development of available computing power has allowed for acoustic simulations capable of modelling vast and complex buildings in which acoustics often play a crucial role, such as theatres, concert halls and cathedrals.

While Notre-Dame has burned before, the 2019 fire is a reminder of the fragile nature of our cultural heritage. Fortunately, acoustic measurements, digital simulations, and digital reconstructions make it possible to recover, and to a certain extent, preserve the sound of humanity's great architectural sites. What's more, the application of these measurements creates tools allowing archaeologists, historians, musicologists, and the general public to discover the lost acoustics of the damaged site. As part of the European Past Has Ears (PHE) and the French Past Has Ears at Notre-Dame (PHEND) research projects, and in conjunction with the acoustics working group of the Chantier Scientifique de Notre-Dame, we have been investigating the acoustic heritage of the cathedral over the centuries.

The contemporary acoustics of Notre-Dame

Despite the notoriety of the cathedral, there are few examples of published data on the acoustical parameters of this space. While some previous studies had been published in the early 21st century [Hamayon, 1996, Mercier, 2002], these reported varying reverberation times for the modern cathedral (e.g. 7.5 s and 6.5 s at 500 Hz, respectively), and did not fully explain the measurement protocols used. However, members of our laboratory carried out two previous measurement campaigns before the 2019 fire. After the fire, we were also able to make further measurements to document changes to the building's acoustic state. The plans from these three measurement campaigns are shown in Figure 1. The first of these, from 1987, was recovered from an acoustic study conducted about a potential organ. While a variety of stimuli were employed, only a few balloon-burst sources were exploitable due to a lack of excitation stimuli details (e.g. anechoic signals, sweep stimuli parameters). While not an ideal omnidirectional source, balloon bursts are valuable in certain situations, offering a portable impulsive source [Pätynen et al., 2011]. The recorded bursts were digitised from the original analogue tape and analysed.

Later, as part of a French research project on Binaural Listening (BiLi), we made a series of acoustic measurements in 2015 almost four years to the day before the 2019 fire. These detailed measurements were made with the modern sine-sweep technique [Farina 2000], with multiple receiver positions spread over a large portion of the floor area, including binaural and ambisonic microphones at select positions (see Figure 2a).

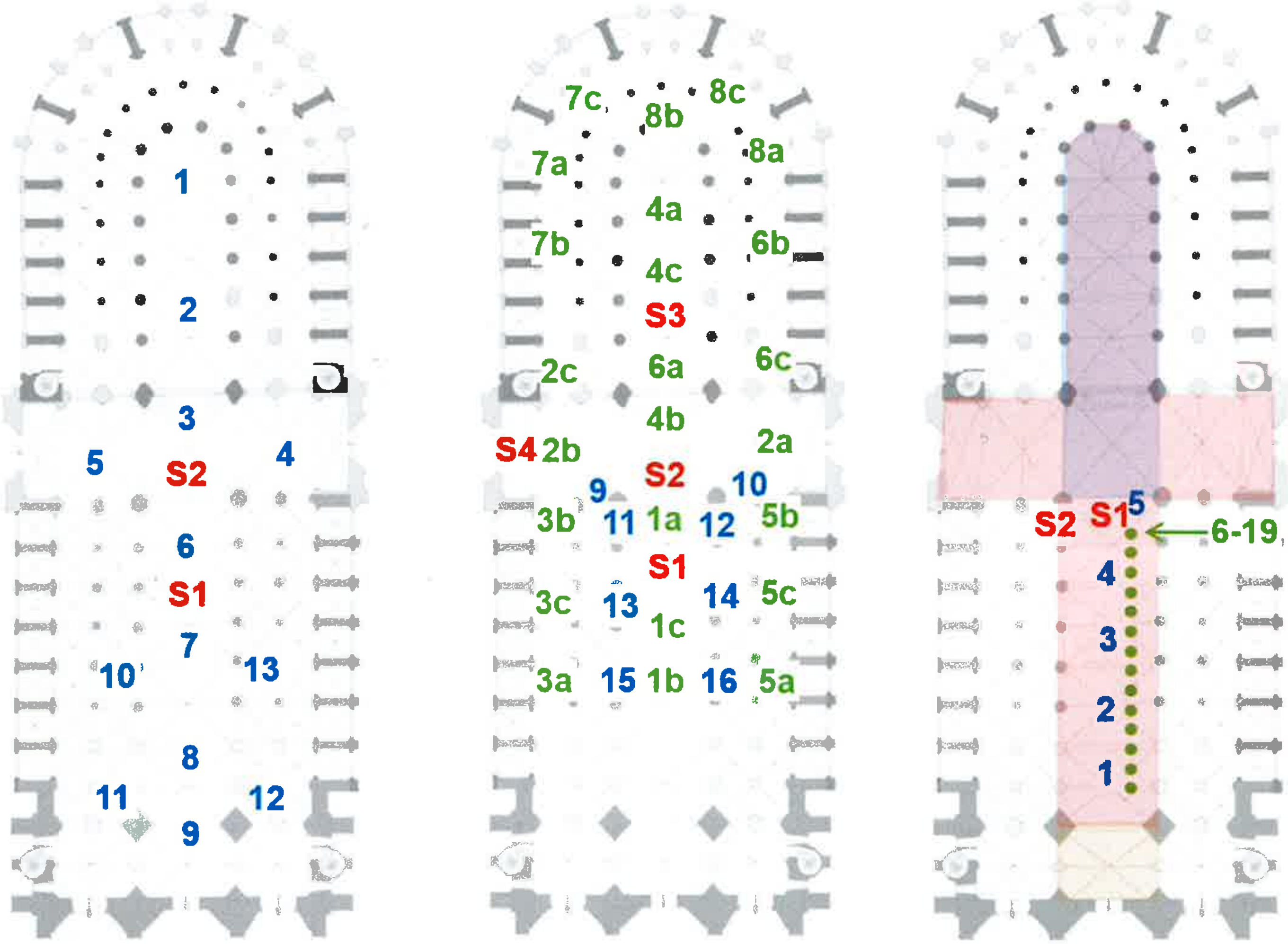
After the 2019 fire, access was granted to the construction site for the third measurement campaign, carried out in June 2020. The spire had damaged the central part of the transept/altar marble floor as it fell. Due to the risk of further falling debris and structural instability, the central nave and transept were off-limits to people, as highlighted in Figure 1c. The choir area was likewise cluttered with debris, and therefore inaccessible. Many of the side altars had 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, as seen in Figure 2b. A short video documenting the measurement session is available online[1].

Comparisons between the results of the two pre-fire sessions (1987 and 2015) show a slight, but significant, reduction in reverberation time (8%), which is likely attributed to the installation of a carpet runner in the 1990s to reduce the footfall noise of circulating tourists. Compared with the 2015 data, the reverberation time after the fire has decreased significantly (20%) [Katz and Weber, 2020].

We have examined the 2015 and 2020 results for comparable source and receiver positions using the marching line multiple slope analysis method [Luizard and Katz, 2014, Weber and Katz, 2019], in the 500 Hz octave band filtered RIRs (see Figure 3c). One can see the general decrease in reverberation times indicated in Figure 3a, while highlighting the problem of using the ISO3382 standard parameters when non-linear decays are present. Analysis 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 neatly separates the cathedral into two acoustically distinct zones, as its high ceiling and lack of subdividing walls creates a 34m wide by 14m deep by 33m tall zone of free-field propagation between the multilevel eastern and western portions of the cathedral. The reduction in decay rates in these volumes also decreases the bending point time and, to a lesser extent, level. 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, P50

Below: Figure 1: Measurement plans for the three sessions at the Cathédrale Notre-Dame de Paris

Below: (a) 1987 **Below:** (b) 2015 **Below:** (c) 2020

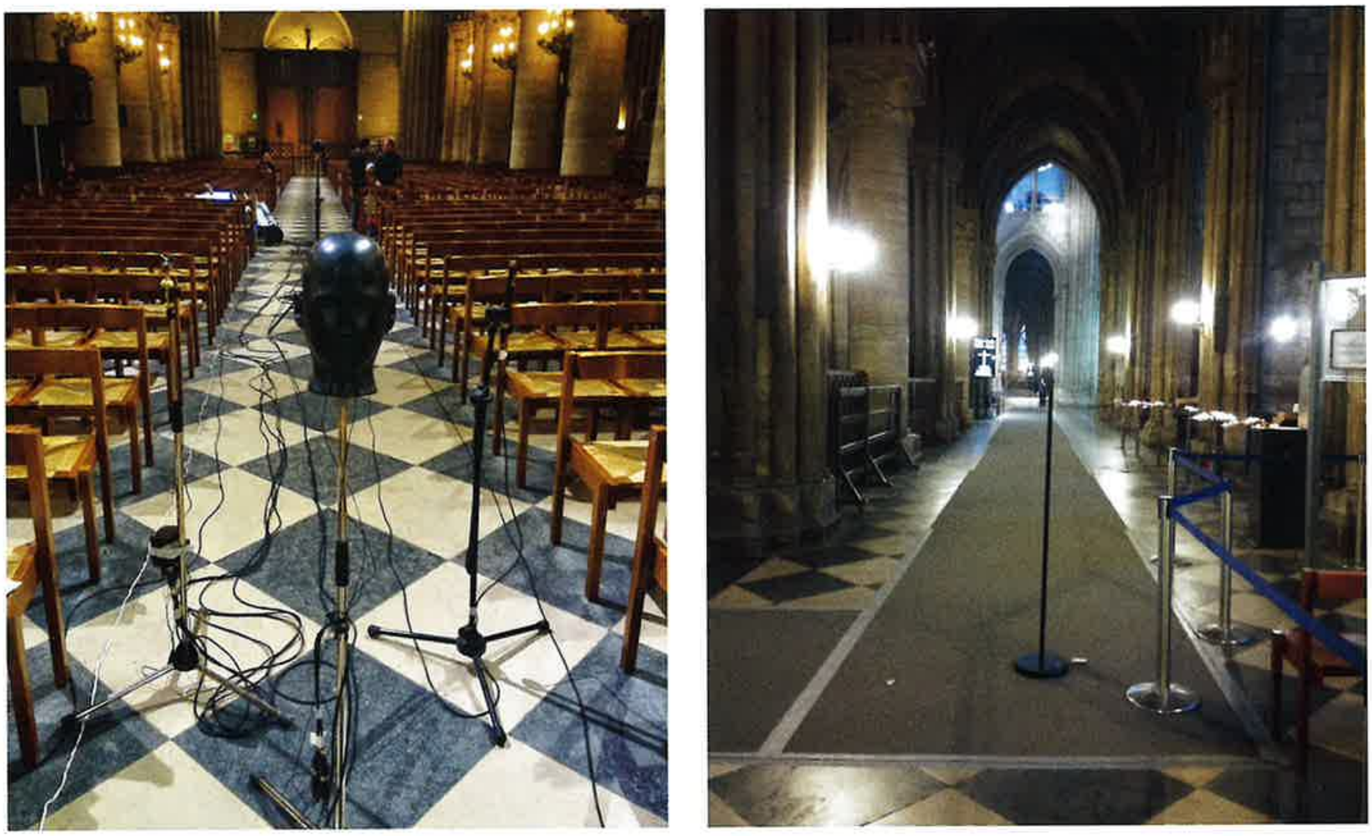


Positions are centred under numbered source (S# (red)) and microphone (# (blue and green)) labels or at points when the measured grid is too dense. The 2020 plan (c) also indicates in shaded regions the scaffolding (yellow), people exclusion (red), and encumbered/damaged ground (blue) exclusion zones where it was not possible to place measurement equipment

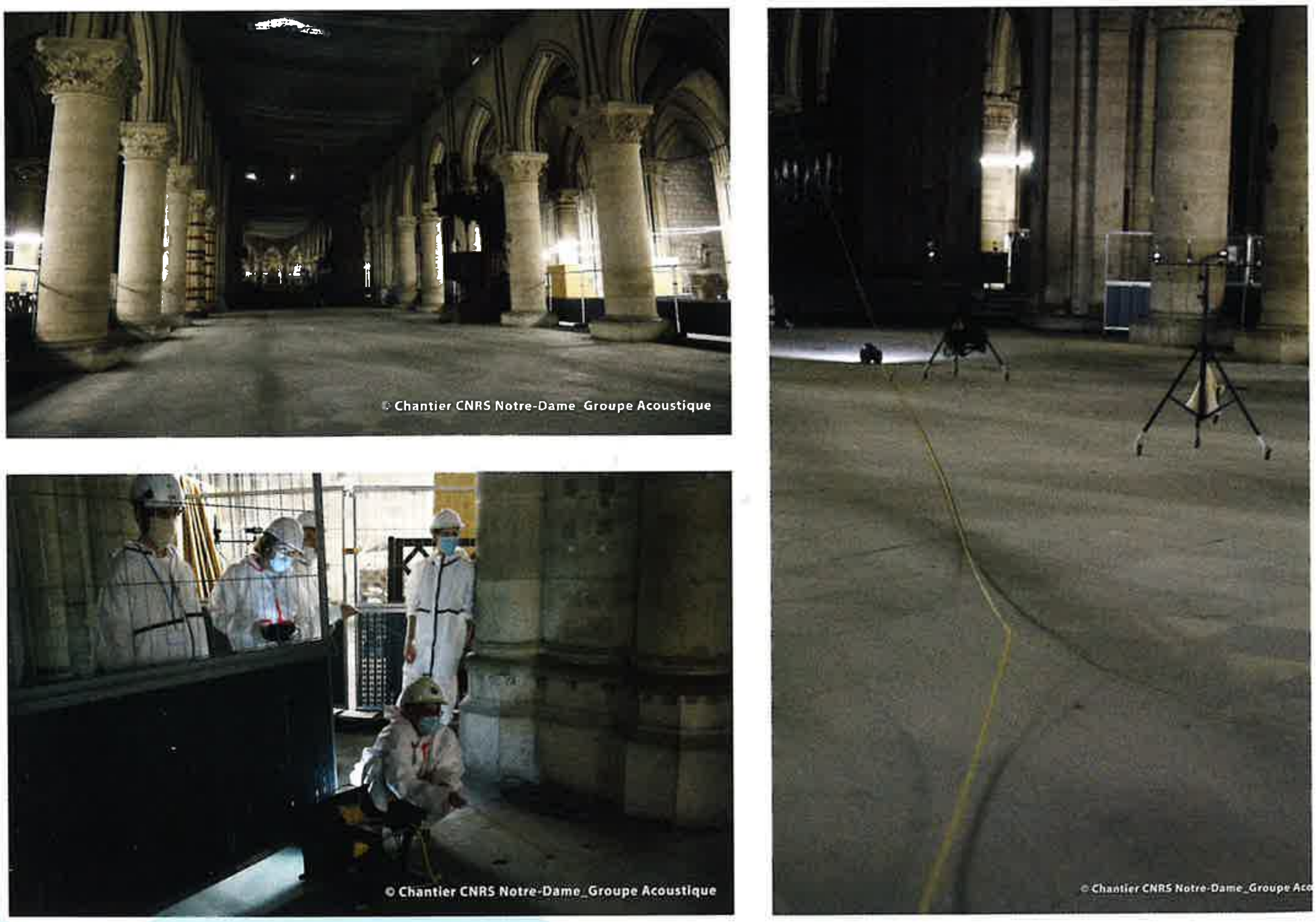
Footnotes

1. https://youtu.be/YLi7ASosKvw

Figure 2: Images highlighting conditions for the (a) 2015 and (b) 2020 measurement sessions

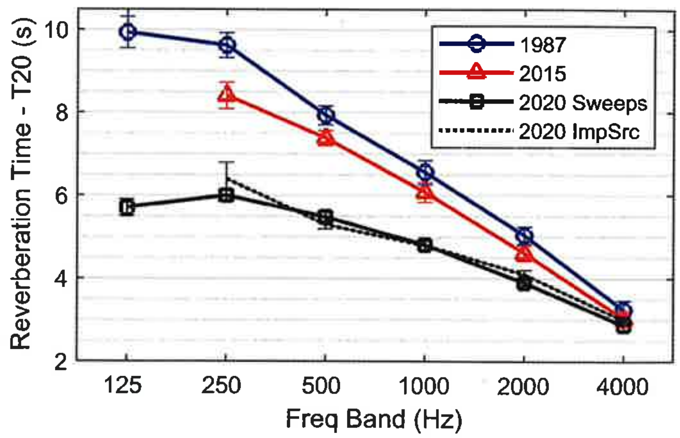


Above: Figure 2: (a) 2015, highlighting measurement equipment in the central aisle of the nave and carpet runner in a side aisle during the measurement session

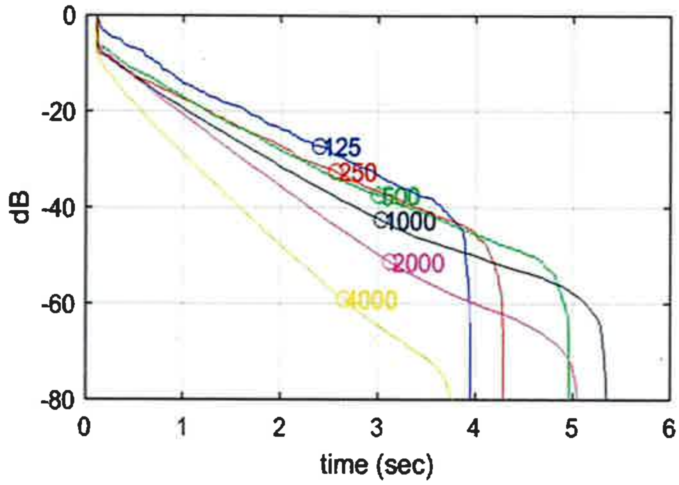


Above: Figure 2: (b) 2020, highlighting the remote-controlled robot-pulled microphone tripods and the general empty state of the nave during the measurements

Figure 3: Summary of (a) mean reverberation time over receivers, (b) example RICs, and (c) coupled volume analysis



Above: (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)



Above: (b) Example of octave band filtered RIC decays, normalised, optimised SNR truncation, 2020 sweep stimuli data-set

leading to more than a simple double-slope decay with higher-order coupling.

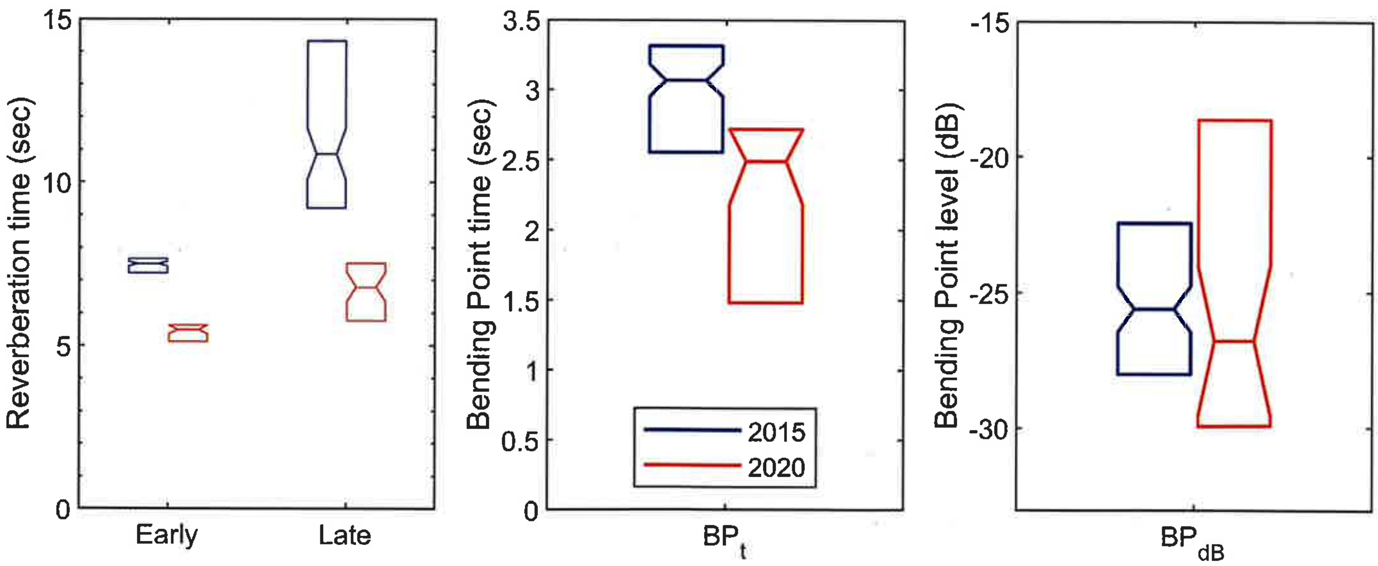
When the reconstruction of the spire, roof, and vaulted ceiling are completed, and the interior scaffolding removed, we look forward to assessing the next iteration of this monumental building's acoustics.

Simulating the cathedral through the ages

There is a tendency among modern visitors to conceptualise a cathedral as a still and constant witness to history. However, the societies that maintained the building over centuries have all left their marks on the cathedral, from architectural renovations to politically-motivated redecorations, re-purposings, and damages. To modify the cathedral is to participate in a cultural legacy of continuous change.

While physical and digital simulations have been used for decades, digital approaches used in the 20th century were initially limited in their utility. As recent studies have shown the improved reliability of numerical simulations for studying complex, coupled acoustic conditions [Weber and Katz, 2019], we can expect such analytical efforts to be credible for Notre-Dame. We have shown in previous studies that geometrical acoustic simulations (CATT-Acoustic/TUCT) can be perceptually comparable to in-situ recordings [Postma and Katz, 2016b].

A geometric acoustic model of the cathedral was thus created and calibrated on the basis of measurements taken in 2015. Subsequent work on the historical acoustics of Notre-Dame P52



Above: (c) Double-slope decay 500 Hz-octave band analysis distributions showing Early and Late reverberation times and the relative time (BP_t) of the identified bending point in the RIC decay curves ([Luizard et al., 2015] for parameter details). Notched boxplots show the median, 95% confidence interval, 25th and 75th percentiles of the data spread has refined this computer model, featuring alterations in interior geometry, closure of lateral chapels, inclusion of the clôture and rood screen, reshaping of choir stalls, and other details. Additional measurements of historical materials and supporting archival documentation are used to modify the simulations, adapting the model to the cathedral's historical or future states. To date, 13 acoustic models spanning the time period from before Notre-Dame was built in ca. 1163 CE to ca. 1712 CE have been created using this same software (CATT-Acoustic v9.1, TUCT v2.0, see Figure 5a).

The ca. 1163 model is a speculative one based on the foundations of a massive basilica found in archaeological digs in 1847 CE [Hubert, 1964, Barbier et al., 2019, Sandron, 2021]. Acoustic measurements and architectural plans of an extant and contemporaneous building of a similar architectural style [Cirillo and Martellotta, 2005] were used to create a calibrated model of the stand-in church, which was then modified to match the architecture of the ruins below Notre-Dame. All models after ca. 1163 CE are based on the GA model reported in Postma and Katz [2016a] and subsequently modified to match the historical states as discussed in Mullins et al. [2022], Canfield-Dafilou et al. [2022, 2023]. These models allow us to examine the acoustic evolution of the cathedral over generations, yielding insights into the experience of previous societies at the church.

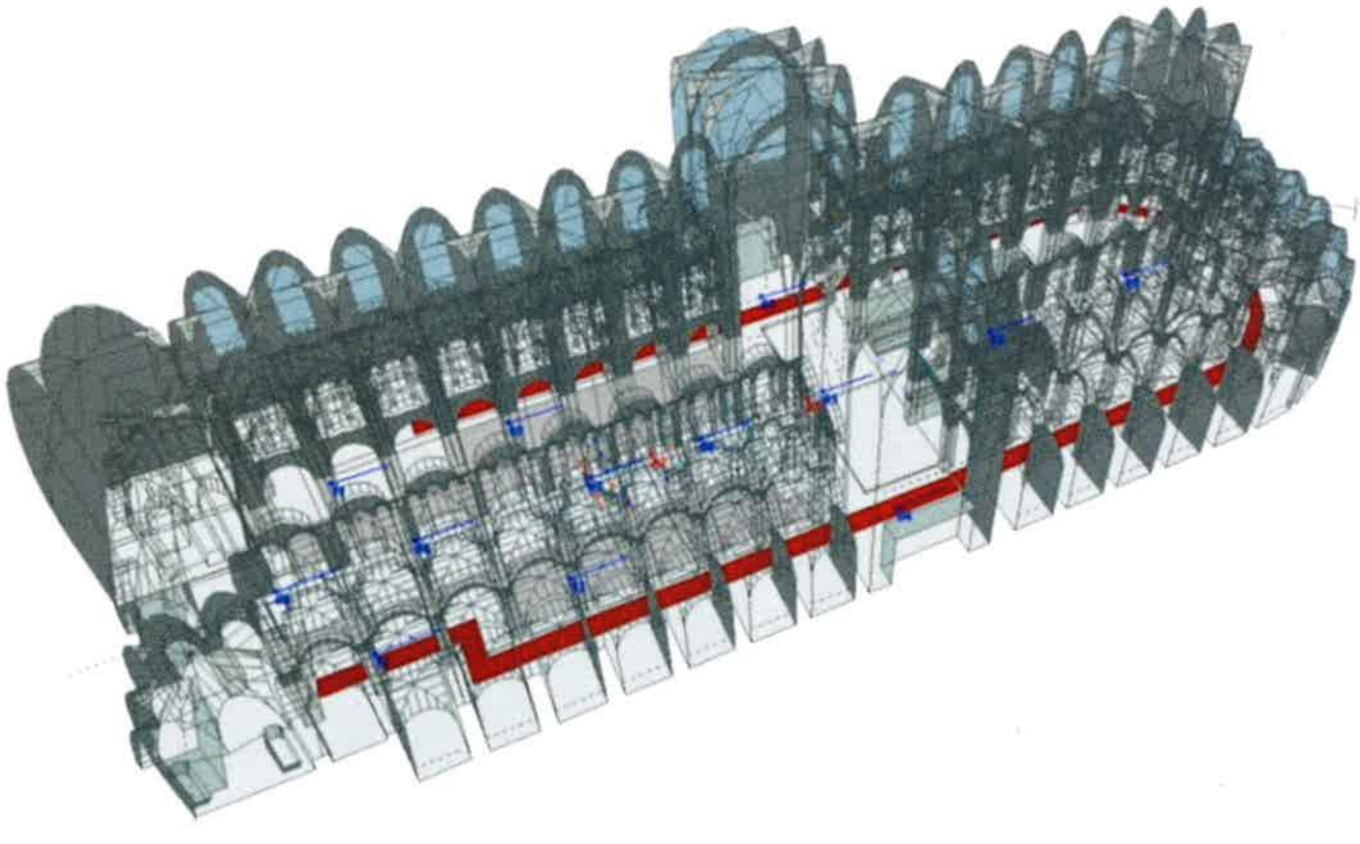
Listening to the past

This type of historically-informed simulation can be a powerful tool for historical studies, providing researchers with a sensory presentation of sound that was previously only available through description and supposition.

In parallel with the construction of the cathedral, a new genre of music developed among the musicians of Notre-Dame. Known as the School of Notre-Dame, these composers and musicians pioneered a virtuosic style of singing that embellished established melodies with prescribed and notated polyphonic ornamentation.

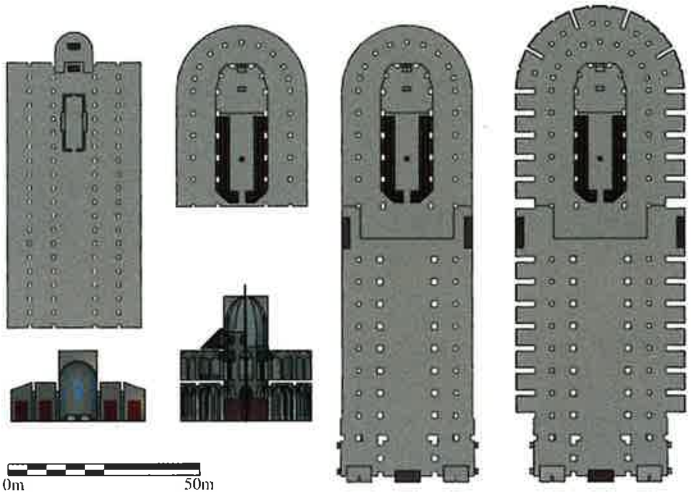
Working with musicologists, acoustic simulations are used to study the potential relationship between these musicians and the

Figure 4: Geometrical Acoustic simulation model of the state before the fire

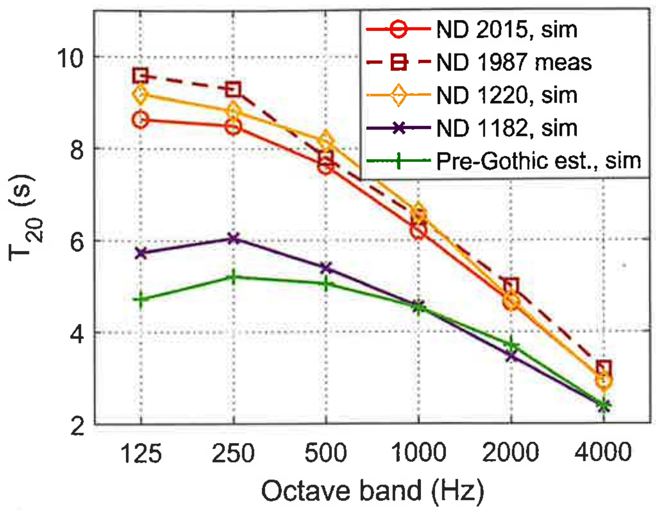


Above: Geometrical acoustic model of Notre-Dame de Paris

Figure 5: Overview of several simulation models and associated reverberation time results



Above: (a) Plans and elevations of ca. 1163, ca. 1182, ca. 1225, and ca. 1350 states



Above: (b) Summary of mean reverberation time

reconstructed acoustics of Notre-Dame and its predecessor. These experiments use real-time, immersive virtual acoustic environments to allow singers to perform as an ensemble in the different simulated acoustic conditions. A choir specialising in medieval singing was studied as they sang *Organum Purum* and *Organum Notre-Dame* in the varying acoustics.

Analysis of musical parameters extracted from their recordings helps to examine what influence the different architectures may have had on musicians' performances. Listening tests with specialists focus on the differences in the suitability of music styles to the historical acoustic conditions. In this way, we hope to provide a new level of insight into the interconnected domains of culture and acoustics at the cathedral in the past.

In addition to the scientific aims, the acoustic model of Notre-Dame has been used to draw awareness to the cultural significance of the aural history of the cathedral. This includes a virtual 'magic carpet' tour of the cathedral while listening to an extract from a performance of Massenet's oratorio *La Vierge*. The intention of this production (entitled 'Ghost Orchestra'[2]) was to capture the acoustics of the cathedral and how they vary according to the position of the sound source and the listener. An extended version, offering the entire concert from several fixed positions, was produced during the COVID lockdown in the form of a virtual sound-only experience[3].

The selected piece of music, actually performed at Notre-Dame for its 850th anniversary, offers a unique experience with musicians positioned both in the transept and in the liturgical choir, in addition to several movements where soloists are positioned high up in the galleries, offering spatially variable sources and a truly immersive experience. These efforts have produced a four part audio-drama series, placing the efforts of the scientific team in an easily accessible format. *Looking for Notre-Dame*[4] plunges us into the mind of the young Victor Hugo as he begins work on his future 'cathedral novel' *Notre-Dame de Paris*. Another public work is the production of a geolocalised audio-guide, *Whispers of the Past at Notre-Dame*[5], an immersive experience in the aural memories of the cathedral Notre-Dame de Paris.

Concluding remarks

Exploring acoustic cultural heritage through digital reconstruction brings an additional perspective and tool-set to researchers in the arts and humanities. Furthermore, it brings a powerful means of communicating and delivering memorable, meaningful, and most importantly, informed multi-sensory experiences. This is evident by the range of projects of this type across Europe. Despite its potential, auralisation is a static representation of how an environment sounds, a snapshot in time, and the final result P54

Footnotes

2. http://www.lam.jussieu.fr/Projets/GhostOrchestra
3. http://lavierge2020.pasthasears.eu
4. http://lookingfornotredame.pasthasears.eu
5. http://whispersnd.pasthasears.eu/

depends greatly on the limitations of the systems and techniques used to create it. When developing a model of any heritage space, the auralisation is only as good as the groundwork research into the source material documenting its history. Perhaps most importantly, our judgements on the auralisation reflect our selves, our experiences, and our expectations. As with many historical conceptualisations, the final results are created from and perceived through our modern state of mind. Despite these caveats, we believe that Notre-Dame is the perfect opportunity to showcase the opportunities of interdisciplinary partnerships. It is our hope that this work contributes to an appreciation of the cathedral's legacy as it moves towards full restoration.

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