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The Past Has Ears at Notre-Dame: Immersive Audio Experiences for Public Engagement

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ABSTRACT

The recent fire at the Cathedral Notre-Dame de Paris has spurred a series of studies to gain a deeper understanding of its acoustics, tracing its evolution through the centuries and exploring its profound influence on music. These endeavours are part of the interdisciplinary research project "The Past Has Ears at Notre-Dame" (PHEND). Through this project, a digital twin of the cathedral, reflecting its acoustic properties, was created. This digital model was a foundation for reconstructing the cathedral's historical acoustics. While primarily dedicated to scholarly inquiry, the project recognises its cultural significance and the importance of sharing its findings with the wider public. Consequently, efforts were made to translate research outcomes into engaging public experiences. Several immersive audio productions have been completed or are currently in development, each leveraging the project's tools and findings to enhance public engagement through storytelling.

1 Introduction

In the archives of architectural history, few accomplishments match the magnificence and importance of Gothic cathedrals, where the acoustic atmosphere emerges with the sonic ambience of these historic locations, epitomising the interaction between their tangible physical attributes and intangible qualities. Our project delves into the detailed examination of France's renowned heritage site, *Notre-Dame de Paris*, utilising measurements, research, and virtual simulations to document, reconstruct, and provide access to its acoustic legacy for scholars and the broader audience. Drawing inspiration from Phé, the Phoenix constellation, and the European project PHE[1],

[1] PHE project: phe.pasthasears.eu

the project PHEND[2] [1, 2], (the Past Has Ears at Notre-Dame) serves as a digital revitalisation of Notre-Dame, studying its historical progression and significance. Separate from scientific aspects, the challenge of public presentation lies in transforming a site's historical narrative into a three-dimensional auditory experience and designing mediation formats tailored to the target audiences.

The PHEND project comprises various initiatives to explore Notre-Dame's historical and musical aspects. One initiative created historically accurate 12th century construction site soundscapes. One production virtually reconstructed a 2013 cathedral concert, with close-mic recordings of musicians projected into the digital twin model of Notre-Dame, offering binaural renditions for various listening positions [3]. A radio-fiction program entertains while conveying PHEND research insights about Notre-Dame's acoustic history using binaural spatial audio to immerse listeners in the cathedral's sonic environment. A didactic experience presents acoustic and historical insights about Notre-Dame through a mobile app's geolocalised audio-guide, featuring binaural spatial audio for enhanced immersion. Lastly, the PHEND project will culminate with a historical and musical documentary film showcasing 11 compositions spanning nearly nine centuries of Notre-Dame's history. Each piece is virtually rendered within the cathedral's digital twin, accompanied by architectural, historical, and musicological insights.

Digital acoustic twins: A digital twin can be described as a digital model of an intended or actual real-world physical system that serves as an effectively indistinguishable digital counterpart for practical purposes, such as simulation, testing, and evaluation. At the core of the efforts is a digital acoustic twin of Notre-Dame de Paris cathedral. In architectural acoustics, numerical simulations have been used for years to analyse and predict the resulting acoustics in various buildings. With the evolving quality of numerical simulations, and associated meticulous calibration, and the design of interactive and immersive systems employing the results of these models, it is possible to provide indistinguishable virtual environments where the acoustics of a space, existing or not, can be examined through subjective evaluation and not just analytical metrics.

Model Calibration In historic auralisations, calibrating the studied building's room acoustic simulation model is often necessary to accurately represent its acoustical environment. A methodical calibration procedure for GA models using room acoustics prediction programs to create realistic virtual audio realities, termed auralisations, has been proposed [4]. Perceptual evaluations of this method have been carried out [5].

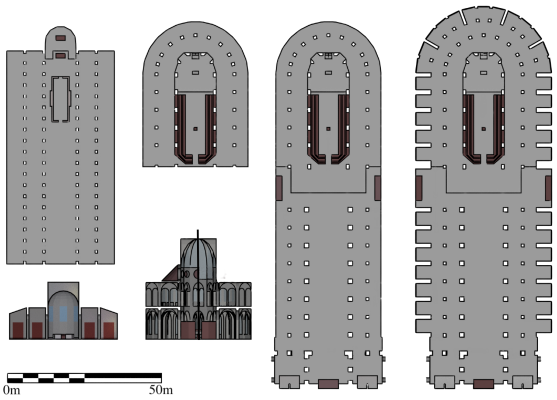


Fig. 1: Acoustic model floor-plans and sections of cathedrals built on Île-de-la-Cité, from left to right: the pre-Gothic basilica underneath Notre-Dame's parvis (before 1163); Notre-Dame at its consecration (1182); completion of the nave (ca. 1220) and lateral chapels (ca. 1350).

Notre-Dame de Paris, A living building: To provide some context, the following section presents a quick overview of the architectural history of Notre-Dame, schematised in Fig. 1. Developmental efforts commenced on the eastern extremity of the cathedral's ambulatory in 1163 while pre-existing church structures were demolished to clear the way. These structures included at least one large basilica underneath the modern forecourt. The inaugural construction phase concluded in 1182, after which a substantial retaining wall was built to allow services to occur inside the chancel while construction continued westward.The construction reached the grand facade by the 1220s, and subsequent construction expanded the cathedral between the foundations of the flying buttresses, resulting in 35 lateral chapels. More details on the early acoustic conditions have been presented in [6, 7]. After the 14th century, the external structure remained largely unchanged until the renovations of the 19th century.[3]

Audio Rendering Tool, Bridging Research & Production: Auralisation, a method for replicating realistic

[2]PHEND project: phend.pasthasears.eu

[3]This video provides a good representation of the architectural history of Notre-Dame: youtu.be/JvvJJzmXdTY.

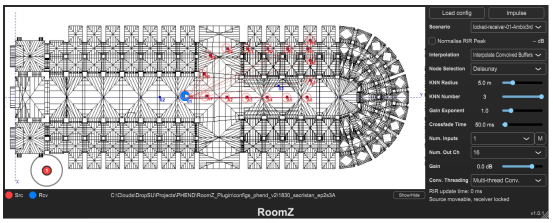


Fig. 2: Example RoomZ Notre-Dame scene with source near transept and moving receiver trajectory.

auditory experiences in virtual settings, is used in architectural acoustics and sound system design [8, 9]. This technique involves convolving anechoic sound with Room Impulse Responses (RIRs) to simulate how sound travels in specific spaces. Dynamic auralisations increase realism by interpolating between RIRs as sources or receivers move [10, 11], though tools for such dynamic simulations are limited [12].

To bridge the gap between acoustic research and practical application, we developed *RoomZ*[4] [13], a VST3 plugin for digital audio workstations. It allows for dynamic auralisations by adjusting source and receiver positions across RIR grids, featuring fast multi-core convolution and custom navigation scenarios with multi-channel outputs (monaural, binaural, ambisonic, etc.). The interface (see Fig. 2) uses a 2D graphical map for panning, dynamically applying weights based on geometric distributions to convolve the input with appropriate RIRs. RoomZ enables the accurate rendering of environments like a medieval Notre-Dame, directly integrating acoustic research into production, thus enhancing virtual and augmented reality applications.

2 Soundscape archaeology

Diachronic Study: The Notre-Dame Construction Sites of the 12th and 19th Centuries: The archaeology of soundscapes is the study and analysis of past sound environments, contributing to the (re)creation of historical soundscapes [14]. These reconstructions are working hypotheses, subject to modification based on new scientific data or interpretations of the sources used. The UNESCO resolution on safeguarding intangible cultural heritage [15, 14] emphasises authenticity. Soundscape archaeology contributes by offering plausible reconstructions of historical heritage while preserving its authenticity. Soundscape archaeology follows the definition of the ISO standard [16], which defines soundscapes as perceptual constructs existing through human perception. Based on this definition, audible models can be proposed. By studying the past from a sensory perspective, analysing traces in archives and current recordings, the soundscapes presented for listening are recordings of real sounds present in the environment, not sound effects. If a sound cannot be recreated due to a lack of data, this is a gap in the reconstruction. However, this does not detract from the overall listening experience, as our natural acoustic environment is rich and diverse. Soundscape archaeology aims to provide precise recontextualisation through sensory experiences, immersing us in history, as in the case of Notre-Dame, to grasp the evolution of the monument, the lives of those involved, and its urban location. It involves drawing from diverse sources to uncover information and understand past links and interactions [17]. Within a soundscape, three major "layers" of sound can be distinguished [18, 19], each with its own characteristics. Geophony refers to sounds specific to a place and those related to weather phenomena; biophony refers to sounds emitted by fauna and flora, including insects; and anthropophony refers to sounds and semiotics generated by human activities.

Drawing on the experience and methodologies developed in other research projects [20, 21], including the Bretez projects for creating sound frescoes and ESPHAISTOSS for recording sound objects, the study of the Notre-Dame soundscape aims to recreate the soundscapes of various periods identified by the team. The examples here focus on the external atmospheres during the construction of the cathedral (around 1170[5]) and during its restoration under Viollet-Le-Duc (around 1850[6]). The geographical space around Notre-Dame in the 12th century differs greatly from today's (see Fig. 3). Over time, it has undergone numerous transformations: expansion of the area, the evolution of urban construction, the raising of the quays, etc. [22], becoming somewhat similar to the contemporary setting when analysed around 1850. Thus, the diachronic reading of the sites shows that while this geographical space remains similar in terms of area, urban morphology, and population density, the most significant transformations are noted to the south, with the transition from riverbanks to quays altering the entire acoustic and sound ecosystem, including the presence of the Hôtel-Dieu (southwest of Notre-Dame), or changes in urban ambiences, such as the mechanisation of shipping with paddle-wheel boats.

If the medieval construction site was a social space

[4] RoomZ: roomz.dalembert.upmc.fr

[5] Audio: soundcloud...chantier...1170-la-seine & 1170-le-parvis

[6] Audio: soundcloud...chantier...1850

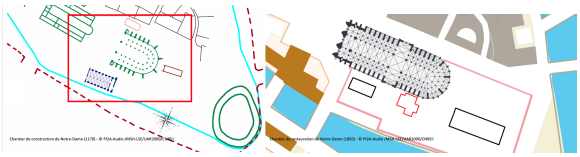


Fig. 3: Plan of the cathedral in 1170 and 1850: Geographical and urban evolution.

where adults and children coexisted, the 19th century restoration site was reserved for workers and craftsmen alone. Regardless of the era, the main actors were carpenters, stone cutters, masons, and blacksmiths. Carpenters erected scaffolding and performed carpentry work, while stone cutters chiselled blocks and sculptures. Indeed, Viollet-le-Duc's intention for a restoration that was faithful to the original did not alter the sounds and noises of activities at the site. Thus, only the peripheral ambiences evolved. Diachronic listening must reveal technological evolutions. All these elements and evolutions must be considered and included to recreate the soundscapes of the past. The work of capture and restitution is monitored, and reports can be read in the research notebook ArcheoSon[7].

3 Webradio concert reconstruction

As part of the celebrations of the 850 year anniversary of the construction of Notre-Dame de Paris, on 24-Apr-2013 the cathedral welcomed a performance of *La Vierge*, under the direction of Patrick Fourniller; this performance was recorded in detail by the Conservatoire de Paris (CNSMDP). In honour of the 2020 International Year of Sound (sound2020.org) and for the 1 year memorial of the Cathédrale Notre-Dame de Paris fire, we created a virtual reconstruction of a performance recording made in the cathedral, recreating the monumental acoustics and the event. To share this performance with those who could not attend and to honour the cathedral, damaged by the fire on 15-Apr-2019, we took these recordings and the acoustical digital twin of Notre-Dame to audibly reconstruct the concert from several listening positions; the place of the conductor, in the first row, middle audience, and rear of the cathedral, offering a unique 3d-audio experience approaching the reality of the moment in the past.

This approach offers the possibility of realistic listening at a given position, which is, of course, not necessarily the ideal seat. Nor is it comparable to the type of artistic mix we have grown accustomed to with broadcast or CD material, which often provides a heightened readability and understanding of the work when compared to what is physically possible. Fully detailed in [3], the content remains available for listening[8].

4 Radio-Fiction

Context: The NARRATIVE production team embarked on creating a radio-fiction project with the dual objective of entertaining a broad audience and disseminating the project's research findings. Central to this endeavour was the strategic use of spatial audio technology, which aimed to immerse listeners in the sonic environment of the cathedral while providing historical context. The concept of the project revolved around a 3D sound narrative that traversed seven distinct historical periods, showcasing various aspects of Notre-Dame's acoustic evolution. The team collaborated closely with researchers to accurately portray historical events and settings while adhering to specific constraints outlined by the research consortium. At the narrative's core was the exploration of Victor Hugo's fascination with Notre-Dame and his quest to understand its acoustic properties during the 19th century. Drawing inspiration from Hugo's writings and historical records, the production delved into the author's imagination as he envisioned the cathedral's sonic landscape.

Looking for Notre-Dame[9] was released freely in four episodes, each 15 min and available in French (*A la Recherche de Notre-Dame*) and English. This mini-series aimed to balance entertainment and education, presenting scientific content in an accessible and engaging format.

Production: The production process involved meticulous sound recording techniques, capturing scenes in studio and anechoic chamber settings. The team leveraged binaural audio technology to create immersive soundscapes, allowing listeners to experience the spatial dimensions of Notre-Dame's acoustic environment. The audio mixing phase was particularly crucial, as it aimed to blend artistic expression with technical precision. By employing 3D binaural mixing techniques, the team sought to maintain the narrative's immersive quality while ensuring the accuracy of spatial effects. In addition to the audio content, the project's accompanying website serves as a hub for supplemental

[7] ArcheoSon: archeoson.hypotheses.org

[8] La Vierge 2020: lavierge2020.pasthasears.eu

[9] Looking for Notre-Dame: lookingfornotredame.pasthasears.eu




Fig. 4: Photos of public presentations during the Night of Museums and the Institut Français.

materials and further exploration. Researchers provided in-depth insights into the project's historical and scientific aspects, offering a comprehensive overview for interested audiences.

Reception: The project's reception was overwhelmingly positive, with public events drawing significant interest and engagement. Collaborations with platforms such as Audible R&D expanded the project's reach, making it accessible to a wider audience through digital distribution channels. Overall, the radio-fiction project successfully merged storytelling and scientific inquiry, demonstrating the potential of immersive audio technology in communicating complex research findings to diverse audiences.

5 Audio-Guide

The Talkartive production team was tasked with creating an immersive and didactic experience centred around the Cathédrale Notre-Dame de Paris. Their goal was to offer visitors a comprehensive understanding of the cathedral's acoustic and historical elements within a museographic context. The resulting audio-guide, embedded in a mobile app, aimed to provide visitors with a rich auditory experience enhanced by spatial audio technology.

Context: Before the devastating fire of April 2019, Notre-Dame was one of France's most visited cultural sites, attracting around 12 million visitors annually. However, the cathedral's closure due to post-fire restoration has significantly reduced on-site visitation. Talkartive developed an exterior geolocalised audio-guide accessible via a mobile app. This initiative aimed to make PHEND's research findings available to the public, bridging the gap between scientific research and general interest.

Notre-Dame Whispers[10], the full version launched publicly 6 May 2023, offers visitors a journey into the sonic history of Notre-Dame. Developed as a research popularisation project, it provides on-site visitors with narrated insights into the cathedral's acoustic heritage. Drawing inspiration from the PHEND radio-fiction, the audio-guide is a companion to visitors, enriching their experience through immersive storytelling.

Design of the Visit: The design process began with an exploratory phase to define the visit route and conceptual framework. By studying the cathedral's surroundings and observing visitor behaviour, Talkartive identified key waypoints for the audio-guide. These waypoints were strategically located to offer visitors visual and auditory experiences relevant to Notre-Dame's history. A walk around the cathedral's restoration site provided valuable insights into potential observation points and visitor demographics. Despite Notre-Dame's closure, the surrounding area remained accessible, allowing for the design of a comprehensive visit route. Specific waypoints offer visitors unique perspectives on Notre-Dame's architecture and history. Each waypoint corresponded to a theme or historical event, providing visitors a multi-sensory experience.

The mediation design centred around three core components: a mobile app for audio-guided tours, binaural audio content for immersive storytelling, and strategic placement of observation points around the cathedral. These components were designed to cater to diverse audiences and foster engagement through gamification and multi-modal experiences. To engage visitors effectively, Talkartive implemented various strategies, including a fictional narrator-character embodying Notre-Dame's persona and a quest-based narrative structure. Visitors were encouraged to explore all waypoints and complete the quest, thereby contributing to the adornment of a symbolic rose window.

Despite the advantages of geolocalisation, it is still possible for those at remote locations to experience the audio guide off-site without this functionality.

Mediation Tool: Using a mobile app as the mediation tool offers several advantages, including offline accessibility, user data collection, and push notification capabilities. The app's user interface was designed (in Unity) to prioritise the auditory experience, with simple navigation and intuitive controls. Four main types of

[10]Notre-Dame Whispers: ndwhispers.pasthasears.eu



Fig. 5: The main screens of the mobile app. From left to right: Map, Audio player, Playlist, and finally the Rose window (shown here where only the first piece of waypoint 1 has been completed).

screens (see Fig. 5) were developed to guide visitors through the visit route and enhance their interaction with the audio content.

The production phase involved crafting immersive storytelling narratives, recording voice-overs, and creating audio pieces. The storytelling process focused on creating compelling narratives and characters to engage visitors. A fictional narrator-character, embodying Notre-Dame's persona, was chosen to guide visitors through the experience. The script was crafted to maximise immersion and realism, with each audio piece comprising multiple phases to enhance the visitor's auditory journey. Additional production details can be found in [23].

Evaluation: Several methods were proposed for evaluating the effectiveness of the audio-guide as a mediation tool, including data analytics and in-situ experiments. User data collected through the app, including visitor behaviour and feedback on audio content, provides valuable insights into visitor engagement and satisfaction. Additional analytics will track key metrics such as app usage duration and completion rates for the quest-based narrative. An on-site public survey will assess the audio-guide's impact on visitor experience and learning potential. Through post-visit questionnaires and interviews, visitors' satisfaction levels and perceptions of the app's usability and effectiveness will be evaluated and presented in a future publication.

6 The Virtual Concert

To illustrate the findings of the PHEND research project, the Paris Conservatoire is organising a virtual concert in the form of an immersive 3D audio film. This event, aimed at both cultural mediation and scientific education for a broad audience, invites exploration of the acoustics of this iconic monument across various eras.

Eleven pieces closely linked to Notre-Dame's musical history have been selected, ranging from 12^{th}–13^{th} century *organum* to 20^{th} century works from the French organ school "revival". Each will resonate within the digital acoustic twin corresponding to its era of creation. The visual creation of the film is handled by DaDa Animation studio.

Unconventional Recording Techniques: Designing the recording for such a project requires a different approach than that of stereophonic sound recording. In two-channel stereophony, a microphone pair is traditionally used, which captures a kind of "spatial photograph" of the musical ensemble in its acoustical environment. From this basis, additional microphones are placed on the instruments (or groups of instruments) to refine their presence in the sound image produced by the pair. The pair, in this case, is the component farthest from the sound sources: the distance between the pair and the source is adjusted according to the desired balance between direct sound and reverberation. The more distant the pair from the sources, the more it highlights the acoustics of the room. Each spot microphone is placed individually closer to the captured source to achieve the best compromise between recording quality and the cross-talk caused by other nearby sources.

To achieve the best results via convolution, sound sources must be free of any preexisting acoustics. They are, therefore, recorded using close mics, ideally in an anechoic chamber, to eliminate all reflections or reverberation, allowing each source to be processed individually in RoomZ (Section 1).

Example 1: Ensemble Pérotin le Grand, Sorbonne University's anechoic chamber, Léonin (ca. 1150-ca. 1210), Organum ludea et Ierusalem: There were 7 singers, spaced 1.2 m apart, arranged in a semi-circle. Each voice is distinct, captured using cardioid head-worn mics (DPA 4088), maintaining a constant distance between the microphone and the singer's mouth, regardless of movements, ensuring a consistent sound quality for each voice. This choice allows for the best isolation of each voice from neighbouring sources.

Example 2: Louis Vierne (1870-1937), Carillon de Westminster, Piece for organ This recording was made at the Saint-Sulpice Church, whose Cavaillé-Coll organ from 1862 is similar to the one at Notre-Dame when Louis Vierne was its organist. The Saint-Sulpice organ consists of approximately 7000 pipes, each a

distinct sound source, spatially arranged in a case partitioned into several sections.

A two-tier microphone ramp, consisting of cardioid microphones (mics 1–6 and 7–9 (Fig. 6), DPA 4011c), is positioned in front of the façade, close to the montre pipes of the organ, *i.e.* the visible pipes that decorate its façade. They are placed to avoid directly aiming the capsules at the mouths of the pipes (targeting the mouth would amplify its sound and the noise caused by the air jet exiting the mouth). This ramp, later processed with RoomZ, provides a realistic reproduction of the instrument's apparent width and radiation. This setup also contributes to the restitution of the different planes of the ensemble of pipes from the various compartments of the case (near/far plans). The organ case is partitioned into several compartments within which additional mics are positioned to achieve overall coverage of the instrument, used to balance the instrument's sound in post-production (see Fig. 6): 10–13 : Neumann KM140, 14–17 and 22–23 : Schoeps Mk21, 18–21 and 26–29 : Schoeps Mk4, 24–25 and 30–31 : Neumann KM184.

3D Mixing: During mixing, each source, captured by a distinct microphone, is adjusted in level and positioned individually within the acoustical model of RoomZ. The listening point is also positioned in this space. RoomZ then performs a third-order ambisonics render and a binaural render, thus simulating the reproduction of these sources at this listening point within the acoustics of Notre-Dame, for the chosen period. In line with video production, RoomZ allows for simulating acoustical changes induced by the movements of the virtual camera.

Video Creation: The visual creation of the film is based on the 3D models of Notre-Dame de Paris cathedral, which has evolved over time. From its construction to the modern era, five major periods of interior architectural modification (choir, rood screen, paving, stained glass, organ, statuary) have been identified, and accordingly, five 3D models become the backdrop for the musical and cinematic presentation of the eleven selected works. Each work is the occasion for its own short film: the camera travels through the building, bathed in changing and specific light, defying gravity to celebrate the architectural and artistic wonders of Notre-Dame, while the presence of the musicians is represented by moving particles. The eleven shorts will be combined into one long film, forming a unique virtual concert, in the form of an immersive film with 3D audio.

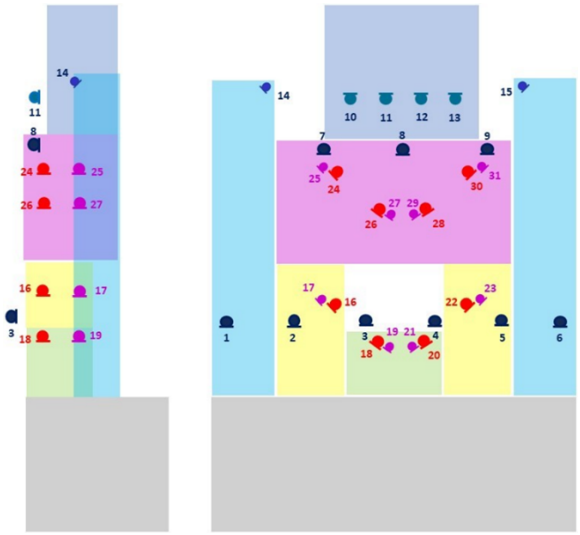


Fig. 6: Microphone installation (left) side and (right) frontal views, Saint-Sulpice organ case.

7 Discussion

In our quest to explore Notre-Dame's acoustic legacy through the PHEND project, we've made significant strides in understanding and preserving its intangible essence. Combining detailed documentation, research, and virtual reconstructions, we've unveiled intricate relationships between its structure and soundscapes. The PHEND project, akin to a digital renaissance for Notre-Dame, has examined its historical evolution and significance and envisioned its future post the 2019 fire. At the heart lies Notre-Dame's "digital acoustic twin", a scientific model capturing its acoustic properties across eras. This digital twin deepens our understanding and serves as a platform for immersive storytelling. Beyond scientific exploration, we've embraced compellingly presenting the cathedral's history. Transforming narratives into sound stories, we aim to create presentations transporting visitors through time and space.

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phe.pasthasears.eu). Additional financial support for these productions has been provided by Audible R&D, the *Collegium Musicae* and *Observatoire des patrimoines de l'Alliance Sorbonne Université*, and the *DIM Patrimoines matériels – innovation, expérimentation, résilience (PAMIR)*. We also thank the *établissement public administratif* responsible for the conservation and restoration of Cathédrale Notre-Dame de Paris for enabling researchers access to the restoration site.

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