VIRTUAL CONCERT FILM WITH ACOUSTIC RECONSTRUCTIONS OF NOTRE-DAME DE PARIS ACROSS EIGHT CENTURIES

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1 INTRODUCTION

Archaeoacoustics examines how past societies utilised and experienced sound. This field encompasses studies of the acoustics of ancient sites such as caves, theatres, or cathedrals, historical musical instruments, and the influence of sound on rituals and communication.[1] It integrates methodologies from archaeology, acoustics, and anthropology with advanced technologies like 3D scanning and acoustic simulations to better understand how sound shaped past human experiences.

The *Past Has Ears at Notre-Dame* (ANR-PHEND) is a research project (2020–2025), applying archaeoacoustics to study how the evolution of the Notre-Dame de Paris Cathedral's architecture and acoustics influenced its sonic history.[2] Researchers of the PHEND project for example examined the impact of organ placements in the late medieval Notre-Dame on sound audibility and clarity,[3] or studied how wave-based simulations could be used to simulate the diffraction of its columns and piers compared to scale model measurements.[4] PHEND is an extension of *the Past Has Ears* (EU-PHE), a larger European project examining room acoustics as cultural heritage focusing on three major historical edifices in Europe.[5]

The *Vaulted Harmonies* animated film is part of the scientific outreach effort of the PHEND project. It was designed to provide an intuitive and immersive experience of how the Notre-Dame de Paris Cathedral and its music evolved from its creation to the modern day. The following sections describe the steps involved in creating this film, available in both French and English on the film's website.[6]

Vaulted Harmonies builds upon the foundations of the *Ghost Orchestra*, a 2015 production that virtualised one of the concerts organised for the 850th anniversary of Notre-Dame de Paris.[7] Leveraging simulated second-order ambisonic room impulse responses (RIRs) and 6-DoF auralisations, Ghost

Figure 1: (a) Vaulted Harmonies poster and (b) photograph from the pre-premiere working session.

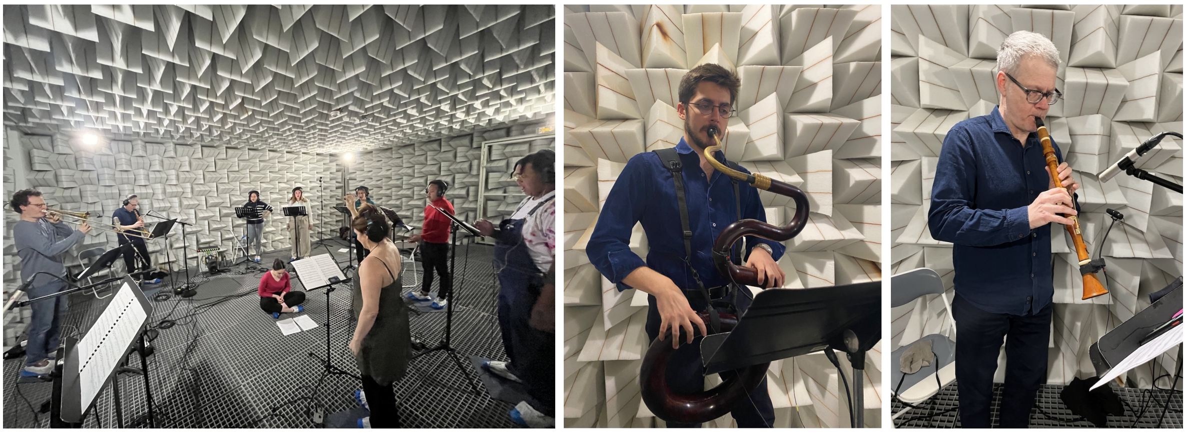
Orchestra projected more than 200 musicians, close-mic recorded live during the concert, into a calibrated model of the modern cathedral. The project was released as both a virtual reality (VR) desktop application and a five-minute online 360° video, enabling users to explore the space and perceive how the acoustics change with position and shape the musical experience. Vaulted Harmonies aspires to push the boundaries of such immersive productions. In addition to advancements in recording techniques, simulation scope, and both visual and acoustic resolution, this 66-minute film aims to interweave science, musicology, and history into a compelling and immersive narrative of the cathedral's heritage. The film's poster image and a photograph from the pre-premiere working session are shown in Fig. 1.

The structure of this paper is as follows. Section 2 introduces the musical pieces performed during the concert, along with their historical and musical context. Section 3 describes the recording process for each piece. Sections 4 and 5 detail the development of the acoustic and visual models of Notre-Dame, respectively. Section 6 explains the workflow for creating the storyboard, which served as a reference for both acoustic and visual rendering teams. Section 7 presents the auralisation process, whereby recorded musicians are projected into the simulated acoustics of the cathedral. Section 8 outlines the post-production and distribution process, including adaptation to various audio and video formats.

2 SELECTING KEY PERIODS AND MUSICAL PIECES

Multiple criteria guided the selection of the concert's musical pieces, carried out in collaboration with the musicologists of the PHEND project. Some works are foundational to the cathedral's musicological heritage, while others represent musical movements associated with specific liturgical periods. Certain pieces were chosen for their connection to historical events that shaped Notre-Dame's past; others were composed for, or originally performed on, one of its iconic organs. The final selection includes six vocal works, one orchestral piece, and four organ pieces, each illustrating a different historical instrument associated with the cathedral.

- **Scene 01 Léonin**, Organum Iudea et Ierusalem (7 singers), Léonin (1150 – 1210)
- **Scene 02 Pérotin**, Viderunt Omnes (7 singers), Pérotin (1160 – 1230)
- **Scene 03 Vitry**, Adesto (Organ), Philippe de Vitry (1291 – 1361)
- **Scene 04 Frye**, Ave Regina Caelorum (Organ), Walter Frye (? – 1474)
- **Scene 05 Brumel**, Ave Maria Gratia Dei Plena (10 singers), Antoine Brumel (1460 – 1515)
- **Scene 06 Sohier**, Kyrie de la Missa Vidi Speciosam (16 singers), Mathieu Sohier (1500 – 1560)
- **Scene 07 Racquet**, Fantaisie (Organ), Charles Racquet (1597 – 1664)
- **Scene 08 Frémart**, Credo de la Missa Eripe me Domine (16 singers, positive organ, viola da gamba), Henri Frémart (1595 – 1651)
- **Scene 09 Gossec**, Hymne à la Liberté (5 singers, clarinet, sackbut, serpent), François-Joseph Gossec (1734 – 1829)
- **Scene 10 Lesueur**, Ouverture de la Marche du Sacre (Orchestra, 48 musicians), Jean-François Lesueur (1760 – 1837)
- **Scene 11 Vierne**, Carillon de Westminster (Organ), Louis Vierne (1870 – 1937)



(a) (b) (c)

Figure 2: (a) Musicians in the anechoic room during the recordings of **Scene 09 Gossec**. (b) Serpent and (c) Baroque clarinet players.

3 AUDIO RECORDINGS

Depending on the number of musicians and the size of their instruments, recordings were carried out under varying conditions. Regardless of these constraints, the objective remained consistent: to capture musically expressive interpretations with minimal room reverberation and as little microphone cross-talk as possible. Ensembles of fewer than 10 musicians were recorded in the anechoic chamber at Sorbonne University's Jussieu campus, offering a floor area of 42 m^2 and a total volume of 240 m^3. Larger ensembles were recorded either in the acoustically dry *Tarrazi* studio or in the *Vincent Meyer* Grand Plateau d'Orchestre at the Conservatoire de Paris (CNSMDP). Fig. 2 shows the musicians during **Scene 09 Gossec** recordings in the anechoic room.

Organ pieces were recorded using close-miking techniques in churches and amphitheatres where the facsimile and historical instruments were installed. In total, eight recording sessions were conducted, involving over 100 musicians and yielding 187 audio tracks. To make the anechoic recordings feel more natural, open-back headphones delivering real-time auralisations of the cathedral's acoustics corresponding to the piece being performed[8] were made available to the musicians.

4 ACOUSTICAL MODELS

Four acoustic models were created to support the film's auralisations, three of which are illustrated in Fig. 3, along with a timeline of the buildings construction and parallels in the evolution of musical style. The modern day model, referred to as **ND$_{2015}$**, was designed and calibrated as part of the Ghost Orchestra production mentioned previously. 3D laser scans of the interior of the cathedral were used to form the foundation of the geometric mesh. Then followed a calibration process to bring global and local parameters of T_{30} and C_{80} into an agreement of ±1 just noticeable difference with on-site measurements for various source and receiver positions.[9,10] T_{30} is a measure of the time it takes for the sound level in a room to decrease by 30 dB after the source of a sound has stopped, extrapolated to 60 dB. Musical clarity C_{80} is a measure of how sounds in a space blur into one another, calculated based on the ratio between the early sound energy to the later reverberant energy in a RIR, divided at 80 ms after the direct sound.

As detailed in a prior study,[11] creating the **ND$_{1500}$** model required only minor architectural modifications compared to **ND$_{2015}$**, such as the replacement of modern choir stalls and altars. However, its

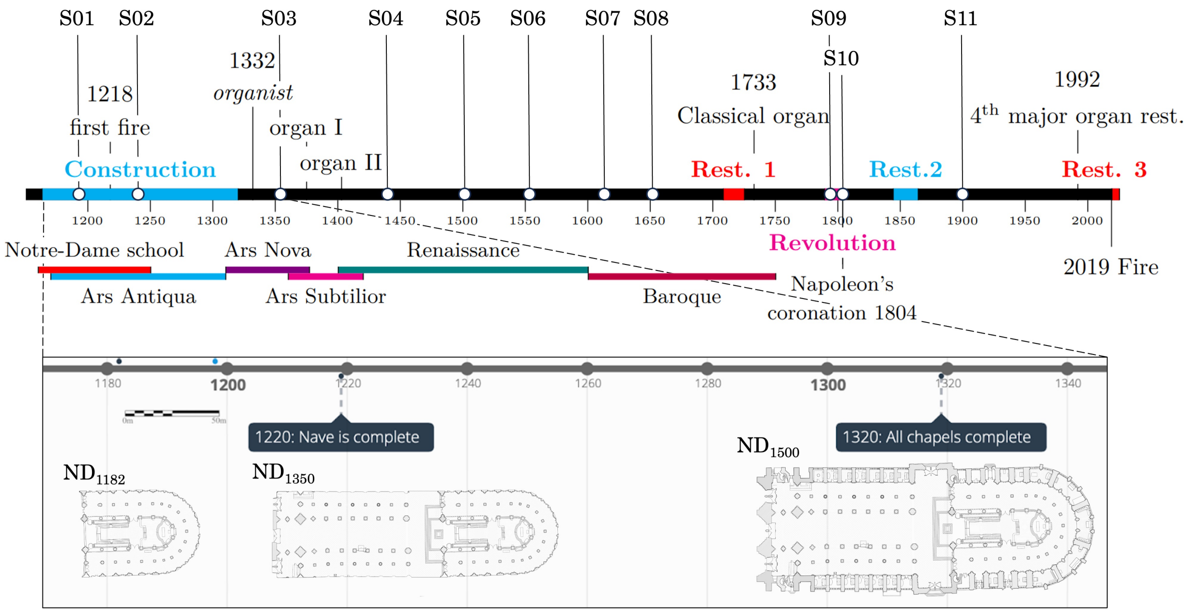
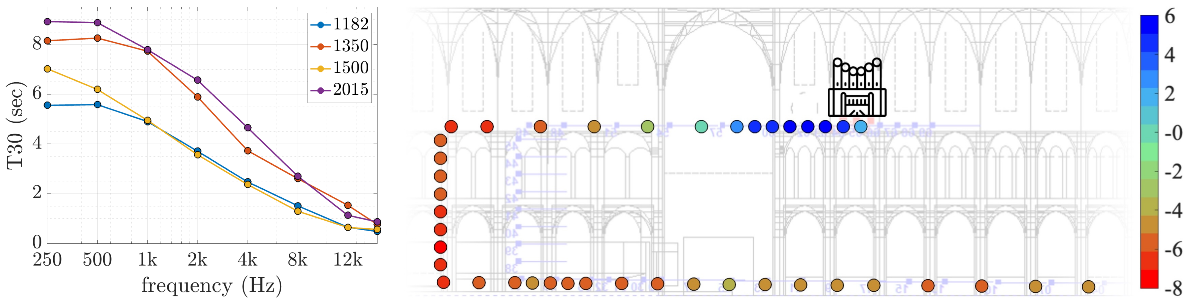


Figure 3: Chronology of Notre-Dame construction, significant events of its history, and musical pieces of the concert (S01, S02, etc.).



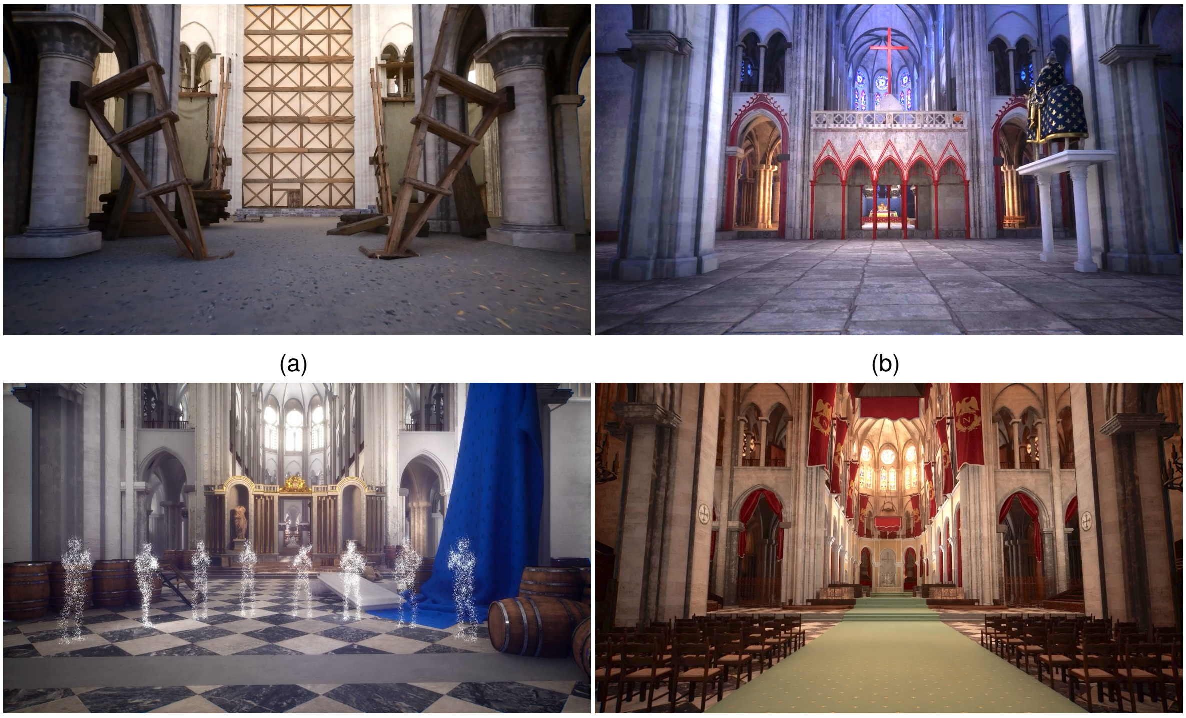
(a)

(b)

Figure 4: (a) Variations of reverberation time (T_{30}) across the four acoustic models of Notre-Dame. (b) Variations of clarity (C_{80}) across listening positions in the $\mathbf{ND_{1350}}$ model for the swallow's nest organ source position along the listener trajectory of **Scene 03 Vitry**.

acoustics differed significantly due to the decorative elements and textile wrappings on the columns, which reflected how the cathedral was adorned during major festivals of the period. In $\mathbf{ND_{1350}}$, the lateral chapels had not yet been constructed, which incrementally **increased** the reverberation time compared to the $\mathbf{ND_{1500}}$ configuration. The space was also more sparsely decorated, further increasing its reverberation, bringing it closer acoustically to that of $\mathbf{ND_{2015}}$.

For the $\mathbf{ND_{1182}}$ model, the entire transept and nave were removed, as they had not yet been completed at the time. This resulted in a drastic change in the cathedral's acoustics compared to the other three configurations. The T_{30} reverberation times from simulations using all four models are shown in Fig. 4, along with an example illustrating how much an acoustic parameter such as C_{80} can vary across different listening positions within the cathedral for a given source.



(a) (b) (c) (d)

Figure 5: Evolution of the visual model between (a) **Scene 01 Léonin** (**ND_{1182}**) during construction of the nave, (b) **Scene 03 Vitry** (**ND_{1350}**), (c) **Scene 09 Gossec** (**ND_{2015}**), and (d) **Scene 10 Lesueur** (**ND_{2015}**).

5 VISUAL MODELS AND ANIMATIONS

The creation of the visual models was based on the same archival research used for the acoustical models. The most striking transformation occurs between the **ND_{1182}** and **ND_{1350}** models, as the cathedral is opened to its newly completed nave and transept. More subtle architectural and material changes further affect how the cathedral looks and feels across different periods. As illustrated in Fig. 5, these include the evolution of the jubé (a liturgical screen or loft in medieval churches that separates the nave from the choir), the transition of the stone floor to the cathedral's signature chequerboard pattern, and the temporary modification of the choir columns for Napoleon's coronation.

Avatars of the musicians were integrated into the scenes as visual anchors for the auralisations. Initially intended as fully animated characters, they were ultimately designed as procedurally animated point clouds, a compromise between visual appeal and implementation complexity. The dry audio track of each musician was used to modulate the size and brightness of the point-cloud particles, effectively turning each avatar into a kind of dynamic level meter.

6 STORYBOARD AND CINEMATOGRAPHY

The film was designed to present subjective auralisations that align with the camera's point of view. Several prototype scenes were developed to design camera animation paths that would support informed decisions when balancing the sometimes conflicting objectives of the project:

- To create immersive and dynamic visuals that support the storytelling while showcasing details of the cathedrals,

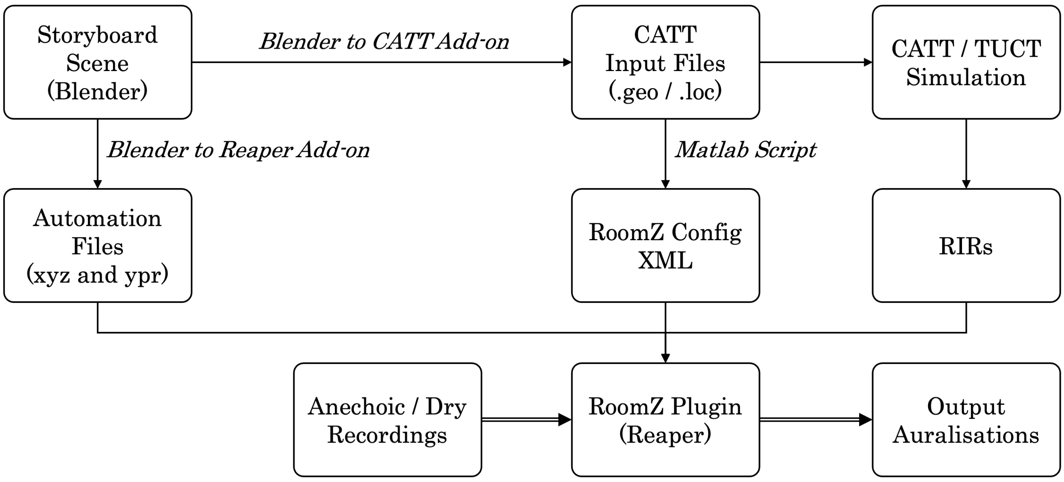


Figure 6: Auralisation workflow.

- To produce auralisations that enhance the music from ideal listening positions,
- To illustrate how changes in listening position affect the acoustics of Notre-Dame and, consequently, the musical experience.

Built in Blender using mock-up meshes of the cathedral, these scenes were used to define the camera animation paths. At this stage, the positions of the musicians and organs were determined for each scene, as they naturally serve as primary focal points for the camera. Whenever possible, these positions were based on historical documentation about the cathedral and the relevant musical genres.[3] The storyboard scenes were also used to feed an early version of the auralisation workflow, described in the next section, allowing for preliminary testing of the interaction between the music and the cathedral's acoustics. Once finalised, the camera animation paths were exported, enabling the two teams, acoustic simulation and visual rendering, to work in parallel.

7 DYNAMIC AURALISATIONS

The auralisation workflow is illustrated in Fig. 6. The FBX exchange format was used to directly import camera animations and musician positions from the Blender storyboard scenes into Unreal Engine for visual rendering. Performing the same operation for acoustic simulation required the development of a custom Blender add-on.[12]

The RIRs for each source-receiver pair were computed using a geometrical acoustics simulation software (CATT-Acoustic v9.1 and TUCT v2.0e:1.02, using algorithm 1 with first-order diffraction enabled[13]). The ray-trace simulation was configured with 1×10^6 rays and RIR lengths matching the T_{30} of each model. Depending on their size, the organs were modelled as clusters of 6 to 15 independent sources.[14] Their directivity patterns were based on measurements taken from a facsimile scale model organ assembled in an anechoic room.[15] Directivity patterns for the other instruments were defined using databases available through CATT-Acoustic's directivity exchange or constructed from published data (*e.g.*[16]). Receivers were configured as 3rd-order ambisonic microphones.

The RoomZ audio plug-in[17] was used to process the 6-DoF auralisations for the project within the audio workstation. RoomZ is essentially a partitioned convolution engine combined with an interpolation stage, capable of managing multiple source auralisations with a moving receiver, or conversely, a moving source with a fixed receiver. Depending on the scenario, interpolation is performed using either two or three neighbouring RIRs to ensure smooth transitions between discrete receiver positions.

8 POST-PRODUCTION AND DISTRIBUTION

The first post-production stage focused on the musical balance and authenticity of the auralisations, the second on adjusting the overall spectrum of the concert to the various distribution formats. To ensure authenticity, the sound engineers used reference recordings captured in situ during the recording sessions using omnidirectional, AB stereo, or binaural microphones. They adjusted the mix gains of the individual musicians prior to convolution so that the final auralisation, rendered at the reference microphone position, matched the balance of voices heard in the original recordings.

To facilitate distribution, the ambisonic auralisation was decoded into a wide range of multichannel formats. Except for the DCP Dolby Atmos version, all the other formats were created using either Panoramix[18] or Transpan,[19] both built on the Spat5 library.

9 CONCLUSION

The overall conception and production of this animated film represents a meaningful milestone in what can be achieved for scientific outreach in the fields of archaeoacoustics and virtual heritage. Vaulted Harmonies is set to be adapted for both VR and dome projection formats in the fall of 2025, a transition made feasible by its original design leveraging Unreal Engine and high-order ambisonics. The primary challenge for the VR version will be maintaining the resolution of both visuals and auralisations despite the software and hardware limitations of current consumer VR devices. For the dome version, the main challenges will include upscaling visual resolution, reimagining the cinematography to prevent cybersickness, and fully leveraging the 360° field of view offered by dome theatres.

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We warmly thank all those who contributed to the creation of the film and concert presented in this study, including the musicians, sound engineers, acousticians, historians, musicologists, scientists, graphic designers, scriptwriters, and the staff of Notre-Dame de Paris. Their expertise and dedication made this project possible. For a complete list of contributors, please refer to the credits at the end of the film.

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