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A "human-centered" approach to aural heritage preservation and access

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ABSTRACT

Aural heritage research documents, reconstructs, and preserves the sonic interactivity of sites important to humans across time and around the world. Here, we discuss acoustical data acquisition per the definition of *aural heritage* we proposed: "spatial acoustics as physically experienced by humans in cultural contexts." Two factors support ecological validity (realism). First, the use of places change over time, so aural heritage documentation and reconstruction should be informed by contextual knowledge of both present-day situations as well as past scenarios suggested by historical records or archaeological materials. Second, and our focus here: aural heritage documentation requires acoustical measurements that represent humanly plausible perspectives on a soundfield, including measurements that document human-surface relationships. To ensure accuracy in the presentation of reconstructions of past acoustics to present-day humans, it is necessary to understand how spatial acoustical data translate across different audio rendering systems used for auralizations. Our "human-centered" approach to data collection addresses ecological validity in aural heritage preservation, and in concurrent research we have conducted perceptual evaluations of soundfields reconstructed from these data in multichannel listening rooms. Aural heritage data collection and auralization research require separate methodologies that intersect in the presentation of past acoustics to present-day listeners.

Keywords: cultural heritage acoustics; archaeoacoustics; virtual acoustics; auralization; multimodality

1. BACKGROUND: ACOUSTICS FOR CULTURAL HERITAGE ENGAGEMENT

Sonic presentation of archaeological or historical scenarios is a reconstructive engagement of cultural heritage that fuses social science interpretation with the acoustical and auditory sciences and audio engineering. Cultural heritage acoustics is a rapidly expanding field, sometimes termed "sonic heritage" [1], that has recently aligned with the explosion of commercial techniques for spatial audio and virtual reality applications [2]. An extension of archaeological practice, accuracy in the acoustical reconstruction of cultural heritage spaces depends upon socio-temporal knowledge of the places being represented. Therefore, archaeological and/or historical research is required to inform acoustical data collection and reconstructive assumptions made to develop auralizations, including any situationally appropriate content that is created as sonic material for reconstructive auralizations. Adding to the cross-disciplinary expertise required for this work, auralization as part of multimedia presentation of cultural heritage acoustics — including immersive virtual reality reconstructions — is further problematized due to cross-modal interaction effects that are increasingly being studied via perceptual experimentation. Informed by these operational considerations, we present here a data collection methodology that we have been developing and testing for extensibility across a range of cultural heritage site settings having distinct research and representation challenges.

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In 2017, authors Kim, Ko, and Kolar formed a cultural heritage acoustics research and technologies development team that subsequently received funding from the National Endowment for the Humanities (NEH) in the U.S.A. for a project that leverages our distinct expertise [3]: Dr. Kim is a specialist in 3D audio and perceptual evaluations of spatial audio, particularly for classical music applications [4]; Dr. Ko is specialist in critical listening and the musical perception of virtual acoustics [5]; Dr. Kolar is an archaeoacoustician specializing in site-responsive methodological development, with a focus on psychoacoustics and the study of human-environmental interactions in prehistorical archaeology [6].

We previously proposed a cross-disciplinary term "aural heritage" with the working definition: "spatial acoustics as physically experienced by humans in cultural contexts." In exploring methodological possibilities for aural heritage preservation, we have identified binaural data collection as the optimal spatial sampling technique for accurate documentation of humanly plausible physical perspectives on soundfields enclosed by both human-built and natural structures in cultural heritage sites [7], and we have adapted standard room acoustics impulse response (IR) measurement techniques to the particular demands of cultural heritage site fieldwork [8]. However, despite the physical accuracy possible in acoustical data collection techniques, the audio reproduction of measured acoustics inherently transforms spatial relationships conveyed in that data. Therefore, the documentation (acoustical data acquisition) and demonstration (auralization) of cultural heritage acoustics must be understood and approached as separate though intersecting research activities.

The technological and physical contingencies of auralization platforms necessitate creativity in the design of the virtual acoustical interfaces that represent measured acoustics, and evaluating the accuracy of these experiences of reconstructed acoustics requires extensive perceptual testing of both rendering algorithms and auralization interfaces. Towards accurate translation of measured to virtual acoustics, we have contributed data collection methodologies and perceptual evaluations of multichannel auralization applications of aural heritage data. Here, we discuss both conceptual and pragmatic considerations for aural heritage documentation and representation, exemplified via key examples from our research.

To ensure physical and perceptual accuracy in the presentation of reconstructions of past acoustics to present-day humans, it is necessary to understand how spatial acoustical data collection methods translate across different audio rendering systems that are used to deliver virtual acoustics to listeners. Therefore, the seemingly paradoxical application of evaluations from present-day listeners regarding reconstructions of past acoustics is not only relevant to the field of cultural heritage acoustics, it is necessary to ensure ecological validity [9]. Accuracy in the translation of spatial acoustics is as crucial to this domain as is fidelity to other aspects of cultural heritage preservation and representation.

2. BINAURAL IRS FOR ECOLOGICAL VALIDITY IN HUMAN-CENTERED ACOUSTICS

2.1 Research rationale

Beyond our research — starting with Kolar's doctoral dissertation on ecological psychoacoustics [9] in prehistorical Andean archaeology [10] — we have not seen an emphasis on ecological validity (realism) as a criterion for cultural heritage acoustics documentation, preservation, and knowledge sharing. This is surprising, considering that cultural heritage conservation mandates precision and situational accuracy; for example, archaeological fieldwork can be summarized as the exacting documentation of materials and their structural organization, in assembled context.

The precision we propone for cultural heritage acoustics relates to the application of site knowledge to three activities, which may be interrelated, according to the availability of materials, spaces, and/or relevant data: 1) the documentation and measurement of soundfields within extant boundaries of site spaces in their current conditions; 2) the reconstruction and computational acoustical modeling of past soundfields within specific boundaries (and further, given particular constituents/modifications, according to socio-cultural information); and 3) the simulation of extant or reconstructed spatial acoustics for present-day listeners, via auralizations (that can be rendered using a range of audio systems, from binaural headphone/earphone delivery to multichannel 3D audio).

Whereas specific multichannel data collection techniques have been shown to be optimized for particular multichannel loudspeaker configurations [11], our focus here is to recommend a baseline data collection technique that can be used for accurate translation of physically possible human perspectives on a soundfield. This human-centered acoustical measurement approach provides a realistic, ecologically valid basis for both documenting and auralizing cultural heritage acoustics, and also anticipates technical considerations pertinent to multichannel spatial audio rendering.

In cultural heritage acoustics research, the proposition of humanly plausible perspectives on the soundfield depends on two key considerations: data collection that is aligned with 1) the spatial dimensionality of human physiology and 2) cultural use scenarios that are contextually substantiated. This paper focuses on our methodological premise for the second point: data collection that accounts for human physiology and anticipates the translation of measured data across a range of spatial audio representation platforms. However, it is equally important to consider documented or archaeologically inferred cultural use scenarios in the design of acoustical data collection, specifically to determine sound source and receiver locations within cultural heritage site spaces. For example, in our study of the Rochester Savings Bank, we located a directional loudspeaker at a plausible location for a bank teller behind the service desk and a receiver on the other side where a client would be in conversation (shown below in Fig. 2); in our research at Chavín de Huántar, we located a loudspeaker source according to both seated and standing human positions around the Lanzón monolith in its small chamber, with receiver microphones at a variety of plausible human head-heights throughout the gallery. Each cultural heritage setting must be studied according to its archaeological and/or historical record and considered functionally, to establish use scenarios that guide measurement configurations.

Aligning acoustical measurements with human physiology depends on the spatial location of measurement instrumentation as a proxy for humanly plausible audition or whole-body sound-sensing. Binaural data collection enables spatially precise human-centering of cultural heritage acoustics measurement according to ear-based hearing; however, a pair of microphone receivers as a proxy for a human's ears does not exclude the reality that sound-sensing is a whole-body sensory experience. Binaurally spaced microphones located at an approximate human head-height in spatial context affords ecologically valid (realistic for humans) soundfield sampling that can be translated to skin and bone conduction as well, when located in places that are contextually appropriate according to site knowledge or functional plausibility. A common critique of this technique is that microphones in space alone do not account for the physical interactions of a human body and/or head, and that a more appropriate tool is a head-and-torso simulator or spherical baffle; however, digital signal processing techniques applied to raw IRs can produce any desired approximation for a human form, including the application of head-related IRs (HRIRs) customized for specific listeners who have had their head-related transfer functions (HRTFs) measured. Therefore, human-centered acoustical data collection based on microphone positionality should be recommended over that conducted using binaural recording structures that are difficult to transport to fieldwork settings, and are neither material nor formal equivalents of a real human, potentially introducing approximation errors.

We propose therefore that binaurally equivalent IRs provide baseline human-centered acoustical data to represent the acoustics of cultural heritage site spaces; data that can be filtered and augmented according to the desired auralization technique and presentation platform, following a range of techniques that have been developed via HRTF measurements and analysis [12]. Recent auralization research has demonstrated good perceptual correspondence for headphone auralizations of measured and geometrically modeled binaural room impulse responses [13], indicating the direct applicability of binaural IRs to headphone representations of measured acoustics. Multichannel rendering of binaural recordings has proven more challenging, and thus benefits from multimicrophone impulse response measurement data collection strategies, as recent research in auralization using Ambisonics recordings suggests [14]. The Ambisonics microphone technique developed in the 1970s by Craven and Gerzon [15] has in the past decade gained currency for spatial audio recording and measurement research, enabling the development of inexpensive and portable audio recording tools that can be used for directionally steerable impulse response measurements in fieldwork [16].

In the aural heritage fieldwork methodology we have developed, in order to leverage the multichannel output and multidirectional capabilities of Ambisonics microphony, yet with simultaneous binaural accuracy, we arrange two first-order-Ambisonics (FOA) microphone arrays with the first capsule per array located in binaural analogy. This double-FOA binaural array affords bidirectional data collection from its binaurally situated channels, as well as the additional directionality of the six remaining channels. Our Ambisonics-based cultural heritage acoustical measurement method is thus binaurally equivalent at the data collection stage, in contrast to the more common technique of approximating binaural reception via audio digital signal processing during audio rendering of Ambisonics-recorded signals [17]. We propose and have implemented research that physically samples the soundfield at locations equivalent to standard binaural spacing (e.g., 17 cm apart as per the commonly used ORTF stereophony standard, which could be extended to 21 cm, a commonly cited interaural distance), using multiple Ambisonics microphone arrays in order to simultaneously leverage the multidirectional features of this composite recording technique across different audio reproduction systems. Measuring the soundfield at binaurally equivalent locations contrasts from signal processing techniques applied to Ambisonics recording that approximate locational differences such as "Bilateral Ambisonics" based on "synthesizing the binaural signals in post processing" from spherical harmonic calculations [18], following the seminal "Binaural B-format" approach [19].

2.2 Examples from fieldwork

Whereas binaural soundfield sampling can produce spatially accurate auralizations for headphone/earbud listening, the translation of binaural IR data/recordings to multichannel loudspeaker arrays presents specific challenges with many interrelated variables [20] [21]. Therefore, in our research to develop an aural heritage preservation and auralization access protocol [3], we have compared and tested several standard and modified acoustical data collection methods and microphone configurations in contrasting fieldwork contexts (examples shown in Fig. 1, below).

Figure 1. Impulse response measurements with spatial arrays and paired first-order-Ambisonics (FOA) microphones. Left: binaurally spaced double-FOA's (RØDE NT-SF1) with height channels, with surround array in NEH project research organized by Kim and Ko at the Rochester Savings Bank, New York, USA (© Digital Aural Heritage Project 2020). Right: binaurally spaced double-FOA (Zoom H3VR) in archaeoacoustics fieldwork organized by Kolar in Chauvet Cave, Ardèche, France (© Équipe Chauvet 2022).

According to the framework of human-centered documentation for ecological validity, we proposed the "W-Ambisonics" technique to leverage the steerability of first-order Ambisonics recording used in a pair configuration to spatially sample the soundfield at binaural locations via the first channels of each array (according to the 17 cm ORTF standard that approximates human head spacing between ear canals) (Fig. 1, right), with additional directional height channel microphones to provide enhanced and stable center imaging and depth as preferred by listeners in perceptual evaluations of multichannel rendering (Fig. 1, left) [22]. The use of two first-order Ambisonics arrays rather than two single-channel microphones located in binaural spacing offers both a binaural baseline documentation of the cultural heritage acoustical context, with the directional leverage and spatial presentation control of the 360-degree Ambisonics format that can be achieved via digital signal processing that is optimized for different multichannel auralization interfaces. If desired for optimal presentation in a particular audio rendering format, each FOA microphone in the binaurally spaced pair can be spatially re-oriented as well as mixed with the height channels that are included in the W-Ambisonics technique.

To explore the perceptual translation of spatial acoustics via the W-Ambisonics microphone technique, we conducted systematic listening evaluations with volunteer participants. Experiment results demonstrated that the W-Ambisonics microphone technique "enhances lateral image precision, provides a wider binaural image than [binaural digital signal processing of] the single FOA method, and scales across multichannel reproduction formats." That scalability makes the W-Ambisonics technique — or its double-FOA binaural basis — particularly useful in human-centered acoustical research and presentation, such as cultural heritage acoustics and soundscape documentation [23], as well as in auralizations for experiential evaluations of archaeological hypotheses (given that present-day humans have physiologically equivalent auditory systems to humans across a six-digit timeline). The identification and weighting of pertinent socio-cultural auditory factors remains a little-studied area that we wish to target in future research.

In summary, for binaural audio rendering of humanly plausible spatial perspectives on the soundfield, the double-FOA microphone configuration with first channels spaced 17 cm apart, facing outward as proxies for human ears, enables accurate spatial sampling of the soundfield. In terms of its spatial-perceptual accuracy, the binaurally spaced double-FOA array can be considered the baseline configuration to provide ecological validity in human-centered acoustical documentation of cultural heritage spaces [24]. It is important to note that the equivalence of acoustical spaces translated to specific auralization platforms depends on the many variables of the auralization translation process, rather than the data collection at binaurally equivalent spatial locations. Designing perceptual evaluations of multichannel auralization interfaces remains one of the most challenging areas of spatial audio research, largely uniformed by cultural heritage concerns. The incorporation of cultural-use scenarios is one contextual factor in the design of such interfaces, with implications for the representation and perceptual understanding of spatial dimensions and surface relationships that acoustics can particularly inform.

3. METHODOLOGICAL CONSIDERATIONS FOR REPRESENTING CULTURAL-USE SCENARIOS IN HERITAGE ACOUSTICS DATA

3.1 Translating socio-cultural context in acoustical measurements: a departure from room acoustics praxis

Room acoustics praxis and standards have developed around the evaluation of well-mixed rooms, starting with centrally located receiver points away from walls and surfaces [25] [26:120]. In contrast, cultural-use scenarios of heritage spaces often position emplaced humans in relationship with boundaries and surfaces. For example, in settings of parietal (wall) art such as decorated caves and rock-art sites, the best-documented human uses of these sites indicate human-surface interactions. Leaping ahead to recent times, architectural surfaces are still important: in the Rochester Savings

Bank, for examples, the communication scenario of bank teller to patron, across the massive installed teller desks, likewise necessitates sound source and receiver positions adjacent to — and interacting with — architectural surfaces.

Figure 2. Surface interactions are important to human uses of cultural heritage spaces across time and context, influencing communication affordances, and therefore they should be documented in cultural heritage acoustical measurements. Client view with loudspeaker source approximating a human teller (left, and teller view (right) of the marble-faced counters at the Rochester Savings Bank, New York, USA (© Digital Aural Heritage Project 2020).

Therefore, acoustical measurements that represent human experiences of sites that have archaeological and historical evidence for human uses of those places should position sources and receivers accordingly, to translate into measured impulse responses the corresponding sound transmission and reception characteristics of spaces according to evinced socio-cultural use scenarios. From an archaeological or historical perspective, it is important to produce accurate documentation of what could have been heard, from where, according to the materially evinced archaeological use scenario.

3.2 Towards quantifying surface interactions: observing early reflections in binaural measurements

Single-point microphone techniques such as first-order-Ambisonics (FOA) arrays and coincident stereo, though frequently used to provide material for spatial audio rendering and auralizations, do not accurately convey the intra-aural differences in acoustical energy that can be measured in soundfields adjacent to surfaces. This is because of the minimal distance between microphone capsules, in comparison to the approximately 17-23 cm distance between an adult human's ears. Here, to illustrate this point, we present two examples from hundreds of IRs we measured in recent fieldwork in which acoustical energy differences can be observed between binaurally spaced microphones.

In archaeoacoustics fieldwork and in speleoacoustics research to prepare for fieldwork at Chauvet Cave [23], Kolar's use of the binaurally spaced double-FOA array revealed acoustical contrasts in hundreds of measurements that we propose are consistent with perceptually important differences between the first channels of each FOA microphone. In ongoing research, we are analyzing these data and developing perceptual research to identify the perceptual implications of measured differences. We share some preliminary observations of the difference in early reflections (reflections from nearby surfaces) between channels in binaurally equivalent impulse response measurements, where directionally oriented channels are positioned 17 cm apart.

As shown below, in these measurements, Early Decay Time (EDT10, ISO 3382, calculated in the RØDETest Fuzzmeasure application) can vary significantly between microphone receiver positions (the first channels of each of the 2 first-order-Ambisonics microphones) that are equivalent to spatial locations for the left and right ear canal for soundfield reception by an analogous human listener. Note that the JND is approximately 5% [25:12]. In the domed-ceiling limestone cave location measured in Figure 3, a strong low-frequency resonance is evident in one channel, but not the other; in the low-mids, similarly — suggesting the placement of the receiver array across a node for each of these resonances that could be related to dimensions of cave features in the short ceiling and lengthy gallery; there are also significant differences at 1kHz, and in the higher mid-frequency bands, between ears. Figure 4 likewise shows contrasts between ear-spaced first channels of the two FOA microphones that may indicate perceptible differences in the soundfield at the measured locations that are only 17 cm apart.

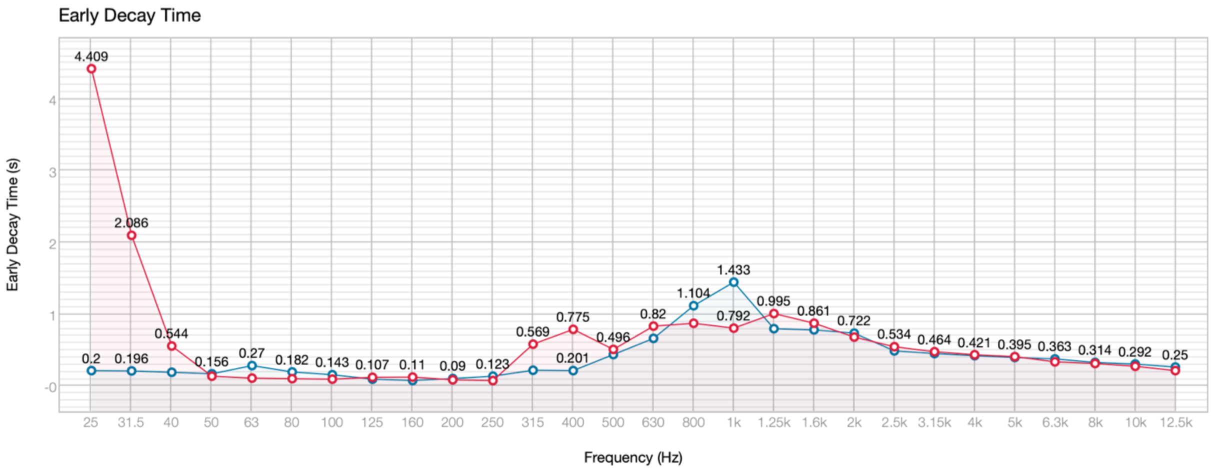

Figure 3. Early Decay Time (EDT) from impulse response measurements under a small, dome-like ceiling structure in Saint-Marcel Cave, Ardèche, France. Data shown (red and blue lines) from the first channels of a binaurally spaced (17 cm apart) pair of first-order-Ambisonics (FOA) microphones as direct proxies for binaural left and right channels; discrepancies between channels may indicate differences in perception of acoustical energy that relate to the proximity of cave surfaces and corresponding resonance effects.

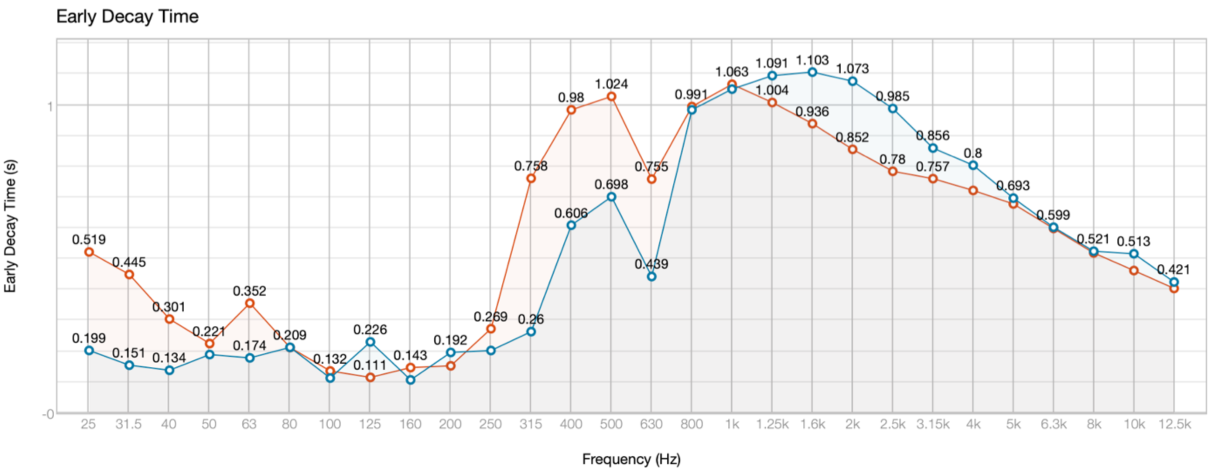

Figure 4. Early Decay Time (EDT) from impulse response measurements under a multi-cavity, smooth limestone ceiling in a large gallery near the archaeological entrance of Saint-Marcel Cave, Ardèche, France. Data shown (orange and blue lines) from the first channels of a binaurally spaced (17 cm apart) pair of first-order-Ambisonics (FOA) microphones as direct proxies for binaural left and right channels; discrepancies between channels may indicate differences in acoustical energy that relate to the perception of surface features.

A single-point microphone receiver would be incapable of measuring these contrasting features, which we have observed in hundreds of measurements. We are in process of conducting subjective evaluations to better understand the perceptual significance of these measured differences using direct auralizations over headphones (the most stable representation translation of binaural IRs) of these and other binaurally equivalent acoustical impulse responses from cultural heritage fieldwork.

4. WORK-IN-PROGRESS & FUTURE DIRECTIONS

To explore the relationship between acoustical measurement strategies in cultural heritage sites and the perceptual translations of measured acoustics in auralizations using these data, it is necessary to design and conduct perceptual research that accounts for spatial relationships as experienced by humans. We are conducting perceptual evaluations of the acoustical differences that can be observed between channels in binaurally spaced acoustical impulse response measurements made in many different cultural heritage sites, as exemplified in Section 3 above, to be reported in future publications. As discussed in another paper presented by our team at ICA 2022 [24], we are also studying cross-modal interactions in immersive virtual representations of cultural heritage acoustics — particularly between hearing and vision, the area of greatest integrative potential for virtual acoustics in this application.

Moving sound sources and receivers deserve research attention, and are another topic we plan to address. Due to the time invariance mandate of impulse response measurement, stationary sound sources and receivers are assumed in most work on room acoustics. However, research in ecological psychoacoustics has set precedents for considering both moving sound sources and human receivers of sound, demonstrating methods for dealing with realistic dynamism [9]. In the measurement domain, multiple source and receiver positions are necessary to provide data for interpolation techniques in rendering systems for audio spatialization [27].

In summary, we have presented a research framework — as well as data collected in cultural heritage acoustics fieldwork — that supports our proposal for human-centered acoustical data collection as a baseline standard for measurements informed by cultural-use scenarios based on site knowledge. We have conducted perceptual research, and continue to develop studies that evaluate the relationship between aural heritage data collection and its demonstration for listeners in a variety of auralization contexts. Our research is part of a growing cross-disciplinary field that interconnects acoustics and perceptual science with the social sciences and Humanities. In collaboration with archaeologists and historians, acousticians, auditory scientists, and audio engineers can design research and demonstrations of aural heritage, to engage a variety of constituencies in explorations of cultural heritage acoustics.

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