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Acoustics:
the past has ears

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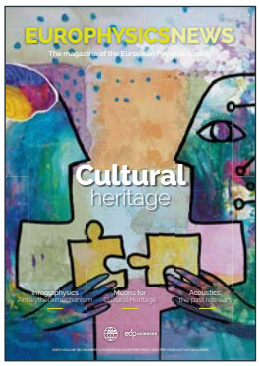
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Cover picture: AI Robot and human cooperation connecting puzzle pieces together.
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Utilizing chemical imaging for paintings



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The "Grotta della Poesia" (Lecce, Italy)



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The past has ears: acoustics for Cultural Heritage

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[EPS EDITORIAL]

Physics and Cultural Heritage

DOI: https://doi.org/10.1051/2025401

For some time, museum curators have used scientific knowledge from physics and chemistry, to analyse, restore, and preserve all sorts of artistic and architectural pieces. As early as the end of the 19th century Louis Pasteur wrote a note entitled « Notes pour les leçons de physique et de chimie appliquées aux Beaux Arts (Notes on the lessons of physics and chemistry applied to the fine arts). The major museums now have dedicated services able to operate all kinds of scientific devices, from X-ray radiography, X-ray fluorescence, UV and IR spectrometry, thermal imaging, to gamma rays induced by particle accelerators. These tools were often originally conceived for fundamental physics research.

The first step in the analysis of a work of art is to identify the elements it contains. This can tell us where, how, and when it was made, by inferring precise information on the fabrication technique.

The basic requirement for the methods of analysis is their non-invasive nature. For example, the use of microscope (optical or electron) may require that a sample of material is removed from the object and is then often excluded.

Techniques like spectroscopy can reveal the chemical makeup of ancient paints without damaging them. X-ray fluorescence (XRF) can peer through layers of history to uncover hidden images or inscriptions. Thermal imaging detects weaknesses in walls and frescoes before they become visible to the naked eye. This means that these methods provide useful information for art history, preservation, and even restoration if needed.

The scope of the analysis covers a wide range of areas: archaeology, architecture, fine arts, and a time range running from paleolithic era to modern times.

One interesting example is provided by the Antikythera Mechanism: fragments of a corroded bronze mechanism were retrieved from a shipwreck off the coast of the Greek island Antikythera in 1901. X-ray, Gamma-ray images, and then X-ray computerised tomography have been used to explore – in a non-invasive way – the structure of the mechanism. Some of the fragments contains gearwheels, and some bear inscriptions. The mechanism is understood to be describing the motions of the Sun, the Moon and all five planets known in antiquity, including complex planetary periods. It can be considered as the first known analogue computer, constructed in ancient Greece back in the late second century BC or the early first century BC.

Another interest of the use of the various methods mentioned above is to determine the authenticity of a piece of art. An art scientist may use mass spectroscopy to identify which pigments were used, X-rays to determine whether a possible forgery is painted on a re-used canvas, and infrared reflectography to reveal underlying layers. There is a market for art, and this may attract forgers. By a careful analysis can help to detect frauds.

Beyond analysis, there is the possibility of « rebuilding the irreplaceable ». There are unfortunately cases where the cultural heritage is destroyed, intentionally or not, during conflicts or by natural disasters and physics helps rebuilding first digitally, and then physically. Art historians used laser scanners to create an extremely accurate digital copy of the cathedral Notre-Dame de Paris, which was essential for its recent restoration.

The use of modern tools of physics is a way to preserve what we inherited from the past and bequeath it to the future generations. ■

Mairi Sakellariadou, *EPS President*

Behind the scenes of international conferences: the 13th Young Minds Leadership Meeting

Yago Radziunas-Salinas*, Alicia Muñoz-Ramos, Alejandro Doval and Celtia Jabares
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One of the most enriching experiences in our scientific careers is the opportunity to attend international conferences: meeting new peers to discuss science, work on future collaborations, and in many cases, go sightseeing and have fun.

Nevertheless, have you ever wondered about the organizational workflow and experience behind an international conference? Come along with us, the Santiago YM Section, as we share our feelings, thoughts, and experience organizing such an important event as the 13th Young Minds Leadership Meeting.

Public outreach is a core value of the European Physical Society (EPS), and for over a decade, our section has worked to make science accessible beyond academia. In recent years, we have integrated diversity and inclusion as key pillars of our approach, building strong connections with local associations, universities, and experts. These experiences prepared us to take on our biggest challenge so far: organizing the 13th YMLM.

When did we begin planning? It all began in September 2024 (almost a year in advance!), with early discussions on logistics, accommodation, budget, and program design. Our goal was clear: create an event that combined scientific sessions with personal development and social awareness topics. The meeting was scheduled for 4–6 June 2025, starting with a welcome reception to break the ice and encourage attendees to connect from the very beginning.

What did the program look like? We curated a blend of physics talks on cutting-edge topics, including cosmology by EPS President Mairi Sakellariadou, quantum materials by Víctor Pardo (researcher at University of Santiago de Compostela, USC), attosecond optics by Bárbara Buades (PhD in Photonics, ICFO), and physics beyond the Standard Model by Meijian Li (postdoc, IGFAE). Broader issues were also addressed, such as AI from a gender perspective by Eva Cernadas (USC), and mental health in academia by researchers from USC's Clinical Psychology Department. Career-focused sessions included a "PhD-to-CEO" roundtable with Pablo Cabanelas (Neutron Insights, USC) and Bárbara Buades (Meetoptics, Barcelona), and a professional development session by Paulo Ferreira (Group Leader and Scientific Coordinator in INL, Portugal). Finally, two poster sessions were held, where the EPL journal prized the 2 most valuable activities from the YM Sections joining the event.

Was there time for fun? Of course! A networking activity, group dinner, and a live concert by the local band Ginko Biloba created a relaxed, friendly environment—essential for fostering connections and collaborations.

How did we manage to plan everything? A clear way of organising the team was fundamental. In our case, we relied on social media to create a community where all the different tasks (accommodation, social diffusion, etc) were discussed. A person was in charge of managing the event, and then individual tasks were assigned to the different team members. In addition, weekly meetings were held to discuss these points. We believe that good organization is key to making such an event work smoothly. Still, we are aware that in academia—where pressure and competition often speed things up—it is not always easy to maintain structure and clear communication.

Who helped us along the way? One of the most important lessons we learned was the value of asking for and accepting support. The EPS Young Minds Action Committee (AC) was incredibly helpful, offering guidance on complex matters like visa procedures. In particular, we would like to thank Damián Rodríguez (AC member), for his advice and constant support throughout

▼ FIG. 1: Welcome reception held on June 4th in Fonseca Palace (USC)





▲ FIG. 2: PhD-to-CEO Roundtable with Pablo Cabanelas, and Bárbara Buades

our journey. We also received significant support from OPTICA, especially for the PhD-to-CEO roundtable, with Yann Amouroux (Director, Europe at OPTICA), along with Lasha Dalakishvili (AC member), contributing both their time and expertise.

Did everything go smoothly? As with any large event, a few hiccups were inevitable (last-minute poster printing, rainy weather, small scheduling changes, *etc.*). These moments reminded us of the value of staying calm and relying on teamwork. The experience of senior members and efficient internal communication helped us respond quickly and effectively.

Was it worth it? This international experience has broadened our minds, not only from a scientific view but also from a personal growth aspect. Running such an important event was a big responsibility, and our major desire was that all the attendees enjoyed the event, the city, and our section in the best way. Throughout the long journey, we gained a lot of expertise in managing logistics aside from the scientific tasks, and we do consider it one of our most valuable professional experiences so far, not only for our Bachelor and Master members, but also for the PhD candidates who will, sooner or later, follow their own professional path. ■

▼ FIG. 3: Networking activity held in the sports hall of our University



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Painting materials in San Salvatore crypt, Italy, confirmed to be from the Lombard Period

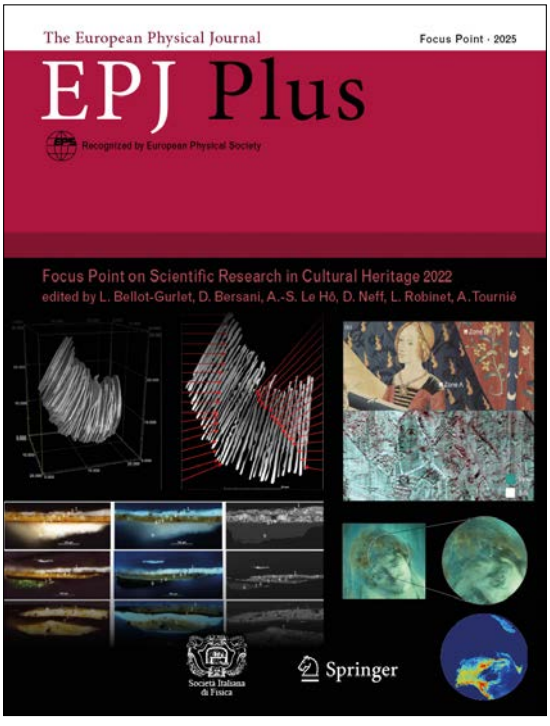
– DOI: https://doi.org/10.1051/epn/2025403

Complemeting PIXE spectroscopy with two further techniques, electron microscopy and Raman spectroscopy, plus infrared photography has allowed a full characterisation of the pigments making up these important medieval paintings.

The European Physical Journal - Plus (EPJ Plus) encompasses all aspects of fundamental and applied physics and welcomes interdisciplinary topics, in particular cultural heritage.
The journal accepts individual articles in this field, but it also publishes focus point issues (topical collections) such as *e.g.*
Focus Point on Scientific Research in Cultural Heritage https://link.springer.com/collections/gdieggcdje
Focus Point on Advances in Analytical Techniques for Archaeological Potteries https://link.springer.com/collections/hahbdahghc
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Focus Point on Advances and Innovation in Heritage Science https://link.springer.com/collections/gejgiidbjc
and proposals for new focus point issues in the field of cultural heritage are highly welcome.
Read this highlight about an article in the field of cultural heritage recently published in EPJ Plus:

The eighth-century church and crypt of San Salvatore in Brescia, Italy is one of the most important pieces of Early Medieval religious architecture in that country, if not in Europe as a whole. The crypt is known for its remarkable wall paintings. The pigments used in these were analysed about twenty years ago using a non-destructive technique, PIXE (Particle-Induced X-ray Emission Spectroscopy), but the results were largely inconclusive. An international group of scientists led by Alessandro Zucchiatti of the University of the Witwatersrand, Johannesburg, South Africa and the University of Genoa, Italy has now performed a much more detailed analysis of these pigments, leading to important insights into their nature. This work is now published in EPJ Plus.

The original PIXE analysis of the painting samples was not sufficient to precisely identify the materials used for two main reasons: the spatial resolution of this technique is relatively limited and the samples had been buried for many centuries. Zucchiatti and his team have now complemented this with two further instrumental techniques, scanning electron microscopy (SEM) and Raman spectroscopy. "This multi-disciplinary approach, starting with the simple [in this case PIXE] and then using more specific techniques to go into details is a common and effective practice in archaeometry", explains Zucchiatti. Archaeometry is the application of techniques from the physical and life sciences to the study of archaeological remains.

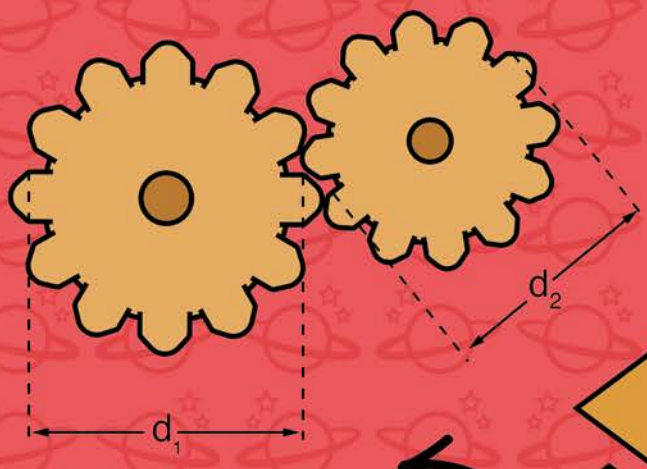


Using this combination of techniques, the researchers were able to identify ochres in the red and yellow pigments, glauconite in the green earth pigment and carbon in the black and grey areas. "The results concerning the green and black pigments were particularly novel and interesting", adds Zucchiatti. Cobalt was discovered in a piece of blue glass from the stucco decoration of an arch. Taken together, these results were in agreement with materials that were in use during the same period as the crypt itself, the Lombard era in Italy. ■

Reference

[1] A. Zucchiatti, S. Roascio, I. Donate Carretero *et al.* PIXE, SEM and RAMAN analysis of pictorial materials from the VIII century crypt of San Salvatore, *Brescia (Italy). Eur. Phys. J. Plus* **139**, 1015 (2024). https://doi.org/10.1140/epjp/s13360-024-05800-0

INFOGRAPHYSICS



Gear ratio

In the core of the mechanism several rings are connected to each other by gears. The speed of each ring is controlled by the the size of connected gears — specifically by
K=d2/d1

The planetarium

According to the reconstruction of the Antikythera mechanism, the Cosmos included Mercury, Venus, Mars, Jupiter, Saturn, the Sun, and the Moon with its phases.

Eclipses

This gear described a saros cycle. A perioid of approximately 18 years, by which the Earth, Sun, and Moon return to approximately the same relative position. It was used to nidicate the months in which an eclipse was likely to happen.

Olympic games

This gear described a Metonic cycle. A period of approximately 19 years, by which the phases of the moon recur on the same days of the solar year. A secondary gear attached to this showed when the Olympics games should take place.

Physics of the Antikythera mechanism

The Antikythera mechanism is the oldest geared instrument in the world. It was a mechanical computer that used complex combinations of gears to translate astronomical cycles into mechanical motion, enabling the estimate of the occurencies of astronomical events. The remaining 82 fragments were discovered in 1901 and only recently[1] a model has been proposed to reproduce the whole mechanism. Thanks to X-ray tomographic reconstructions and to interpretatoins of the writings found on the back and front peices of the rests of the mechanism, scientists were able to reconstruct ancient astronomical predictoins.

[1] *Sci Rep 11, 5821 (2021)*

DOI: https://doi.org/10.1051/2025404

Dr Vittorio Aita
Editor
Nature Communications

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The Laplacian spectrum of language: experiments with linguistic families from the Americas

– DOI: https://doi.org/10.1051/2025405

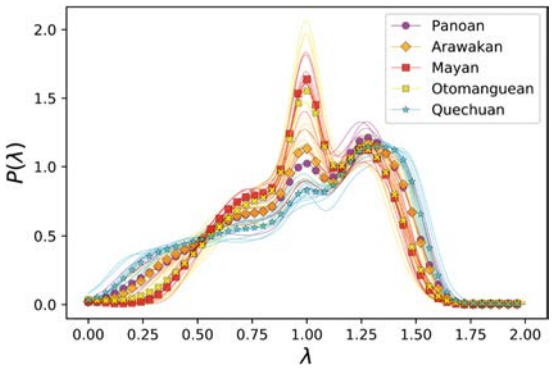
What can physics offer to the study of endangered languages? In a world where only a small fraction of the approximately 7,000 spoken languages are represented in the current wave of artificial intelligence—through tools like machine translation, voice assistants, or large language models—most Indigenous languages, especially those of South America, remain digitally invisible.

Their absence is not just a technical limitation; it reflects deep inequalities in how knowledge, culture, and language are treated in the digital age.

This work explores how tools from statistical mechanics, and in particular spectral graph theory, can contribute to the computational representation of low-resource languages. Using parallel translations of the Universal Declaration of Human Rights, word co-occurrence graphs are constructed for 85 languages of the Americas. In each graph, nodes represent unique words, and edges are created between words that appear within a short distance of each other in the text. The edges are weighted according to how often the word pairs appear together. These graphs offer a simple, language-agnostic way of encoding the structure of the text.

To analyze these graphs, a normalized version of the Laplacian matrix is computed. This matrix captures the graph's internal structure by describing how each word is connected to its neighbors. The eigenvalues of this matrix—known as the Laplacian spectrum—form a statistical signature that summarizes key features of the graph. In physics, such spectral profiles are widely used to study the dynamics and geometry of complex systems. Here, they are repurposed to describe patterns in human language.

The analysis shows that different linguistic families—such as Quechuan, Arawakan, Mayan, and Otomanguean—produce distinct spectral patterns. These patterns are closely related to known linguistic properties. For instance, the frequency of one particular eigenvalue (commonly associated with node duplication in graph theory) is negatively correlated with word entropy, a measure of lexical diversity. Languages with richer morphological systems tend to show higher entropy and lower frequencies of this eigenvalue, suggesting that meaningful structural differences are reflected in the spectra.



▲ Laplacian spectra of linguistic families from the Americas. The figure displays the average Laplacian spectra of five major linguistic families spoken in South America: Panoan, Arawakan, Mayan, Otomanguean, and Quechuan. Each curve is constructed by averaging the spectral profiles—sets of eigenvalues from the normalized Laplacian matrix—across all languages within a family. These spectra are derived from word co-occurrence graphs based on translations of the Universal Declaration of Human Rights, using a graph radius of two. Peaks at specific eigenvalues suggest the presence of structural regularities shared within linguistic families. These spectral shapes offer a compact, data-light way to detect typological differences and similarities, especially valuable in the context of digitally marginalized languages. By translating linguistic variation into spectral form, the figure illustrates how physical tools can reveal hidden dimensions of cultural diversity and contribute to the computational visibility of endangered languages.

One key advantage of this approach is that it does not require large datasets, linguistic annotations, or deep language-specific knowledge. Instead, it offers a lightweight, interpretable, and reproducible method to study languages with limited digital presence. This makes it especially suitable for endangered and marginalized languages that are often left out of computational linguistics and AI development.

Beyond its technical contribution, this study encourages a broader reflection on how physics can support the digital humanities. Graph-based methods, long used in physics to model interactions and flows, can also reveal the hidden geometries of language. The Laplacian spectrum becomes not just a mathematical construct, but a way to detect structure, similarity, and diversity across languages—even in minimal texts.

Ultimately, applying classical tools from physics to cultural data is also a gesture of inclusion. It points to new roles for physics in building digital infrastructures that are more equitable and representative. By making small, endangered languages visible in a computational sense, this work contributes to a more inclusive vision of how data—and science—can serve cultural diversity. ■

Reference

[1] J. Vera Zúñiga, The Laplacian spectrum of language: Experiments with linguistic families from the Americas, *EPL* **150** (2025) 22001. https://doi.org/10.1209/0295-5075/adb450

Biography of Hans Joachim Specht

DOI: https://doi.org/10.1051/epn/2025406

Having known Hans for nearly two decades—sharing countless in-depth discussions on physics and science policy, and exchanging hundreds of emails and phone calls (always beginning with his unmistakable "Specht here")—I thought I had a fairly complete picture of the man. But after reading this exceptional biography of Hans Joachim Specht, published by Springer, I realized just how much more there was to discover about his remarkable life and scientific contributions.

This biography offers a rich, comprehensive account of a physicist whose career has been driven by an insatiable curiosity—not only to advance fundamental physics but also to bring those advances to practical applications. Hans once told me that his work on hadron cancer therapy was his most important legacy to humanity, a statement that underscores the deep purpose behind his research.

Born in 1936 in Unna, Germany, Hans began his academic journey at the Ludwig Maximilian University of Munich and ETH Zurich, earning his doctorate in 1964 under the supervision of Heinz Maier-Leibnitz. The book traces sixty years of groundbreaking physics work, a true tour de force through multiple disciplines—from Atomic and Nuclear Physics to Ultra-Relativistic Heavy-Ion Physics and Medical Physics, much of it conducted at major accelerator facilities.

Among his many achievements, Hans discovered shape isomerism in heavy nuclei—demonstrating that nuclei can exist in a deformed, cigar-shaped state before undergoing fission—a major contribution to nuclear structure physics. In the early 1980s, he pivoted to high-energy physics at CERN, becoming the spokesperson for the HELIOS/NA34-2 experiment in 1984, and later founder and spokesperson of CERES/NA45, and a key figure in the NA60 experiment. His work in these collaborations significantly deepened our understanding of the quark-gluon plasma.

Hans's foundational contribution to ALICE, particularly in developing the conceptual design for a dedicated LHC heavy-ion experiment, was instrumental in transforming the idea of heavy-ion physics at the LHC into reality. His leadership within ECFA and his strong advocacy for institutional support from Germany were critical in shaping ALICE into one of CERN's flagship experiments.

Equally impactful, however, has been Hans' leadership in science policy and research infrastructure. As Scientific Managing Director of GSI Darmstadt (1992–1999), he played a key role in initiating tumor therapy with carbon ions, an effort that eventually led to the establishment of the Heidelberg Ion-Beam Therapy Center (HIT)—Europe's first facility of its kind. During his tenure, the groundwork for the future FAIR (Facility for Antiproton and Ion Research) was also laid, as discussed in this biography.

Hans's passion for music, combined with his polymath nature, fueled his curiosity about the intersection of physics, music, and neuroscience—investigating early processing in the brain related to music perception. His lectures on these topics, delivered around the world, along with publications in Nature, remain both memorable and impactful. This interdisciplinary spirit was emblematic of his drive to bridge diverse scientific domains.

What makes this biography particularly compelling is how it intertwines Hans' scientific achievements with personal anecdotes and reflections from colleagues, collaborators, and friends. These nearly 30 personal notes provide a well-rounded and deeply human portrait of Hans—as a scientist, a leader, and a friend.

I wholeheartedly recommend this book to anyone who knew Hans or who is interested in the broader story of scientific progress through the lens of one of its most dedicated and visionary contributors.■

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Physics and Cultural Heritage: endless paths to discovery

by Teresa Cacace
Institute of Heritage Science, National Research Council – DOI: https://doi.org/10.1051/epn/2025407

The words "cultural heritage" will often evoke images of manuscripts, paintings, and other treasures of art and history, far removed from a laboratory. Yet, behind many of today's most remarkable discoveries and preservation efforts lies Science.

Cultural Heritage Science has emerged as a dynamic, interdisciplinary field that bridges the traditional divide between humanistic and scientific studies. STEM scientists work together with conservators, historian and archaeologist to advance knowledge in dating, authentication, conservation, restoration, and risk management. Using state-of-the-art instruments and techniques, they not only answer long-standing questions, but also open entirely new lines of inquiry.

Within this broad landscape, physics plays a powerful role. From probing atomic structures to imaging entire buildings, it enables the study, safeguarding, and interpretation of cultural heritage with unprecedented precision.

Take paintings, for example. Reflectance and X-ray fluorescence spectroscopy provide a non-invasive means to identify and map the pigments and binding media. In the opening article of the EPN 55/4 mini-theme, John K. Delaney and Kathryn A. Dooley showcase chemical imaging to uncover hidden details, from Bellini's concealed trees and Vermeer's unfinished portrait to the rare pigments of a Spanish manuscript. Their laboratories, at the National Gallery of Art, stand as a model of interdisciplinary collaboration.

Meanwhile, in Grenoble, one of the temples of modern science is welcoming cultural heritage scientists. Georgina Roberson *et al.* describe how the European Synchrotron Radiation Facility (ESRF) is implementing "Historical Materials Block Allocation Group". This model allows hundreds of samples to be studied in a single run, greatly increasing efficiency of synchrotron usage. Their case study on Song Dynasty ceramics demonstrates micro-diffraction data can unearth surprising information on firing condition and regional production practices. With the forthcoming SHARE database, these and future datasets will remain available for reanalysis, so that today's results may nourish future discoveries.

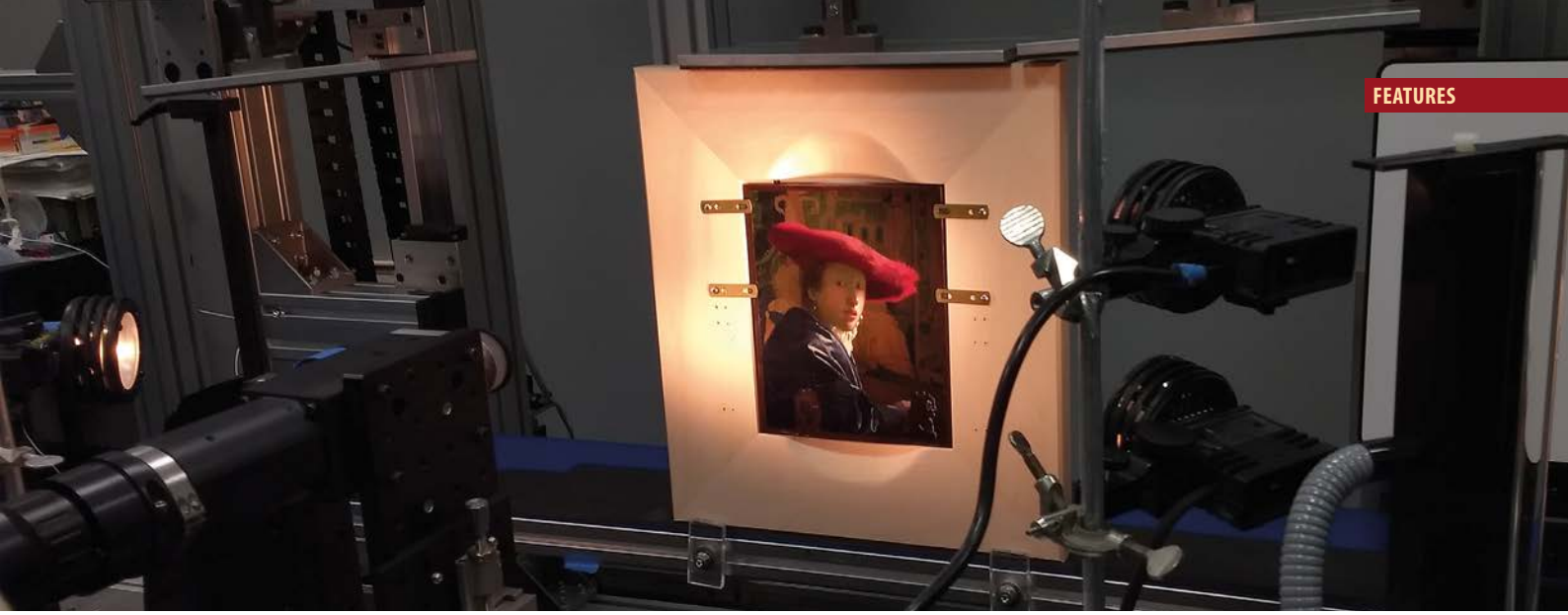
While synchrotron facilities provide controlled, high-intensity beams, some researchers turn to what Nature offers. Muography harnesses cosmic-ray muons, particles continuously passing through us and the Earth, to image dense or inaccessible structures (see Andrea Giammanco's paper). This technique has revealed hidden chambers in Khufu's Great Pyramid and exposed vulnerabilities in medieval structures. New developments aim to extend muography to medium-sized heritage objects, while accelerator-produced muon beams promise high-resolution imaging.

Closer to the ground, geophysical methods also play their part. An example comes from the study of the Grotta della Poesia in southern Italy by De Giorgi and colleagues. By combining seismic tomography and electrical resistivity methods, the researchers mapped fracture zones and assessed cave roof stability. Their work highlights the importance of geophysical surveys in safeguarding archaeological sites where invasive interventions are impossible.

Finally, physics can even allow us to hear the past. In archaeoacoustics, acoustic measurements and physical modelling reconstruct and preserve historical soundscapes. The final paper, by Brian F.G. Katz and Damian T. Murphy, offers a window into this field. They share their experience, from the 19th century House of Commons, where architecture shaped what could be heard, to the Notre Dame Cathedral, whose acoustic fingerprint they captured before the 2019 fire. By translating their research into immersive experiences, they allow today's audiences to listen to history as it once sounded.

Together, these contributions illustrate some of the many ways physics enriches heritage science, highlighting the value of interdisciplinary collaboration. Scientists in this field must combine the spontaneity of serendipitous connections with the deliberate effort of planned collaborations. Only through shared effort, it is possible to achieve novel insights and to deepen our understanding of objects and societies.

This collection can capture only a fraction of what is possible nowadays. Much more is being done, and much is yet to uncover: the questions to answer and the paths to follow are as numerous and varied as heritage itself. ■



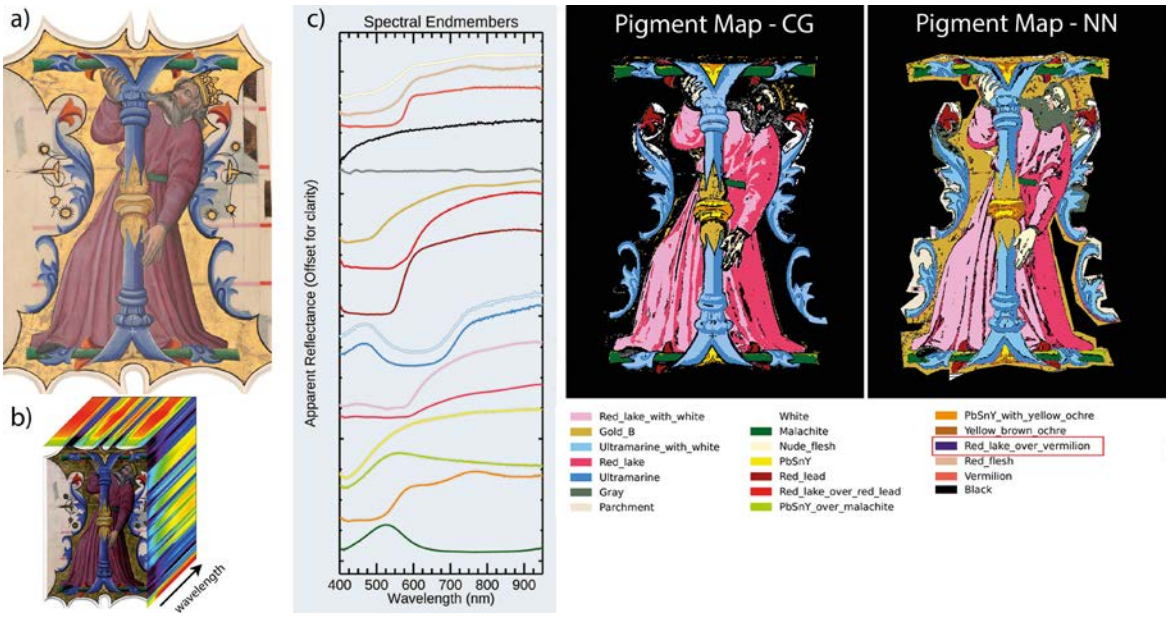
UTILIZING CHEMICAL IMAGING FOR PAINTINGS: MAPPING ARTISTS' MATERIALS AND UNDERSTANDING ARTISTIC TECHNIQUES

John K. Delaney and Kathryn A. Dooley – DOI: https://doi.org/10.1051/epn/2025408
Scientific Research Department, National Gallery of Art, Sixth St and Constitution Ave NW, Washington, D.C. 20565, United States.

Reflectance and X-ray fluorescence imaging spectroscopies are increasingly essential tools in cultural heritage, aiding in the preservation of paintings and addressing significant art historical questions. In this focus paper, we introduce these techniques and provide three examples involving a 15th century Spanish work on parchment, an Italian Renaissance painting, and a Dutch Golden Age painting.

Imaging spectroscopy has become an essential tool for identifying and mapping materials in objects where physical sampling is not possible. This technique can utilize various imaging modalities, including reflected light, emitted light such as fluorescence, or even Raman scattering. A significant example of this is the use of reflectance imaging spectroscopy to search for and map hydrated minerals—such as clays, hydrated silica, and sulfates—on the surface of Mars with the Compact Reconnaissance Imaging Spectrometer (CRISM). The CRISM instrument, which orbited Mars until 2023, employed solar light reflected off the Martian surface to create mineral maps. The presence of hydrated minerals suggests that liquid water existed on Mars in the past. Consequently, maps indicating the locations of such minerals are invaluable for selecting sample collection sites in the quest for evidence of past life on Mars.

Sampling a fine art painting to identify the artist's materials, such as the pigments and organic binding media in the paint layers, is significantly less challenging than sampling rock outcroppings on Mars. However, this sampling is limited to existing paint cracks and areas of damage, where only a small fragment about 200 micrometers in size or less can be taken. Sampling in pristine areas of a painting is not permitted. To help address this limitation, scientists are now using techniques like reflectance imaging spectroscopy and X-ray fluorescence imaging spectroscopy. These methods allow them to explore pristine areas of paintings and gather information about the pigments present on the surface as well as those ● ● ●



▸ **FIG 1:** Painted illumination from a 15th century Spanish choir book titled *Initial I with David*, 1430s, attributed to the Master of the Cypresses. (a) color image, (b) 3-D reflectance image cube, (c) reflectance spectra obtained using a convex geometry algorithm and associated pigment map (CG) and pigment map using Neural Network (NN).

• • • beneath it, sometimes revealing previously abandoned compositions.

Many artists' pigments are derived from minerals, which is why the imaging instruments used to study artworks resemble those employed for remote sensing of the Earth, Moon, and Mars. The spectral range of the reflectance imaging spectroscopy instruments we use extends from deep blue (400 nm) through the visible (400 to 750 nm) and into the near and shortwave infrared (NIR and SWIR, 750 to 2500 nm), with a spectral sampling of a few nanometers. Within this spectral range, various electronic and vibrational transitions occur, which are diagnostic for many inorganic and organic pigments used by artists, as well as for organic paint binders that contain lipids and/or proteins.

Imaging spectroscopy produces a three-dimensional data cube, which consists of a stack of images. Each image is captured within a narrow spectral band, typically just a few nanometers wide for reflectance measurements. The third dimension of this cube contains the spectral information that can be used to identify various artists' materials.

There are several types of instruments available for collecting this 3-D data. These include single-pixel scanners, line-scanning spectrometers, and imaging spectrometers equipped with 2-D detector arrays, such as imaging Fourier transform spectrometers. The volume of 3-D data generated can be substantial, ranging from a fraction of a gigabyte to several hundred gigabytes.

Analyzing these complex data sets has become a significant area of research, leading to the development of novel algorithms designed to condense the data into a manageable number of spectra that describe the scene. These algorithms identify the materials present based on spectral features and provide maps showing the distribution of these materials across the imaged area. The analysis tools used in this process draw from various fields, including physics, chemistry, signal theory, and even artificial intelligence.

Mapping pigments across a 15th century Spanish illumination of King David

The colorful miniature paintings or illuminations in Medieval religious books from Europe are often too pristine for sampling. Here, the combined use of reflectance and X-ray fluorescence imaging spectroscopies has allowed the identification and mapping of pigments used. An example of the reflectance imaging results from such a study applied to a painted illumination from a 15th-century Spanish choir book titled *Initial I with David*, 1430s, attributed to the Master of the Cypresses, is shown in Figure 1. The artist painted this illumination of King David holding the initial I with a wide range of colors.

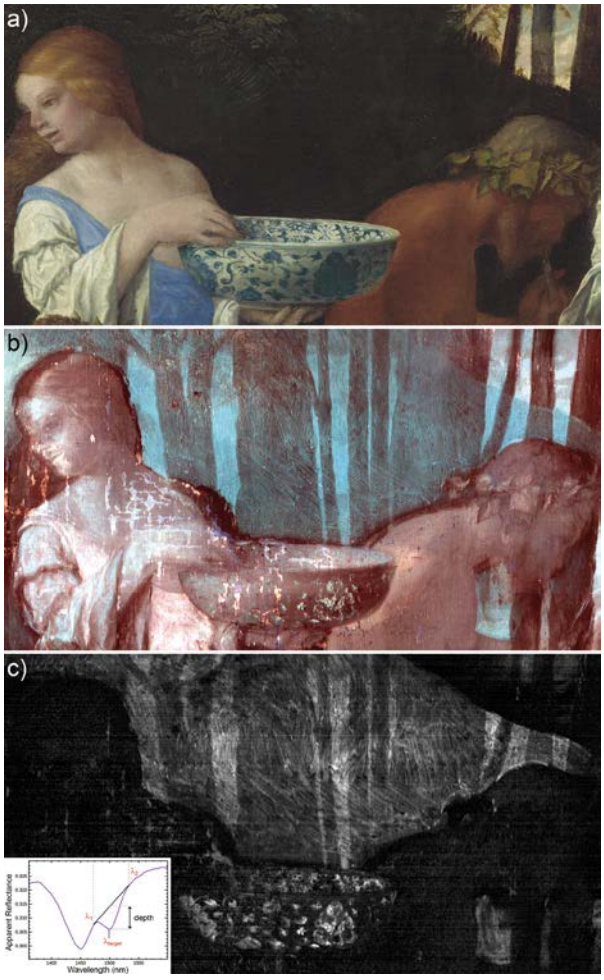
Reflectance imaging spectroscopy was utilized to identify and map the pigments employed by the artist. Analyzing the 3-D reflectance image cube (see Figure 1b) with multivariate analysis based on convex geometry revealed 15 different paints composed of one or more pigments. Most of these pigments could be identified from their reflectance spectral features alone (refer to Figure 1c). The pigment map labeled Pigment Map-CG indicates that the artist used a red lake pigment—derived from a soluble dye obtained from insects and precipitated onto a substrate like chalk to create an insoluble pigment—for King David's robe. The blue in the letter "I" and the surrounding leaves utilized ultramarine, an expensive pigment derived from processing lapis lazuli ore. The green horizontal bars in the letter "I" were painted with malachite, complemented by highlights of lead tin yellow. The orange and red leaves were created using red lead and red lake pigments. The multivariate convex geometry-based algorithm employed to analyze the reflectance image cube is semi-automated, often requiring several hours to run. This has prompted researchers to explore machine learning tools, including neural networks, to significantly

reduce analysis time to just minutes, particularly when examining a large set of related paintings. Results from a recently developed neural network trained on other works by the same artist show that this method yields very similar outcomes and performs better in mapping flesh tones as well as the gold background (see Figure 1c, Pigment Map-NN).

Revealing Giovanni Bellini's hidden trees in the *Feast of the Gods*

Often, the visual surface of an artwork hides a longer history of revisions and reworkings that reside below the surface and cannot be seen by eye. Reflectance imaging spectroscopy can be a valuable tool in such cases, since most artists' pigments absorb less and scatter less photons in the NIR and SWIR spectral regions compared to the visible region, and therefore can allow us to collect subsurface information. Such is the case with the Renaissance masterpiece *Feast of the Gods*, which was originally painted by Giovanni Bellini in 1514. The patron who commissioned the painting also requested ● ● ●

▼ **FIG 2:** (a) Color detail from *Feast of the Gods*, Giovanni Bellini and Titian, 1514/1529. (b) False-color infrared reflectance detail (B:1875 nm, G:2050 nm, R:2375 nm) revealing the location of original Bellini trees beneath the surface. (c) A map of the blue pigment azurite obtained using a characteristic absorption feature near 1500 nm in the reflectance spectra (see inset). Azurite is present in brushy paint strokes in the hillside associated with the intermediate landscape, as well as the blue design in the nymph's bowl.



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▲ FIG 3: (a) Johannes Vermeer's painting *Girl with the Red Hat*, c.1669. (b) Infrared false-color image (rotated 180 degrees) showing some of the underpaint of an earlier painting of a man in a black hat obtained from reflectance imaging spectroscopy. (c) The optimized lead map (rotated 180 degrees) showing the use of mainly lead white in the painting of a man in a black hat obtained using X-ray fluorescence imaging spectroscopy.

• • • two reworkings of the background behind the gods, including the final mountainous landscape we see today, completed by Titian in 1529. Reflectance imaging spectroscopy helps to visualize and identify pigments in the original Bellini wooded landscape, consisting of many trees, as well as the intermediate landscape depicting a hillside. A detail of a satyr and nymph holding a bowl is shown in Figure 2a. The false-color infrared reflectance image in Figure 2b reveals the location of original Bellini trees beneath the surface as well as brushy paint strokes associated with the intermediate hillside. Figure 2c shows a map of the blue pigment azurite. Azurite was originally identified in the first paint layer applied over Bellini's trees in a paint sample, known as a cross-section, from the background landscape. Here, the azurite map shows the pigment is distributed throughout the brushy paint strokes associated with the intermediate landscape, as well as the blue design in the nymph's bowl.

Learning more about the painting of a man in a black hat beneath Johannes Vermeer's painting *Girl with the Red Hat*

Given the wide range of materials used by artists, it is not surprising that scientists also make use of spectral modalities such as X-ray fluorescence to help identify the pigments present. While reflectance spectroscopy provides molecular information, X-ray fluorescence provides information about the chemical elements (*i.e.*, lead, iron, copper, cadmium, tin, *etc.*). While element information does not always allow a unique assignment of a pigment, when combined with results from reflectance spectroscopy, an identification can often be made. For example, pigments made from semiconductors have simple reflectance spectra from which only the energy of the electronic transition can be determined, which is not sufficient to identify the specific pigment, but when combined with the elements present, it is possible. X-ray fluorescence uses X-ray energy to excite inner core electrons, and the emitted X-ray radiation gives spectra that allow the elements present to be identified. The development of high-sensitivity X-ray spectrometers allows scientists to make maps of the elements present in paintings. The combination of reflectance imaging spectroscopy and X-ray fluorescence imaging spectroscopy has not only allowed us to make better pigment maps, but it has also allowed us to obtain clearer images of an unfinished painting as described below.

Underneath Johannes Vermeer's painting *Girl with the Red Hat* (Figure 3a) is an unfinished portrait of a man in a black hat. The identity of the man is unknown as well as if Vermeer painted him or if the portrait is the work of another artist. The combination of infrared reflectance and X-ray fluorescence imaging spectroscopies has given us new, detailed images of the painting of the man. The false-color infrared image shows a brushy application of black paint that denotes the man's hat, facial features, and paint strokes in his garment (Figure 3b). The mathematical processing of high and low energy lead maps obtained from X-ray fluorescence imaging spectroscopy results in a clearer image of the man's face, his shirt collar, the sleeve of his garment, and even his wavy long hair. These images offer art historians the opportunity for further scholarship regarding the identity of the sitter as well as the artist who painted him. ■

About the Authors



John K. Delaney is a senior imaging scientist and currently serves as the acting head of the Scientific Research Department at the National Gallery of Art. He also oversees the Chemical Imaging Laboratory. His research focuses on developing new imaging-based spectroscopic methods for studying paintings.



Kathryn A. Dooley is an imaging scientist in the Chemical Imaging Lab of the Scientific Research Department at the National Gallery of Art. She is interested in spectroscopic techniques that allow for the identification of many materials without requiring a sample and that also enable mapping their distributions across the surface of an artwork.

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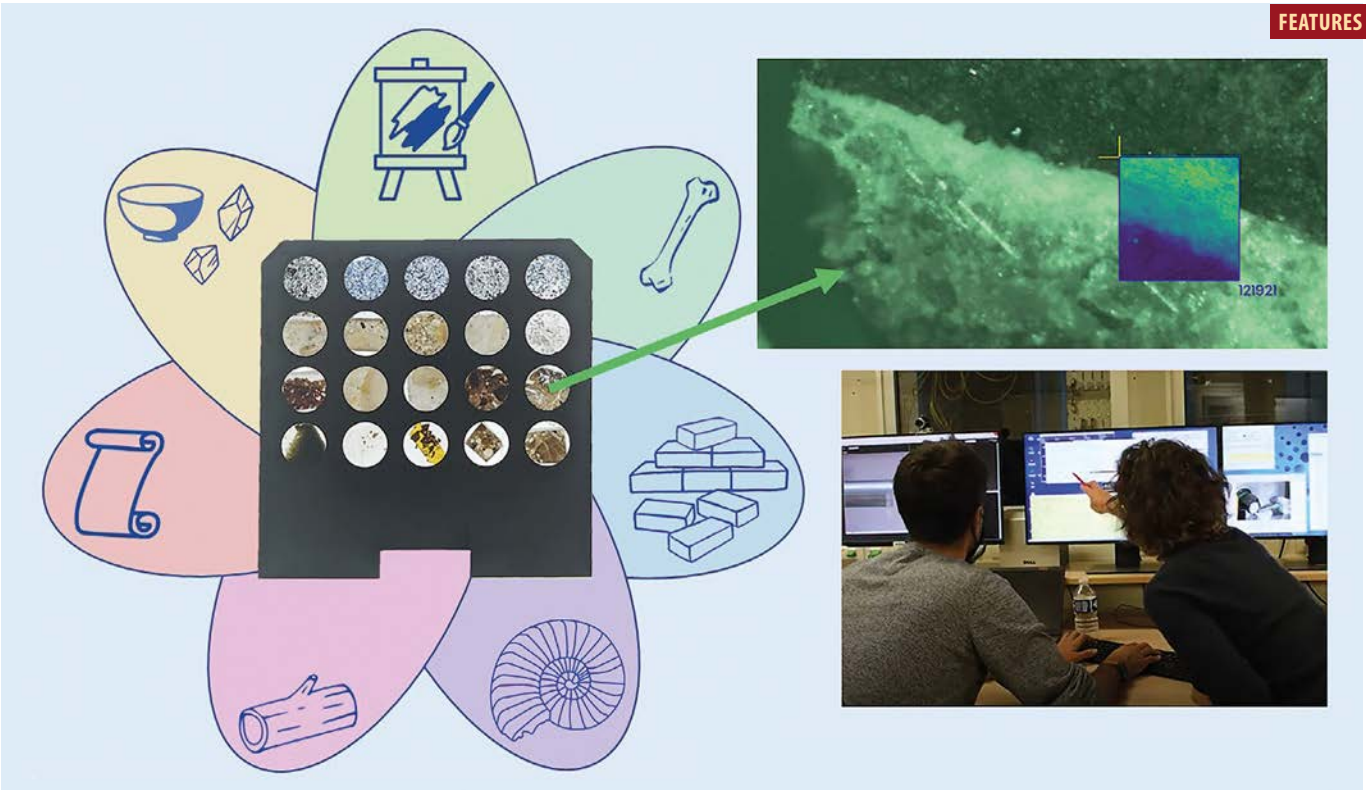
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SIMPLIFYING ACCESS AND USABILITY OF ADVANCED SYNCHROTRON RADIATION MICROSCOPES FOR HERITAGE SCIENCE

Georgina P. Robertson[1], Clément Holé[1] and Marine Cotte[1,2] – DOI: https://doi.org/10.1051/epn/2025409

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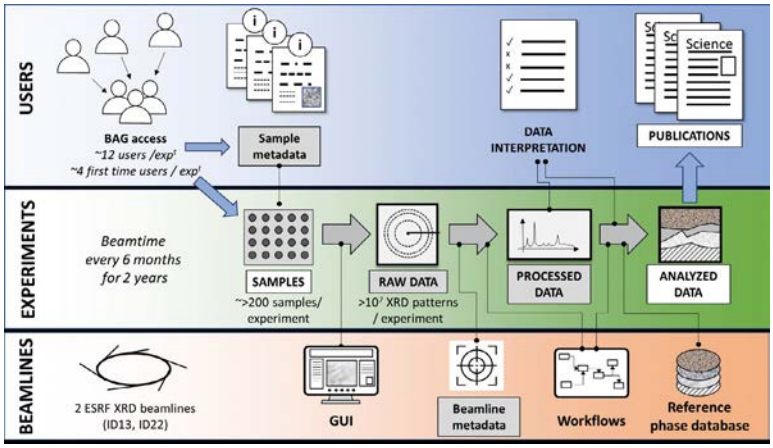
[2] Sorbonne Université, CNRS, Laboratoire d'archéologie moléculaire et structurale (LAMS)

At the European Synchrotron Radiation Facility (ESRF), heritage research has become far more accessible and effective. Following the recent ESRF upgrade, this user community is benefiting from regular and facilitated access, and efforts are dedicated to Open Science, to make the data collected on these valuable materials accessible to everyone.

The early applications of synchrotron techniques to Heritage

Among the many analytical techniques available to study cultural heritage, those based on synchrotron sources have seen a marked increase in their use[1,2]. Their advantages include a high X-ray beam brilliance allowing rapid analysis, high signal-to-noise ratio data, and sub-micrometre beam focussing. These are exploited together in a variety of structural and chemical mapping methods, for example micro X-ray diffraction (μXRD) or micro X-ray fluorescence (μXRF), allowing identification and location of components within precious, complex and heterogenous ancient and artistic materials. X-ray, UV-Vis and infrared spectroscopy techniques, enabled by the energy tunability of the synchrotron sources, also facilitate investigation of the artefacts' manufacture and degradation. The • • •

▲ Heritage research facilitation at ESRF



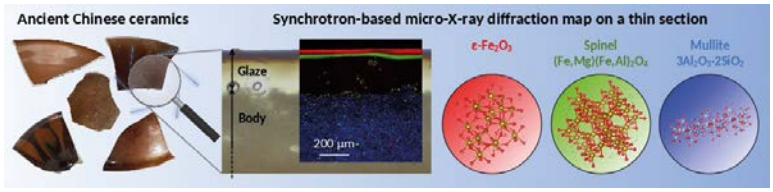
▲ **FIG 1:** Process of a typical ESRF Historical Materials BAG experiment (illustrative numbers are given for ID13). Boxes in grey highlight the information (data and metadata) that will be gathered in the SHARE database.

coherence of synchrotron beams has also led to new tomography methods, such as those based on phase contrast, which regularly offer invaluable discoveries in the field of palaeontology. Many of these techniques have been used for the first time on heritage materials at the ESRF (Grenoble, France), for example to reveal the composition of Ancient Egyptian cosmetics or Bamiyan Buddhist wall paintings [2]. During this early research, experiments usually involved only a few expert groups, with most heritage scientists considering synchrotrons exotic and synchrotron scientists being unfamiliar with the field of heritage. Access to experiment time is challenging to obtain and use effectively for newcomers unfamiliar with proposal procedures, sample preparation, beamline equipment, or data processing software, further discouraging heritage researchers from exploring synchrotron techniques. However, things have changed since these pioneer experiments! Heritage and synchrotron communities are now used to working together [3]. At synchrotron facilities, efforts are daily dedicated to improving instruments and making experiments faster and more user-friendly. Yet, it is important to consider data acquisition as only one of a series of many steps that all need to be improved. Here, we outline recent and on-going actions implemented at the ESRF to ease and improve synchrotron use for heritage researchers and improve the data FAIRness (Findable, Accessible, Interoperable, and Reusable) and results of these experiments.

The Historical Materials "BAG": a group access mode

The ESRF's extremely brilliant source upgrade increased beam brilliance by two orders of magnitude, allowing vastly more samples to be measured during an experiment due to much faster data acquisition. This motivated the implementation of the new 'block allocation group' (BAG) access mode for the crystallographic analysis of historical materials. This access allows researchers from multiple institutions to share experimental time with a standardised data collection procedure (Figure 1), further increasing the efficiency of sample measurements. The Historical Materials BAG started in 2021 and gives access to two XRD beamlines, ID13 and ID22, every six months for a two-year period. It has been renewed twice since inception [4]. At ID13, μXRD maps are collected in transmission (with simultaneous μXRF) using a micrometric beam to determine the nature and 2D distribution of crystalline phases. Sample holders and graphical user interfaces (GUI) have been developed to make the X-ray microscope as easy to use as an optical microscope [5]. Samples are mounted in groups of ~20-50, to reduce time lost in exchanging sample holders. Thanks to a custom user interface, it is easy to navigate over the samples, define regions of interest, and queue multiple acquisitions. During a 4-day experiment at ID13, over 200 samples are typically analysed, a factor of 10 more samples than a standard heritage experiment. At ID22, high angular resolution powder XRD data allows detailed phase identification and quantification, with automated sample change for uninterrupted acquisition.

With more than 87 users over 16 visits in 4 years resulting in 25 publications thus far, the BAG has been used to investigate paintings, ceramics, marbles, manuscripts, and more, from artists as major as Leonardo da Vinci, Rembrandt, Picasso, and Miro. The BAG brings together researchers from many specialisations, promoting collaboration and bonds within the wider community. In addition to experience gained during experiments, ESRF hosts workshops for BAG users for synchrotron data acquisition and software training as well as sharing of their own research.



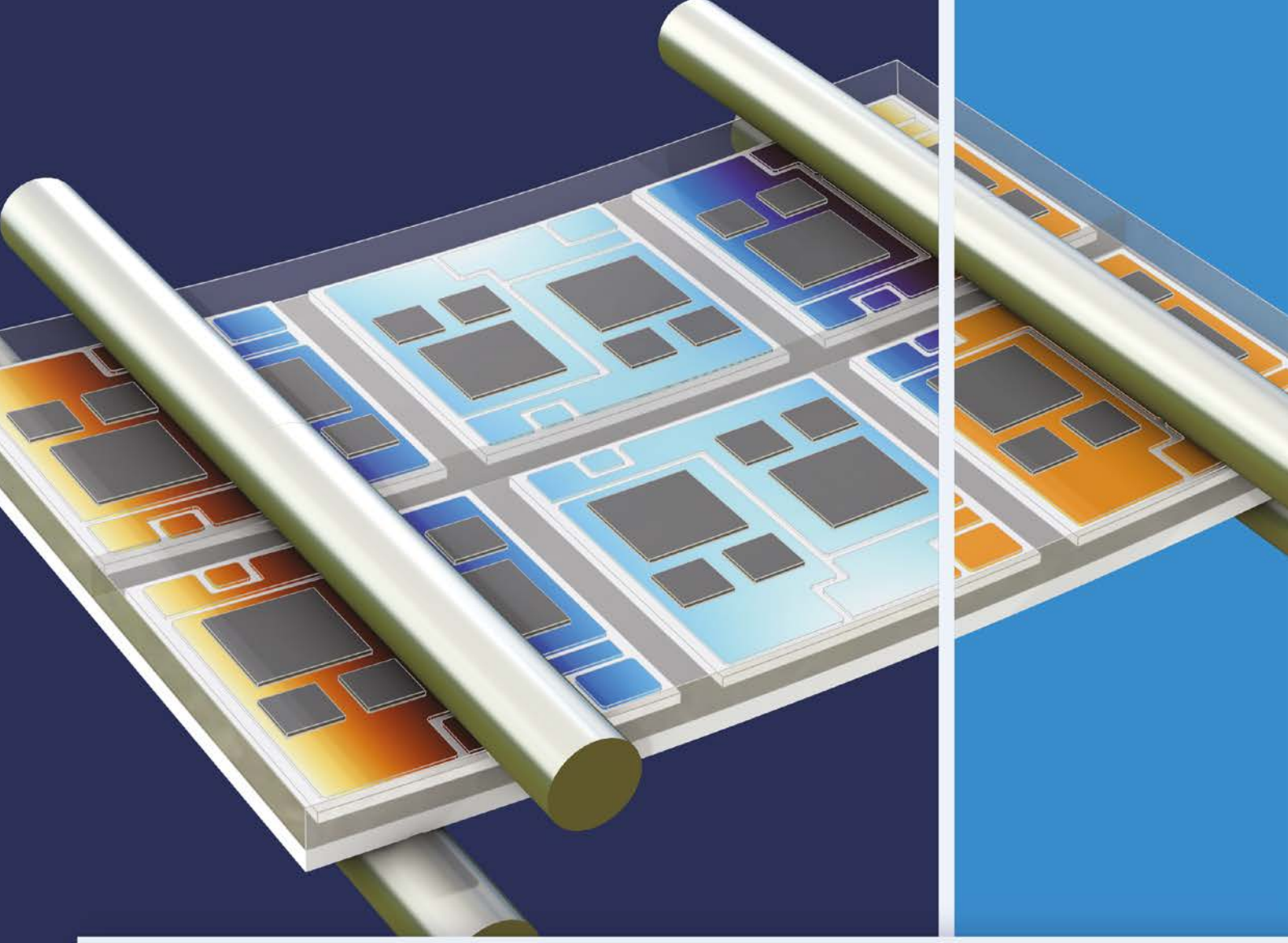
▼ **FIG 2:** Ancient Chinese ceramic shards (left) and μXRD phase map representing the distribution of ε-Fe_2O_3 (red), iron-bearing spinel phase (green) and mullite (blue) phases, overlaid on an optical microscopy image of a thin section (right).

Processing and re-processing data

The maps generated by ID13 (one XRD pattern per pixel, >10^4 patterns per map) require batch integration methods. These have been integrated into the workflow so 1D XRD patterns are generated automatically. Processed data is then returned to the user interface, giving a real-time view of the phase mapping. By comparison with crystallographic databases, main components are identified, and different software packages/workflows are available to calculate the phase maps. It is also possible to reintegrate/reprocess data from outside ESRF.

Towards open science: Metadata identification and collection

Analysing our heritage is not just important for understanding the past; it is also vital in preserving it for the future. This research is inherently collaborative, meaning that data should be openly accessible to advance our collective understanding. To this end, and thanks to funding from the OSCARS project (Open Science Clusters' Action



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• • • for Research and Society, grant 101129751), we are developing the SHARE (Synchrotron X-ray analysis of Heritage Accessible to and Reusable by Everyone) database.

While it is critical that both raw and processed data are stored efficiently and organized for easy access, it is equally important that the context surrounding a dataset is recorded as well. We have therefore identified the core information needed to fully describe an experiment and ensure that data can be identified, reprocessed and reanalysed by anyone. This includes metadata about the sample (artist, period, material, *etc.*) and the experimental setup (X-ray energy, detector geometry, *etc.*). Standardised sample metadata is collected pre-experiment through an online form that can be added to afterwards with significant findings. Ultimately, this will allow searching via keywords, as is already the case for the ESRF's Paleontology and Human Organ Atlas databases. Setup metadata is automatically recorded during measurements, then stored within the raw data files, within an online logbook, and within the ESRF data portal. It will be available to view alongside the sample metadata within the SHARE database website, currently under development. Ultimately, the SHARE project will allow any researcher (after an embargo period) to re-investigate data with new scientific questions and new data analysis processes that will certainly emerge in the coming years.

A BAG case study: Deciphering the firing conditions of Song ceramics

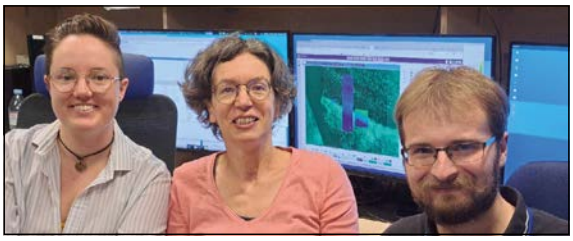
The brown-glazed ceramics manufactured during the Song Dynasty constitute an essential group in the history of Chinese ceramics. These objects, manufactured all across the Song Empire, were particularly appreciated for tea drinking, as their dark glazes aesthetically contrast with the white froth of the whipped tea. Interestingly, the characteristic brown hue of these ceramics is due to the presence of ε-Fe_2O_3 dendrites at the surface of the glazes, an otherwise rare ferric oxide. Understanding the growth of such structures is key to providing insights on the firing conditions of these products. Knowing the nature and spatial distribution of the crystalline phases across the glazes is therefore essential.

18 shards excavated from several Northern Chinese archaeological sites (Yaozhou kilns and Yingou site, Shaanxi province; Xin'An kilns, Henan province) were analysed at ID13 through the BAG. µXRD maps as large as 800 × 800 µm^2, 2µm step size, were recorded in only 1 hour. Besides the standard data processing described above, the data were further exploited to develop statistical procedures aiming at extracting phase maps more efficiently [6].

This analysis revealed a typical stratigraphy, common to most of the samples: a layer of ε-Fe_2O_3 at the glaze surface, above a a layer containing an iron-bearing spinel phase, covering the mullite-containing ceramic body (Figure 2). Interestingly, the spinel layer extends to different depth depending on the ceramic's provenance, indicating that different firing processes were used in neighbouring provinces to produce similar-looking glazes. This is also the first recording of the presence of the iron-bearing spinel layer to such an extent, and its thickness confirms our previous hypothesis that the growth mechanism of ε-Fe_2O_3 is diffusion-driven [7].

This case study is only one among the many projects which benefitted from the BAG access, more examples can be found on the Historical Materials BAG webpage [8]. We welcome new potential users, and encourage anyone interested to get in contact! ■

About the Authors



Georgina Robertson (ESRF, left) is a post-doctoral researcher, developing tools for streamlining the ID13 beamline and using µXRD mapping to investigate the degradation of pigments. **Marine Cotte** (ESRF and LAMS, CNRS, middle) is a beamline scientist, developing and applying synchrotron micro-analyses, with a particular interest on cultural heritage. **Clément Holé** (ESRF, right) is a post-doctoral researcher, applying micro-X-ray spectroscopy and diffraction techniques to study the manufacturing process of ancient Chinese ceramics.

Acknowledgements

This highlights the work of numerous talented colleagues at ESRF, including Simon Delcamp, Marjolaine Bodin, Andy Goetz, Stuart Fisher, Edgar Gutierrez Fernandez, Manfred Burghammer and Catherine Dejoie. We also acknowledge the other Historical Materials BAG coordinators and the BAG partners. The BAG is supported by European Union's Horizon 2020 research and innovation programme, grant agreement 870313, Streamline. The case study is a collaboration between ESRF, CEMES-CNRS (Ph. Sciau) and Shaanxi University of Science and Technology (T. Wang).

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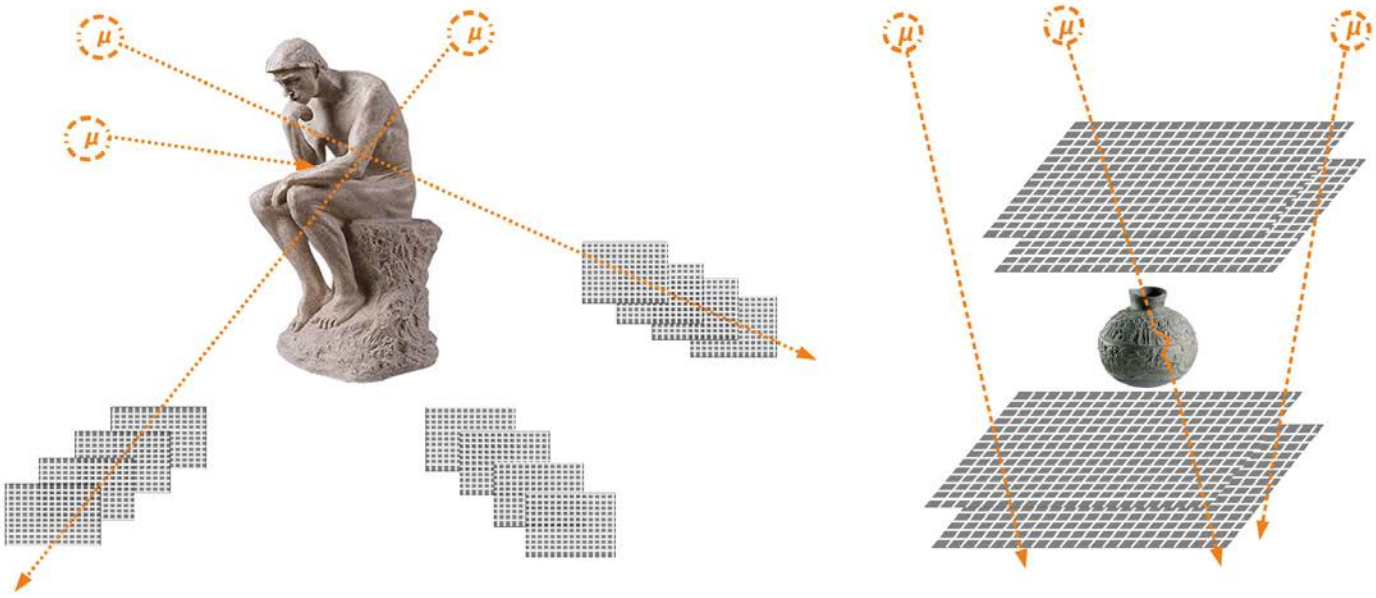
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MUONS FOR CULTURAL HERITAGE

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Muons can be found in Nature, freely and steadily produced by cosmic-ray interactions in the atmosphere, and can be produced by particle accelerators. These elementary particles are increasingly becoming popular for non-destructive imaging of large structures, using particle detectors originally conceived for fundamental physics.

Muons are elementary particles similar to electrons but with a mass approximately 200 times greater. They are produced naturally in the upper atmosphere by the interaction of cosmic rays with atomic nuclei and can also be generated artificially in accelerators. Muons interact less with matter compared to other charged particles such as electrons or protons, allowing them to penetrate substantial thicknesses of dense materials such as rock, concrete, or metal. This high penetration power makes muons particularly valuable for non-invasive imaging applications, especially in contexts where conventional radiation (*e.g.*, X-rays) is insufficient.

This property of muons, together with the fact that cosmogenic muons are naturally and freely produced and are easy to detect, forms the basis of "muography". Its first documented application dates back to 1955, to measure the overburden of a tunnel in Australia. The second, and most famous, application was published in 1970, when L. Alvarez's team used cosmic muons to search for hidden chambers inside Khafre's pyramid in Egypt. More applications followed, especially in the 21st century, and muography is nowadays a booming research area, with a steadily growing trend of publications.

Cosmic-ray muography

Two main muography techniques are used, as illustrated in Figure 1. *Absorption muography* relies on the energy loss of muons through ionization as they pass through matter. Muons lose energy via ionization and eventually decay, leaving no detectable signal. Muon trajectories are reconstructed using a tracker placed downstream of the object, and the deficit of muons with respect to the free sky is used to infer the amount of matter traversed. This technique is directly sensitive to the material's density, allowing researchers to test different hypotheses about an object's internal composition. *Scattering muography* instead exploits the angular deflection of muons caused by interactions with atomic nuclei. The average deviation depends strongly on the atomic number (Z, *i.e.* number of protons) of the material, enabling elemental discrimination. To measure this deviation, the muon path • • •

must be tracked both before and after crossing the object, requiring it to be "sandwiched" between two trackers.

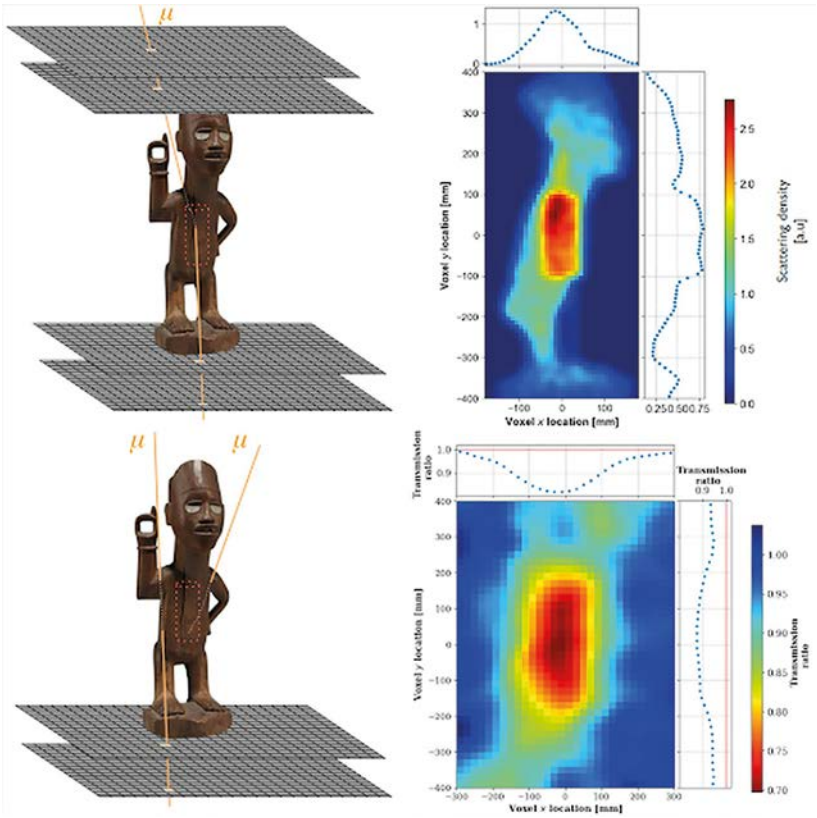
Each method has distinct strengths and limitations. Absorption muography requires only one tracker and yields 2D density projections, which can be combined from multiple angles to form a 3D density map. However, it does not distinguish between material properties beyond density, and lacks sensitivity for small features. Scattering muography inherently provides 3D information and is sensitive to atomic composition due to the dependence of scattering angle on Z. Yet, it demands a dual-tracker setup and is unsuitable for human-sized statues unless the object can be placed between detectors or a complex detector installation is undertaken. Thus, it is best suited to relatively small objects.

From pyramids to domes: muography in cultural heritage studies

Muography has already proven effective in studies of large-scale cultural heritage. A landmark example is the ScanPyramids project, which used three detector types (plastic scintillators, micro-pattern gaseous detectors, and nuclear emulsions) to reveal a low-density anomaly in Khufu's Great Pyramid in 2017. Additional data have been collected since then, leading to the announcement in 2023 of a corridor-like structure of about 9 m length with a transverse section of about 2 m by 2 m. Ground Penetrating Radar and ultrasonic tests reinforced the findings, leading to a successful visual confirmation via endoscope (Figure 2). Other recent successes of muography include the detection of potential structural hazards in the Xi'an city wall (China) – Figure 3 - the identification of unknown internal features and voids in the Svyato-Troitsky Danilov monastery (Russia), and evidence for unknown structures in an archaeological site in Naples (Italy), located 10 meters below street level, including one compatible with the hypothesis of a hidden, currently inaccessible, burial chamber.

The examples above all rely on absorption muography, but alternative approaches have also been proposed. One such proposal involves using scattering muography to detect iron chains within the masonry of Florence Cathedral's dome, supported by a successful proof-of-concept on a mock-up wall. A newer approach, alignment-based muography, has been proposed for the Palazzo della Loggia in Brescia (Italy). It uses the fact that muons travel in straight lines in the absence of electromagnetic fields. It requires two muon telescopes: one fixed to a reference structure and the other on the element being monitored. Misalignment of reconstructed muon tracks indicates displacement, enabling long-term structural stability monitoring.

▾ FIG. 1: Scattering (top) and absorption (bottom) muography of a small statue. Study based on simulated data, to illustrate the different imaging quality achievable with the two methods for a relatively small object (80 cm height). Reproduced from: iScience 28, 112094 (2025)



A research gap: muography for medium-sized cultural artifacts

In all the examples discussed so far, the muon detectors used are relatively large and not easily transportable. This is because large heritage structures significantly attenuate the cosmic muon flux, requiring detectors with a wide cross-sectional area (on the order of a square meter) to collect sufficient data within a reasonable time. However, muography remains under-explored for medium-sized cultural heritage objects, such as human-sized statues. These are too large for X-ray or microwave imaging, yet too small for standard absorption muography, which suffers from poor resolution at this scale. Their intermediate size presents a unique challenge, calling for tailored detector designs and advanced reconstruction methods to make muography viable for such artifacts. In this regime, scattering muography offers better spatial resolution as well as the advantage of material discrimination through sensitivity to atomic number, but its requirement for detectors on both sides of the object creates extra logistic challenges in many cultural heritage settings.

Muography may be useful for detecting hidden features or internal anomalies in heritage objects. It can also serve as a non-invasive moisture sensor: water infiltration alters the effective density of porous materials, leading to detectable variations in muon attenuation. The detection of internal cracks or defects in statues remains a challenging application of muography. However, • • •



◂ **FIG. 2:** A hidden corridor inside Khufu's Great Pyramid photographed by an endoscope. The existence of the corridor was first discovered using muography (Nat. Commun. 2023; 14:1144) and confirmed by an independent team using GPR and ultrasonic testing (NDT E Int. 2023; 139, 102809). Photo: Egyptian Ministry of Tourism and Antiquities.



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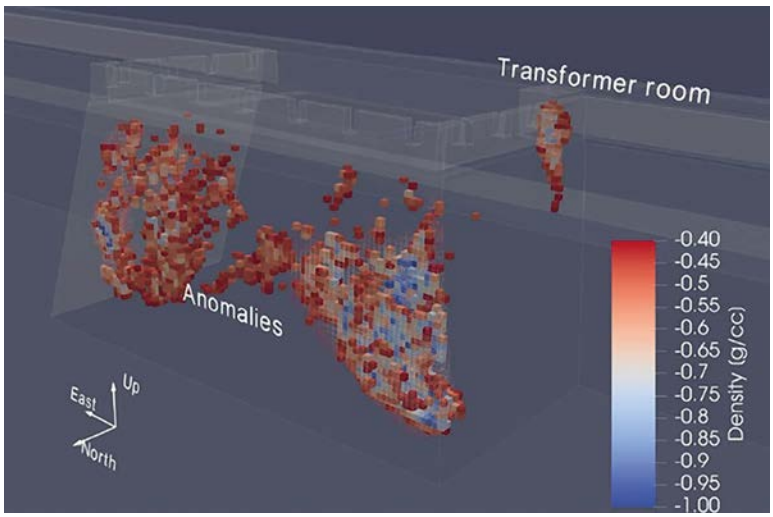
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▲ FIG. 3: Low-density regions identified via 3D inversion of muography data in the Xi'an city walls. These include a known cavity (the transformer room) and an unexpected pattern near the northern surface of the rampart, hinting at a potential issue for its stability. Reproduced from J. Appl. Phys. 133, 014901 (2023) .

• • • ongoing research in civil engineering, using muography to inspect aging infrastructure, may drive developments that could benefit cultural heritage studies as well. Addressing this research gap will benefit from compact, portable muon detectors. In confined spaces like museums or churches, equipment must be small, easy to install, and possibly removable outside of public hours.

From the cosmos to accelerators

Cosmic-ray muography also has some fundamental limitations, the most blatant being that the muon flux is relatively small, of the order of 100 Hz/m^2; *i.e.* roughly a muon per minute through the surface of a thumb. This means that very long exposure times - from several hours to several months, depending on the size and density of the object to be imaged - are needed in order to form a useful image. Moreover, cosmic muon direction and energy cannot be controlled. One can, however, overcome these drawbacks by using a muon beam produced by a particle accelerator. A few facilities in the world, *e.g.*, CERN and PSI in Switzerland, ISIS in the UK, TRIUMF in Canada, FNAL in USA, and J-PARC in Japan, are able to produce muon beams with precisely controlled energy and high intensity. While mostly produced for the purposes of fundamental physics experiments, these muon beams can be used for cultural heritage studies. A technique called Muonic Atom X-ray Emission Spectroscopy (μ-XES) or Muon Induced X-ray Emission (MIXE) exploits beams of negative muons at sufficiently low energy to be stopped (through energy loss by ionization) inside the object of interest. Stopped negative muons form so-called "muonic atoms" by displacing an electron in one of the outer atomic shells, and these atomic systems relax to their lowest-energy state by emitting X-rays, which are in turn detected and whose spectra depend on the atomic number Z of the material. With respect to the conceptually similar PIXE and PIGE techniques, which rely on proton beams, MIXE has the advantage of probing deeper in the material, thanks to the large muon penetrating power. Moreover, activation of the material is negligible with respect to irradiation with neutrons or protons.

While this method is very promising for the analysis of relatively small objects (it has been used *e.g.* for the study of ancient Roman and Japanese coins), it suffers a fundamental limitation: the objects to be analyzed have to be transported to one of the few existing muon beam facilities in the world. Some very ambitious ideas have been proposed toward a transportable muon generator, but artificial muon production must necessarily start from high-energy collisions of other particles, which implies radiological hazards, like all methods based on an artificial particle source, because of the byproducts of the collisions.

Conclusions

Muography is a promising nondestructive subsurface imaging technique for cultural heritage analysis, thanks to the excellent penetration properties of muons. The inherent availability of cosmogenic muons led to the recent boom of cosmic-ray muography, making it a low-cost and portable alternative to other imaging methods, especially for large structures. The use of artificial muon beams from particle accelerators is becoming increasingly promising, and complementary, as they offer controlled flux, directionality, and energy, overcoming many limitations of cosmic-ray muography and enabling high-resolution imaging and elemental analysis of smaller cultural heritage objects. ■

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THE "GROTTA DELLA POESIA" (LECCE, ITALY): STUDY THE CONSERVATION DEGREE USING GEOPHYSICAL METHODS

Lara De Giorgi, Dora Francesca Barbolla, Ivan Ferrari, Francesco Giuri and Giovanni Leucci* –
National Research Council –Institute of Heritage Science, Lecce – *giovanni.leucci@cnr.it – DOI: https://doi.org/10.1051/epn/2025411

2D seismic tomography and 2D electrical resistivity tomography (ERT) were combined to the instability of the hypogean archaeological site named "Grotta della Poesia". The interpretation of integrated geophysical data resulted in evaluating some rock mass parameters, such as rock quality designation, linear fracture density, and fracture density.

A study on the instability assessment of the archaeological site "Grotta della Poesia", located 20 kilometres east of Lecce near the Melendugno village (Lecce province, southern Italy), was performed by combing geological and geophysical methods. Two large dolinas (named respectively Large Poesia and Small Poesia) are the main surface landforms of a hypogean karst system developed inside a tabular coastal plain which is presently a few meters elevated above sea level. The system is furtherly made of intervening galleries, a large dome cave, some minor cavities and a gallery which connects the Small Poesia to the sea cliff (Fig. 1). In detail, is the Small Poesia which has a special importance by virtue of an impressive number of signs, symbols and inscriptions datable between the Second Millennium before Christ and the Republican Roman Age. The name derives from the Greek term "poesia", which points out the rising of sweet water and, in fact, in the small cave a spring flowed until few years ago [1].

Archaeological and geological studies have shown that the Small Poesia has suffered some morphological changes, evolving from an underground cave to a large dolina through a series of collapses of the ceiling, caused by a composite karstic and sea erosion phenomena probably triggered by artificial mediaeval excavation [2]. The zone of "Roca" is carved in soft calcarenites referable to the Upper Pliocene and it is elevated about 10 m above mean sea level.

This bedrock is covered by recent and present beach and dune sands. Landward, the lansdcape grades down to a number of depression, placed at about 1 - 2 m a.s.l., and filled by sandy-clayey deposits. In the northern part of the area, thick layers of calcarenites and calcirudites with abundant macrofossils crop out; they have been referred to the "Calcareniti del Salento" Pleistocene unit by [3].

Numerous karstic caves occur in the area, some of them recorded in the regional inventory of the "Federazione Speleologica Pugliese" [4] (such as "Grotta dello Spezzale", "Grotta della Poesia Grande" and "Grotta della Poesia Piccola").

The calcarenitic and calcilutitic layers are affected by four systems of fractures, clustering around the directions N-S and E-W [2]. These fractures, to a large extent sealed by carbonatic concretions, show varying spacing from some decimeters to some meters. Fractures constitutes the preferential surface of detachment of numerous rockfalls occurring along the coastline. Some karstic caves develop at the base of the cliff along the fractures. The analysis of the spatial distribution of the density of fracture point out a substantial uniformity of the degree of the fracture. In some small tracts of the coastline, the density of fractures increases to about 0.65 m/m2 [5]. Fractures are generally sealed by calcitic concretions; however, some fractures are widened by karstic dissolution. Fractures of this last type show at present openings of the order of some millimeter to some meters in the case of complete development of galleries. Some fractures are partially or totally filled by colluvial deposits.

Material and methods

Two geophysical methods, electrical resistivity tomography (ERT) and seismic traveltime tomography were used. In the ERT method the distribution of the electrical resistiv ity of the subsoil is obtained by injecting electrical current (by the current electrodes) into the ground and measuring the po tential difference (potential electrodes) at two determined points of the surface. The method is based on the application of Ohm's law

$$\rho = k\,(\Delta V/I)$$

where ρ is the apparent resistivity, k is a geometric factor that depends only on the reciprocal positions of the current and potential electrodes; ΔV is the measured potential difference, and I is the intensity of the injected current. The apparent resistivity values depend on the true resistivity distribution. The true resistivity distribution in the investigated medium can be estimated by an inversion procedure based on the minimization of a suitable function [6,7].

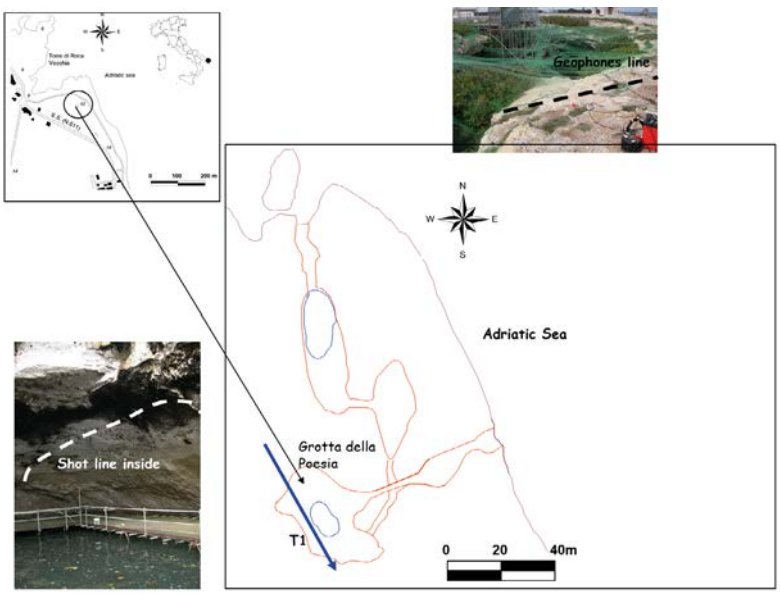
For the ERT survey a 48-channel Syscal-R1 Resistivitymeter (manufactured by the Iris Instruments), in multielectrode configuration was used. Resistivity field data were collected using 48 electrodes with 0.5m spacing. The selection for electrode arrays was dipole-dipole. The dipole-dipole array is very sensitive to horizontal changes in resistivity, but relatively insensitive to vertical changes in the resistivity. This means that it is good in mapping vertical structures, such as voids, but relatively poor in mapping horizontal structures [6].

In the seismic refraction method, the seismic waves, cre ated by artificial sources such as a hammer, propagate through the medium and are refracted at interfaces, where the seismic velocity or density changes. Geophones laid on a single line record the waves returning to the surface after travelling different distances through the ground. By measuring the travel time between the break and the recording of a seismic signal, the seismic velocity in the subsurface and the depth of the inter faces may be inferred. Conventional analysis of seismic refrac tion data sets makes simplified assumptions about the velocity structure that conflict with observed heterogeneity, lateral discontinuities, and gradients [7]. Refraction tomography is designed to resolve velocity gradients and lateral velocity changes, enabling it to be applied in settings where traditional techniques fail. The method used in this paper utilizes non-linear travel time tomography consisting of ray tracing for forward model ling and simultaneous iterative reconstruction technique (SIRT) for inversion.

In this method the velocity model is rep resented by quadrangle cells. The width of each cell is chosen as the receiver interval. First-arrival travel times and ray paths are calculated by the ray tracing method based on Huygen's principle [7]. A ray is expressed as a line connect ing the nodes arranged on the cell and the travel time between a source and a receiver is defined as the fasted travel time of all ray paths. A model is update by the SIRT (for more information see [7]).

The seismic tomography was performed along one line (Figure 1) by distributing 48 geophones and 29 source locations (Figure 2a). 48 vertical geophones (14 Hz) with 1 m spacing and 29 shot points were located along two parallel lines. The geode instrument was used. The elastic signal was generated by striking a rod with a hammer. The 48 receivers were placed at the measurement surface (z = 0) every 1 m, and 29 shot were placed inside the cave every 1 m. The geode instrument were used.

The source-receivers geometry is show in Figure 2a.



▼ FIG. 1 : The "Grotta della Poesia" with the location of seismic and electrical profile.

Rock quality parameter

The degree of fracturing can be estimated by evaluating the ratio between the seismic velocity in the fractured rock and the not-fractured one. The number of fractures per unit length defines the linear fracture density (Γ). Its value is obtained by counting the number of fractures intersecting a unit length of the scanline. The fracture density parameter C is defined as [5]:

$$C = \frac{\Gamma}{\langle \cos\theta_i \rangle \bullet (1 - \ln r_{min})}$$

where θi is the orientation of the i^{th} set of fractures (θi = 0° for vertical fractures assuming vertical flow), ⟨.⟩ denotes average, Γ is the linear fracture density and r_{min} is the smallest fracture length.

The rock quality designation (RQD) parameter, based on number and spacing between fractures, is simply defined as the sum of lengths of rock pieces (intact lengths) or fracture spacings greater than 10 cm expressed as a percentage of the total length of the scanline. Table 1 shows the rock quality classification based on RQD parameter.

Once the thickness of the rock that forms the roof of the cave had been estimated, a seismic traveltime tomography survey was undertaken.

RQD %	ROCK QUALITY
0-25	Very low
25-50	Low
50-75	Discrete
75-90	Good
90-100	Very good

◂ **TABLE 1:** Rock quality classification based on RQD parameter

Geophysical results

Seismic refraction tomography allows to obtain information about the seismic waves velocity in the roof of the cave. Figure 2b illustrates the seismic wave velocity variation model. A low seismic velocity area is noted, labelled L (300 < Vp < 600 m/s).

Using the relationship 1 is possible to obtain the parameter density of fracture C (Figure 2c).

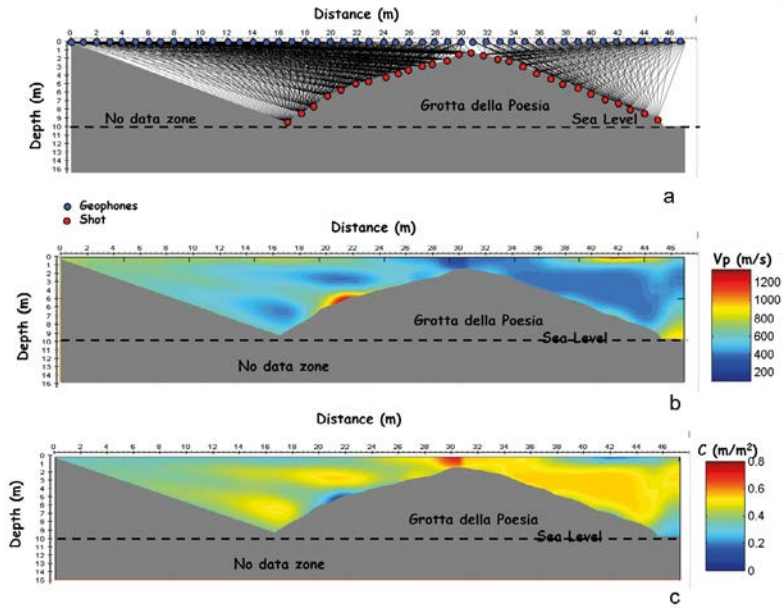
Figure 2c show an higher density of fractures (H) in corrispondence with the low (L) seismic velocity.

The geological model established by means of a 2-D resistivity imaging profile (Figure 3), allows for two different zones to be detected. The first zone (upper 1–2 m):

- the high resistivity zone (about 400 ohm m), labelled H in Figure 5, clearly indicates a zone of poor quality rock.

The resistivity values indicate that the zone consists of fractured carbonate rock;





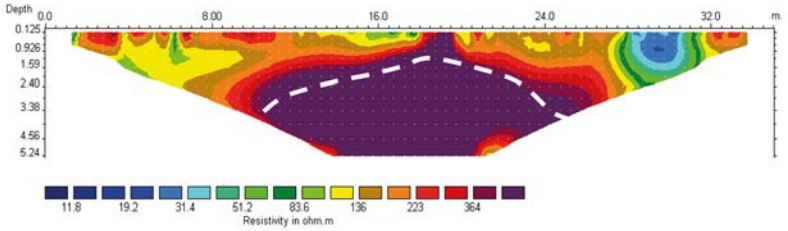
▲ **FIG. 2:** a) The traveltime tomography acquisition geometry; b) Seismic velocity Vp distribution; c) The density of fracture C distribution.

- the low resistivity zone (about 30 to 40 ohm m), labelled (L) in Figure 5, corresponds to the fractured carbonate rock, although the resistivity values are low enough to indicate that the carbonate rock is fractured and the fractures could be filled with clay or "terra rossa".

Conclusions

Geophysical methods are crucial for assessing and maintaining rock stability because they provide non-invasive ways to investigate subsurface conditions, identify potential hazards, and monitor the behavior of rock masses. These methods help characterize the physical properties of rocks, locate fracture zones, and assess the impact of factors like water content and weathering on stability. In this research it was used an integrated interpretation of the results obtained from ERT and seismic tomography data sets to identify fractures in a calcarenite and therefore to assess its quality in order to perform a preliminary evaluation of the stability of the roof of the Grotta della Poesia. The ERT method provided estimates of the resistivity distribution in the shallow subsoil. By combining resistivity and P-wave velocity distributions in the subsoil ambiguities in the interpretation were minimised. The integration of the two geophysical methods is a useful tool in carrying out geognostic investigations at restricted sites, where invasive techniques such as drillings cannot be performed. The integrated geophysical analyses outlined, in the studied area, a highly unstable region in the zones labelled L in the seismic results that indicates very intense anomalies, most likely referable to open fractures.

▼ **FIG. 3:** 2D distribution of the resistivity.



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THE PAST HAS EARS: ACOUSTICS FOR CULTURAL HERITAGE

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When we think about great architectural achievements in European history, such as ancient amphitheatres or Gothic cathedrals, their importance is strongly tied to their acoustic environment, an intangible consequence of the building's tangible construction and furnishings.

Acoustic phenomena like reverberation, focusing, and whispering galleries have shaped political, religious, and symbolic spaces for centuries. With hearing central to human communication, advances in archaeoacoustics and computing now enable precise measurement and simulation of past soundscapes, significantly expanding cultural heritage research [1].

Preserving acoustics: Archaeoacoustics

Archaeoacoustics, a sub-field of archaeology and acoustics, can be defined as studies on the relationship between people and sound throughout history. The recent fires at *Notre-Dame* in Paris (2019) and *Teatro La Fenice* opera hall (1996) shined a light on the fragile nature of acoustic heritage. Acoustic measurements, numerical simulations, and digital reconstructions, offer the possibility to document the acoustics of important sites and allow for exploration and experiencing of lost acoustics by scientists (*e.g.* acousticians, archaeologists, historians, musicologists) and the general public. These efforts are exemplified by recent studies on the Cathédrale Notre-Dame de Paris and the Houses of Parliament in London.

Room acoustics

Architectural acoustics aims to provide optimal sound quality suited to a room's function. Indoors, sound ●●●

• • • reaches listeners both directly and via reflections off walls and surfaces. The lingering reflections form *reverberation*. Multiple paths between sound source and listener create complex interactions, forming the *room impulse response*.

Long before modern acoustics was theorised, the Greeks engineered open-air amphitheatres for optimal voice projection, avoiding the reverberation issues caused by enclosed spaces. Reverberation's impact depends on its duration, intensity, and the sound type. Now a key acoustic metric, reverberation time varies with space and positioning. In the late XIXth century, Wallace Clement Sabine formalised the study of room acoustics with a formula linking reverberation time to room volume and surface materials.

Optimal reverberation time depends on a room's function—shorter times suit speech-focused spaces like theatres, enhancing clarity. Excess reverberation can hinder intelligibility, requiring slower speech. Today, architects and acousticians use 3D modelling and material assumptions to predict and refine acoustic performance. These techniques also aid researchers in reconstructing the soundscapes of historical sites.

Acousticians describe a space's sound using standard metrics derived from room impulse responses. The most basic, Reverberation Time (T_{30}), measures how long sound takes to decay by 60 dB after the source stops, indicating how 'live' or 'dry' a space is.

Modelling acoustics

Physical and digital reconstruction methods have long been used in acoustics. Advances in computing have greatly enhanced acoustic simulations, allowing calibrated models to closely match real recordings [2]. These models enable exploration of architectural layouts, listener positions, and historical contexts, turning descriptive accounts into immersive, sensory experiences and offering powerful tools for historical research [3].

Accurate 3D models with material properties can simulate how changes in geometry or materials affect acoustics over time, reflecting structural evolution and cultural shifts. Most heritage acoustics studies use geometric acoustic models, tracing sound like light rays [4] (see Fig. 1). These methods approximate the room impulse response effectively, they lack low-frequency precision due to wave effects. Wave-based methods solve equations of motion directly for higher accuracy but demand greater computation, prompting research into hybrid models that blend geometric, wave-based, and statistical approaches [5].

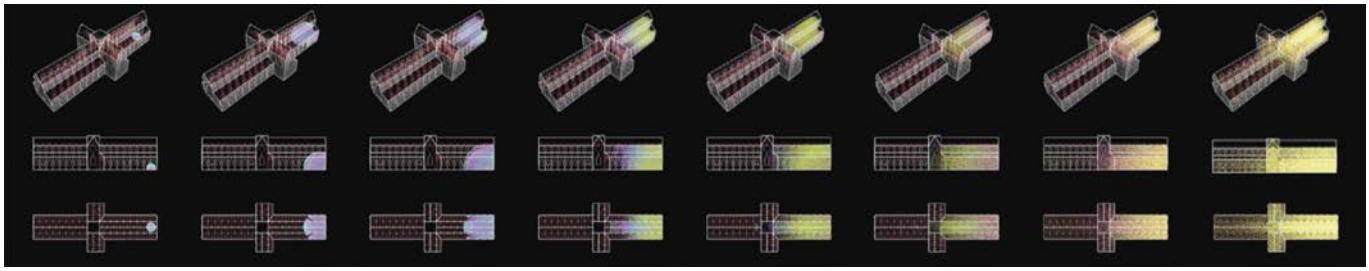
Experiencing acoustics

"Auralisation" is the auditory counterpart to visualization, allowing listeners to experience acoustic models via headphones or speaker arrays, simulating spatial properties as if present on site. Unlike vision's often external viewpoint (*e.g.*, bird's eye), auditory perception is inherently immersive and egocentric. Modern virtual reality (VR) renderings combine spatial audio with visual, as visuals influence auditory perception.

The Historic House of Commons Chamber, Palace of Westminster, London

The acoustics of the House of Commons Chamber, prior to its destruction by fire in 1834 and subsequent redesign and relocation within the Palace of Westminster, have been comprehensively studied through an interdisciplinary methodology, combining historical research with modern acoustic simulation techniques [6]. A poignant historical interest lies in exploring the acoustic properties of the ventilator space above the ceiling, where women gathered from the 1820s to listen to debates from which they were otherwise excluded. This research aims to understand how intelligible political speeches were to these women, revealing aspects of gender, privilege and space in 19th-century politics [7].

The methodology involved creating a detailed acoustic model. Historical evidence, including architectural plans, minutes of meetings, engravings, and paintings (*e.g.*, Sir George Hayter's "The House of Commons, 1833"), provided critical information on layout, fabric, and use. Features such as seating arrangements, galleries, the Speaker's chair, carved



▼ **FIG. 1:** Geometric acoustic numerical simulation showing a graphical representation of the propagation and build-up of sound from an impulse-like source at the west end of a 3D model of the now ruined St Mary's Abbey Church in Museum Gardens (www.york.ac.uk/research/themes/sixteenth-century-acoustics), York, UK. This image sequence shows the first 400ms of sound diffusion through the Abbey, with the full simulation indicating it takes nearly 6s for sound energy to decay beyond audibility. At the west end of the nave, reverberation dominates over direct sound, reducing intelligibility compared to locations nearer the source.

decorations, windows, and the unique ventilation system with metal grilles were incorporated, attributing appropriate acoustic properties. Results were calibrated against acoustic measurements from similar, existing contemporary spaces.

Acoustic simulation software was used to analyse propagation for a simulated male voice to predict speech intelligibility, considering background noise from external (*e.g.*, coal barges, paddle steamers) and internal (*e.g.*, smoking room chatter) sources.

Important results showed a fully-occupied house was less reverberant (T30: 0.70s to 0.90s) and objectively more suitable for speech than a half-occupied house (T30: 0.92s to 1.27s). Speech intelligibility was uneven, highly dependent on both speaker position and orientation. Galleries and under-gallery areas generally had poor intelligibility, aligning with historical accounts. A half-occupied house resulted in poorer overall intelligibility, supporting the observation that, "the fewer persons the worse the hearing" [7].

For those women listening from the ventilator space above the ceiling speech intelligibility varied from poor to fair. Under certain conditions (*e.g.*, half-full house, specific speaker positions), it is hypothesized that women in the ventilator would experience more intelligible speech than many Members of Parliament within the main chamber. This finding, contradicting some historical reports, supports others like Lady Frances Shelley's view that "the sound ascends so perfectly that, with attention, not a word is lost", [7].

The research highlighted that 19th-century architects, while identifying acoustic challenges, lacked a full scientific understanding of sound propagation, misattributing issues to the "elasticity" air instead of modern principles like direct line-of-sight. This work offers valuable, scientifically plausible reconstructions for parliamentary historians, providing insights into political culture, seating dynamics, and oratorical strategies within the pre-1834 House of Commons.

Cathédrale Notre-Dame de Paris

Research into the acoustics of Notre-Dame has been undertaken as part of interdisciplinary endeavour bringing together acousticians, musicologists, and historians to explore the cathedral's soundscape before the 2019 fire and its evolution through the centuries.

The methodology centred on creating a digital acoustic twin of the cathedral, reflecting its acoustic properties and enabling reconstruction of historical or future states. Based on calibrated geometrical acoustic models validated against 1987 and 2015 on-site acoustic measurements, it incorporates historical architectural changes such as the lateral chapels, choir stalls, and the jubé (rood screen), along with decorative elements like tapestries and paintings, and organ positions. Interviews with musicians and choirmasters added qualitative insights into perceived acoustics [8]. Real-time auralisation systems allowed professional choirs to perform in simulated historical acoustic environments, observing their adaptive behaviours as a function of musical genre [9].

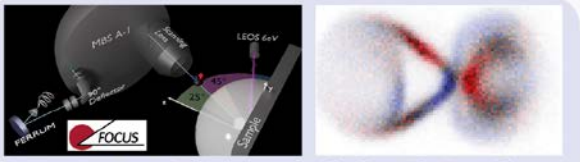


▲ **FIG. 2:** The House of Commons 1692–1707, remodelled as part of the "Virtual St Stephen's Chapel Westminster Project" (www.virtualststephens.org.uk). This 3D graphical model provided part of the foundation for the 1800 acoustic model as developed and tested in [6, 7]

The importance of the results is multi-faceted. While Notre-Dame's acoustics were "remarkable," musicians reported them as "difficult to tame," particularly during rehearsals. The model confirmed T30 was significant (up to 9s for low frequencies in an unoccupied state) and that poor early-stage support on the podium negatively ● ● ●

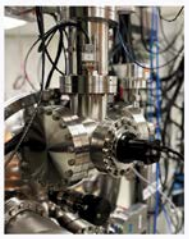
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impacted singers' ability to hear each other and maintain clarity. Despite these challenges, occupants developed adaptive strategies, adjusting their vocal delivery and repertoire.

The transept was identified as an acoustic barrier, reducing musical clarity between the choir and nave, consistent with historical observations. Organ placement and elevation significantly affected sound propagation and clarity within different parts of the cathedral [10].

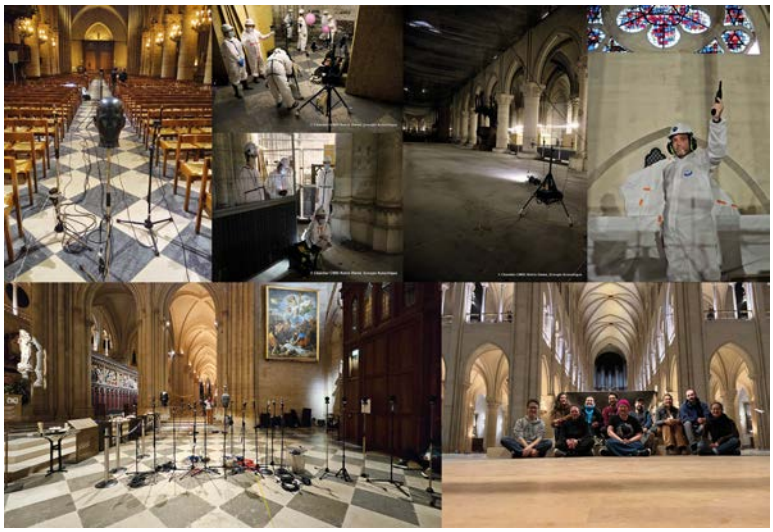
The research demonstrated the perceptible acoustic evolution of the cathedral over centuries from its early Gothic construction (1160-1230), to addition of lateral chapels (1225-1320), and later decorative additions. The research also recreated historical soundscapes of construction sites and urban environments.

Beyond scholarly inquiry, a key aspect of the project is translating research into freely available public experiences, including an immersive radio-fiction (Looking for Notre-Dame, http://lookingfornotredame.pasthasears.eu/), a geo-localised audio-guide (Notre-Dame Whispers, http://ndwhispers.pasthasears.eu/), and a virtual concert (Vaulted Harmonies, http://vaultedharmonies.pasthasears.eu), utilising the digital twin and binaural audio to immerse listeners in the cathedral's sonic history [11].

Concluding remarks

Acoustic reconstruction enriches historical research and public engagement, offering immersive insights into past soundscapes. Yet, auralisations remain interpretative, shaped by modelling choices, technological limits, and contemporary listening perspectives. Like all reconstructions, they reflect both historical evidence and the present-day lens of their creators.

Digital reconstructions offer a tangible form for hypotheses drawn from history, architecture, and acoustics – but should not be mistaken for absolute representations of the past. Even the most rigorous models remain informed approximations. ■



▼ FIG. 3: Photos from acoustical measurement sessions at Notre-Dame, before the fire of 2019, during the restoration work, and after reopening in 2025.

About the Authors



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Herwig Schopper 1924 – 2025

Herwig Schopper, EPS President from 1995 to 1997, passed away at the age of 101.

Herwig Schopper passed away on 19 August at the age of 101. A brilliant scientist, manager and diplomat, he will be remembered by most for his leadership of DESY and CERN. However, in a career spanning almost 80 years, he made a lasting impact on global science that reaches far beyond particle physics in Europe.

Born on February 28, 1924, in Landskron (today Lanškroun) in a german-speaking part of Czechoslovakia, Herwig enjoyed a protected childhood. He developed his interest in science, music, and sport, and learned fluent English. Drafted into the Luftwaffe signals corps during World War II, he served mainly on the Eastern front, ensuring communications with the military headquarters. At war's end, he found himself a prisoner of the British military who, thanks to his language skills, engaged him as a translator. His friendship with an English captain facilitated his admission to Hamburg University, where he began his research career.

Starting in 1951, several sabbaticals shaped his path: in Stockholm with Lise Meitner, in Cambridge with Otto Frisch, and at Cornell with Bob Wilson. In Cambridge, he published one of the first experimental confirmations of parity violation in weak interactions, for which Lee and Yang received the Nobel Prize in 1957. At Cornell, he learned the science of electron synchrotrons, a step up in energy which established him as an experimental particle physicist.

Back in Germany, he held chairs at Erlangen, Mainz, and Karlsruhe, where he laid foundations for today's Karlsruhe Institute of Technology. He built user groups for DESY and CERN, pioneered superconducting RF studies, and new calorimetry techniques which are still used in present-day experiments.

By that time, Herwig had established a reputation not only as a brilliant physicist but also as an equally competent manager. In 1970 he joined CERN as head of the Nuclear Physics Division, only to return to Germany in 1973 to lead DESY. There, the electron-positron storage ring PETRA was constructed under his watch and the gluon discovered in 1979.



In 1981 he became Director-General of CERN, tasked with securing approval for the Large Electron-Positron collider LEP. The construction of LEP provided ample opportunity to demonstrate his unique blend of managerial and diplomatic skills, and his ability to take unpopular decisions without dividing the community: to build the machine in a constant budget envelope, he had to shut down the Intersecting Storage Rings (ISR), world's first hadron collider; his insistence on a 27 km long tunnel, despite some controversy, paved the way for the LHC and ultimately the 2012 discovery of the Higgs boson. His leadership set out the blueprint of CERN for decades to come.

Herwig turned 65 two months after stepping down from his CERN position, but retirement was never on his mind. Instead, he started to deploy his unique skillset on an even grander scale. From 1992-94, he was President of the German Physical Society where he managed the integration of the Physical Society of the defunct German Democratic Republic, the first merger of two major scientific societies following the reunification of Germany. From 1995-97, Herwig served as President of the EPS, a term that was marked by another unpopular decision: he steered our society calmly through a tumultuous period when the seat relocated from Geneva to Mulhouse, saving our society from an existential political and financial crisis and building a solid basis for the universal representation of European physicists which the EPS is today.

Subsequently, Herwig held important positions at UNESCO, chairing inter alia the advisory committee for the International Basic Science Programme. Most notably, he steered the creation of SESAME, the synchrotron light source in Jordan modeled on CERN. Mastering the political challenge of establishing this organisation with its most improbable constellation of Members was arguably Herwig's greatest post-retirement achievement, which will remain in the textbooks as a shining example of visionary science diplomacy. He was delighted to see his tenacity rewarded when SESAME started delivering world-class results during his lifetime.

Herwig Schopper was a rare blend of scientific and diplomatic genius, humanitarian, and gentleman. He married Ingeborg Stieler in 1949, and is survived by his children Doris and Andreas, three grandchildren, and his partner Ingrid. With his passing, science loses a unique leader whose legacy will endure. ■

James Gillies, Rolf Heuer and Rüdiger Voss (CERN)
https://doi.org/10.1051/epn/2025413

An extensive biography can be found in Open Access in: https://link.springer.com/book/10.1007/978-3-031-51042-7

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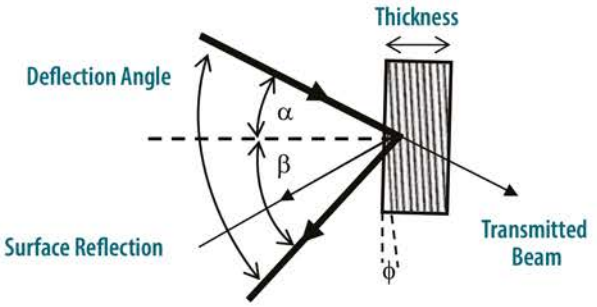
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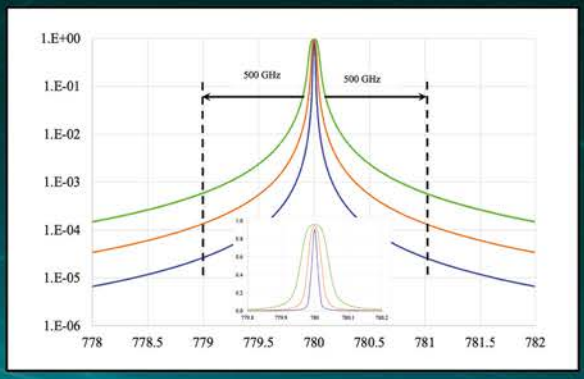


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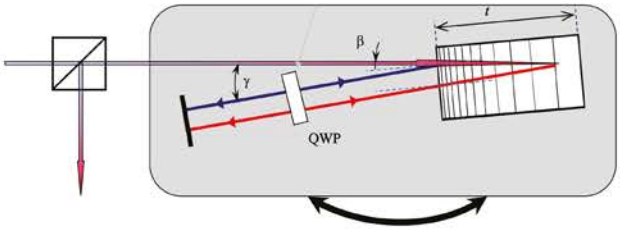


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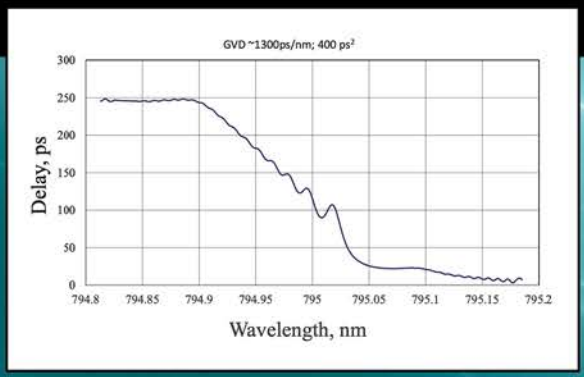
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