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Proceedings of the 2° International Symposium on The Acoustics of Ancient Theatres

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SAAT 2023

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AURA - Auralisation of acoustic heritage sites using Augmented and Virtual Reality. Project overview and methodological approach.

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ABSTRACT

Auralisation, taking a listener to a concert or an opera in a virtual environment as bridge to new technologies, can offer a wide range of opportunities of building new audiences, new business models, new performance practices, exciting new aural experiences. In doing so, AURA creates a model for cross sectoral collaboration to foster creativity, to promote European heritage in new ways and to demonstrate European excellence in the world of music.

Keywords: auralisation, virtual reality, theatre

1. INTRODUCTION

Modern technologies are increasingly used for the enjoyment of cultural heritage. Theatre and musical performances are by their nature “immersive”. This latter feature is achievable thanks to the tool of auralisation. Auralisation is the technique used for creating virtual soundscapes starting from 3D-models that recreate the sound environment of a real space. This implementation allows to define an immersive experience in which the user can move around in space and can experience how the architecture influences the sound.

The partnership of AURA (Auralization of acoustic heritage sites using Augmented and Virtual Reality) Project led by BGZ Berlin International Cooperation Agency GmbH includes the HTW Berlin University of Applied Sciences, Konzerthaus Berlin, University of Florence, Vie en.ro.se. Ingegneria S.r.l., Lviv Polytechnic National University, Lviv Tourism Development Center and Magnetic One. The AURA Project aims at setting immersive experiences of three theatres, investigated as case studies. Moreover, guidelines for the auralisation of virtual spaces will be drawn up, in order to make auralisation of cultural places accessible to future developments and uses.

New technologies will offer a wide range of opportunities to build new business models, new performance practices, new exciting auditory experiences. In this way, AURA will create a model of cross-sector collaboration to foster creativity, to promote European heritage in new ways and to demonstrate European excellence in the world of music.

Among the activities of the project, collecting the future users’ feedback, such as the point of view of musicians, singers, designers and theatre-goers, has a crucial role for the implementation of the tool. Assessing audience experiences in auralised 3D models gives a key for understanding how and in what conditions auralisation can represent a rich and exciting alternative to the immersive nature of the live performance.

This latter aspect is of interest particularly for understanding how young people, who are the age group least likely to attend theatres [1], perceive the theatre experience

On the other hand, the experts’ opinion is important for a meticulous comparison between the real and the virtual experience and for the definition of a model which can better fit the reality.

2. THE DEFINITION OF THREE VIRTUAL ENVIRONMENTS

2.1 The three theatres

The opera and music theatres of Berlin, Florence and Lviv, supported by technological and marketing partners, are committed to exploiting the potential that auralisation offers to musical arts and performances. The project investigates the result of three case studies that create a reproduction of the environments and produce new ways of experiencing music.

The three theatres which have been modelled and simulated in virtual reality are the Teatro del Maggio Musicale Fiorentino located in Florence, the Konzerthaus of Berlin, and Lviv National Academic Opera and Ballet Theatre named after Solomiya Krushelnytska in Lviv. The theatres differ in terms of architecture style and period of construction as well as acoustic features. As a matter of fact, they are characterized by different volume, number of seats and reverberation time, which affect the acoustic performance of the theatre. The above-mentioned values are presented in Table 1.

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Table 1 – Features of the theatres

Concert Hall Theatre **Location**	***Plan shape***	***Construc-tion year***	***Volume [m³]***	***Number of seats***
Grosser Saal Konzerthaus Berlin, Germany [1]	Shoebox	*1818-1821*	15000	1575
Sala Grande Teatro del Mag-gio Musicale Fiorentino Florence, Italy [2]	U-shaped	2009-2011	18000	1800
Lviv National Academic Opera and Ballet Thea-tre Lviv, Ukraine [3]	U-shaped	1897-1900	4549	1050

The synergic collaboration between the University of Florence and the HTW Berlin University of Applied Sciences resulted in the definition of three application for the simulation of virtual reality. Following theatres surveys, the Department of Architecture of the Univer- sity of Florence has developed the visual 3D models of the inside, whereas the HTW dealt with the implemen- tation of the audio reproduction. The combination of these two aspects makes the experience of immersion inside the theatre realistic: the more auralization and visualization are carefully implemented, the more they correspond to reality.

Figure 1 – Inside view of the 3D model of the “Kon-zerthaus” in Berlin, Germany.

Figure 2 – Inside view of the 3D model of the “Teatro del Maggio Musicale Fiorentino” in Florence, Italy

Figure 3 – Inside view of the 3D model of the “Lviv Na-tional Academic Opera and Ballet Theatre” in Lviv, Ukraine.

2.2 Implementation of apps

Thanks to the definition of 3D visual and acoustic models, the three theatres have been implemented in a specific software (Unity) and three applications for per-sonal computers have been set.

In each of the theatres, the user can walk inside the room and make the instruments play.

For an easier control of the user experience, orga-nized within the Project, some significant listening points have been set in order to allow a quick reposi-tioning of the participant who is wandering inside the theatre. In the light of this, the most common listening positions (such as in the first row, in the last row, on the balcony) as well as positions only accessible to the per-formers (such as on the stage) have been defined.

For the audio simulation, two violins, a cello, a dou-ble bass, a flute, an oboe, a clarinet, a trumpet, a harp, a drum, a viola, a piccolo flute, a bassoon, and a horn have been positioned on the stage. The set of instru-ments can be switched on and off independently by the user of the application. The orchestra plays the 4th part "Golliwogg's Cakewalk" from "Children's Corner", a composition by Claude Debussy, During the exhibition, the avatars of the musicians are displayed, as shown in Figure 4, together with the corresponding audio repro-duction.

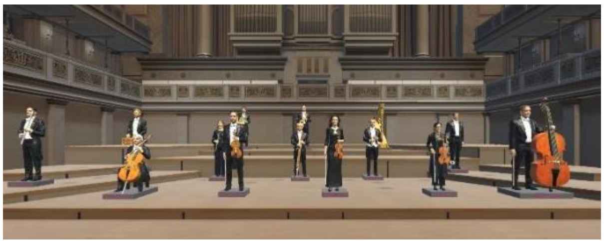

Figure 4 – The avatars of the musicians playing inside the Konzerthaus of Berlin.

3. AN IMMERSIVE EXPERIENCE FOR THE PUBLIC

3.1 The audio and audio-video experience

Participants take part in an immersive experience designed by Vie en.ro.se Ingegneria S.r.L.: the two main activities consist of an audio experience and an audio-visual experience. At the beginning, the user listens to an auralized audio track of the Konzerthaus, the different listening positions inside the theatre and the different combination of instruments playing are written on the screen. During the listening, visual references of the inside of the theatre are not provided. The second part of the experience consists of an audio-visual immersion: the user listens to the auralized audio tracks of the three theatres and visualizes the corresponding space. This simulation is carried out with the Oculus, a virtual reality headset that allows to play the audio and the 360°-view of the space. The experience is repeated in the different listening points of the three theatres, play-ing different instruments. For the interaction of the participants, in order to simulate the use of virtual reality, the user is asked to independently choose the listening positions and instruments to be played within each of the three theatres.

The experience is held in the DIDA Extended Reality Laboratory in the Department of Architecture of the University of Florence. Inside the room five simulation stations are set with oculus connected to personal computers for a 1-hour experience.

During the simulation, users are asked to fill-in a questionnaire which is differentiated according to the prior knowledge of the users. Round Tables are organized for experts and technicians, whereas a quiz is arranged for involving younger participants.

Figure 5 – Test of the tool for the immersive experience using Oculus

3.2 The sample of participants

The sample considered for the investigation has been divided into three categories in order to understand how subjects can differently be enriched and positively influenced by the auralisation process. For this reason, the user experience and the analysis of their perception are differentiated.

Most of the participants (approx. 70) belong to the "General Audience", which includes students from middle and high schools and general non-expert public. The other two categories consider subjects who are interested in the theatres' features because of their jobs: on the one hand, "Experts" who perform inside the theatres, such as musicians, singers, conductors, actors, general expert public, music schools' students, and theatre lab participants (approx. 40); on the other hand, "Technicians" who deal with the design of spaces, such as architectural designers, acoustic designers, and architecture students (approx. 40).

Voluntary participants have been identified during academic courses organized by the University of Florence, other participants come from schools, music schools, and theatre labs. For a wider sharing, brochures have been published on social media.

Figure 6 – The arranged brochure for the identification of Technicians and Experts.

3.3 Questionnaires, Round Tables, Games

In order to receive the users' opinion on the immersive experience of auralisation, the assessing of the audience follows the participation to the experience.

Three questionnaires, one for each of the defined categories, have been drawn up by Vie en.ro.se Ingegneria S.r.L. and divided into sections. Participants are asked to fill-in the questionnaire, implemented on Google Form, during the experience. The first two sections can be filled-in before the start of the audio experience and allow to define the investigated sample, collecting personal information, and habits and behaviours related to the fruition of theatres. For experts and technicians, a deeper analysis is made on professional experience.

For the General Public, four additional sections are asked to be filled-in and concern the assessment of the audio experience (to be filled-in as soon as the audio experience is over) and of the audio-visual experience (to be filled-in as soon as the audio-visual experience is over). At the end of the whole simulation, a comparison between the two experiences and an opinion on future developments of the tool is investigated.

For questions related to the characterization of the samples and their assessment of different kinds of music performances, a literature review on the field has been done [4],[5],[6],[7].

Round Tables are organized for experts and technicians, in order to collect experts' ideas concerning pro and cons of the tool, and potential use. Participants of these two categories are divided in groups and a list of topics is projected on a monitor as a starting point for a collective discussion.

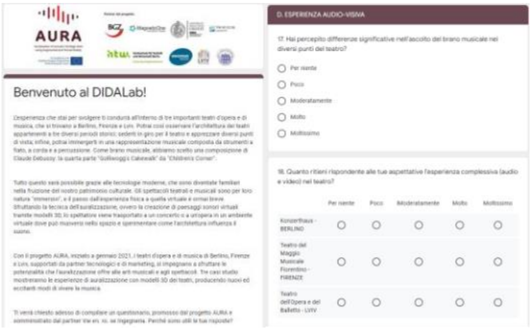

Figure 7 – An extract from the Questionnaire for General Public implemented in Google Form.

The following questions are presented to the participants of the "Experts" category:

- Have you ever worked with immersive technologies (apps with augmented or virtual reality)? And if so, in what context?
- Do you think that the possibility to activate /deactivate the different instruments on stage is useful for your work?
- Do you think that listening from different points in the theatre is useful for your work?
- Do you think that this tool could be more effective for a specific kind of theatre (e.g., opera house, drama theatre, concert house, etc.) and a specific kind of performance (e.g., classical concert, jazz/modern concert, opera, prose, musical)?
- Do you think that knowing the architecture and the acoustics inside the theatre before your exhibition could be important for facilitating your performance?
- Do you think this tool can attract new audience to the theatre?
- Additional suggestions

Questions related to the design of enclosed spaces are introduced to the participants of the "Technicians" category:

- After this experience, do you think it is important that this could become a commonly used tool to ensure a better architectural/acoustic quality of a theater project?
- Do you think that the auralisation tool is useful for your work?
- For acoustic designers: how do you think the auralisation tool can be useful for your work?
- For architectural designers: how do you think the auralisation tool can be an added value compared to traditionally used tools (e.g., rendering)?
- Do you think this tool could be useful for the choice of materials from an architectural and acoustic point of view?
- Can you think of another application in your field for which an auralisation like the one you just experienced would be useful?
- Additional suggestions

All the considerations and suggestions elaborated by experts and technicians are collected.

For involving younger participants, a link for having access to an online quiz is provided. The quiz is filled-in in real-time on mobile phones during the audio experience. During playback of different scenarios, people are asked to recognize the instrument, or the kind of instruments playing and define how far from the stage their listening position is.

4. CONCLUSIONS

The AURA Project has investigated the potential that auralisation offers to musical arts and performances. The tool of virtual reality has been implemented for three opera and music theatres in Berlin, Florence and Lviv. Thanks to the definition of audio-visual 3D-models a new way of experiencing theatres is presented. The aim of the activities of the project is profiling the different typologies of participants, both theatre-goers and people that usually do not go to theatres, regarding their habits and preferences with classical music performances. This experience allows to make them approach to the auralisation experience and receive feedback about the tool. The virtual reality is not intended to replace live performances but promote the use of theatres.

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Analysis Of Auralisation Techniques For 3d Models Of Music Theatres

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ABSTRACT
The work displayed in this paper was achieved during the AURA project, a Creative-Europe-funded project with mul- tiple international partners both with technical and cultural expertise. The paper describes current auralisation techniques and recites the past course of the project. It draws comparisons to similar projects before developing an own concept for an auralised application. This will include one application using a hand-modelled 3D object of the Konzerthaus Berlin, which opened in 1821, and one which will use a laser-scanned model. These applications, using the different types of models, will be further analysed regarding audio and video quality as well as overall performance. Furthermore, the de- velopment of a neural network for instrument positioning relative to the listener will be described. A conclusion on the suitability of the two model types for auralised applications will be drawn and a further outlook on the ongoing work in the AURA project will be given.
Keywords: Auralisation, Virtual Reality, 3D modelling

1. INTRODUCTION

State-of-the-art technology usage in the cultural sector has risen immensely in the past years. Especially since the Covid-19 pandemic, more and more cultural institutions had to switch to an online concept [1], making modern technology an integral part of how we experience art, music and culture in general. With digital tour guides omnipresent in almost all museums and exhibitions and musical plays and concerts being live- streamed, technology is indispensable in our cultural lives nowadays.

The rise of technology usage in music venues has also increased the popularity of auralisation techniques. By using auralisation a realistically sounding 3D model ofany musical theatre around the world can be virtually visited and experienced. The use cases for auralisation are widespread and can range from experiencing the soundscape of ancient heritage sites or hearing thesame piece of music in multiple different musical venues without the need for travelling.

The AURA project, a Creative-Europe-funded project with multiple international partners from Germany, Italy and Ukraine, focuses on exactly this kind of technology usage in music venues.

The paper will give detailed insights into state-of- the-art technology regarding auralisation and present a concept for an auralised application using two different models from the Konzerthaus Berlin, one of them being hand-modelled, the other one produced using the laser-scanning technique. These will be the foundation for an analysis of both model types. The audio, video quality and overall performance will be analysed, before then giving insight into an analysis of listener and instrument location using a neural network. A conclusion will be drawn on which 3D modelling is more suitable for auralisation and how instrument placementand listener location can influence the visitor's experience.

Figure 1 – Music venues from the AURA projectin Germany, Italy and Ukraine

2. STATE OF THE ART

Auralisation is the virtual reconstruction of sound fields [2]. Taking into consideration the material parameters of all objects located in the room, how theobjects react with sound, as well as the room geometryin general, a realistically sounding audio experiencecan be created.

Over the course of the AURA project, three music venues have been auralised. First, a prototype wasmade using a hand-modelled 3D object from the GreatHall of the Konzerthaus Berlin. After laser scans and the 3D modelling process of the Teatro del Maggio in Florence were finished, the completed 3D object was auralised as well, using the same technique as in the previously developed prototype. The next step was thelaser scan of the Konzerthaus Berlin, which resulted in a second 3D model from the Great Hall. The outcome was two

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comparable auralised models of the GreatHall in the Konzerthaus Berlin which will be analysedin the 4th chapter.

The auralisation was done using the Steam Audio plugin for Unity [3]. Steam Audio adds functionality to create spatial audio in applications developed in the Unity editor. Features like material parameters and geometry specifications can be added to all object components. A fundamental part of spatialisation is the use of head-related transfer functions, short HRTFs. HRTF describes how sound from a specific point within the environment will travel to the listener's ear [4]. Steam Audio gives the developer the option to substitute the default HRTFs with their own SOFA file and thus the ability to create sound experiences specific- ally customised for each user.

During the APOLLO project[1], carried out by the INKA research group, a digital 3D model of Konzerthaus Berlin (KHB) and all its halls had been created by hand. The model was used for several projects including a guided tour in virtual reality. This model was reused for the first auralised prototype for the AURA project.

Figure 2 – Small Hall from the Konzerthaus Berlin, de-veloped during the APOLLO project

The laser scan of the Konzerthaus Berlin was produced by the DiDa lab, the department of architecturefrom the University of Florence, one partner of the AURA project. Many previous digital surveys have been conducted. One of them was the analysis of the St. George Church in Girne, Cyprus. During a digital survey campaign, the volumes and architectural features of the church were studied and morphological data, drawn up through the use of laser scanners, was integrated with the material information acquired through Structure from Motion (SfM) methodologies. This resulted in a complete textured 3D model [5]. The same approach was taken for the digitalisation of the Konzerthaus Berlin and the production of the 3D model of the Great Hall.

3. APPLICATION CONCEPT AND IMPLEMENTATION FOR ANALYSIS

Both KHB models were imported into the Unity Editor. The concept was based on the previously developed auralised models using both Unity and the plugin Steam Audio [3]. The models vary in the number of polygons and therefore also in size. The material parameters for the auralisation were the same. The following table gives an overview of the models' geometry parameters.

Figure 3 – Laser scan data during the digital survey of the Great Hall in the Konzerthaus Berlin

Table 1 – parameters of both models

	Hand-modelled	Laser-scanned
File size	37,6 MB	191,8 MB
Objects	63	1 116
Vertices	1 470 066	2 356 068
Edges	2 439 618	3 525 955
Faces	1 171 600	1 549 111
Triangles	1 171 600	1 551 095

Each model was then placed in the prepared scenes. To further analyse the two versions of the Great Hall the target platform was changed from virtual reality glasses to Windows/macOS. Therefore, the interaction system was changed as well. Position switches can bedone by pressing the numbers 1 to 8 on the keyboardof the used laptop or PC. Musicians can be enabled and disabled by pressing the keys F1 to F10. This helped in making the testing simpler and more efficient.

4. ANALYSIS

After preparing the scene setup for both models ofthe KHB Great Hall, test runs were done analysing a handful of graphic parameters. All tests were done in the Unity Editor on a MacBook Pro 2016 with a 2,6 GHz quad-core Intel Core i7 CPU. Recording over the course of 1 minute from the same position in both models the FPS, meaning the number of frames Unitydraws per second, was captured. Even though the laser-scanned model has a more complex geometry, the FPS were between 104 to 114, averaging at around 108 FPS. The number of FPS for the hand-modelled version was more consistent however a lot lower in com- parison, being between 54 and 58.

Next, the CPU usage was measured. This took into consideration the total amount of time taken to process one frame as well as the time taken to render one frame. Again for 1 minute, both scenes were measured.For the scene of the laser-scanned model, the CPU took between 8.1 and 9.6 milliseconds to process one frame and between 1.6 and 2.2 milliseconds to render.In comparison, the hand-modelled Great Hall model was averaging between

[1] https://inka.htw-berlin.de/project/apollo/

17 and 19 milliseconds and 0.7to 1.1 milliseconds to render. The number of batches drawn is for the laser-scanned model at 544 a lot high-er than 166 for the hand-modelled one. This explains the difference in time.

The optical analysis revealed big differences in dimensions, lighting and textures. The laser-scanned model is accurate to the centimetre whereas the hand-modelled one was done using approximate measurements. This led to very different sizes of the stage, and overall dimensions of the hall. The laser-scanned mod el seems a lot more spacious and realistic. The lighting and textures vary as well. Even with the same lighting settings, the laser-scanned model is darker and has more muted tones. The hand-modelled version is brighter and has more white tones.

Figure 4 – Optical comparison from same position (left hand-modelled, right laser-scanned)

The auralisation is based on the model's geometry. As already mentioned, the laser-scanned model is ac- curate to the centimetre resulting in a more realistic auralisation. However, these differences are very minor and did not make for a noticeable audible dis- tinction between the two models. The overall performance of both scenes on the testing device was good. The higher number of FPS made camera movement in the laser-scanned model significantly smoother. Even with far fewer vertices and objects in general, the hand-modelled version was slower and had more anti-aliasing. This can solely be attributed to the visualisation and not the auralisation part since all settings and parameters remained the same for both models.

The analysis confirmed the suitability of accurate laser scan models for the AURA use case. The graphical rendering is more performant, making the visualisation overall superior. Especially for virtual reality applications the higher number of FPS makes for a better experience and can possibly prevent motion sickness. Generally speaking, frame rates below 90 FPS can lead to disorientation and nausea for the user[6]. Even though there was no distinct difference in sound between both models, for larger scaled auralisations the difference in audio can be more significant.

5. NEURAL NETWORK DEVELOPMENT

There are significant differences in the placement of musical instruments on stage or in the orchestra pit. The selection, arrangement and choosing of the number of musical instruments are related to the achievement of creative tasks. However, from an acousticpoint of view, the number of musical instruments is associated with sound balance problems. Some musi- cal instruments differ significantly in their dynamic and frequency range, direction characteristics, and timbre. Such large differences can undoubtedly lead to masking one group of instruments to another. More- over, the concert hall brings significant changes to the overall sound picture. Only a proportional selection ofthe number of instruments and the correct location on the stage can give the desired result.

Therefore, it is advisable to analyse the listener's location depending on the instrument he wants to hear. In addition, good visibility of the performance andsound quality are also important factors.

5.1 Materials and methods

To determine the best location, multi-criteria parameters were taken into account, including [7]:

- The convenience of viewing the play (two number characteristics – upper and lower border),
- The viewing angle,
- The sound level of the group of instruments (the number of parameters is determined by the number of instruments and their location - in the orchestra pit or on stage),
- Physical parameters of the room,
- Frequency ranges of instruments,
- Physical parameters of the spectator placement quadrant.

The task of classification is set. Class labels are the quadrant numbers of the listener's placement.

A fairly simple neural network architecture was experimentally selected, which was a compromise between the accuracy of the classification and its speed. The architecture of the network will change for each concert hall and the number of musicians involved in the performance. 98 traits (input parameters) were se- lected for the pre-workout.

A fully connected neural network to complete the task is chosen. Four fully connected layers with the number of neurones 256, 128, 64, 10, respectively, were used, followed by batch normalisation [8] and the dropout technique with probabilities of 20%, 20%, and 50%, to avoid retraining. The architecture of the neural network is presented in Fig. 5.

5.2 Implementation

The dataset was collected based on Lviv Opera House [9]. The Artificial intelligence module (AI module) was developed in Unity using C# and has the following file structure:

- Constants - a file that contains constants that willnot change during the program.
- Features_extracting - a file containing functions for direct work with audio files. The get_features

function picks up audio in digital format and returns a list of selected features.

• Model - a file in which data is pre-processed, normalised, created and trained neural network. Contains only one main function, which takes the input path to the dataset and then normalises it, creating and training the neural networks based on the specified dataset. The result of the function is a trained neural network, which is stored on a disk, and then used in the main part of the program.

• Main - implements the basic algorithm of the program. Contains a predict_place function that classifies the best user's location (quadrant).

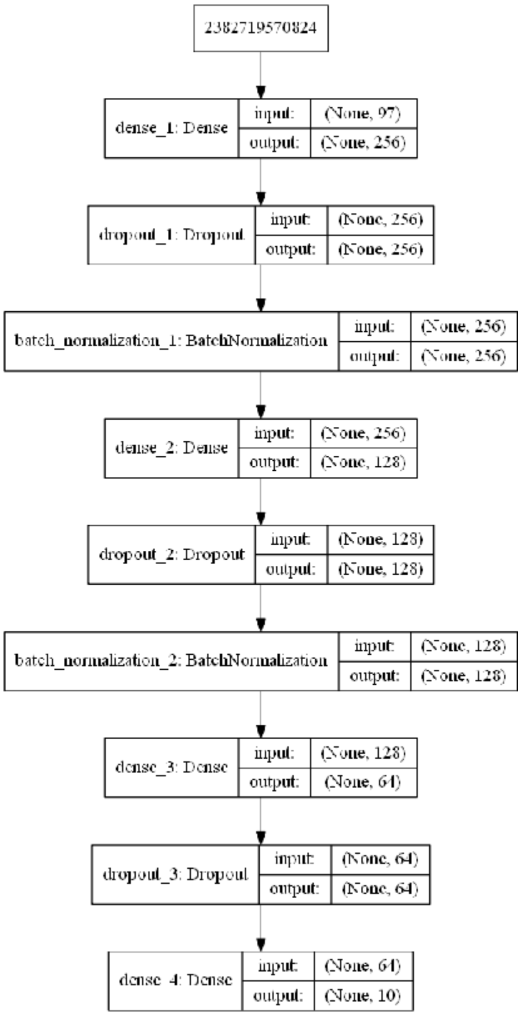

Figure 5 – The architecture of the artificial neural network

The developed neural network was trained on the dataset of the Lviv Opera House but will be applied to the Konzerthaus Berlin and Teatro del Maggio Florence during the further course of the project.

6. CONCLUSIONS

The analysis gave a clearer view of the differences between both model types. It confirmed the choice to use the laser-scanned version for further development and testing. It gives the most realistic result and is best suited for virtual reality applications.

The developed neural network will be used for the conduction of a case study, which will be the main focus for the future months of the AURA project. Business models will be created using the instrument placement analysis to give visitors the best seat location based on their preferences.

The finished auralised models will be used for testruns with experts and laymen in the next steps. Case studies for educational purposes are planned and will take up most of the remaining running time of the project.

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Aural Augmented and Virtual Reality Applications: Best Practices and Challenges

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ABSTRACT

Emerging technologies can help to create new kinds of interesting audio-focused applications. Especially augmented and virtual reality can allow experiencing audio in new ways since AR and VR allow new types of interactions and can also create a sense of immersion. However, there are some difficulties to consider while implementing an audio-focused AR/VR application. In this paper, we discuss these difficulties and demonstrate some best practice examples.

Keywords: Augmented Reality, Virtual Reality, Human-Computer Interaction

1. INTRODUCTION

New technologies can be used to create applications that allow experiencing the audio content in a novel manner. AR and VR applications are particularly interesting since they allow new ways for intuitive interactions which can help to create new ways of natural interactions with audio contents. From the auditive point of view are AR and VR applications also interesting because the immersion created by these technologies greatly depends on audio contents [1].

This paper describes challenges that arise while the development of audio-focused AR and VR applications. The discussed challenges are shown in already existing AR and VR applications. All presented applications were developed as part of the cooperative research project APOLLO by the research group INKA at HTW Berin and the Konzerthaus Berlin with the aim to teach the basics of classical music and to awaken an interest in classical music in general.

Four different AR/VR applications are presented and the challenges are explained using these examples. The presented AR applications are the digital "Virtual Quartet" and the "OrchestraBox" both applications are au- dio-based and the main aim is to develop and implement new interaction formats and to teach young people clas- sical music. The VR application "VR Tour and Orches- tra" shows how VR can help to create an immersive auralization of concerts and how this helps to make 3D environments more believable. The VR application "Umwelten" puts the users in a world with abstract visuals and audio and offers different interactions. After an introduction and state-of-the-art chapter, we will describe our current research and show our AR and VR applications. Then we will discuss challenges, our approach, and the development of audio-based AR/VR applications. In the end, we will summarize and discuss the future work.

2. BACKGROUND

Some definitions of VR require not only a virtual environment but also require these environments to be immersive [2]. The capability to create a sense of immersion is important for VR applications since it can make the user believe that the presented virtual environment is real. Besides the visual component of VR applications, audio plays an important role for immersion [1][3]. The sense of immersion in VR can be improved through realistic sound effects in the virtual environment and music. Music can also have a great impact on the emotions of the user in immersive environments [4].

In AR applications audio can also help to increase the sense of immersion, for instance by adding realistic sound effects to virtual objects. The main purpose of audio in AR however is to enhance the real environment of the user with audio contents. There are two different types of AR: marker-based and markerless. Marker-based AR uses image tracking algorithms such as SIFT [5], to connect virtual content with some physical objects (= markers). Markerless AR on the other hand does not need any markers and tracks the position of the camera through the extraction of the feature points from the user's surroundings. Thus, markerless AR allows the user to place virtual objects freely in his environment. For example, in some AR apps users can annotate real objects with audio [6] and other applications allow attaching music to the real objects and the user can combine the attached music by combining the physical objects [7]. There are also the so-called Auditive-AR (AAR) applications that are solely based on audio content and do not provide any form of visual input for the user. Some examples of this kind of applications are

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museum guides [8] and audio games [9].

An important aspect of AR and VR applications is the new way of interactions that they offer. For example, some AR and VR Head-Mounted-Displays (HMD) allow tracking of user hands which makes it possible to interact with such devices in a natural way (e.g., HoloLens or Oculus Quest). Natural interactions make it easier to create applications that allow intuitive interactions with audio content. In such applications, the users can not only hear the music but can also change it intuitively [10][7].

3. VR PROJECTS

3.1 VR Tour and Orchestra

The goal of this immersive virtual tour is to show users the impressive architecture of the Konzerthaus, the history of the building and to provide a glimpse of its orchestra in action [11]. Since audio plays a very important role in all of the activities surrounding the Konzerthaus, the VR application has to provide not only stunning visuals, but also immersive audio that makes the experience more believable.

Visually, the Konzerthaus building is presented as a high-resolution 3D model in which users are guided through the halls. Additionally, there is a short recording of a string quartet (see also Section 4.1) embedded into the Small Hall of the Konzerthaus. The second part of the VR application shows another recording of a full orchestra that can be viewed from four different viewpoints. Each viewpoint consisting of 360° spheres with 4k video and an ambisonic audio source for spatial audio.

Both additions are accompanied by spatial audio that is carefully placed within the 3D environment. Extensive user and playtesting of the application showed that the additional emphasis on the auditive components played a vital role in the overall experience.

One of the major challenges was to keep interaction techniques simple so that a wide range of users could enjoy the experience. This was achieved by implementing an intuitive interaction technique called *gaze and wait* where users simply look at a symbol and wait until the action is triggered. (This technique is now widely used within VR applications.) The app introduces the mechanic early on and constantly reminds users how to trigger certain elements. Again, extensive user testing showed that spatial audio cues are important to steer the gaze of users in the right direction.

3.2 Interactive composition in VR

Umwelten is a cooperative project of the research project APOLLO, the Konzerthaus Berlin, the visual artist Julian Bonequi and the composer Mark Barden [12].

The VR application transports users into an alien-like, eccentric 3D world where they can interact with 3D models and activate AudioSources that are attached to them.

Each of the 3D models features multiple different audio sources, that can be activated by i.e. grabbing them, drawing on them with a drawing ray or sometimes just by entering their vicinity.

At first, some of the 3D models featured up to 30 different audio sources each and would have multiple interaction concepts that could activate audio.

One of the problems with this while user testing the application was that users couldn’t always discern which behaviour activated what audio and would get overwhelmed by the many different interaction possibilities. One specific interaction used a drawing ray that would activate audio upon touching an object in the scene that had an audio source. This drawing ray would however work on the object directly in front of the user as well as objects floating in the sky of the 3D world.

Figure 1 – VR user using Umwelten (Photo: Markus Werner)

One part of the solution to this was to use spatial audio. This meant that users could understand the correlation of the 3D models and their respective audio sources. Only the objects in the direct vicinity could be heard and it was therefore clearer what the sound belonged to. Some of the objects in the sky would still be able to be activated, as preferred by the artists working on the project.

So, a second part of the solution was to implement colour feedback when activating an object. The material of the triggered 3D model would change colour for a few seconds in order to indicate its activation and that another sound would be started.

User feedback on these changes was good, the audio activation was easier to understand and the origin of the sound easier to discern both with the spatial audio as well as the colour feedback.

4. AR PROJECTS

The next chapter will cover two AR projects of the research project APOLLO. They both dealt with the synchronisation of multiple audio tracks, both during the content creation and inside the final application.

4.1 Virtual Quartet

The virtual quartet is one of the marker-based AR applications that were developed in cooperation with the Konzerthaus Berlin [13]. The application works with four different markers, that resemble quartet cards from a playing card game. Each AR marker is connected to a musician and upon scanning the cards a visual representation of this musician is placed onto the card. In addition to this the musician's respective part from Franz Schuberts "Death and the Maiden" starts playing.

Figure 2 – The audio recordings in the anechoic chamber at TU Berlin (Photo: Annette Thoma)

The audio users can hear depends on how many markers are currently recognized in the camera view of the smartphone or tablet. Users can therefore create their own composition with i.e. only the violin, only the cello and viola, and so on. To achieve this the musicians had to be recorded separately in an anechoic chamber, resulting in four separate audio tracks, one for each musician.

The challenge for the musician was to play their piece individually. Normally, even though they have the music score, they are also playing off each other, reacting to changes in tempo etc. This could be partially solved by the musicians having earpieces with the other musician's recordings playing while they were recording their part.

The next challenge was to also have a visual recoding of their playing. This could not take place in the anechoic chamber but had to be done in front of a green screen, so that the videos could later be chroma-keyed to remove the background.

An important part when developing the application was the synchronization of the different audio tracks. Even slight inaccuracies in the playing and starting times could be heard. This was even more apparent when the video of the musicians was also introduced into the application.

In the final application, whenever a new marker is scanned, the musician is registered to a global manager class. The manager class gets the time of the video and starts the musician's audio at the respective time. This way, the audio is always in sync with the video. Fortunately, the asset sizes allow for almost no delay in starting the audio, meaning that the four quartet musician audios are also in sync with each other when they are started using the videoplayer time.

One point of discussion concerning the auditive experience was also when to first start the video-/audio playback. Early versions of the application started the audio and video whenever the first marker was recognized. However, this had to be changed since the delay in recognizing the markers meant users couldn't hear the start of the music piece with all four musicians playing.

The solution for this was to only start the audio after all the markers were scanned once. In order to give users the option to only listen to single musicians, a playbutton was introduced. While not all the musicians are scanned yet, a playbutton is attached to the first recognized musician, allowing users to start the audio and video by clicking it.

4.2 OrchestraBox

The OrchestraBox is a music box that was developed for musical education lessons at school [14]. The developed music box is playing a composition that was recorded by 18 musicians. All 18 musicians were recorded separately which allows for selecting which musicians should be audible while playing the composition. The musicians can be selected by placing their 3D printed figurines on the top surface of the music box. Since each figurine has an RFID chip attached to its bottom side, the OrchestraBox can recognize the figurines with its RFID antennas mounted on its top surface. By placing the figurines on the top surface of the OrchestraBox the user can select which musicians should be heard while playing the composition.

Figure 3 – left: the OrchestraBox with all musician markers, right: the underside of the box with the RFID antennas

All 18 musicians were recorded separately from each other in an anechoic chamber to provide the best audio quality. One of the challenges for the given project was the fact that the combining of 18 audio tracks in real-time requires a lot of computational power because of that a lightweight, low-power computer couldn't be used. Thus, an Intel-NUC computer was used instead of a portable and more lightweight Raspberry Pi 4B.

Also, the RFID antennas generate an electromagnetic field that affects the audio transmitted through the AUX cables, which results in noise while playing the audio. This problem was solved by rearrangement of hardware components of the OrchestraBox and better placement of the audio cable, so the RFID antennas have only a little effect on audio transmission.

5. DISCUSSION

In audio-focused AR and VR applications, it is often useful to record many different sounds that can be used to create an interesting virtual or augmented environment with interactable audio objects. However, it could become a problem if the application offers too much content (as it was the case in the Umwelten project) since it could confuse the user. Audiovisual cues can be used to direct the user's attention which could help to solve this issue.

With the effect of immersion, VR intensifies and changes the way people listen to music. Also, VR and AR offer some new ways of interacting with virtual content. Some AR and VR devices can track the hands of the users which allows them to interact with the application intuitively. This could open new ways for interaction with audio content, for example using hand gestures or activating audio content by touching it.

Overall AR and VR can help to experience audio in a new way and can make audio content more interesting and interactable.

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Digital survey and 3D modeling to support the auralization and virtualization processes of three European theater halls: Berlin Konzerthaus, Lviv Opera House, and Teatro del Maggio Musicale in Florence. A methodological framework

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ABSTRACT
This paper shows three different approaches to the issue of morphological/dimensional survey of theater halls, aimed at creating a 3D model to support the processes of auralization and immersive virtualization to create a reliable basis for the ArchViz and acoustic auralization processes. The chosen three European case studies of the Konzerthaus in Berlin, the Opera House in Lviv, and the Teatro del Maggio Musicale in Florence provided the fundamental basis for the development of the AURA project.
Keywords: AURA, digital survey, 3D modeling

1. INTRODUCTION
The paper presents some results of the activities within the European project AURA - Auralisation of acoustic heritage sites using Augmented and Virtual Reality - co-financed by the Creative Europe program. The research proposes the construction of multisensory virtual 3D models to support and encourage new opportunities to use and disseminate Cultural Heritage for Cultural and Creative Industries (ICC). The work provides the construction of multisensory environments related to three major European theaters seen as case studies: the Konzerthaus in Berlin (DE), the Lviv Opera House (UA) and the Teatro del Maggio Musicale Fiorentino in Florence (IT). Finally, by creating models for immersive experiences in VR, the project aims to integrate the visualization of the architectural space of the three case studies with the related acoustic landscapes through auralization techniques to increase the opportunities offered by the VR world-specific entertainment and musical sector. [1]

The sector's interest has grown enormously in recent years, also with the effects of the COVID-19 pandemic, which imposes the development of alternative proposals for the use of the Artistic and Cultural Heritage, aim to implement technologies for new commercial horizons to attract new audiences [2]. The acoustic characteristics find increasing place also in the context of documentation and safeguarding of cultural heritage. In 2017 UNESCO, through the document "The importance of sound in today's world: promoting best practices" [3], underlined how the sound of existing or historical places constitutes one of the factors of interest for the protection of the Heritage [4].

The acoustic features of an environment of cultural and patrimonial interest are an immaterial consequence of its construction, from the materials to the furnishing systems that make these spaces usable [5].

Studying the three case studies at the European level made it possible to develop an appropriate methodology dedicated to digitalization and virtual reconstruction. These processes aim to obtain reliable assets to set the subsequent auralization processes and develop multisensory 3D models, reliable and performing both in terms of graphic rendering and virtual use and in terms of acoustics.

Figure 1 – The three case studies of the AURA project and its partnership

2. AIMS AND METHODS
The paper aims to show three different approaches to the issue of morphological/dimensional survey of theater halls, each aimed at creating a 3D model to support the processes of auralization and immersive virtualization.

The methodology started with the dimensional accuracy of digital surveys conducted by TLS instruments for the subsequent 3D modeling processes. Simultaneously, the construction elements present in the various rooms were identified and subdivided semantically and materially. Based on this classification, an investigation was carried out on the values of the acoustic parameters of the respective

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materials present, in order to create a parametric and codified acoustic database to support the subsequent auralization procedures. The latter and all other virtualization operations have been developed by exploiting the multiple potentialities offered by the game-engine software *Unity*. This platform allows, through specific plug-ins, both the interaction between a variety of textured and untextured 3D models to simulate and optimize the *ArchViz* of environments, and their auralization through the setting of music sources and sound materials associated with the values of the acoustic parameters investigated and the respective surfaces of the imported 3D models.

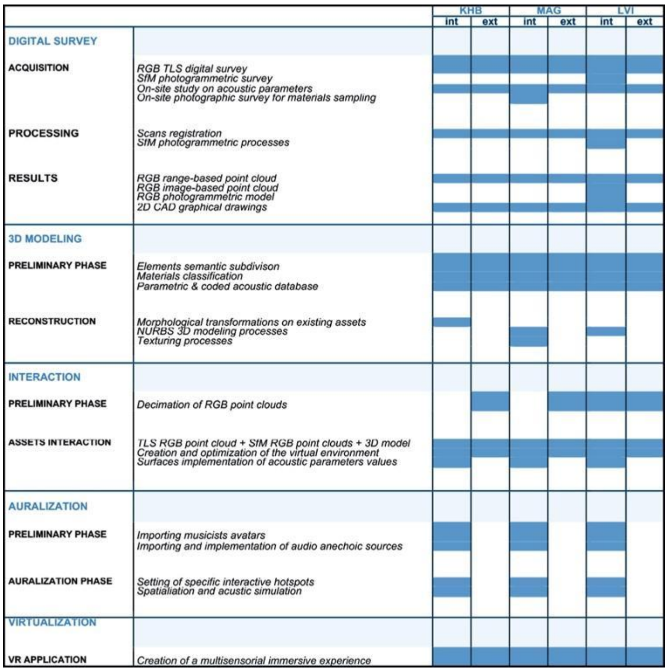

Figure 2 – Methodological worfklow

3. FROM DIGITAL SURVEYS TO 3D MODELING

What follows is a brief summary of the digital survey process to develop the 3D models of the case studies.

3.1 The Konzerthaus in Berlin

The Konzerthaus in Berlin is a neoclassical-style building initially built to a design by the architect Karl Friederich Schinkel, destroyed by bombing during the Second World War and rebuilt and reopened only in 1984 as a concert hall [6].

The documentation activities started in September 2021 with the digital survey of the Gendarmenmarkt square, the foyer, the main hall using a *Z+F 5016* instrument, and the stairwells and side rooms using a *Faro Focus M70*, acquiring a total of about 500 color scans. The research team used the *Leica Cyclone 2020* software to process the large amount of data obtained from the laser-scanner survey campaign and verify the reliability of the alignment of the point clouds. The portion of the three-dimensional point cloud relating to the main room was unified, exported, decimated, and, subsequently, became the metric support for the dimensional adaptation of the 3D model.

3.2 The Lviv Opera House

The second case study is the Opera and Ballet Theater of Lviv (Ukraine). The theater was built in the city center in the late 19th century based on architect Zygmunt Gorgolewski's project. The project provided the burying of the Poltva river for constructing the new complex and thus preparing one of the first examples in Europe of reinforced concrete foundations.

The theater is Neo-Baroque style with an Italian main hall with some Art Nouveau elements and enriched by stuccos, statues, and oil paintings. The main facade is set at the end of a long tree-lined avenue that, over the years, has become the heart of the historic center, now under UNESCO protection [7].

The digital survey required two different temporal tranches. At the beginning of 2021, the first campaign acquired internal geometric data of the room, foyer, and corridors with 160 B/W scans using a laser scanner *Leica C10*, combined with SfM photogrammetric surveys to acquire the colors. At the end of 2021, the second survey campaign provided 160 RGB colored scans of the external areas and the internal environments with a *Faro Focus M70*. The acquired data required the same processing previously described to develop point clouds at different metric and graphic detail levels.

3.3 The Teatro del Maggio Musicale Fiorentino

The third case study is the Teatro del Maggio Musicale Fiorentino, designed by the architect Paolo Desideri of the ABDR studio and opened in December 2011. The building represents one of the most relevant contemporary design interventions in the Florentine architectural scene. Inside there are three large theatrical venues: a recently opened auditorium, an outdoor *cavea*, and the main hall of the opera house, enclosed within a stereometric volume in the shape of an “iron of horse” [8].

The digital survey campaign of the complex was carried out in the first months of 2021, acquiring geometric and chromatic data using two different TLSs, respectively, obtaining a total of 180 colored scans with a *Z+F 5016* and 120 B/W scans with a *Faro Focus M70*. These then underwent the same processing process described above. The global point cloud obtained became in this way the metric basis for the main room's graphic rendering and 3D modeling phases.

Figure 3 – Berlin Konzerthaus’s main hall point cloud

4. FROM 3D MODELING TO VIRTUALIZATION FOR AURALIZATION

The 3D modeling phase of the three case studies is presented following the digital survey activities. The morphological assets on which to set the three main halls' subsequent auralization and virtualization processes were elaborated.

To exemplify this operational workflow common to the three cases, a specific methodological aspect addressed during this research experience is presented below.

4.1 The Konzerthaus in Berlin

As a partner in the AURA project, the Konzerthaus institution made available for this case study a textured 3D model of the main hall previously prepared for another project. However, as a result of specific morphological analyses conducted on the digital survey results, it turned out that this model did not metrically reflect the real dimensional aspects of the environment, making some morphological modifications based on the more reliable point cloud indeed necessary.

The hall model was thus resized through specific morphological transformation operations and referred to the coordinate system set for the global point cloud so that it could be integrated within the environmental context of the square. Next, as we will see for the other cases, a semantic classification of the elements in the main hall was developed. Each surface of these was assigned and coded with a different virtual material in order to facilitate the association of the respective acoustic values necessary for the development of the subsequent auralization processes.

4.2 The Lviv Opera House

The descriptive and geometrically more defined B/W point cloud of the hall was thus exploited to create an untextured NURBS model of the theater environment, which also featured the semantic and textural subdivisions necessary for auralization.

The texture obtained from the room's photogrammetric processes was exploited to associate the color data with these surfaces. The photographs were initially aligned within the *Agisoft Metashape* software, thus obtaining a scattered point cloud that was subsequently densified using specific algorithms and referenced with points homologous to that developed by the TLS survey. Finally, the previously realized model was imported as a mesh, which, sharing both morphology and spatial coordinates with the dense cloud, was mapped using the textures of the photographic data used for photogrammetry.

In this way, for the immersive virtualization project of the main hall, it was possible to experiment with the interaction between two different assets, inserting within the same *Unity* virtual environment - and according to the same coordinates - both the 3D model equipped with separate surfaces that can be associated with the acoustic parameters of each material, and the textured model, which is visually more faithful. The two 3D assets, overlaid with each other and made the former invisible during the VR experience, thus ensuring both the environmental acoustic simulation developed by the auralization of the 3D model and the realistic graphical rendering of the theater complex.

4.3 The Teatro del Maggio Musicale Fiorentino

As with the other case studies, three-dimensional processing was conducted within *Rhinoceros* software, using which, exploiting the potential of NURBS modeling, the 3D model of the main hall and its elements was created, based on 2D elaborates developed from range-based data and, for some complex geometries, directly on portions of the decimated point cloud. As set forth above, the modeling operations were conducted by referring to a semantic and textural subdivision of the architectural components present, categorizing them into typological categories and associating coded virtual materials.

From this point of view, in addition to the modeling of the architectural elements of the hall, the modeling of the acoustic reflector systems, such as *scattering* panels or acoustic curtains, and the furnishing elements, such as seats, whose wide presence (more than 1700) is highly relevant in the acoustic study of the hall, and consequently, in the auralization processes, was considered of great importance.

Finally, before proceeding to the latter and immersive virtualization on *Unity*, photographic campaigns were conducted aimed at sampling the actual materials in the room, for each of which a photorealistic texture was created to map all the surfaces of the 3D model, optimizing their graphical rendering for the *ArchViz*. [9].

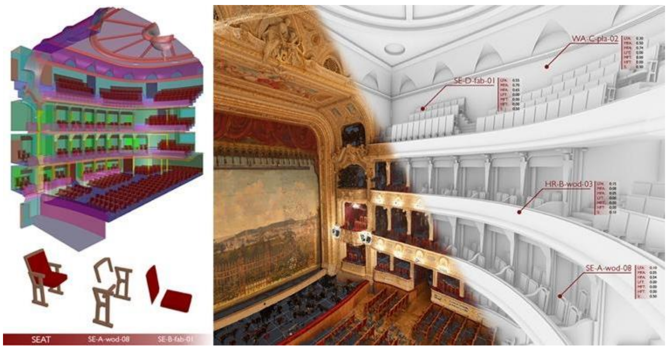

Figure 4 – 3D Modeling workflow and acoustic data enrichment for the Lviv Opera House case study

5. CONCLUSIONS

The solution proposed within the AURA project and presented in this paper for the three case studies of the Berlin Konzerthaus, Lviv Opera House and Teatro del Maggio Musicale in Florence foresees not only to develop multisensory 3D models based on reliable metric-morphological supports but mainly to create a scientific and replicable methodology of the workflow of the elements classification and virtual reconstruction aimed at auralization. The evolution of technologies in the field of investigation and protection of tangible cultural heritage has significantly increased the possibilities as new LIDAR tools and modeling and rendering methodologies combined to recreate a virtual double of the object investigated preserving and protecting its memory and image.

The project started experimenting with the possibility of collaborating specialists who can interact within virtual workspaces and immersive multimedia systems, starting to investigate the possibilities of using the data produced as valuable tools for dissemination and communication and entertainment. By integrating auralization and a reliable and realistic visual experience based on data acquired through integrated TLS digital survey and Structure from Motion (SfM) photogrammetric techniques, it is possible to investigate the mutual influence that visual and acoustic stimuli have on the perception of the virtual experience. These outputs will allow the user to experience, through Virtual Reality applications, a perceptually multisensory experience, associating an immersive visual representation with an acoustic simulation.

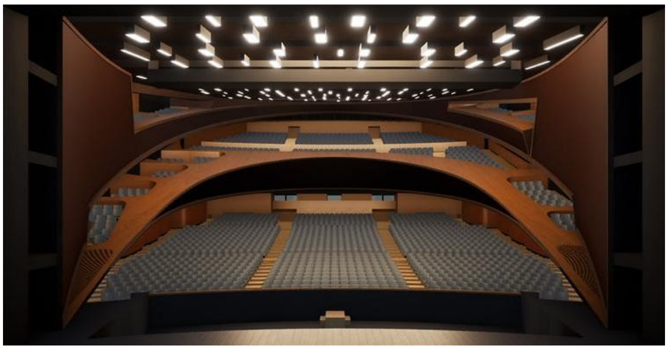

Figure 5 – Virtualization of the Teatro del Maggio Musicale Fiorentino

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Stefano Bertocci wrote the paragraphs "1 - Introduction" and "5 - Conclusions".

Andrea Lumini wrote the paragraphs "2 - Aims and methods" and "4 - From 3D modeling to virtualization for auralisation".

Federico Cioli wrote the paragraph "3 - From digital surveys to 3D modeling".

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Finally, the credits of the activities carried out by the respective technical partners of the AURA project are briefly presented.

The HTW team, coordinated by Prof. J. Sieck, was responsible for the auralization of the models and the development of apps for their virtualization and use. The team of UNIFI-DIDA, coordinated by Prof. S. Bertocci, has carried out the activities of digital survey and data processing, as well as the 3D modeling of the theaters. The UNIFI-DIEF team, coordinated by Prof. M. Carfagni, has dealt with the preparatory investigation for the auralization of the values to be assigned to the acoustic parameters. The LPNU team, coordinated by Prof. I. Savchyn, carried out the first digital survey activities, TLS and SfM, of the Lviv case study. The Konzerthaus musical institution provided the textured model of the Berlin theater.

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Challenges in open-air theatres simulation and analysis

PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

Time-frequency diffraction acoustic modeling of the Epidaurus theatre

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ABSTRACT

This work investigates the contribution of sound diffraction in the acoustics of the ancient theatres, with reference to the theatre of Epidaurus. It is increasingly evident that in such theaters, the most important elements in the acoustic field are related to sound diffraction at the edges of the tiers, especially for the distant listener positions. For computational reasons, this study is limited to a 3D model of an elementary slice of the "koilon", evaluated in the time and frequency domains. The analysis accounts for direct, reflected, diffracted and mixed reflection - diffraction paths, and calculates the theatre's acoustic response in various positions along the tiers. The model contains detailed parametrisation of the seat geometry and allows for comparisons by including or neglecting diffraction in the composite acoustic field.

The contribution of the diffracted sound to the total sound field is evaluated through the estimation of energy-based acoustic parameters and the frequency response. The differences that occur in the typical acoustic parameters by accounting for diffraction are discussed. The ascending and descending components of the sound field are also analyzed regarding their composition and contribution to the predicted speech intelligibility.

Keywords: Epidaurus theatre, diffracted sound, speech intelligibility

1. INTRODUCTION

The significance of wave diffraction for the analysis of many acoustic propagation phenomena is only recently receiving attention, one prominent case study being the acoustics of the ancient open amphitheatres [1-7]. Diffracted acoustic components in the ancient theatres is not coincidental, but in period, it appears to be a designed property. A description by only surviving relevant text by Marcus Vitruvius Pollio (approx. 70-15 B.C.) [8], states that: *"…the height of the benches and the radius of the cavea (koilon) must be designed in such a way so that the sound reaching the listeners will be harmonic and clear without any interferences.…"*. Such design principles by the ancient architects are most prominent for the Epidaurus theatre, especially for the choice of a double slope to account for the extended upper koilon, as was also illustrated by Canac [9]. The tier edge-generated diff∑raction for this theatre was analytically studied more recently by Declercq and Dekeyser [2] employing a geometric-based acoustic modelling method incorporating multiple orders of diffraction and concluded that the backscattered sound from the cavea "…*amplifies high frequencies more than low frequencies*..". However, this prediction is contradicted by in-situ measurements [10] as is also the claim that this is responsible for the theatre's exceptional speech intelligibility. However, [2] introduced an important geometric metric for the "periodicity" for each amphitheatre's properties as a predictor for the 2nd order diffraction contribution to the spectral response. Farnetali et al. [6,7] studied open theatre reflection-diffraction effects with measurements both in-situ and in scale models. Additional effects from the ground floor and cavea tier steps specular reflections and edge diffraction were also studied in [9,10,11]. The significance of modelling diffraction paths during simulations of the acoustics of the ancient theatres was demonstrated by Economou and Charalambous [1], whilst Kaleris et. al. [5] also examined diffraction effects on a detailed 2D section of the theatre profile following a precise calibration of the simulation parameters to measured impulse responses. Such approach allowed categorization of specular reflections, edge diffraction and their combinations, considered also an "ascending" or "descending direction" along the cavea. It was found that the significant diffracted sound field has non-negligible impact on the theatre's acoustics by enhancing low-mid frequency energy (as opposed to the Declerq work [2]) and increasing speech intelligibility. Subsequent work by Menounou et. al. [3,4] provided a method for predicting and identifying propagation paths and elaborated on the concept of reflective and diffractive paths for the Epidaurus geometry. This analytic solution in frequency and/or time domain thereafter referred to as the Diffraction Kernel [4].

Even though diffraction-related simulations are recently becoming feasible via available software, e.g. [12, 13], complex 3D geometries such as a complete model of an ancient theatre entail heavy computational load, especially for higher order diffraction paths. Here,

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to assist implementation of efficient filter-like representations of diffraction propagation, the above analytic Diffraction Kernel (DF) is incorporated into the study of Epidaurus theatre acoustics focusing on the detailed evaluation of such reflection / diffraction effects in the receiver position. A precise matching of the measured theatre's time and frequency responses to the simulated responses is achieved, allowing for the first time the detailed examination for the relative contribution of reflective and diffracted components on the response and spectral profile. The proposed simplified diffraction kernel model provides an efficient linear filter platform to simulate and evaluate spatial acoustic properties, allowing also binaural representation for such soundfield components.

2. THE AMPHITHEATRE'S SOUND FIELD

2.1 Time and frequency response analysis

From past work [5, 7, 9-11] it is evident that the sound
field of open-air amphitheatres is generated via the combination of different reflection, diffraction and propagation mechanisms. Here, with the aid of the theatre's computer model (see Section 3) such mechanisms can be visualized and for simplicity are categorized in 3 classes, as:

a) **direct (*δ*) and early reflected paths (*r*)** formed from different order reflections (Fig.1(a))
b) **diffracted paths (*d*)** originating from the source. As can be seen in Fig. 1(b), due to the double slope of Epidaurus' koilon, diffraction paths are generated via 2 upwards moving mechanism (purple line): one from the lower diazoma tiers and one from the upper diazoma tiers, just below the listener. Additionally, there are downwards moving diffractions (yellow line), generated by tiers above the listener. For the more distant listener positions, such paths are fewer.
c) **reflected and diffracted paths (*rd*)** originating from reflection in the orchestra (Fig. 1 (c)) and upwards moving diffractions from lower and upper diazoma tiers (cyan line) and downwards moving diffractions from the tiers above the listener (orange line). These latter paths arrive at later instances (e.g. beyond 100msecs) and having low amplitudes will not be considered further in this analysis.

To express these linear combinations of the individual components in the time-domain soundfield s, in a simplified fashion we can write:

$$s \approx \delta + r + d + rd \qquad (1)$$

and for a direct signal $s(t) = \delta(t)$ implying a time shift that places $s(t)$ at t=0, the general form of the impulse response received at any position of the koilon, based on the mechanisms of eq(1), will be:

$$h(t) = \delta(t) + \sum_{r=1}^{N_r} A_r\, h_r(t-\tau_r) + \sum_{d=1}^{N_d} A_d\, h_d(t-\tau_d) + \sum_{rd=1}^{N_{rd}} A_{rd}(h_r * h_d)(t-\tau_{rd}) \qquad (2)$$

where $h_r(t)$ is the response of the reflective surface material, τ_r is the time delay of the reflection relative to the direct signal and A_r is the amplitude attenuation due to the propagation distance, i.e.: $A_r = \frac{r_0}{r_0 + c\tau_r}$ with $c = 343m/s$ being the the speed of sound in air and r_0 the distance between source and receiver for the specific path. Similarly, $A_d = \frac{r_0}{r_0 + c\tau_d}$ is the amplitude attenuation of each contributing edge diffraction source due to its propagation and τ_d is diffracted signal's propagation time.

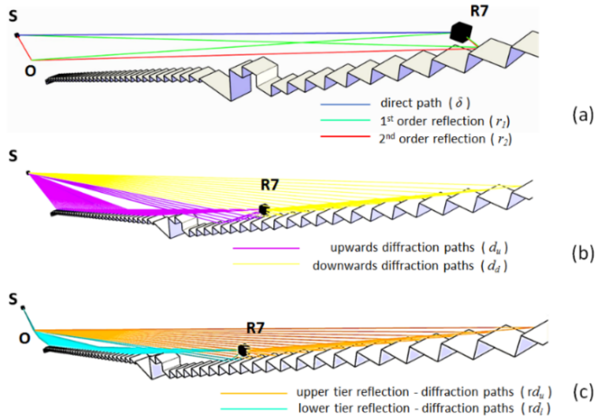

Figure 1–simulations of three acoustic path classes for the Epidaurus soundfield between source (S) located at the orchestra (O) centre and receiver (R7 as defined in [5,10]): (a) direct and early reflections, (b) only diffractions, (c) reflection and diffractions

The simulations indicate the significant contribution from diffractions following the reflection from the orchestra. These composite reflected – diffracted paths are described by the last term of eq. (1), with the amplitude attenuation and time constants A_{rd} and τ_{rd} respectively, while their temporal profile can be described by the convolution of the reflection and diffraction kernels, i.e: $h_{rd}(t) = h_r(t) * h_d(t)$. In this analysis, diffusion effects, either due to discrete reflections or due to the late reverberation tail, as well as ambient noise will not be cosnidered. In practice, the direct path component will diversify from the ideal delta function excitation, potentially exhibiting excitation Source-dependent time, frequency and directivity response. Direct Fourier Transformation of eq. (2) provides the complex Transfer Function of the path to the specific receiver:

$$H(\omega) = 1 + \sum_{r=1}^{N_r} A_r\, H_r(\omega) e^{i\omega\tau_r} + \sum_{D=1}^{N_d} A_d\, H_d(\omega) e^{i\omega\tau_d} + \sum_{rd=1}^{N_{rd}} A_{rd}\, H_d(\omega) H_r(\omega) e^{i\omega\tau_{rd}} \qquad (3)$$

where $H_r(\omega)$ is the spectral profile of the reflecting surface which depends on the acoustic characteristics of the material and $H_d(\omega)$ is the spectral profile of the diffraction kernel. It occurs that the spectra of the composite reflected-diffracted paths result from the multiplication between the reflected and the diffracted kernels' spectra.

3. MODEL IMPLEMENTATION

As can be seen in Fig.2, the theatre's model utilized both generic simulation s/w [12] as well as custom s/w for modeling the theatre's soundfield [13]. Generic s/w was mostly used for setting up the 3D geometry (a full-scale model implemented via OTL), studying and identifying transmission paths (eq. 2) and their corresponding attenuation parameters.

The path parameters were fed into custom MATLAB [14] code that numerically evaluates the combined response (eq. (1)) using also the diffraction kernel proposed in [3,4].

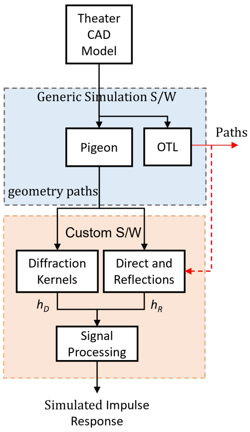

Figure 2 – approach for simulation of the theatre's soundfield

4. RESULTS

4.1 Time domain model and soundfield analysis

The model's output follows computer evaluation of the theatre's impulse response (see eq. (1)) for the appropriate listener position, assuming an omni(directional) source at the centre of the orchestra. As was shown in [5], the model geometrical parameters were fine-tuned in order to match the actual response measurements made in -situ [10]. Here, a comparison between model predictions and actual measurements are shown for position R7 as shown in Fig.3

The model appears to predict very accurately the theatre's early IR, noting that higher order reflection, diffraction and their combinations, along with diffusion and noise were not considered. Given that the model predicts accurate the composite theatre's IR, it is now feasible to separate, trace and examine separately the contributions of the individual mechanism described in Section 2.1.

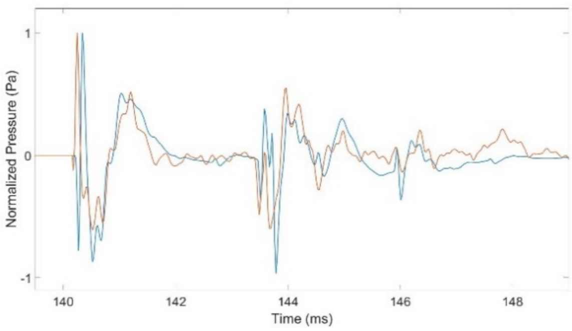

Figure 3 – comparison between model IR simulation and actual IR measurement for position R7 (first 50msec)

Figure 4 shows such a model-derived IR decomposition, noting also that the direct path has been component has been represented by the source actual pseudo-anechoic IR as was used during the in-situ measurement.

The analysis clearly illustrates that accumulated diffraction energy arrives from the lower tiers immediately

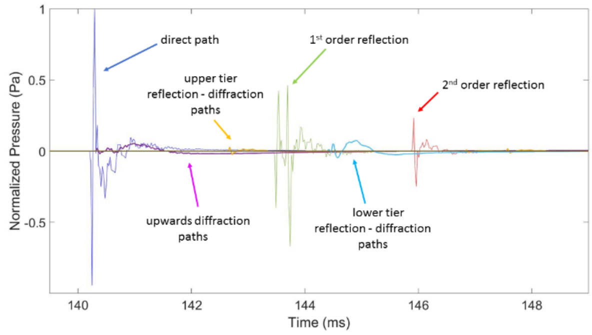

Figure 4 – decomposition of the model IR into separate soundfield components (first 50msec)

after the direct signal. Similarly, significant diffraction path energy is generated also from the reflection on the orchestra floor, arriving within 6mesec after the direct signal. Such contribution is stronger for the more distant positions in the upper diazoma and as was found in [5] to increase the early IR level and improve speech intelligibility.

4.2 Frequency domain model and soundfield analysis

From the estimated IRs, the spectra were extracted and a typical (1/12 octave smoothed) version is compared to the in-situ measured spectrum as is shown in Fig.5.

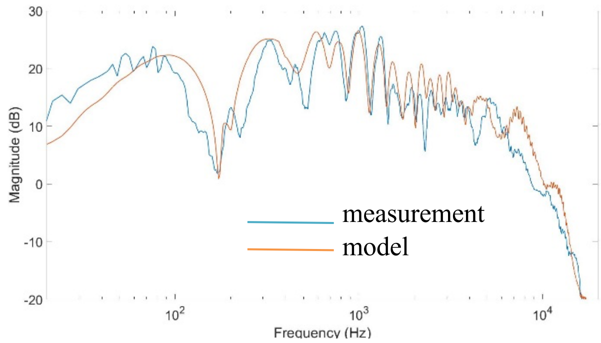

Figure 5 – comparison between model response spectrum and actual measurement for position R7

It is clear that the model provides sufficiently accurate estimation of the theatre's spectral response and thus it is feasible to expand the modeled spectrum into the individual components according to eq. (3), as is shown by Fig 6. Here it is shown that the diffracted paths enhance spectral content in the low and mid frequency range, hence improving SNR at this range and the speech intelligibility.

4.3 Speech intelligibility

Table 1 shows the Speech Transmission Index (STI) for four different source levels and assuming a NR-35 ambient noise profile, calculated from the simulated impulse responses at position R7. Here, STI is evaluated considering different components of the impulse response, **i.e.**: $\delta+r$, $\delta+r+d$ and $\delta+r+d+rd$, **(**see eq. (1)**).** The diffractions both from the direct and the reflections were found to increase STI especially for weak source levels.

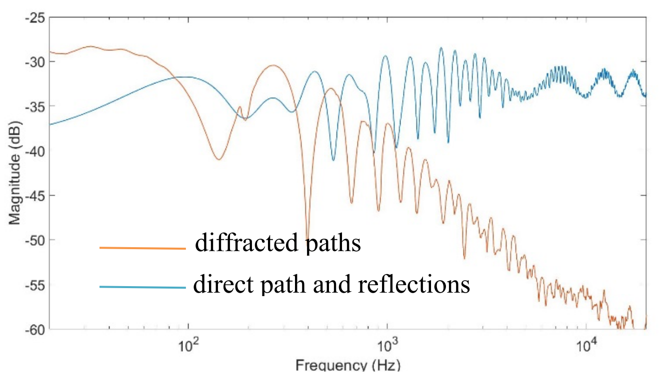

Figure 6 – decomposition of the model spectral response into separate soundfield components

Table 1 – STI for different source levels and for the different propagation mechanisms

	δ+r	δ+r+d	δ+r+d+rd
86 dB	0.999	1	1
70 dB	0.933	0.946	0.949
65 dB	0.805	0.825	0.836
60 dB	0.644	0.666	0.674

5. CONCLUSIONS

Following an ellaborate analysis appoach of the different sound propagation mechanisms in the Epidaurus theatre, a detailed study of the properties and contribution of the direct, reflected, diffracted paths, along with their combinations has been presented. The analyis is based on a simulation model derived from precise calibration of its parameters to in-situ measured impulse responses. Such a controlled simulation platform allows for precise matching of the estimated response both in time and spectracl domain to the measurements, as well as categorisation of specular reflections, edge diffraction and their combinations, along with the direction of arrival to the receiver (considered here as following an ascending or descending direction).

This analysis reveals a more detailed diffraction mechanism which here due to lack of space was discussed specifically for one receiver position in the middle of the second cavea (R7). As was shown, for the upper cavea (koilon) which has a steeper slope than the lower cavea section, the direct signal generates edge diffraction components from the rows just below the listener which arrive nearly simultaneously with the direct signal. The orchestra floor reflection also generates diffracted components, but in this case, these are produced from the rows of the lower cavea section. All these upwards moving signals arrive at close instances after the direct signal leading to an increase in the level of the total signal that significantly contributes to the speech intelligibility, especially given the reduction of the level of the direct signal at such distance. An additional second order diffraction mechanism appears to be formed by the back of each seating row which, although arriving nearly simultaneously with the previous components, increases the overall early signal level. Here it was verified that the total theatre response is composed from significant diffracted sound field component. The edge diffraction spreads and increases the early time response and contributes to the low-mid frequency energy of the overall spectral response of the theatre, a result that questions the findings in [2]. Such contribution in the low-mid frequency range appears to increase the speech intelligibility, especially for the distant listener positions and for weaker source signals.

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Theoretical investigation of diffraction phenomena in the ancient theatre of Epidaurus

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ABSTRACT

The effect of edge diffraction in ancient theatres is investigated. A cross section of the theater of Epidaurus simplified as right-angled steps is considered. A recently presented solution for computing the impulse response around a rigid wedge is employed for the theoretical study of diffraction by the edges of the steps. It is shown that diffracted signals coming from edges below a listener come close together and with relative small amplitude. Diffracted signals from edges above the listener come further apart, some with very large amplitude and almost all with negative polarity. A new parameter is proposed that predicts the effect of edge diffraction based solely on geometrical characteristics. It is shown that the height of the source and the inclination of the steps affect the diffraction contributions the most. The effect of the various diffraction contributions to acoustic indices is considered next. For the computation of the acoustic indices the relative strength between geometrical and diffraction contributions, which are different in nature, must be determined. In the present work this is done via the unit step responses. Upper diffractions affect negatively the acoustic indices, considerably more than lower diffractions.A source positioned at the height of a deus ex machina improves the acoustic indices compared to a source at the height of a standing actor.Large inclination angles of the steps affect negatively the acoustic indices. Finally, results including the effect of all geometrical and all diffraction contributions are compared with published measured data for the theater of Epidaurus.

Keywords: Edge diffraction

1. INTRODUCTION

The effect of sound diffraction on the acoustics of ancient theatres is investigated. Consider a cross section of the ancient theatre, a point source at the centre of the orchestra and a listener seated at an arbitrary seat row as shown in Fig.1. Sound emitted from the source reflects on the orchestra and on the surfaces of the steps, diffracts on the edges of the steps or follows a combination of reflections and diffractions until it reaches the listener. The subject of the current work is the diffraction caused by the edges of the steps.

The aim of the present work is not to present a new prediction method for the acoustic field. Many commercial, as well as in-house predictions tools are available (for example ODEON, CATT, OliveTree Lab). The present work focuses on analyzing the diffraction phenomenon and the signals it causes. In the first part of the work the impulse responses of the diffracted contributions are analyzed, while in the second part the effect of diffraction on acoustics indices is investigated. For the first two parts of the work only the incident signal and the diffracted signals caused by it are considered, while the geometry is a simplified step geometry, i.e. without the diazoma separating the lower from the upper koilon, and without taking into account the different inclination angles in the upper and lower koilon (see Fig. 1). Finally, in the last section, all geometrical (direct signal/reflections) and al diffraction contributions are considered for the cross section of the theatre or Epidaurus (including the diazoma and the different inclination angles).

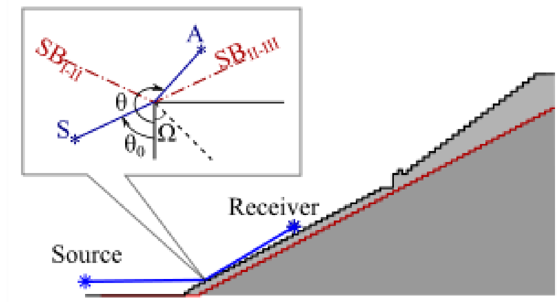

Figure 1 – Cross section of the theatre of Epidaurus (black line), of a simplified step geometry (red line). A source-wedge-receiver configuration is demonstrated in the inlet.

A previous work by Farnetani et. al. [1] also investigated the diffracted signals by employing a different edge solution. The primary concern was the application and validation of the edge solution for configurations of ancient theatres. The present work goes further into the investigation of diffracted signals, presenting new parameters that can describe diffraction based

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solely on geometrical characteristics, and identifying the geometrical parameters that play an important role. Furthermore, unlike the previous work, the effect on acoustic indices is investigated in the present work. For this to be accomplished, the total impulse response must be considered and the relative strength of diffracted and geometrical acoustics contributions must be determined.

2. DIFFRACTION CONTRIBUTIONS

Consider a wedge of angle $2\Omega = 90^{\circ}$, a point source S and a receiver A around the wedge. For the theoretical study of diffraction an approximate solution is considered that provides the impulse response at A [2]

$$p_{irf}(A) = -\frac{1}{4\pi}\frac{1}{\sqrt{rr_0}}\frac{2}{\sqrt{t^2-t_d^2}}\sqrt{2}\gamma\sqrt{\frac{t}{t_d}+1}\cdot\gamma\bar{t}\Phi_{\pm}\cdot$$
$$\cdot\left(1/\left(2(t-t_d)\left(\bar{t}\gamma^2-\cot\left(\frac{\pi}{\gamma}\right)\gamma\bar{t}\Phi_{\pm}\right)+(\gamma\bar{t})^2\Phi_{\pm}^2\right)\right), \quad (1)$$
$$\Phi_{\pm} = \gamma\left(\cos\left(\frac{\theta\pm\theta_0}{\gamma}\right)-\cos\left(\frac{\pi}{\gamma}\right)\right)/\sin\left(\frac{\pi}{\gamma}\right), \bar{t} = \frac{rr_0}{Lc}$$

where (r_0, θ_0) and (r, θ) are the coordinates of source and receiver respectively, (see Fig. 1), Ω is the half angle of the wedge, $L = r_0 + r$ the path the sound travels from the source to the receiver after undergoing diffraction on the edge of the wedge, and $t_d = L/c$ *(arrival time)* the time the diffracted signal arrives at the receiver. Finally, it is noted that for wedges with angle $2\Omega = 135^{\circ}$ the diffracted signal is identically zero. As a result, in our geometry only the wedges with $2\Omega = 90^{\circ}$ produce diffracted signals.

The area around the wedge is separated into three regions by two shadow boundaries SB_{I-II} and SB_{II-III} (see dashed lines in Fig.1). The diffracted signal obtains its largest values close to the shadow boundaries. Also, at the shadow boundaries the diffracted signal undergoes a change of polarity (a positive signal on one side of the shadow boundary becomes negative).

Consider the cross section of the simplified step geometry, a point source at the centre of the orchestra 1.5m above the ground and a listener seated at an arbitrary seat row0.2mfrom the outer edge of the seat and 0.8mabove the seat. Consider that there are no reflections on the surfaces of the theatre. The impulse response at the listener is the summation of the incident signal coming directly from the source and of all the diffracted signals coming from each one of the diffracting edges. Figure 2 shows the diffracted signals from all edges at the listener location. Blue coloured pulses correspond to diffracted signals coming from edges lower than the listener (*lower diffracted signals*), while red coloured pulses correspond to diffracted signals coming from edges higher than the listener (*upper diffracted signals*).

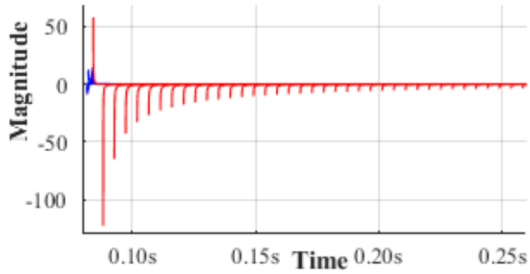

Figure 2 – Diffracted signals arriving at a listener at the 20th step.

3. CHARACTERISTICS OF DIFFRACTED SIGNALS

In this section the characteristics of the diffracted signals are discussed. Lower diffracted signals arrive close together and with relatively small amplitude. Upper diffracted signals arrive further apart, some with very large amplitude and almost all with negative polarity (see Fig.2).

Figure 3(left) shows the arrival times of the diffracted signals. For edges that are higher than the listener the arrival times increase significantly the further above the orchestra the diffracted edge is located (red marks). For edges that are lower than the listener the arrival times remain roughly the same (blue marks). Accordingly, the lower diffracted signals come close in time, while upper diffracted signals come further apart,(being almost resolved in time). Furthermore, the arrival time for some of the lower diffractions seems to be the same with some of the upper diffractions. This explains the partial overlapping of lower and upper diffracted signals in Fig. 2. A final observation can also be made. For the upper diffracted signals, the arrival rime increases linearly. As e result, the first upper signal comes from the edge that is immediately above the listener. The corresponding change for lower diffracted signal is not linear. As a result, the first lower diffracted signal comes from a few steps below the listener.

Figure 3(right) depicts a *polarity plot*, derived directly from Eq. (1) for $\Omega = 45^{\circ}$, that shows the polarity of the diffracted signal as a function of the angular position of source and receiver for each diffraction problem. The red marks correspond to upper diffracted signals, the blue marks to lower diffracted signals. Marks in the yellow areas indicate signals of negative polarity. Marks in the green areas indicate positive diffracted signals. The straight diagonal lines correspond to the shadow boundaries. Marks close to the shadow boundaries indicate diffracted signals with large amplitude. Marks close to the curved line indicate signals with small pulse amplitude.

Finally, it is emphasized that the time evolution of the diffracted signals is quite different from that of geometrical acoustics contributions. The latter are described mathematically as Dirac functions, while the former have an infinitely large amplitude at the arrival time and a long lasting time decay.

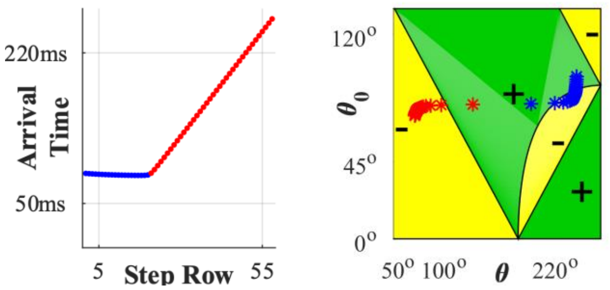

Figure 3 – Time arrivals (left) and polarity (right) of the diffracted signals shown in Fig.2

4. A NEW PREDICTION QUANTITY

Based on Eq. (1) a new quantity is proposed to predict the amplitude and polarity of the diffracted signals based solely on geometrical parameters:

$$M = -\left(\Phi_{+}^{-1} + \Phi_{-}^{-1}\right) / \sqrt{r \cdot r_0} \qquad (2)$$

The parameter M is computed for the case considered in Fig.2. The parameter M for each diffracting edge (each step) is presented versus the arrival time that corresponds to such step (see Fig.3). The combined parameter $M(t_d)$ (shown in Fig.4) correlates very well with the diffracted signals shown in Fig.2.

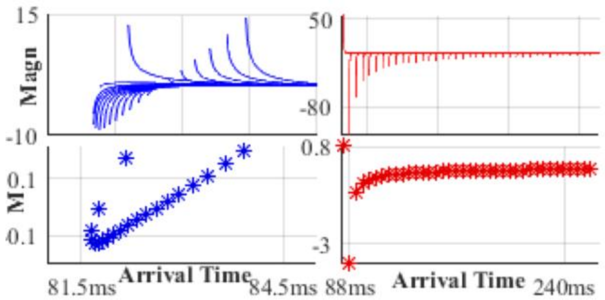

Figure 4 – The parameter M correlates well with the lower and upper diffractions shown in Fig 2.

5. EFFECT OF GEOMETRICAL PARAMETERS

The quantity $M(t_d)$ shows that the effect of diffraction can be almost completely analyzed based on the geometrical characteristics. In this section, changes in the geometry of the source-edge-receiver configuration are considered.

Changing the step on which the listener is seated, does not change the characteristics of the diffracted signals.

Changes in the location of the receiver on a given step (for example, moving the receiver closer or away from the back of the seat) do not affect the diffracted signals.

Changes in the height of the source can affect the diffracted signals considerably. Figure 5 shows the diffracted signals that arrive at a listener at the 20th step for two different source heights: 7.5m and 15m. As the source height increases, the lower diffracted signals arrive more resolved in time, they overlap more with the upper diffracted signals and they obtain larger amplitudes. Indeed, the arrival times for the different source heights are shown in Fig. 6(left), where the effect, particularly on the lower diffracted signals, can be observed. The larger amplitude of the lower diffracted signals shown in Fig. 5 compared to those shown in Fig. 2 is attributed to the different location of the shadow boundary as the source height increases. Figure 6(right) shows the shadow boundaries (dashed lines) of the diffraction contribution originating from the 8th step that reaches the listener at the 20th step. As the source height increases, the shadow boundary SB_{II-III} at the 8th step changes its angular location. The receiver at the 20th step is closer to the shadow boundary. Accordingly, the diffracted pulse has larger amplitude.

Changes in the inclination of the steps can also affect the diffracted signal. The higher the inclination angle, the later the diffraction contributions arrive.

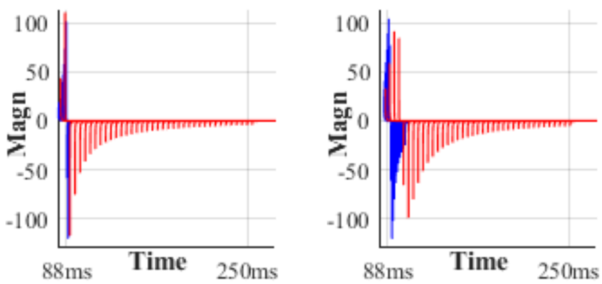

Figure 5 – Diffracted signals arriving at a licenser at the 20th step for two different source heights: 7.5m (left) and 15m (right) above the orchestra.

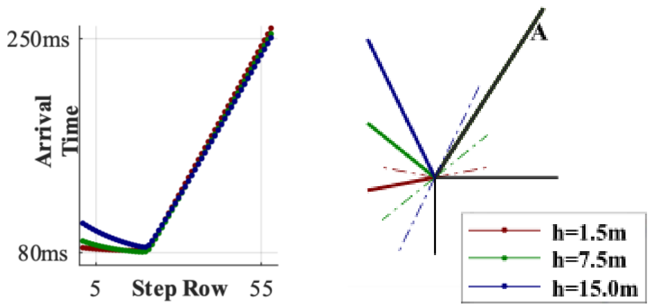

Figure 6 – (left): Time arrivals of the diffracted signals at a listener at the 20th step for three different source heights; (right): shadow boundaries of the diffraction contribution at the same listener originating from the 8thstep.

6. EFFECT ON ACOUSTICS INDICES

In the present section the effect of diffraction is expressed in terms of acoustic parameters/indices. Specifically, the echo criterion (TS)

$$TS_{speech} = \left(\int_0^{\tau} t \cdot |p(t)|^{2/3} \, dt \right) / \left(\int_0^{\tau} |p(t)|^{2/3} \, dt \right) \qquad (3)$$

is considered, where $p(t)$ is the impulse response at the listener and smaller values of TS are acoustically preferable. In the following, improvement of the acoustic index will mean decrease of its value. It is emphasized that the values of TS presented are a mere indication of the general trend.

An important observation before presenting the results is merited. Because of the different nature of geometrical acoustics contributions and diffraction contributions, their relative strength in the total impulse response cannot be determined. The corresponding unit step responses must be used instead. The diffraction solution employed here [Eq. (1)], unlike other solutions, is integrable with time and the unit step response can be obtained analytically.

Figure 7 shows the relative importance of the various contributions (incident signal, lower diffractions, and upper diffractions) expressed in terms of TS for all steps. It can be observed that diffraction contributions deteriorate the acoustic index: the lower diffractions by little, the upper diffractions considerably. Also, diffraction seems to homogenize the acoustic index among the different steps.

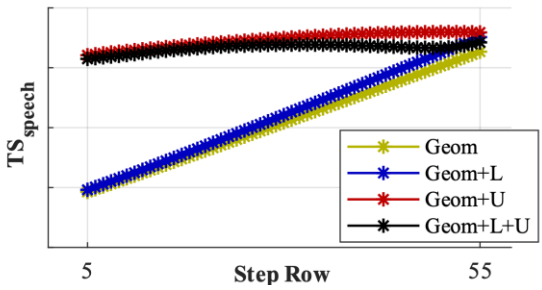

Figure 7 – The effect of lower and upper diffractions in the value of TS at all steps.

Figure 8 shows the effect of the source height and of the inclination angle (discussed in the previous section) on TS. Compare two source heights [Fig.8(left)]:1.5m corresponding to a standing actor (red) and 7.5 m corresponding roughly to a deus ex machine (green). The source at the deus ex machine height offers a better acoustic index. On the right side of Figure 8, the effect of the inclination angle is presented. Three inclination angles are considered, 24°, 30° and 45°(creating cross sections that roughly correspond to the theater of Epidaurus (black), of Aosta (red) and of a Mayan theater (green), respectively).The acoustic index is better for small inclination angles and worse for large inclination angles.

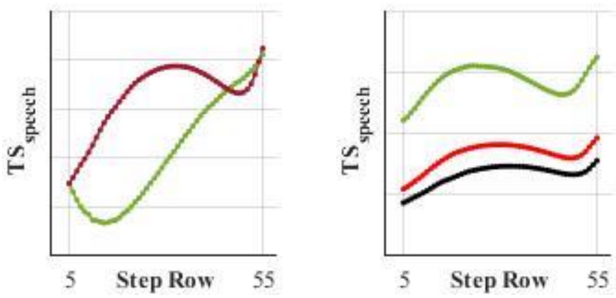

Figure 8 – Effect of source height (left) and inclination angle (right) in the value of TS at all steps.

7. SOUND FIELD AND ACOUSTIC PARAMETERS

The preceding analysis describes the diffraction contributions originating from the incident signal. Similarly, sound after reflecting on the orchestra reaches the edges of each step and produces a similar pattern of diffracted signals. Geometrical acoustic contributions coming after reflections on the seats and on the back of the seats also produce diffracted signals. Figure 9 shows all geometrical contributions and all diffracted signals generated by each one of the geometrical acoustics contributions for listeners at step 5 and step 29 in the theatre of Epidaurus (see Fig. 1). In the inlet the comparison of the clarity index C_{80} computed by in-situ measurements (taken from Ref. [3]) and by the analytical impulse responses is reported.

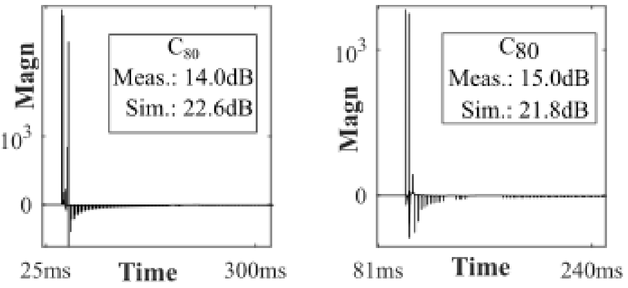

Figure 9 – Impulse response containing all geometrical and diffraction contributions at step 5 (left) and 29 (right) of the theatre in Epidaurus.

8. SUMMARY

The effect of edge diffraction in ancient theatres is investigated. The diffraction contributions depend mainly on geometrical characteristics: the length between source-edge-listener, and the proximity of the listener to the shadow boundary. A new quantity is derived to describe this dependence. Regarding the diffracted signals: diffracted signals coming from edges below a listener (lower diffractions) come close together and with relative small amplitude; diffracted signals from edges above the listener (upper diffractions) come further apart, some with very large amplitude and almost all with negative polarity. Regarding the acoustic indices: upper diffractions affect negatively the acoustic indices, considerably more than lower diffractions; a source positioned at the height of a deus ex machina improves the acoustic indices compared to a source at the height of a standing actor; and large inclination angles of the steps affect negatively the acoustic indices.

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Revisiting archaeoacoustic methodology in the studies of acoustic vessels:application to Brittany and Serbia

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ABSTRACT

Ceramic vessels are found embedded in the walls of sacred edifices, built from the medieval to modern period across Europe and the Mediterranean. To better understand the acoustical, building, and religious ideas underneath this practice, the research results need to be mutually comparable. Therefore, this paper suggests a compliant approach that would enable such comparisons. Almost two decades of fieldwork experience led us to define the archaeoacoustic research methodology of acoustic vessels that includes: (1) data collection, (2) data analysis, and (3) a "multi-channeled" dialogue among scientific disciplines. These three phases mainly, but not exclusively, consider the fields of history of religion, archaeology, history of art and architecture, acoustics, and musicology. We draw upon the previously defined methodological requirements, that ensure avoiding anachronism and misinterpretation, and then translate them into practice. We tested the methodology on several case studies from two distinct regions in Europe - Catholic churches in Brittany (France, 15-17th c.) and Orthodox churches in Serbia (9-15th c.). Our findings showed that the proposed methodology is particularly important for results comparisons regarding archaeology and acoustics, while the results originating in the field of musicology, religion, and history of art and architecture could be comparable within culturally similar regions.

Keywords: archaeoacoustics, acoustic vessels, church architecture

1. INTRODUCTION

We recently presented our general approach to archaeoacoustic facts, limited to the societies with written record, based on two main principles: 1) to avoid any anachronism by contextualising as much as possible, and 2) to start from low-level hypotheses even if these may seem illusory today [1]. Analytical grid created this way was then, as we emphasize in this article, used in relation to our multidisciplinary research on ceramic acoustic vessels.

Within the framework of a Franco-Serbian research programme, we tested the methodology in two distant regions of Europe - Brittany and Serbia. For the comparison to be effective, it was necessary to develop a common methodology for the historical, archaeological, and anthropological aspect of this acoustic practice in building churches. Our research also included data collecting - geometric and acoustic measurements of both the vessels and the churches. Due to the pandemic, the last part of the program - acoustic measurement campaign in Serbia – could not be carried out yet. Therefore, in this article we focus on the French part of the study and limit the comparison with the Serbian churches only on the aspect of vessels placement.

2. METHODOLOGY DETERMINED BY THE LARGE STUDY CONDUCTED IN FRANCE

2.1 Two main principles

The first principle of our general archaeoacoustic approach is to avoid any anachronism. Here are three main recommendations to achieve that:

- Put aside current acoustic knowledge and document the history of (practical) acoustic knowledge at the time of building
- Give priority to written sources related to the particular church (i.e. architectural treatises, mentions of trades (masons, potters), abbey chronicles, etc.) [2].
- Study the texts themselves and the evolution of the acoustic vocabulary [3].

The second principle - to start from low-level hypotheses - is reflected in the following recommendations:

- Do not try to demonstrate any a priori theory, especially if it comes from recent knowledge. Numerous studies tended to show the absorption efficiency of acoustic vessels, but this is difficult to prove because there are too few vessels and they are often tuned to frequencies. In addition, their acoustic effectiveness does not explain the acoustic intention of builders. A low-level hypothesis would be, for example, to assume that the builders had acoustic intent, or that they chose the vessels in a certain way [4].

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- Diversify the sources of hypotheses; even something that is known to be false today should not be dismissed from the analysis if there are written records about it or archaeological facts that support a bizarre interpretation. For example, the historic texts always mention the amplification of voices regarding acoustic vessels. The acousticians dismiss the idea of amplification because it is usually not effective in large volume churches in which vessels are generally inserted. However, this hypothesis could be considered in the case of the undercroft of Noyon [5].

- Carry out studies at two levels: statistical data collection and monographic studies. Monographic studies are often carried out, but they do not allow generalisation and usually provide more questions than answers. Statistical studies provide an overview and a better understanding of cultural context [4].

- Accept unexpected results. The association of, for example, iconography and the vessels or the symbolism of the vessels' distribution in walls (i.e. triangle or cross formation) imply that the acoustic aspect, in the sense in which we understand it now, was not the only concern of the builders [5].

2.2 Interpretation of acoustic vessels practice

While it is clear that the vessels are related to the acoustics, there are three possible interpretations that we call by Latin terms to simplify and summarise:

- **VOX** represents the interpretation according to which the actors seek to act on the voices whatever the presupposed acoustic intention was (absorption, amplification, modification ...). There is a considerable amount of evidence to support this interpretation.

- **LOCUS** represents the interpretation that actors seek to affect the acoustics of the building. This is a bold assumption but one that is often favoured by acousticians despite a lack of effect. However, texts and some archaeological data show that this intention was present.

- **TRANSITUS** represents the interpretation that the vessels promote a link between speech and song on earth and the afterlife. Their association with iconography, their distribution in space and some texts show that this interpretation was at work.

These three interpretations are not exclusive, and they can coexist in the same place. Sometimes, one can hardly see any more than a symbolic interpretation to explain a device in a particular church.

2.3 The choice of acoustic vessels

The choice of pottery used for the acoustic purpose is particularly important. The analysis of our entire database (over 50 churches visited, over 1100 pots measured) implied that the acoustic vessels were often chosen by their resonance frequency. We observe 4 categories that cover almost the entirety of our corpus:

Type A: unimodal set with only one model of vessel;

Type B: continuous distribution of frequency, generally over one octave;

Type C: bimodal set with two main frequencies 'tuned' in fourths or fifths;

Type D: discontinuous distribution of frequencies over one octave (or less) either in the form of a third, fourth, fifth, octave or, rarely in smaller steps (of the order of a tone).

All these characteristics offer a relevant analysis grid for comparing other corpora, even if it is important to remain open to other possible interpretations or other configurations that could occur in each territory.

3. APPLICATION TO A COMPARATIVE STUDY

This section will present cultural and historic context of acoustic vessels practice emerging in the region of Brittany and Serbia. We will particularly consider the number of embedded vessels, their position in the church and arrangement, as well as the TRANSITUS interpretation.

3.1 Acoustic vessels in Brittany

The re-emergence of acoustic vessels started in central regions of Western Europe (Rhine and Rhone valleys) in the 10th century, and it is possibly related to the Carolingian renaissance. In peripheral regions, such as Brittany - the north-west region of France, this acoustic practice emerged later. The reasons for this might lie in the very favourable economic conditions of 15-17th c. Brittany (having one of the most important fleets in Europe and strong linen trade with the northern countries), when numerous parishes rebuilt their religious buildings. It could also be related to the development of polyphony [5]. This acoustic practice undoubtedly appeared at the time as a possible solution for general sound control.

The region of Brittany contains the significant number of churches with acoustic vessels [6]. There are 53 churches in our inventory and if we add eight churches with vessels from Loire-Atlantique (North) which is part of historical Brittany, we arrive at 61 churches out of a French census of more than 200 churches [7]. The peculiarity is that most of the buildings in Brittany were built from the 15th to the 17th century with vessels inserted during building, and for the older churches, for those that we were able to visit, the vessels were inserted subsequently.

The Brittany Corpus on which we worked is 19 churches (among the 61 listed) in comparison with the French ones (50 among the 200 listed). The Brittany Corpus churches are medium in size, between 1000 to 6000 m^3, while the whole French corpus is between 200 to 14000 m^3.

The relative number of parish churches is superior in the Brittany corpus than the French corpus (table I), and the pots are mainly positioned in the nave. In the whole corpus, we have remarked that the monastic churches have more often vessels in the liturgical choir above monk or nun seats [4], as seen in figure 1.

Another interesting parameter is the mean number of vessels inbuilt per church. In the French Corpus, the mean is 23 vessels per church, while in Brittany the number reaches 31. The highest number of vessels is found in the Abbaye des Anges in Landéda with 110 vessels and Ploaré close to Douarnenez with 108 estimated vessels (96 present). The last interesting point is the number of sophisticated systems of frequency choice (C and D) regarding simple ones (A and B), which is 18/32 (0.56) in the French corpus and 8/12 (0.66) in the Brittany ones (table II).

Figure 1 – West wall of the liturgical choir of the Abbey "Couvent des Ursulines" formely "Saint-François de Cuburien", Saint-Martin des Champs (close to Morlaix), 16th century (Photo credit: B. Bertholon)

Concerning the TRANSITUS interpretation, few churches have vessels organised with Christian symbolism. We only found 3 churches which pots in triangle organisation, most of churches have linear organisation.

In Brittany we found the highly refined multi-frequency system of acoustic vessels, large number of vessels per church located all over the place with a larger grouping in the choir. The delay in the development of acoustic vessels practice in Brittany might be the reason for more rational choices of vessels than in other parts of France.

3.2 Acoustic vessels in medieval Serbian churches

The boarders of medieval Serbia changed over time occu- pying a significantly larger territory than today, particularlytowards south and south-west. In this paper, we consider only the medieval churches that are under the jurisdiction of the Serbian Orthodox Church today. Acoustic vessels are found in fifteen of those churches, approximately seven vessels per church. Medieval Serbian churches were built in three architectural styles (Raška, Byzantine, and Morava style) that are corelated with political and cultural strivings of the time. It is interesting to notice that the most of churches with acoustic vessels (7/15) were built in Raška architectural style (12th-13th c.) during the period when Serbian medieval state and Serbian Orthodox Church was formed under the Nemanjić dynasty. Acoustic vessels were not found in the churches of Byzantine style, but they appear again in Morava architectural style (14th-15th c.). In most cases, they were secondarily used for acoustic purposes and predominantly positioned under the central dome, in spherical surfaces such as pendentives and dome drum. These vessels were pots, jugs and pitchers, with the hight from 20 to 50 cm. In each church the vessels were similar in shape, embedded horizontally, with mouth or pierced bottom oriented towards the church interior space [8]. The exception is the Trg church, in which the vessels were found inbuilt vertically, upside down, behind the finishing layer of a wall in naos [9].

Churches built in medieval Serbia had small volumes – approximately from 400 to 3000 m^3, and reverberation times from 1 to 3 seconds. Consequently, the number of acoustic vessels was relatively small. In some cases, only one vessel is found in each pendentive under a central dome (Figure 2). The largest number of 20 acoustic vessels was noted in the Mileševa Monastery. The exact number and the positions of originally embedded acoustic vessels in medieval Serbian churches are difficult to determine, because the churches were partly ruined and rebuilt during the turbulent history, and walls were often repainted, sometimes covering the vessels' openings with mortar. In several cases, the vessels were extracted from the walls during recent conservation works and then stored in museums (Trg, Komarane, Davidovica) [7].

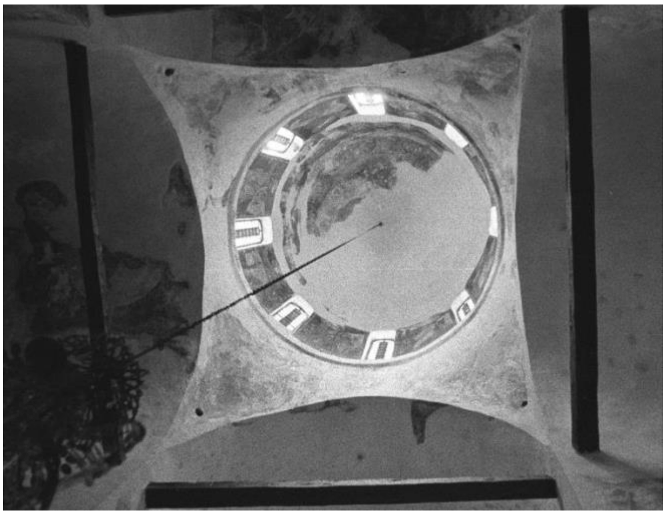

Figure 2 – central dome of Nova Pavlica monastic church (14th c.) with one acoustic vessel in each pendentive (Photo credits: Documentation of the Republic Institute for Protection of Cultural Monuments Belgrade)

In medieval Serbian church, Byzantine chanting tradition was adopted. This vocal and monophonic music has gradual melodic flow and rhythm that supports lyrics, thus providing each spoken word a quality of a song. The chanting was performed from chanting apses at northern and southern side of a central dome. It was important to ensure both the understanding of the chants and readings, and to acquire spiritual experience enhanced by chanting.

Concerning the TRANSITUS interpretation, it is worth noting that acoustic vessels were usually placed in pendentives which were also the places for the frescoes of four evangelists. Acoustic vessels could be interpreted in line with the understanding that pendentives represent a transitional element between physical (earth) and spiritual (dome, heaven) worlds.

3.3 Comparative overview

Table 1 – Location of vessels in the liturgical space

	Monastic Parish	Liturgical choir or under the central dome	In the whole church (nave)
French corpus	M	11	12
	P	4	17
Brittany corpus	M	3	2
	P	2	9
Serbian corpus	M	12	2

Table 2 – Type of organisation regarding frequency (type A, B, C, D when it's possible to classify)

Corpus	A	B	C	D
French	10	4	10	8
Brittany	2	2	4	3

4. INSTEAD OF A CONCLUSION

The object of the paper is to test the previously proposed archaeoacoustic methodology on acoustic vessels found in two distant regions in Europe – Brittany and Serbia. If we apply this methodology in numerous countries, we will be able to outline the original idea and acoustic intention of the builders, and also explain the dispersion of this acoustic practice throughout Europe.

Comparing the whole French corpus to the one of Brittany, which is far from the probable re-emerging area, we have observed similarities but also some specificities. As the development of acoustic vessels practice was late in Brittany, the builders were more skilled and sophisticated in the technique, taking advantage of the experience from the close regions. They employed larger number of vessels that also covered a wider frequency range. The vessels had better organization in the probable intention to be more efficient.

Serbian and French corpus are significantly different. Acoustic vessels are mainly found in medieval monastic churches in Serbia, while in Brittany they were employed in both monastic and parish churches. Conversely to the French corpus where the vessels were embedded in the walls, the vessels in Serbia were generally placed in the area under the central dome. From the acoustical point of view, although the Serbian churches are not very large and the reverberation time is not long, it is expected that annoying acoustic effects occur under the dome and disturb the chanting, because of focalisation or delays. The system of acoustic vessels might be devised as a solution of these effects.

The application of the proposed archaeoacoustic methodology to acoustic vessels found in Brittany and Serbia contributes to our understanding of this acoustic practice in two aspects: 1. Its application in significantly different architectural spaces, 2. Its relation to the polyphony in the Western Europe and the monophony in the Eastern Europe.

ACKNOWLEDGEMENTS

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Adapting the EST method to ancient theatres: a proposal.

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ABSTRACT

The paper investigates under which assumptions the EST method, initially developed for modelling the propagation of acoustical energy in flat spaces such as hallways and open space offices, can be adapted to unbounded spaces such as ancient theatres. It turns out that it mainly requires that the air column above any position in the open theatre contains finite acoustical energy, whatever its height. This is indeed the case since at high altitudes above the theatre, energy decreases with the square of the height due to the increasingly accurate assimilation of the theatre to a point source. In other words, one must use high enough elements, so that the intensity on the top of the elements can be considered as negligible, leading to negligible absorption and scattering on the top boundary. Therefore, one only needs considering absorption and scattering at the bottom boundary of the elements; and the integration on the elements must be revisited to account for the decrease of intensity with altitude. The corresponding bi-dimensional equations will be presented and solved for a variety of absorption and scattering coefficients on the surface of the theatre, and compared to measurements in an actual theatre. **Keywords:** energy-stress tensor, unbounded spaces, simulation.

1. INTRODUCTION

The energy-stress tensor (EST) formalism was introduced by Dujourdy *et al.* [1] to generalize the diffusion equation formalism of Ollendorf and Picaut [2, 3]. Indeed, where the diffusion equation arbitrarily introduces a gradient type relationship between sound intensity and total energy, the energy-stress tensor formalism introduces instead the conservation equation for intensity. When integrated in disproportionate enclosures, the stress-energy tensor yields both absorption and scattering on the boundaries. Dujourdy *et al.* showed that this formalism is able to simulate actual measurements in flat rooms, be they one-dimensional (hallways, [1]) or two-dimensional (open-space offices, [4]), which was later confirmed by Meacham *et al.* [5] in a hallway, taking into account source directivity. Common to all these simulations is the consideration that the vertical dimension is negligible, which is accounted for by integration on this vertical dimension while taking due consideration of the relevant boundary conditions, both on the floor and the ceiling.

The present paper intends to adapt the EST formalism to the opposite case of unbounded spaces, specifically to spaces without a ceiling, such as ancient Greek and Roman theatres. We shall show that it requires that the air column above any finite surface on the theatre contains finite sound power, an assumption that is obviously satisfied since any sound source emits finite sound power at any instant. After reviewing the background for the EST formalism, we shall derive the relevant equation by proper vertical integration, and solve the equation for a simplified theatre geometry with the code developed in [4]. Lastly, we shall compare the results with measurements in a Roman theatre.

2. BACKGROUND

2.1 The EST Formalism

Dujourdy *et al.* [1, 4] have shown that the wave equation, satisfied by the velocity potential, can be extended by a set of conservation equations that reduces to the conservation of the energy-stress tensor $\bar{\bar{T}}$:

$$\vec{\nabla}.\bar{\bar{T}} \tag{1}$$

with

$$\bar{\bar{T}} = \begin{pmatrix} E_{tt} & E_{tx} & E_{ty} & E_{tz} \\ E_{tx} & E_{xx} & E_{xy} & E_{xz} \\ E_{ty} & E_{xy} & E_{yy} & E_{yz} \\ E_{tz} & E_{xz} & E_{yz} & E_{zz} \end{pmatrix} \tag{2}$$

where $E_{tt} = E$ is the total energy, $(E_{tx}, E_{ty}, E_{tz}) = \vec{J}$ is the sound intensity vector, and where the remaining tensor is the wave-stress tensor introduced by Morse and Ingard [6]. Thus the two conservation equations

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are:

- the conservation of energy:

$$\frac{1}{c}\partial_t E + \vec{\nabla}.\vec{J} = 0 \quad (3)$$

- the conservation of intensity:

$$\frac{1}{c}\partial_t \vec{J} + \vec{\nabla}.\bar{\bar{E}} = 0 \quad (4)$$

Dimensional reduction was obtained by integrating eqs. 3 and 4 on the vertical dimension, respectively introducing the modified absorption coefficient *A* and the modified scattering coefficient *D* on both the floor and the ceiling. Dujourdy *et al.* [4] justify the form of these coefficients in terms of energy balance at the boundary, but the discussion goes beyond what is needed here. It should only be noted that the integration on the vertical dimension also introduces the mean free path that reduces to $\lambda = 2l_z$ for flat rooms, where l_z is the height of the room, leading to the system of equations:

$$\frac{1}{c}\partial_t E + \partial_x J_x + \partial_y J_y + \frac{\text{A}}{\lambda}E = 0 \quad (5)$$

$$\frac{1}{c}\partial_t \vec{J} + \frac{\text{D}}{\lambda}\vec{J} + (\partial_x, \partial_y)\begin{pmatrix} E_{xx} & E_{xy} \\ E_{xy} & E_{yy} \end{pmatrix} = 0 \quad (6)$$

Dujourdy *et al.* [4] further show that closing the system of equations requires to postulate that $E_{xx} = E_{yy} = E/2$ and $E_{xx} = 0$, amounting to isotropic distribution of energy in the horizontal directions. They then obtain a linear second-order hyperbolic equation, known as the Telegraph equation:

$$\frac{1}{c^2}\partial_{tt}E - \Delta\frac{E}{2} + \frac{\text{A} + \text{D}}{\lambda c}\partial_t E + \frac{\text{AD}}{\lambda^2}E = 0 \quad (7)$$

2.2 Dimensional Reduction in Unbounded Case

Dimensional reduction in the unbounded case is obtained in much the same way as in the flat case, except that energy densities are replaced by surface densities. Let us take the energy conservation. Integration of eq. 3 along the vertical axis *z* leads to:

$$\frac{1}{c}\int_z \partial_t E dz + \int_z \partial_x J_x dz + \int_z \partial_y J_y dz + \int_z \partial_z J_z dz = 0 \quad (8)$$

Following the suggestion of [1], we relax the hypothesis that E, J_x and J_y are independent of the vertical coordinate, and consider instead the value of E taken at the bottom of the air column to define an equivalent "acoustical layer" of height l, so that total acoustical energy in the vertical column is equal to El. This makes it possible to define in turn an equivalent acoustical intensity, with takes the values J_x and J_y along the x and y axes, so that the vertical integrals of values J_x and J_y are equal to values $J_x l$ and $J_y l$. Taking further into account that J_z must be null on the top of the air column ($J_z^+ = 0$) because of the finite density assumption, the previous equation reduces to:

$$\frac{1}{c}\partial_t El + \partial_x J_x l + \partial_y J_y l - J_z^- = 0 \quad (9)$$

where J_z^- is the vertical sound intensity into the floor. We then introduce the absorption coefficient α that links J_z^- to the energy density at the bottom of the air column:

$$-J_z^- = \alpha E \quad (10)$$

and obtain for the conservation of energy in the whole air column:

$$\frac{1}{c}\partial_t E + \partial_x J_x + \partial_y J_y + \frac{\alpha}{l}E = 0 \quad (11)$$

Similar integration leads to a new formulation of the conservation on sound intensity in the air column in the case of isotropic distribution of energy in the horizontal directions:

$$\frac{1}{c}\partial_t \vec{J} + \frac{\beta}{l}\vec{J} + \frac{1}{2}(\partial_x + \partial_y)E = 0 \quad (12)$$

where β is a scattering coefficient. The telegraph equation then becomes:

$$\frac{1}{c^2}\partial_{tt}E - \Delta\frac{E}{2} + \frac{\alpha + \beta}{lc}\partial_t E + \frac{\alpha\beta}{l^2}E = 0 \quad (13)$$

Dujourdy *et al.* [1] have shown that the steady state solution of eq. 13 becomes asymptotically proportional to $\exp\left(-\frac{\sqrt{2\alpha\beta}}{l}r\right)/\sqrt{t}$ for large values of r, the source-receiver distance.

3. MEASUREMENTS

As in [1, 4], the absorption and scattering coefficients are derived from measurements. But in the present case, we have one more unknown: the equivalent height of the acoustical layer. As the floor of ancient theatres is made of stones, we choose to fix its absorption coefficient, using values from the literature, and evaluate the equivalent height from reverberation time measurements.

3.1 The Roman Theatre of Carthage

In the summer 2014, we had the opportunity to carry out extensive measurements of the Roman Theatre in Carthage, Tunisia [7]. We therefore choose these measurements as references for simulations.

Figure 1 – The Roman Theatre of Carthage

The Roman Theatre of Carthage (Figure 1) was erected in the 2nd century AD and destroyed by the Vandals in the 5th century. Rediscovered at the end of the 19th century, it was subject to archaeological excavations in 1904-1905, and briefly again in 1967 prior to its reconstruction for the Festival of Carthage [8]. This reconstruction cannot be considered as faithful, as is evidenced by the vestiges that stick out of its cavea. It has a capacity of 10 000 spectators. Figure 1 presents a photo of the theatre taken during our measurement campaign. Note the superstructure on the left, remnant of the original theatre, which is used as sound booth during the Festival. And Figure 2 presents an approximate plan of the theatre including the measurement positions.

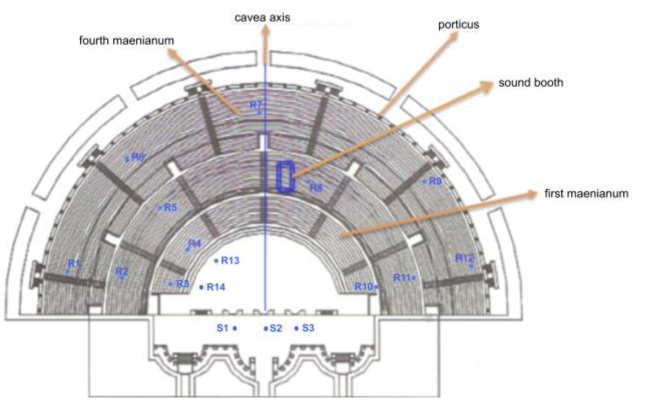

Figure 2 – Approximate plan of the Roman Theatre of Carthage. S: source positions; R: receiver positions

3.2 Reverberation Times

The mean reverberation times measured in the Roman Theatre are presented in Figure 3 for three aggregated bands corresponding to the low frequencies, the medium frequencies, and the high frequencies. The standard deviations show that they are relatively constant in the theatre. Consequently, computing average logarithmic decrements $c\alpha/l$ for the aggregated bands is meaningful: they are given in Table 1, where LF corresponds to the octaves 62, 125 and 250 Hz; MF to octaves 500 and 1k Hz; and HF to octaves 2k, 4k and 8k Hz.

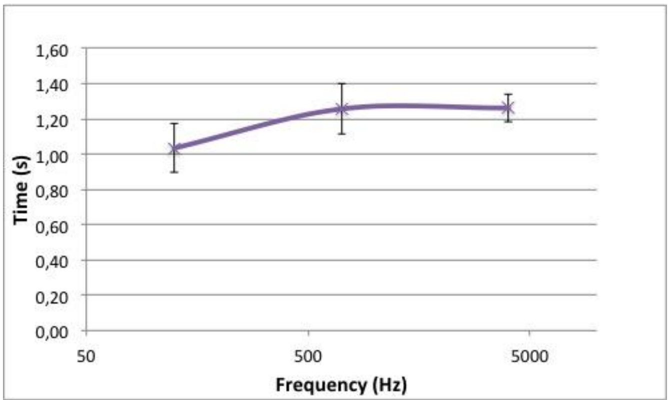

Figure 3 – Mean reverberation times and standard deviations in the Roman Theatre of Carthage

It turns therefore out that the height of the equivalent acoustical layer remains of the order of the meter, that is, it is consistent with the height of the listeners' ears above the ground level of the cavea tiers.

Table 1 – Mean logarithmic decrements, absorption coefficients and heights of "acoustical layer"

	LF	MF	HF
decrement	13.4	11.0	10.9
abs. coeff.	0.03	0.04	0.07
layer height	0.79	1.27	2.24

3.3 Spatial Decay

Spatial decays as measured in the Roman Theatre are presented in Figure 4 as functions of the source-receiver distance for the three aggregated bands: low frequencies, medium frequencies, and high frequencies.

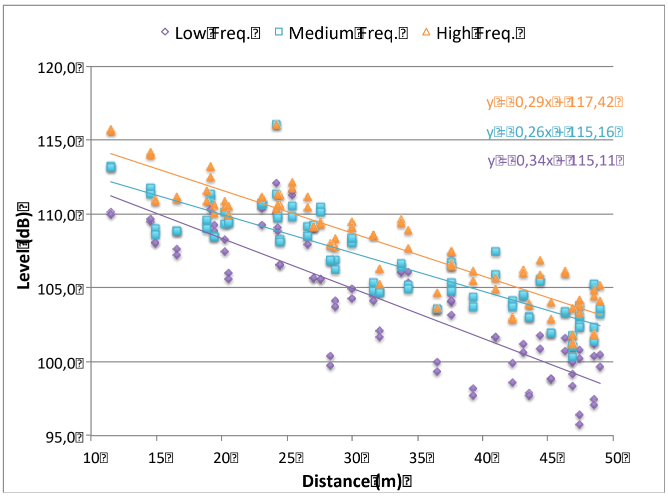

Figure 4 – Spatial decays in the Roman Theatre of Carthage

Short distance measurements in Figure 4 correspond to receiver positions located in the orchestra (R13 and R14), and do not behave differently than receiver positions in the cavea. Note the rather large dispersion of measured levels for similar source-receiver distances, probably due to air turbulence as is expected over long distances in open-air. Cicadas were also constantly singing at a recorder level of 30 dB, and probably interfered with the measurements at the furthest receiver positions. As levels were monitored at on fixed position in the orchestra, it should be possible to reduce dispersion; but this has not been further investigated at the present stage.

For distances above 20 m, the data of Figure 4 indicate a spatial decay for all three bands consistent with the asymptotic expression of spatial decay in the EST model. From the regression lines, we can estimate the scattering coefficients for the three bands: they are given in Table 2, which shows that scattering coefficients are only slightly larger than absorption coefficients, but for high frequencies. According to [1, 4], it indicates that accurate evaluation of the absorption and scattering coefficients need iterations to obtain exact values.

Table 2 – Mean logarithmic decrements and scattering coefficients for spatial decays

	LF	MF	HF
decrement	0.07	0.06	0.08
scatt. coeff.	0.05	0.07	0.22

It should be noted, however, that investigations of a few impulse responses selected randomly showed that they are dominated by the direct sound and a few strong reflections - see Figure 5 for an example corresponding to S2R5.

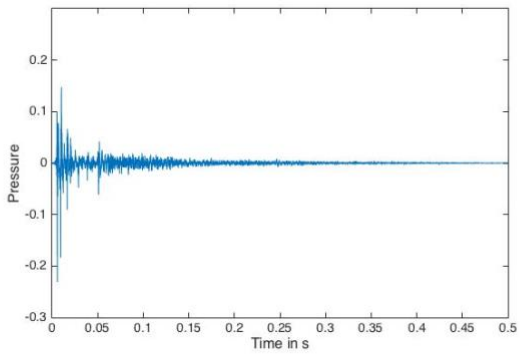

Figure 5 – Typical impulse response measure in the Roman Theatre of Carthage

4. DISCUSSION

Our measurement data in the Roman Theatre of Carthage are consistent with the spatial decays of the energy-stress tensor model that generalizes the diffusion model of Ollendorf and Picaut [2, 3]. However, preliminary investigations, using raw measurement data that were not properly compensated for the changing setting-ups of the measuring equipment, did not show this consistency. As a consequence, we did not carry out simulations of the Roman Theatre of Cartage with our EST code. Nevertheless, the impulse responses are dominated by the direct sound and two or three strong reflections. According to Canac [9], these reflections are created on lower tiers on the opposite side of the cavea. But apparent on Figure 5 is a residual reverberation field below these strong components. It suggests that removing the direct sound and the strong reflections in order to recover the diffuse reverberant field could improve the consistency with the EST model. Indeed, the EST model is only valid for diffuse reverberant fields. Removing strong reflections could be achieved using Matching Pursuit as in [10]. Another technique is manual removal of the reflections, and filling the gap with data derived from signals before and after the gap, as proposed by [11] for removing clicks in old gramophone recordings. None of these methods has been tested so far.

5. CONCLUSIONS

The energy-stress tensor method, in short EST method, was developed to efficiently simulate the diffuse reverberant field of an enclosed space. Despite the fact that the impulse responses of an open space are dominated by the direct sound and a few strong reflections coming from opposite lower sections of the cavea, there exists a diffuse reverberant field, as illustrated in Figure 5, that is sufficient to make spatial decays in open-air theatres consistent with the EST model. There remains to check whether the EST method can predict this reverberant field, and whether a hybrid simulation procedure, similar to Meacham *et al.*'s hybrid procedure for hallways [12] can be applied to open-air theatres.

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Ancient Greek theatre – impulse response simulation

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ABSTRACT

Based on Vitruvius' "De Architectura libri decem" about proportions of the Greek theatre supplemented with the size data from Epidaurus, we reconstruct the impulse response and process the recordings of ancient and modern music. All theatres preserved till today, had sound deficiencies which Vitruvius recommended to solve using bronze vases. The wooden theatres didn't have these deficiencies so simulating their impulse response gives us the effect intended by the old masters. The simulated impulse response can be used for filtering music signal to achieve this effect.

Keywords: acoustic reconstruction, Vitruvius' design of ancient theatres, diffusion into walls

1. INTRODUCTION

The reconstruction of ancient theatre acoustics is the topic raising a vivid interest among researchers, professionals, students and general audience. The long-term motivation for this work was to discover what effect is caused by the ancient theatre as its design seems to be optimally chosen from other options. Thus, it may indicate subjective quality effect which could be important in modern music as well.

The field is vividly investigated in different aspects and different methods of simulation.

The concept of simulation of the impulse response of the theatre in Epidaurus was investigated already in [1]. The lower frequencies were modelled with Finite-Difference Time-Domain method, while higher with beam tracing. Thus, the impulse response was reconstructed. The authors correctly took into account the existence of the stage which is not preserved in the theatre.

Another research on Epidaurus theatre was reported in [2]. The approach undertaken there is to perform measurements of the sound propagating from the middle of orchestra or from the point close to it analyzed in the positions of receivers installed at the various locations on the theatre's cavea. The study fosters the results about speech intelligibility across the whole cavea. Also the occupation of the cavea by auditors does not have much impact on the acoustical properties of the theatre.

The topic was also covered by the research project ERATO under the EU 5th Framework "Preserving and using cultural heritage", Project ICA3-CT-2002-10031 running from 1 February 2003 to 31 January 2006 [3].

Another example to the fact that the field is vividly investigated are the results of N. Declercq and C. Dekeyser [4] or the material in Nature based on their work. [5] Let us observe that here the propagation is analyzed by the calculation of amplitudes of the propagating signals of the specific frequencies, so the time-frequency effects are not taken into account.

The paper [6] discusses the influence of the stage building on the acoustical properties of the theatres in Greece.

The focus of our work was also to transfer the simulation result into the signal processing algorithm that would yield an experimental way to validate the conjecture that the Greeks had great experience in acoustics and sound arrangements despite the relatively poor technical means they had at disposal. Another important contribution was to focus on time-frequency effects known today in modern psychoacoustics that have a crucial impact on the subjective impression of music. As the core material for analysis we certainly used the findings of the acousticians working in the field and gathering the measurement results but we also kept in mind that the important source of information is "De architectura. Libri Decem" by M. Vitruvius Polio [7], who in Book V gives a quite precise account how a theatre with good acoustics has to be built, adding a special emphasis that the way it's built results in the sound propagating in the optimal way and providing most of the pleasure to the auditorium.

Let us review the above research papers from the perspective of the contents of Vitruvius' description. In [1] the authors did not include the closing wall behind the stage that should be as high as the roof of porticus. The paper [6] also does not include the wall only the building behind the stage. The wall behind the stage and

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its important acoustical influence is discussed in [7].

As for the research in [2] the authors did not, however, consider Vitruvius' recommendation to equip the stone theatre with resonating vessels.

In the current paper we also do not take into account the resonating vessels. Instead, we assume the theatre material to be wood. As explained in Vitruvius' description, the wooden theatres did not require the vessels.

It should be mentioned also that the theatre of Epidaurus belongs to the type called by Vitruvius "Greek theatre" so the venue constructed for the musical performances. Thus the feature it has is the propagation of the music.

The known solution [4] analyzes only the impact of the antique theatre for the specific frequencies and does not take into account the delays. Moreover, it relates to the preserved parts of the theatre but does not take into account those that were in use but have not been preserved till our times, and that were still designed to have an acoustical influence.

The approach from [8] is based on the measurements of the impulse responses, which however are prone to errors due to the noise and the measurement conditions. The accuracy of the measurement is most probably .001, so -60 dB. We simulate the Impulse Response which for most of the delays up to 2 sec is under -60 dB.

Our approach considers the time-frequency structure of the processed signal and of the reconstructed impulse response and as such results in high accuracy reconstruction.

The paper is organized as follows. In Section 2 we give an overview of the method, while Section 3 contains the examples and applications. We end with some conclusions.

2. THE METHOD

Our approach to the reconstruction of the acoustical properties of ancient theatres relies on the simulation of impulse responses with which then the sound of music is digitally filtered. The impulse responses are pure simulation not based on the other measurements, but based on the actual geometrical properties of the ancient theatre. Thus, we are able to approximate the sound conditions as they were in the original theatre despite the erosion and the partially preserved elements of the construction.

Our approach is to reconstruct the impulse response (up to 2 sec of delay) and apply it as FIR – Finite Impulse Response – via convolution to the signal of original music. To obtain the Impulse Response we simulate trajectories propagating from the initial point (the actor's lips, the actor standing on the middle of the edge of the stage) following the geometric acoustic rules and registered if within 2 sec they reach the endpoint (the ears of the person sitting in the middle of the first row).

When the generated trajectory hits the walls of the theatre, we model the propagation of the sound in the theatre walls. The paradigm here is to exploit the wave – particle duality which assumes the propagation according to diffusion equation – contrary to D'Alembert equation which results in the geometric acoustics rules of propagation. The solutions to the diffusion equation are Wiener processes trajectories, over which the delay and attenuation are evaluated [9].

Reconstruction of the impulse response up to 2 sec allows to consider the time – frequency effects like dynamic changes in pure tones propagation. The delays and attenuations are computed over every straight line segment of the trajectory (so called partial delays and attenuations) and then combined – delays added and attenuations multiplied – to get the final values for the trajectory. The attenuations for different trajectories with the same delay are added. Thus, we obtain for the specific delays the specific sum of attenuations. So, we arrive at the overall Impulse Response.

The simulation is based on generating the trajectories in the air by means of forward ray tracing (see [10]) and supplemented by generating the trajectories in the theatre walls as we assume part of the energy is consumed to traverse the walls and comes back to the original wave with some delay. Hence, if we want to reconstruct the impulse response with the length up to 2 seconds, we need to take into account the sound propagating to the walls.

Thus, we supplement the standard forward ray tracing method with the trajectories through the walls analyzed according to Feynmann-Kac theorem. [9] And we apply this method to the geometries provided by the plan of the actual ancient theatres.

2.1 Forward ray-tracing

From the initial point we generate the trajectories composed of the segments of sound propagation in air and of the segments of sound propagation in the material of the walls. The sound propagation in the air follows the rules of the geometrical acoustics.

The amplitude is inversely proportional to the distance the sound wave is propagating to during the segment of trajectory between the subsequent reflection points. Thus, the attenuation F is proportional to the distance travelled:

$$F = S. \tag{1}$$

where S - the distance travelled by the sound in the segment of trajectory.

The next except the first segments that cross the air are selected consistently with the rule that the angle of reflection is equal to the angle of incidence.

The simulation takes into account that the sound is perceived by a human, the ability of sound localization is modelled by using Head Related Transfer Function [11].

2.2 Diffusion model

The fragment of trajectory is randomly selected from the 3-dimensional Gaussian distribution with mean 0 and standard deviation depending on (proportional to) the speed of sound in the respective material.

$$W(n)(x,y,z) \sim \mathcal{N}\left(0, \frac{V}{N^{1/2}}\right). \quad (2)$$

2.3 Delay/attenuation pairs

We assume the propagation in the air when the wave leaves the wall and travels a short distance in the air. The attenuation F and the delay T are given by the formulae:

$$F = SD^{1/3} \quad (3)$$

$$T = \frac{S}{V}, \quad (4)$$

where V - the sound velocity in the component (air/wood),

S - the distance travelled by the sound in the component,

D - the density of the component.

2.4 Wall material

The light wood (pine, fir, spruce) has a density of 400-500 kg/m^3 and the respective sound velocity is 4000-5000 m/s. The choice of density 400 kg/m^3 and the sound velocity 4000 m/s is, in our opinion, a good representation of the true material.

2.5 Design

The design of the theatre was implemented as C++ functions into the C++ code CEZAM performing ray tracing algorithm. The effects of propagation of the sound inside of the wall material were simulated in R (also for the multiple reflections) as pairs of attenuations and delays – see equations (3-4) – and recorded as an additional input to C++ software.

2.6 Theatre proportions

The theatre proportions are found according to the description from Vitruvius [7] and the size of the theatre in Epidaurus. The theatre is assumed to be built from 10 cm thick wood and to have a closing wall behind the stage. Other details follow description from Vitruvius' Book V. It should be mentioned that in Epidaurus the higher part of seats was added only in Roman times. Earlier there was a colonnade. So, in the simulation we assume the theatre building with the closing wall and colonnade. Hence, the length of the seats is corrected as in Table 2.7.1.

The useful modification is to place the sound source in the orchestra where the choral parts were performed from.

The geometry of the theatre is mostly transparent so it is fairly straightforward to prepare the code implementing the function returning for the three-dimensional data the value 1 for the air found at these coordinates, 2 for wood and 0 for the open space above the theatre building. The most important features that were to be implemented are the angle of the audience, the angle of the slope and the size of seats.

We needed also another function to return the direction of the normal to the theatre surface.

2.7 Measurement data

The measurement data comes from the paper [4] and was supplemented with the data from Vitruvius' description of the Greek theatre: the angle of audience and the height of stage

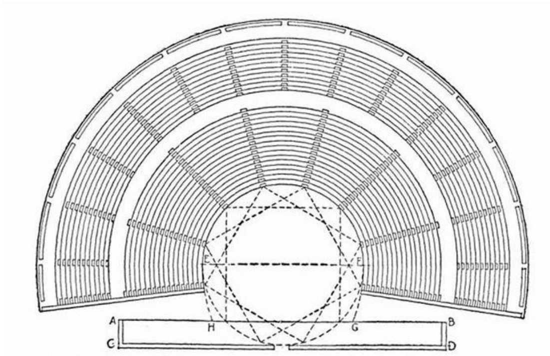

Figure 1 – Ancient Greek theatre according to Vitruvius' description

2.7.1 Data from Epidaurus

Table 1

Parameter	Unit	Value
Width of the seats	meter	.746
Height of the seats	meter	.367
Slope of the theatre	degrees	26.6
Distance between centre of the orchestra and lower seat row	meters	22.63
Length of the seats	meters	49.88
Length of the seats (corrected)	meters	44.78

2.7.2 Data from Vitruvius' description of the Greek theatre

Table 2

Parameter	Unit	Value
The angle of audience	degrees	210
Height of the stage	meter	3-3.6

3. EXAMPLES AND APPLICATIONS

3.1 Available solutions

The presented algorithm was coded into an Android application designed to imitate the described effect of ancient theatre acoustics. Also, if a shorter delay is needed (Android has got this parameter around 250ms), a software implementation on the Texas Instruments DSP C6748 hardware device (with 10 ms delay) was implemented.

The impulse response of the reconstructed ancient theatre acoustics is available with the VST tools like SIR or others.

3.2 The music applications

In pilot tests the difference of the original and the processed signal is described as "richer, deeper, and more reverberation." To support that we can plot the spectrogram of the song "*La voce del silenzio*" sung by Andrea Bocelli. The parameters of the time-frequency decomposition: Hamming window, in ERB (equivalent rectangular bandwidth - a perception based frequency scale), window length 50 ms, overlap 95% (i.e. redundancy 20). The software used is STX [12],[13].

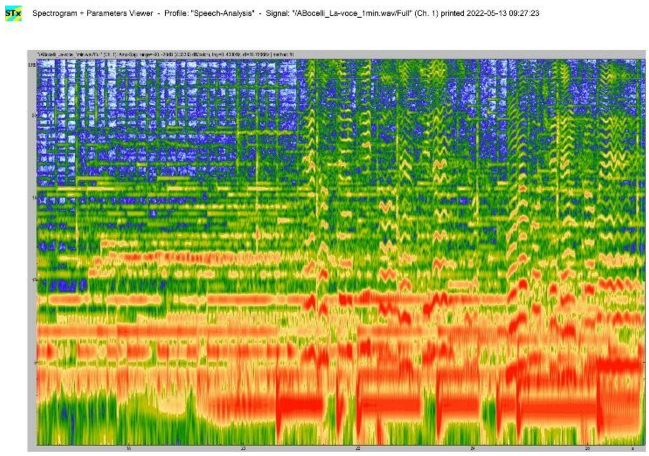

Figure 2 – Spectrogram of the original recording "La voce del silenzio" by Andrea Bocelli.

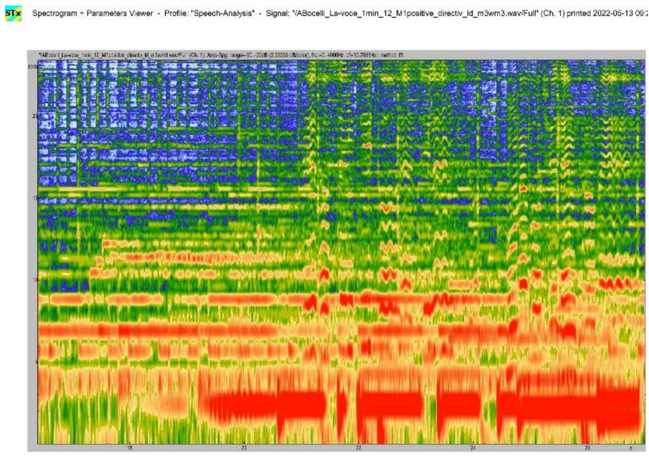

Figure 3 – Spectrogram of the recording "La voce del silenzio" by Andrea Bocelli processed by the simulated impulse response of the Greek theatre.

4. CONCLUSIONS

We introduced the method consisting in implementing the proportions of the Greek theatre and simulating the effect of propagation of the sound into walls by means of Wiener process. We simulate the trajectories from the stage to the middle of the first row and convolve the music signal with the obtained Impulse Response. The result has got plausible features that were analyzed.

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Challenges in calibration of acoustical models for historic virtual reality auralizations

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ABSTRACT
The digital acoustic simulation has always been subject to discussion among experts in relation to the type of software employed and relative setup. The application becomes more challenging, especially in the context of unroofed performance spaces like ancient theatres. This paper deals with the calibration process within two geometrical acoustic-based software. The simulations have been performed in order to assess the calculation methodologies upon impulse responses (IRs). The evaluation has been carried out by placing the same number of sources and receivers into a digital model realized with Autocad software and representing the architectural features of the Greek-Roman theatre of Tyndaris. Thereafter, the outcomes gathered by the calibration process have been compared with the on-site measured values related to the main acoustic parameters as outlined by ISO 3382. The model calibration has been characterized by the determination of absorbing and scattering coefficients applied to different finish materials.

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The Acoustics of Ancient Theatres

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Caveats and pitfalls in acoustic simulation of non-existing buildings

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ABSTRACT

Acoustical reconstruction of ancient spaces, existing in very different conditions or not existing anymore, is becoming an increasingly popular activity in different research fields. Availability of several softwares brought acoustic simulation out of specialized labs and made it possible for a much broader audience to take advantage of their potentials. However, like any other simulation tool, reliability of the results needs to be carefully pondered as it depends on a number of factors pertaining to proper knowledge of the simulation process and of the characteristics of the building to be simulated.
Keywords: acoustic simulation, geometrical acoustics, archaeoacoustics

1. INTRODUCTION

Acoustic simulation has become a largely popular instrument to support scientific research since the publication of the seminal paper by Krokstad et al. in 1968 [1]. In that paper, the foundations of geometrical acoustic (GA) simulation were laid, showing that ray tracing could be used for computing time-energy responses and showed its applicability to practical room acoustic design. However, it was in the early 90s that a number of modelling tools became commercially available to the broad public, and since then a number of research papers described the details of the different algorithm [2], while others compared their accuracy [3-5], and the different sources of uncertainty [6]. A thorough overview of the state of the art of geometrical acoustic simulation was summarized by Savioja and Svensson in 2015[7], with one of the most interesting outcomes of the last years being represented by the availability of free open-source tools.

However, in parallel with the development of GA simulation tools, the exponentially growing computational power, in particular offered by parallel computing using GPUs, paved the way to more hard-core simulation techniques like those based on the numerical solution of the wave equation, which, for acoustic purposes, finds in the Finite Difference Time Domain (FDTD) approach its ideal tool. From the early low-frequency attempts [8], this technique can now be applied to full frequency range [9], with specific application to those cases where diffraction of focussing effects play a major role [10]. However, these tools are still circumscribed to academic researchers.

As far as acoustic simulation tools became available to a broader audience, a number of potential applications became evident, from the acoustical design of spaces to reconstructions of non-existing buildings (archeoacoustics), to virtual worlds for the gaming industry. A Google Scholar search using «archaeoacoustic» as a keyword returns 993 documents published, while before 2010, there were only 79 papers, and before 2015, they raised to 301. A Google Scholar search using «soundscape+ancient+spaces» as keywords returns 16800 documents published. It is more and more evident that the idea that acoustics is an «intangible» cultural heritage is now fully recognized by the scientific community and the topic of the acoustic reconstruction of non-existing buildings is becoming a mainstream issue for a much larger and interdisciplinary community of researchers. However, while this is creating new opportunities of research for the acousticians' community, at the same time it raises a number of concerns on the accuracy and reliability of many simulations when they are carried out without a proper understanding of critical acoustic problems pertaining to both simulation algorithms and modelling techniques.

2. PITFALLS DUE TO GA ALGORITHMS

The following considerations will apply to GA modelling as it is the most widespread and easily available tool (although, in most of the cases, at a non-negligible cost). Most commercial software has been improved from the early versions to include geometrical modelling tools or, at least, some tool to import geometry from third party 3D modelling software. For unexperienced users, the major task is usually represented by the creation of the geometrical 3D model which, in the worst case is just an adaptation from an existing, hyper-detailed architectural model. In the best case, the model is made on purpose, having clearly in mind the acoustical needs and the rule that "all geometry details should be an order of magnitude larger than the longest wavelength of interest in the simulation, [while] the finer details should be smoothed out" [7], but how they should be addressed remain open questions, having potential

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implications on the choice of the absorption and scattering coefficients (see below).

The problem of the level of detail (LOD) of the model is virtually impossible to find a proper solution as the polygons, must be large compared with wavelengths that, to cover the audio frequency range, need to span over three decades. It is well known that a high level of detail will lead to unnecessary long computation times, while a low spatial resolution in the polygon model, may result in more accurate low frequency response and late time response, where the late decay is largely influenced by scattering rather than by deterministic specular reflections in a detailed polygon model[6]. One of the most interesting advantages of FDTD techniques vs. GA methods is their robust handling of different LODs. Another issue that has significantly limited the accuracy of a GA acoustic model is related to a proper treatment of diffraction phenomena resulting in diffraction waves appearing at polygon edges. The approach that best fits room acoustical simulations is based on the use of a secondary edge source approach, which permits the study of finite edges and higher-order diffraction [11]. Such approach has been implemented in some modelling tools and allows to obtain more accurate and realistic simulations in presence of obstacles and reflector arrays [11].

A last issue that is strictly related to both the previous ones is the discretization of large curved surfaces that are approximated by a number of planes. Curved surfaces produce very special features like focal points that may not be correctly simulated if the approximation of the curve is too rough and if the number of rays and properties of the surfaces are not set correctly[6]. Proper inclusion of diffraction effects also proved to yield a smoother spatial response, more similar to what is obtained when wave based methods are used.

In addition to the previous problems, that are intrinsically associated to GA methods, it is important to mention other aspects that should be less risky, in principle, but might equally originate serious inaccuracies if not properly set. Most of the tools share similar settings like the number of rays or the time duration of the impulse response to simulate, in addition to more specific settings (from choice of algorithms, to transition from image source to ray tracing, to other non-trivial options). All of these setting, starting from the very basic number of rays to cast, require the user to be fully aware of the algorithms working behind the scenes, and their needs and limitations that might otherwise strongly affect the results and need to be adapted to the specific case under analysis to account for presence of openings, curved surfaces, etc. Large openings, in particular, will usually require much more rays to compensate for the lack of reflections.

3. PITFALLS DUE TO SURFACE PROPERTIES

In a room acoustic simulation an accurate simulation of wave surface interactions is an essential feature to obtain reliable results, particularly when the room does not meet the ideal requirements for diffuse sound field. A sound wave hitting a surface is partly absorbed and partly reflected. The reflection can be specular or diffuse (scattered). Thus, in a reverberant space, for each boundary surface one should know frequency dependent absorption coefficients and scattering coefficients.

With reference to the first set of coefficients, which apparently are those that can be more easily found in the literature, technical sheets and data sets, a first important issue needs to be considered: absorption coefficients are supposed to be the frequency dependent, diffuse field values of the ratio between absorbed and incident energy. Thus, such coefficient does not coincide neither with diffuse field Sabine's absorption coefficients as resulting from application of ISO 354 [12] standard, nor with normal incidence absorption coefficients resulting from application of ISO 10534-2[13]. Nonetheless, the first are generally used without any significant concerns (apart from the cases in which α_{sab} is greater than one), and many researchers also use the second without using proper conversion formulas. Clearly, none of the approaches is theoretically correct but the large uncertainties affecting the measurements, combined with the common practice of "calibrating" the model with measurements contribute to limit the bias. Dependence of absorption coefficients on the angle of incidence is considered by several modelling tools, but the use of such feature also requires a much more sensitive and theoretically aware approach about surface properties. Finally, sound absorption coefficients are usually available for generic typologies of finishing or for commercially available materials, while most of the real-world data used in existing and historical buildings is left aside and data can only be derived from inference or direct measurements. Complex multi-layer structures may also contribute to make the task even more difficult to accomplish for unexperienced users, while transfer-matrix approaches are available to compute absorption coefficients of such structures provided that details of material properties (like flow resistivity) are available. With reference to scattering coefficients, apart from some differences existing among modelling tools in terms of how to input data, they represent the fraction of reflected energy that is not specularly reflected. The way such scattered reflections are handled is algorithm dependent and may result in a significant increase of computational burden, but proper understanding of the way such reflections are treated is essential to fit to specific needs of the space that is modelled. In fact, GA methods may treat scattered reflections as randomly distributed from the impact point (i.e. a proportional amount of reflected rays is sent to random directions), treat them deterministically (i.e. actually spreading them in all directions, but this significantly increases the number of rays to handle and, hence, the computational burden), or use techniques to speed up calculation like the "diffuse rain" approach, where the visibility of all the diffuse reflections to the receivers is checked and each visible path is recorded to the receivers taking into account the angle of reflection and the solid angle covered by the receiver [7]. The way scattering is handled will consequently have clear influences in terms of accuracy of the results, particularly for early part of an impulse response, as well as implications on the way scattering coefficients should be set [14].

Assigning proper scattering coefficients to surfaces may consequently become a relevant part of the acoustic model preparation and also a non-trivial part. In fact, in addition to the algorithm-dependent variations, scattering coefficients suffer a substantial lack of data compared to absorption coefficients. Despite the existence of an international standard (ISO 17497-1[15]), the number of measured data is limited to commercial "sound diffusers" and relatively few archetypal diffusing treatments based on simple geometries [16-17]. In the other cases, it is possible to use simplified formulas that take into account the roughness of the surface or numerically model the surface pattern. In all the cases, a substantial dependance on the user experience and sensitivity appears, as scattering coefficients may affect the diffuse field behavior of a space, which, particularly in non-mixing geometries, may be strongly dependent on surface properties.

Finally, as a result of simplification in room geometry to comply with expected LOD, absorption and scattering coefficients may be adequately corrected to compensate for rich decorations and other surface patterns.

4. ACOUSTIC SIMULATION IN PRACTICE

Given all the above limitations and uncertainties one would hardly believe that GA modelling has become so popular. In fact, from acoustical consulting, where it represented a significant step forward in terms of ease and cost efficiency compared to other prediction techniques, GA modelling was used also in the room acoustic research field, usually to complement on-site measurements. Finally, in the last years, such tools have been often used in humanities studies (musicology, archaeology, art history, etc.), mostly as a consequence of the acknowledgement of "sound" as an intangible cultural heritage and the implications acoustics may have had on other fields. Thus, resulting in an interest towards acoustic reconstructions of non-existing buildings.

While the latter case will be discussed in the last section, with all its potential risks, it is worth pointing out the good practices that are needed to obtain an accurate acoustical simulation. The most common approach, at least where this is possible (i.e. excluding the professional consultancy world where no comparison is possible), is that of starting first from a "calibrated" model, where simulation can be compared with actual acoustic measurements. Along time, different approaches have been proposed for the calibration steps, with more or less accurate comparisons depending on both the amount of available data and purpose of the comparison.

One usual approach [18], typically used in large mixing spaces, assumes that scattering coefficients are given based on roughness of the surfaces, then absorption coefficients, after a first assignment based on literature data, may be iteratively changed (primarily starting from those with more uncertainties), until the spatially averaged reverberation time matches measurements, and then a more refined analysis of the model is carried out to have point-by-point agreement on spatially dependent parameters like clarity, center time, etc. Prediction errors are compared to just noticeable difference (JND) so to obtain the smallest possible values.

A more detailed approach involving a proper adjustment of scattering coefficients has been proposed by Postma and Katz [19], implying that the sensitivity of the GA model to variations of scattering coefficients is quantified by setting all scattering coefficients first to 0%, then to 99%, with absorption coefficients unchanged. Then the adjustment of surface properties follows a basically similar process as described in the previous case, so to minimize the standard deviation (SD) of pairwise differences in reverberance and clarity parameters. Use of the same tool to calculate acoustical parameters is also recommended so to treat measured and simulated results in the same way. Once such calibration processes have been successfully carried out, any subsequent use of the GA model to investigate other source or receiver positions, to investigate the effect of occupancy or changes in surface finishings, could be trusted. On the contrary, without a solid reference, results may significantly diverge from reality.

5. PROBLEMS WITH NON-EXISTING BUILDINGS

What happens when no calibration is possible because the space we want to acoustically simulate no longer exists? As said before, a large part of recent studies in the archaeoacoustic field rely on GA simulations of spaces that have been reconstructed in some way, making hypotheses about the geometry and, even more importantly (based on possible acoustic implications), on surface finishings. Acoustical results will be affected by those hypotheses which, at least, need to be stated very clearly to ensure repeatability. And, in any case, they will represent only one of the many possible (and equally probable) scenarios.

With reference to the space geometry, the question has much broader implications in other fields, and whatever the shape that is finally adopted, it will result from historical, artistic, and archival research and having obtained some sort of consensus among the relevant scientific community. However, in terms of acoustic effects, even assuming that geometry is properly rendered with the appropriate LOD, there is still much to define before a reliable simulation may be obtained.

In order to have trustworthy results it could be possible to start from an existing building where measurements could be done (or are available in the literature), that has comparable features to the one to be simulated. In this way, a calibration could be carried out and any subsequent variation in shape or material properties could return more convincing results. Acoustic characterization of surface treatments and, possibly, complete multi-layer structures, could also be carried out to provide a scientifically robust starting point for a simulation. Non-destructive, on-site absorption coefficient measuring techniques are available (based on ISO 13472-1[20]), and could be used to test existing surfaces having characteristics with the surfaces to be modelled. The method is not immune by uncertainties but could certainly contribute to have a firm basis to start from. On-site measurements could also be obtained using an indirect approach, like in reverberant chambers, in case the sample of material can be moved easily [21]. Similarly, it could be possible to reconstruct a small sample of a surface, including all the underlying layers, and test it in a standing wave tube or, in case larger samples could be obtained, in a reverberant chamber.

Finally, in case none of the previous approaches could be used, it might be useful to include in simulations some sort of sensitivity analysis showing the range of possible variations following reasonable changes in material properties. Such an approach might honestly declare the limitations of each study, also allowing the reader (and the same researchers) to draw conclusions that at least cover a wider range of possibilities and not just one arbitrary choice. Obviously, this should be done assuming that all the other critical aspects discussed before have been tackled in the best possible way.

6. CONCLUSIONS

In this paper, the main limitations of geometrical acoustic simulation have been presented, spanning from those inherently due to the simulation algorithms, to those that are more related to a proper knowledge of material and surface properties. Absorption and scattering coefficients need to be assigned with criterion possibly accounting also geometry simplifications. With reference to non-existing buildings, finding existing buildings or surface treatments that could be used as a reference to calibrate the models is essential to obtaining more reliable results, otherwise proper uncertainty ranges should be stated to account for lack of information.

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Past challenges in the studies of ancient open-air theatre acoustics: Cases from Asia Minor

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ABSTRACT
Over hundred ancient open-air theaters are still standing in Turkey. Acoustics of these theaters are of great interest and attract attention by visitors. Within the scope of a pilot study completed in 1995, three ancient theaters in the Mediterranean region were investigated. Measurements were made in these theaters, namely, Termessos (Hellenistic, Pisidia), Perge and Aspendos (Roman, Pamphilia). An impulsive sound source was used to record sound on a portable tape recorder at audience locations to be later analyzed in the laboratory on computer, upon analog-to-digital conversion for comparison to simulation results. This paper addresses then-challenges faced in conducting measurements in these spaces located sparsely in the country side. Ways to confront and overcome problems of the lack of electrical power and transportation infrastructure, and difficulties to cope with meteorological conditions have been detailed. Insufficiency of analysis and simulation tools is also outlined. Lastly, these historical amphitheaters are comparatively discussed in this paper by introducing a contemporary amphitheater in Central Anatolia. Although, this contemporary case is architecturally reminiscent of a classical Roman amphitheater in its initial design, the construction had ended up with a shelter over seating area, providing a semi-open space, and a disputable sound field.

Keywords: Acoustics of ancient theatres, in-situ acoustic measurements, acoustic simulations.

1. INTRODUCTION AND METHOD

1.1 Ancient Theatres

Acoustics of ancient open-air theatres is said to be satisfactory for most seating places, although their seating capacities can vary is from a few hundred to a couple thousand. Only a few studies on acoustics of ancient theaters are devoted to the causes of good acoustics. Neither acoustic measurements nor detailed acoustic analyzes were discussed in these studies for theaters in Asia Minor and ancient theaters elsewhere before 1990. The main reason for studying the acoustics of ancient theaters by including computer simulations based on geometric room acoustics was the lack of extensive research on this subject. It is also believed that uncovering the reasons for good acoustics will serve as a powerful tool in the design of new outdoor theaters.

The most important and oldest surviving research on the acoustics of open theaters is recorded by M. Vitruvius Pollio [1]. A historical survey had been conducted to define locations, capacities and conditions [2] of possible candidates for this detailed study. The theatres of Aspendos, Side, Perge and Termessos were originally selected for measurements. The proximity of the theatres to each other and their well-preserved status appeared to be the prominent factors which supported this selection. Side, Aspendos, Perge are Roman theatres in Pampfilia while Termessos is well-known Hellenistic period theatre in Psidia. Side Theatre was omitted from the study as acoustical measurements would not be performed at Side due to presence of intercity bus terminal nearby, capable of producing high levels of unsteady background noise(Table 1).

1.1.1Acoustical Measurements in Theatres

An impulsive sound source was used as the source of excitation. In-situ sound measurements were conducted in these theaters by recording analog signals on ½ inch magnetic tape. An instrumentation tape recorder (RACAL STORE 4DS) equipped with two FM channels and powered by a portable car battery were employed in data acquisition. Two -half inch free-field microphones (B&K 4165) enhanced by GenRad preamplifiers were used to pick up acoustic pressure signals in measurements. A sample measurement microphone positioning at location D2 in Aspendos and Perge theaters is illustrated in Figure1.

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Table 1 Theatre Information

	Perge	Aspendos	Termessos
Normalized Average Distance (NAD)	0.54	0.63	0.52
Seating Capacity	13595	9054	4199
Number of Receiver Positions	20	25	20

Analog recordings of acoustical pressure signals collected from several receiver positions in theatres with no audience were to be later analyzed in the laboratory on a DataGeneral MINC-23 minicomputer after Analog-to-Digital Conversion process, in the laboratory at the Department of Mechanical Engineering at Middle East Technical University in Ankara. Temperatures varied from 12 to 21.5 degrees Celcius while the wind speed fluctuated between 1.6 m/s and 2.4 m/s during the measurements taken in successive years of May 1989 and May 1990. Relative humidity was fairly constant about 50%.

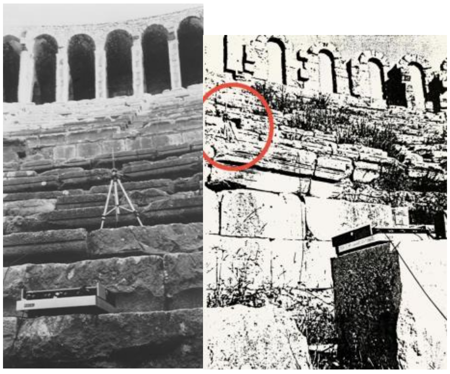

Figure 1 –Microphone Positioning at Aspendos and Perge Theaters

Configuration of receiver locations is shown in Figure 2 for AspendosA typical response to impulsive excitation in Aspendos Theatre is displayed in Figure 3 for a selected receiver location coded D2.

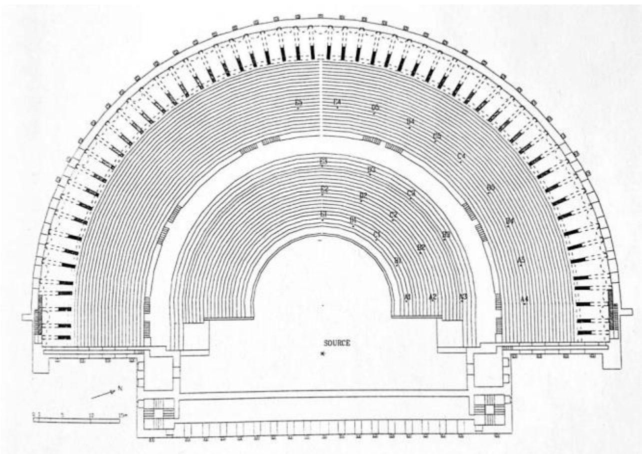

Figure 2 – Assigned Receiver Locations in the Theatre of Aspendos.
[2]

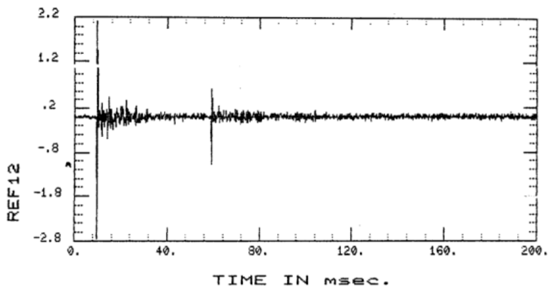

Figure 3 – Measured Impulse Response in the Theatre of Aspendos at Recevier Position D2.

1.1.1 Simulations

Sound reflections from orchestra surface and stage walls were simulated by both ray tracing and method of image sources. Reflection patterns obtained from analytical and experimental studies were evaluated and receiver positions with and without echoes were diagnosed. A three dimensional model was devised for analysis of sound field due to image sources. The direct and reflected paths of sound have formed formed a tetrahedron as shown in Figure 4. Dimensions of Termessos Theater was used in this model.

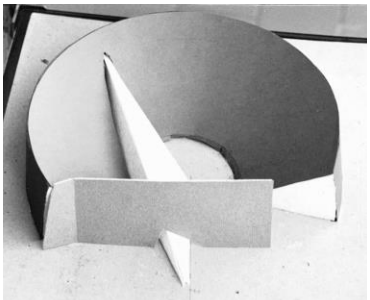

Figure 4 – Three-dimensional tetrahedron model of direct and reflected rays of sound[2].

Acoustical characteristics in these three theatres were simulated by method of image sources by home-grown software at ME Department of METU. Impulse response characteristics of theatres were obtained from simulations for specified source-recevier pairs (Figure 5, Figure 6).

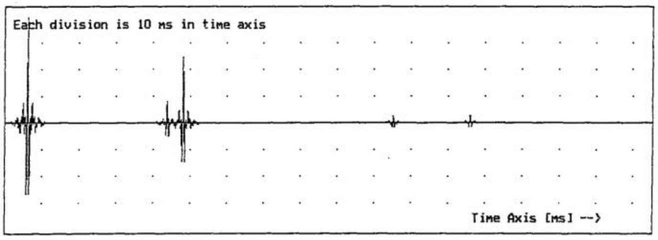

Figure 5 – Simulated Impulse Response from Reflection Pattern by Method of Images, Aspendos Theatre Impulse Response Receiver Position D2[2].

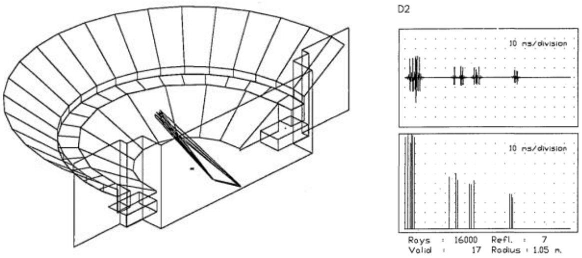

Figure 6 – Simulation by Ray Tracing, Aspendos Theatre Impulse Response Receiver Position D2.

1.1.2 Evaluations of Results

The main findings of the study with respect to acoustical design characteristics of the Aspendos, Termessos and Perge theatres can be summarized as follows:

- The significance of the skene and orchestra surface is pronounced; these architectural elements have an important role on the reinforcement of the direct sound by the strong first order reflections.
- The semi-circular forms of the ancient theatres are very suitable for reducing normalized average distance. This characteristic is important, especially, for open-air theatres from the standpoint of shorter direct sound paths. The sloped auditorium forms an advantage for increasing the hearing angle.
- The side walls of the skene are observed as problematic surfaces with respect to practical sound source locations on the orchestra. These surfaces cause the undesirable late reflections. Hence, to minimize this effect, these components should be covered by absorptive materials in the possible future uses of ancient theatres. The portable surfaces should also be positioned on these side walls in order to change the reflection-angle.
- The lack of ceiling cover in the form of an orchestra shell in open-air theatres studied is a drawback. However, a temporary or portable can be constructed for the future-use of ancient theatres. According to the characteristics of performances, the reflectors can be formed and angled.
- The theatre of Aspendos is shown to possess superior acoustical characteristics on basis of slope, hearing angle, stage back wall height, smooth orchestra surface. Excellent to very good speech transmission index figures were obtained through simulations even in the unoccupied uses of all three theatres while Aspendos possesses the best figures.

1.2. A contemporary case: Bilkent ODEON, Ankara, Turkey

In contemporary age the performance spaces either open, semi-open or closed are mostly used for multifunctional activities, due to economic considerations. This is one of the basic challenges for room acoustics designers in this era. One example is a semi-open amphitheater Bilkent ODEON, which is a gathering place for speech related activities including school ceremonies, or large-scale meetings as well as a performance place of orchestral music and recitals. ODEON with 4000 seating capacity is designed to serve Bilkent University's and the capital Ankara's educational and artistic activities.

The amphitheater was initially built as a fully open space, but later in order to accommodate performances under harsh climatic conditions a curvilinear roof is added to the structure as a sheltering element (see Figure 7. The Amphitheatre's architecture, while reminiscent of a classical Roman amphitheater, highlights the features of high technology with its steel structure roof covered by a textile membrane, besides glass and a cable network system. The architectural form is a synthesis of two architectural styles separated by 2000 years. Although, the form and the synthesis of architectural styles results in an innovative building typology, the acoustical problems have arisen after the addition of this technological roof. Mostly concave and sound reflective roof membrane has caused multiple sound foci positions and thus un-even distribution of sound within audience seats. The structure has studied in previous years for possible acoustical interventions by field test tuned acoustical models [3,4].

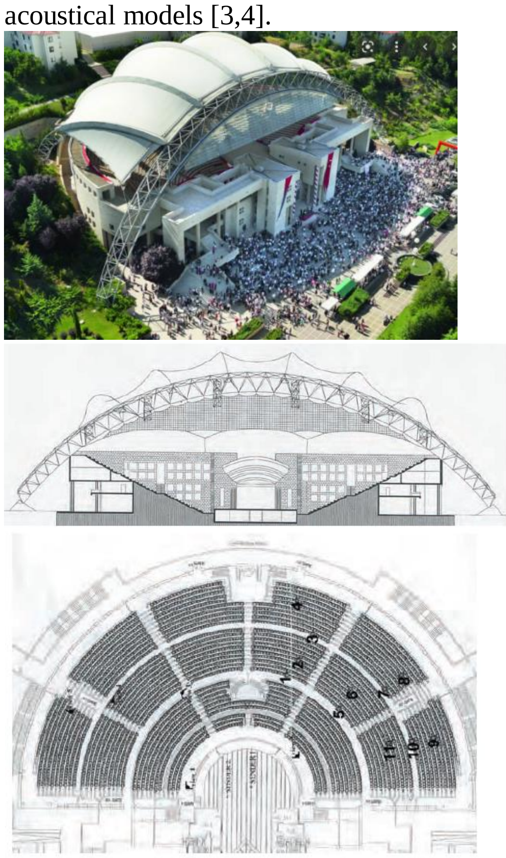

Figure 7 – Bilkent ODEON; arial photo (on top), section view (in the middle), plan view with source receiver positons (at the bottom)

The computer simulation of the hall for the unoccupied condition is performed using ODEON 6.01 (in 2006). comparison of the real-size measurements for the unoccupied

hall to computer modelling in the same condition of occupancy for model tuning. The second simulation is made for the fully occupied (present) hall, which is much crucial as much closer to the real conditions.
For the occupied state and for its current conditions the average T30 of the hall for mid frequencies is estimated to be 3.05 s, while the average is 6.67 s for unoccupied hall. The uneven distribution of the sound is observed in distribution maps (see Figure 8), which supports the present complaints by the audience.

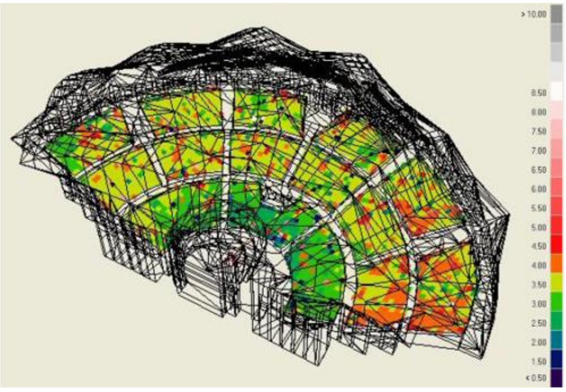

Figure 8 – Early decay time distribution map for 500 Hz and for the fully-occupied hall, Bilkent ODEON

The problems were even greater before the current state. As in order to heal the harsh reflections and hot spots sound absorbing acoustic fabrics are partially attached in between steel trusses at the back zone. However, this treatment has not yet satisfied the desired acoustical quality of the hall (Figure 9). The overall form of the roof has to be re-shaped otherwise sound absorptive treatment application has to be widely applied under the PVC membrane. In order to prevent acoustical hazards caused by the shelter creating an immense volume underneath, it is a necessity that the sound absorption area should be drastically increased. Maybe, in this era too we should respect the mostly open tradition of ancient amphitheatres settled at the hill sides, and leave the audience open to the atmosphere and fed by the direct sound arriving from the stage only.

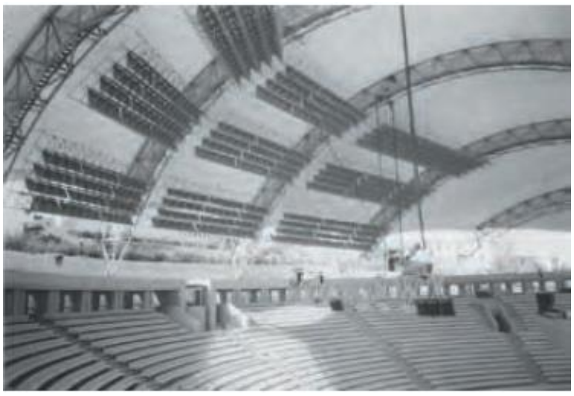

Figure 9 – Interior view showing the sound absorptive panels at the rear zone of the amphitheatre

2.CONCLUSIONS

In this paper, the striking difference in the analysis results of ancient and modern day open-air theatres gives clues to challenges faced 30 some years ago. These challenges will be grouped and addressed below:
a. Analog versus digital instrumentation:
Inflexibility of analog means of measurement in those old days is a major drawback challenging researchers.
b. Deficiency of infrastructure:
Electrical power was not available in all three theatres. The measurement team had to rely on battery powered instrumentation. 12-VDC car battery was the only option for the researchers
c. Transportation: Some of these theatres were located at the top of the hills as the cities they serve were setup at high altitude and in distant places due to security issues. Reachability as well as transporting the measuring equipment has posed major problems when the theatres were visited for measurements. The size and weights of equipment were much bigger than the digital counterparts.
d. Early days of simulation tools:
In those days simulation software was in the development phase. Researchers had to abort to "homemade" software lacking calibration and justification. Theoretical basis for some simulations were still under development.
Even with all these drawbacks it was still possible to analyse the acoustics of such structures of the past. It was possible to point out locations where critical acoustical problems could be faced.

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The Loggia Cornaro (1524) as a bridge between the ancient and the modern theatre.

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ABSTRACT

In ancient open-air Roman theatres, the *scaenae frons* increases the directivity of the sound source to better convey the actors' speech to the audience. Since such an acoustic effect is closely related to the presence of architectural elements such as awnings and columns, specific insights are needed for each case. The present work concerns the acoustics of the Loggia Cornaro in Padua (Italy), an outstanding example of Renaissance columned portico (1524) with a well-preserved Roman-style *scaenae frons* intended to host open-air theatre performances. Acoustic measurements were performed in the Loggia and the adjacent forecourt according to ISO 3382 -1. In addition, a numerical model of this hybrid indoor-outdoor site was developed and tuned till the match with the measurements' outcomes. Bayesian multi-decay analyses determined the actual influence of the scenery on sound propagation throughout the audience area. The main results prove that the Loggia not only increases the sound source level but also leads to different multi-slope sound energy decays depending on the sound sources' location, which are typical traits of modern indoor theatres.

Keywords: open-air theatres, acoustic simulations, multi-decay analysis, cultural heritage.

1. INTRODUCTION

Ancient open-air Roman theatres often include a portico with a colonnade as an integral part of the whole complex. The *scaenae frons* contributes to enhance the sound propagation throughout the audience area. During the Renaissance era the general attention to the past gave the concept of Roman theatres a new life. The Loggia Cornaro in Padua is the first tangible reconstruction of ancient theatres' architectural concept dating back to the XVI Century [1]. This performance space belongs to one of the most interesting Venetian architectures of that historical period [2, 3]. Such an open-air space was conceived as an ancient theatre since the beginning, when it was designed by the architect Falconetto for the patron of arts Alvise Cornaro [4, 5]. According to historical writers, the Loggia is the perfect interpretation of Vitruvius theatre: from the *columnato* ("colonnade") to the *cavea* (the seating area in ancient theatres). This is confirmed by Falconetto's renowned expertise in terms of ancient theatres' architectural features. Even though the stone employed in the construction is particularly sensitive to the deterioration caused by time, atmospheric agents, and pollution, the space is so well preserved that it is still nowadays used for theatre performances (see Figure 1). The presence of the audience located in the forecourt is witnessed by several manuscripts [3, 6]. The same historical references confirm the exploitation of the Loggia for Ruzzante's plays and comedies.

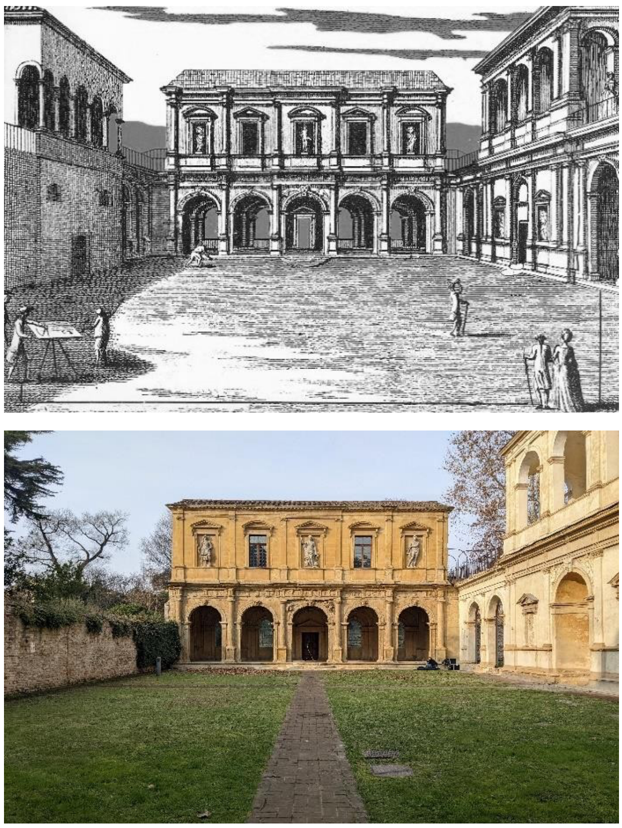

Figure 1 – Historical picture and current view of the Loggia Cornaro (Padua).

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The present study explores the acoustic properties of the Loggia Cornaro with a specific focus on the different effects provided by the portico on the signal depending on the location of the sound source. A 3D model was built basing on in situ geometric surveys. Then, it has been tuned on the experimental results (ISO 3382-1 room criteria) through ray-tracing techniques. The main outcomes prove the place to be acoustically similar to an indoor theatre, confirming the role of the Loggia as a unique bridge between the ancient and the modern theatre [7]. Unsurprisingly, a few decades later and not far from Padua – in Vicenza - the renowned architect Andrea Palladio designed the Teatro Olimpico ("Olympic Theatre"), which is one of the first examples of indoor theatres [1-5].

2. ACOUSTIC MEASUREMENTS

In February 2022, a geometrical and an acoustic survey of the Loggia Cornaro were carried out. The aim was to create a reliable 3D virtual model of the space and to investigate the acoustics of such a particular place. The main geometrical features of the Loggia are provided in Table 1.

Table 1 – Main geometrical features of the Loggia.

Feature	Quantity
Length [m]	20
Depth [m]	6.2
$h_{portico}$ [m]	5.8
h_{total} [m]	10.7
Arches [n°]	5
Forecourt [m^2]	620

The most significant room criteria have been collected according to guidelines outlined for Renaissance-Baroque theatres and in compliance with ISO 3382-1. Also, the layout of the acoustic measurements was set according to the guidelines outlined for Italian opera houses [8, 9]. Therefore, the Loggia was considered as a stage, and the forecourt as the stalls area of a theatre. Three points were selected for the location of the dodecahedron (omnidirectional sound source): the first on the proscenium (S1); the second at the centre of the portico (S2); the third one in the forecourt among the receivers (S3), as it is shown in Figure 2. Nine monaural microphones were used as receivers and placed according to a regular grid (3x3) throughout the outdoor court. Regarding the reverberation time, the main experimental results are reported in Table 2. The mean value of measured reverberation time is 1.58 seconds (125 – 4kHz), considering all the source-receiver pairs. As expected, when the sound source is at the centre of the columned portico (S2) the measured values of reverberation time are longer than the rest of the values (T_{30} = 1.67 s). By contrast, when the source is in the audience area (S3), the values obtained are shorter than in the other cases (T_{30} = 1.51 s).

Figure 2 – Two of the three sound source locations employed: on the proscenium below the main arch (S1) and at the centre of the portico (S2).

Instead, the sound strength values are very similar for the three source positions (st. dev. < 1dB), proving that the *scaenae frons* together with all the surrounding buildings behave as a single volume. Moreover, the high value of measured G (mean values equal to 8 dB) proves that the hybrid indoor-outdoor theatre contributes to significantly increasing the sound source level at the receivers, as it happens in indoor theatres [10,11]. With this purpose, the trend of G values as functions of source-receiver distance has been analysed. Figure 3 shows the spatial distribution of measured G values at mid frequencies (500 – 1 kHz) compared to the predic- tive trend according to Barron and Lee's *revised theory* (input data T_{S1} = 1.57 s; T_{S2} = 1.67 s; T_{S3} = 1.51 s; V = 7000 m^3). It is interesting to notice that the spatial distribution of the sound strength is in line with the slope of the predictive curves, which have been developed for concert auditoriums [12]. Moreover, as expected, the most significant gain is given when the sound sources are in the Loggia (S1 and S2). Such data justify the intended use of the hybrid indoor-outdoor space as a place for theatre performances, where proper voice support and adequate speech intelligibility are required even at 20 meters from the speaker.

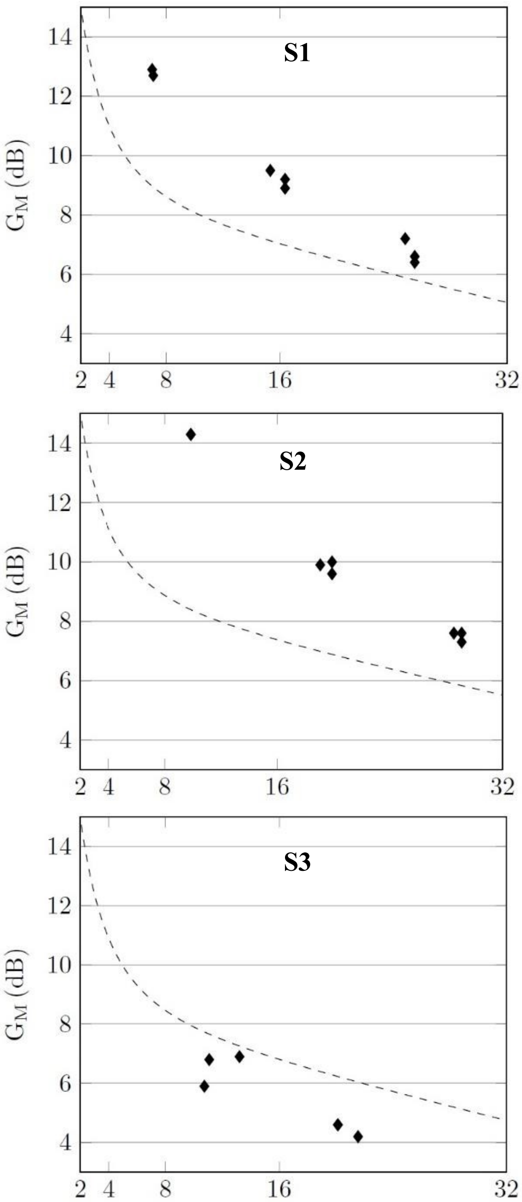

Figure 3 – Measured G_M values as functions of source-to-receiver distance. "M" subscript indicates the values averaged over the central octave-bands 500 -1 kHz. Dashed curves are the *revised theory* curves by Barron and Lee [12].

3. NUMERICAL MODEL

A ray-tracing time-dependent approach was adopted to better analyse the acoustics of the Loggia and the adjacent buildings (ODEON Room Acoustics). The 3D virtual model of the whole space was created according to the geometrical acoustics (GA) state-of-the-art (see Figure 3) [13]. The calibration of the model was achieved by considering two main materials - the stone and the grass - with the equivalent area of all the surfaces involved. The α coefficients in octave bands are provided in Table 2, along with the comparison between measured and simulated T_{30} at the end of the calibration process. The scattering value was set equal to 0.5 for the surfaces corresponding to the capitals' decorations, and equal to 0.1 for the remaining surfaces (floors, columns, ceilings). A transition order equal to 2, an impulse response length of 2 s, and 60 k rays were used during the simulations.

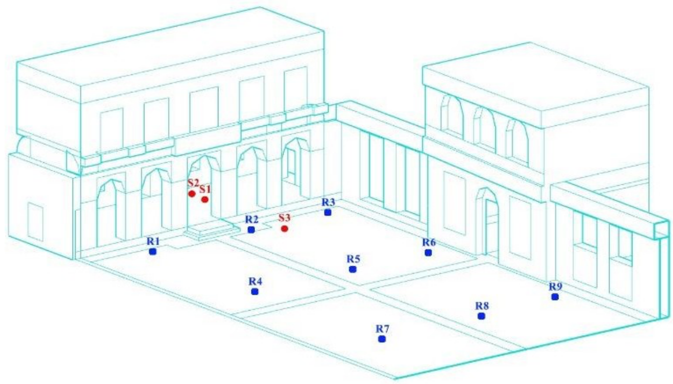

Figure 4 – Layout of sound sources (red) and receivers (blue) in the 3D model (Sketchup 2021).

Table 2 – Measured and simulated T_{30} values along with the absorption coefficient of the materials employed in the numerical model.

	125 Hz	250 Hz	500 Hz	1k Hz	2k Hz	4k Hz
S1 Meas.	1.86	1.69	1.61	1.61	1.49	1.17
S1 Sim.	*1.93*	*1.76*	*1.71*	*1.57*	*1.48*	*1.17*
S2 Meas.	2.03	1.85	1.68	1.67	1.54	1.22
S2 Sim.	*1.96*	*1.78*	*1.73*	*1.59*	*1.51*	*1.20*
S3 Meas.	1.72	1.60	1.61	1.57	1.45	1.14
S3 Sim.	*1.76*	*1.57*	*1.53*	*1.40*	*1.32*	*1.04*
$\alpha_{sandstone}$	0.02	0.03	0.03	0.04	0.04	0.05
α_{grass}	0.05	0.06	0.06	0.06	0.08	0.20

4. MULTI-DECAY ANALYSIS

A Bayesian multi-slope analysis was carried out on the decay curves obtained from the measured room impulse responses (RIRs) [14]. Figure 4 shows the results for the three locations of the sound source, considering the receiver at the centre of the forecourt (R5). According to the following expression:

$$H_s(\mathbf{H},\mathbf{T},t_k) = \sum_{S=1}^{2} H_s e^{-13.8 t_k/T_s}$$

H_s is the Schroeder curve, **T**= T_1, T_2, and **H** = H_1, H_2 are the decay parameters shown in Figure 4 [14]. It is possible to notice that the non-linearity of the decay curves is slightly detectable for S1-R5 pair, totally absent for S2-R5 pair, and clearly visible for S3-R5 pair. This is also confirmed by measured EDT/T_{30} ratios at 1 kHz:

- 0.89 for the sound source located in S1,
- 1.02 for the sound source located in S2,
- 0.76 for the sound source located in S3.

The significant appearance of double slopes in S3 is probably due to early reflections' behaviour throughout the forecourt and to the proximity to the sound source [15]. Finally, the calibrated model was employed to confirm the multi-slope decay curves corresponding to the different locations of the sound source (simulated EDT/T_{30} ratios: 0.92 for S1, 1.03 for S2, 0.66 for S3).

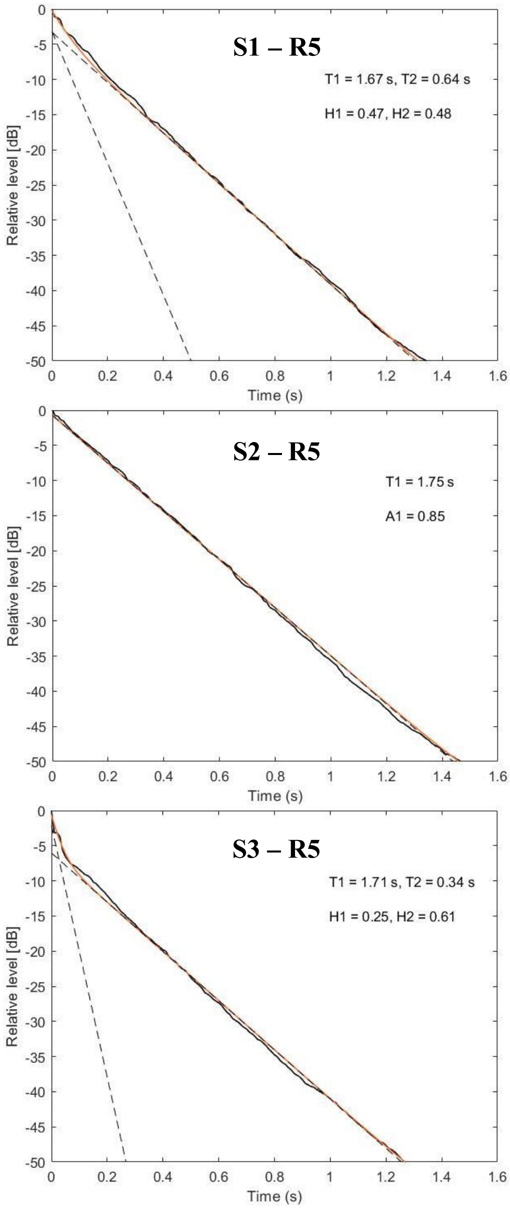

Figure 5–. Multi-decay analysis of measured IR at 1000 Hz with the sound source in S1, S2, and S3 positions and the receiver located in R5 (see Figure 3) [16].

Therefore, even though the Loggia Cornaro shows typical traits of ancient theatres, such as the *scaenae frons* and the small proscenium for an orchestra, the presence of surrounding buildings contributes to giving the performance space the acoustic features of indoor theatres [16].

5. CONCLUSIONS

The present work investigates the acoustics of a Renaissance *scaenae frons* (1524) intended to host open-air theatre performances. The experimental results confirmed the increase in the sound source level and clarified the distinct acoustic behaviour depending on the location of the sound source. High values of sound strength (up to 14 dB) have been obtained for all the sound sources involved. This is probably the consequence of a natural amplification caused by the Loggia and the surrounding architectures on the sound signal. The multi-decay analysis and the EDT/T_{30} ratios (measured and simulated) confirm the different acoustic behaviour depending on the location of the sound source. Since the Loggia combines elements of the past with typical acoustic traits of opera houses, it can be considered as an interesting bridge between the acoustics of the ancient and the modern theatres.

ACKNOWLEDGEMENTS

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From Terrestrial Laser Scanning to Room Acoustics Simulation: Recent Approaches to 3D Modelling for the Investigation of Late Antique and Early Medieval Acoustics.

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ABSTRACT

Recent archaeological investigations of late antique and early medieval acoustics reassess how digital technologies and interdisciplinary approaches shed new light on the history of sound. This paper outlines some of the questions and methodological problems raised by historical acoustics, and discusses digital modelling techniques to tackle them. It shows how information on the acoustics of existing and recreated buildings can be obtained using different datasets and tools.

Keywords: Laser scanning, modelling, intentionality

1. INTRODUCTION

Recently digital technologies allow for acoustics simulations in 3D virtual models of existing, reconstructed, or non-existing spaces. For this purpose, scholars and entrepreneurs have been discussing how to produce models that can be designed in a reasonable time, cope effectively with the limits of available software, and maintain sufficient accuracy to perform reliable simulations [1]. However, modelling has been seldom discussed in relation to the theoretical problems imposed by historical reconstruction. The extent to which different models can be used to address more appropriately some research questions rather than others needs to be carefully considered when reconstructing past acoustics. The present paper explores the interplay between modelling and reconstruction. It focusses on structures built between Late Antiquity and the Middle Ages in the Mediterranean area and in Britain. The acoustic analysis of the case studies is not discussed in detail here as it will be the object of specific forthcoming publications. Instead, this contribution provides a theoretical introduction to the relationship between virtual modelling techniques, research questions, and research outcomes in the study of past acoustics.

2. MODELLING TECHNIQUES APPLIED TO THE STUDY OF HISTORICAL ACOUSTICS

Two typologies of virtual models for digital acoustics simulations are discussed in this paper: 1) Models aimed at reproducing accurately the geometry of a building; 2) Models aimed at reproducing conceptual interpretations of a building.

The first typology is suitable to investigate how the geometry of a space impacts on sound reflection. Their accuracy limits the effect of surfaces deconstruction into polygons – typical of mesh models – on the results of acoustic simulations.

The simplified design of models belonging to the second typology reduces the time of software calculation, and makes them particularly suitable for highly-precise digital simulations of acoustics.

2.1 Models from 3D laser scanning.

Precise structural surveys are necessary to design virtual models that are suitable to investigate the interplay between sound and space. Minimal differences in the orientation of modelled surfaces can dramatically impact on the results of acoustics test [2]. With some exceptions [3], models for acoustics simulation are generally designed after available plans and elevations. However, recent research [4] shows that architectural drawings published in hard-copy can be unreliable for accurate analyses. 3D laser scanning overcomes this problem by providing exceptionally precise surveys. The infrared beam emitted from a laser scanner returns thousands of measured distances per second from the surrounding environment. These measurements can be visualised in software as 3D point clouds. The error range of the correctly processed point cloud of a building rarely exceeds 3 millimetres.

Three buildings have been investigated using digital models derived directly from 3D laser scanning data: the sixth-century basilica of S. Apollinare in Classe near Ravenna (Italy) [4, 5] (Fig. 1, A), the experimental reconstruction – at the local Museum in Jarrow (UK) – of a fifth/sixth century CE timber structure (Building A) excavated at Thirlings in Northumberland (UK) [6, 7], and the rural church of Agios Ioannis Theologos at Adissarou in Naxos (Greece) [8, 9, 10].

Laser scans of each structure were obtained using a FARO laser scanner Focus3D X 330. An optimised triangular mesh was produced from the point cloud of each building using FARO Scene, and exported in the .ply format. Each mesh was opened in MeshLab and re-exported as a .3ds file to be segmented into its main structural elements in Autodesk 3Ds Max Design. The mesh

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was then exported in the .dxf and AutoCAD format to repair its leaks and faulted geometry. All the unspotted leaks were identified in 3Ds Max Design using the "open edges" view and repaired in AutoCAD. Finally, using AutoCAD, the triangles of the mesh were grouped into layers according to the elements and materials that they represent. At this point, the models were imported into ODEON Room Acoustics.

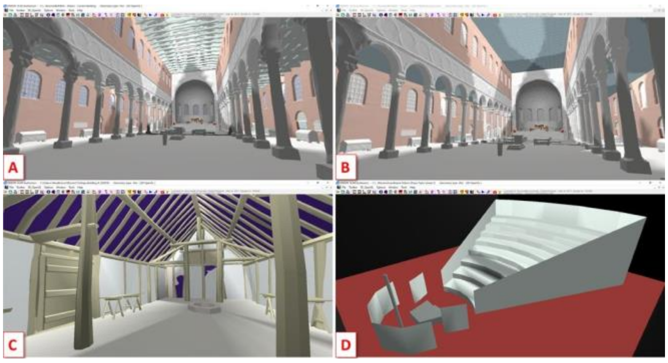

Figure 1 – Selection of 3D digital models of the case studies mentioned in the text, visualised in ODEON Room Acoustics (G. Foschi).

For faster calculations, the meshes were simplified into models with fewer surfaces. To prevent geometrical distortions during the simplification, each layer of a mesh can be imported into MeshLab, its border selected, the selection inverted, and the new selected surface decimated or smoothed to an acceptable extent. Since its borders are untouched, the simplified surface will fit into the rest of the mesh once reimported into AutoCAD. This procedure was applied to the model of Agios Ioannis Theologos at Adissarou. An alternative method is the manual creation of a geometrically simplified "shell-mesh" matching the main features of the digital model. This procedure was applied to the reconstruction of Building A from Thirlings [Fig. 1, C], obtaining a model of 5368 surfaces.

The geometry of the meshes derived from laser scanning can be altered to test different architectural settings and furnishing, or to reconstruct previous phases of the building. This method has been used to explore how acoustics is affected by a coffered ceiling [Fig. 1, B] or a lower presbyterium in S. Apollinare in Classe, by a wooden floor in the reconstruction of Building A from Thirlings, or by other furnishing and architectural solutions in Agios Ioannis Theologos at Adissarou.

2.2 Manually designed models.

The second typology described in this paper is constituted by virtual models reproducing conceptual interpretations of historical sites. Conceptual models convey information beyond the archaeological record and therefore entail historical reconstruction to a larger extent. Gaps in the knowledge of how the features of a building were conceived need to be filled with hypotheses and speculations. Data from excavations, wall stratigraphy, written sources, metrology, and information on design techniques must be critically considered for this purpose. Nevertheless, any outcome of tangible or intangible heritage reconstructions is inevitably influenced by subjective theoretical backgrounds [11]. In order to obtain meaningful results and address unavoidable biases, archaeological theories and historiography [12] must be taken into full account. For this reason, it is best practice to consider a range of alternative hypotheses, and maintain a clear distinction between features designed on the basis of the archaeological record and features that are hypothetically reconstructed [13].

Conceptual models have been adopted for the acoustic analysis of four case studies. The first is the Lateran basilica in Rome (Italy) as it could have been in the 4th century CE [14, 15]. The dimensions of the model were based on the laser scanning survey of the basilica's fourth-century foundations and on a thorough scholarly reconstruction of its possible elevation [14]. The second case study is S. Apollinare in Classe [4, 5]. A total of 3,794 manual and 794 calculated measurements were performed in AutoCAD directly on the point cloud from laser scanning. This enabled the identification of possible units of measurement used during the construction of the basilica, an assessment of its layout quality, and formulation of hypotheses on how the building was conceived. The conceptual model of the building was designed on the basis of these results. The third case study is the wooden 'grandstand' excavated at Yeavering in Northumberland (UK), dated to the 6th/7th century CE [16]. A simplified virtual model of the hypothetical structure (Fig. 1, D) was designed based on excavation drawings published in 1977 [16], which constitutes the most accurate record of the building to date. The last case study is Agios Ioannis Theologos at Adissarou [10]. A thorough archaeological analysis of the church assisted the reconstruction of its possible conceptual design and the study of its chronological phases. On this basis, four virtual models of previous hypothetical buildings were designed to explore how acoustics change according to the main typologies of early churches known on the island of Naxos and in the Mediterranean (e.g. three-aisled vaulted or timber-roofed basilicas, with one or three apses).

3. METHODOLOGICAL RESULTS

3D surveys obtained with terrestrial laser scanning turned out to be an ideal starting point for the analysis of historical acoustics. The use of different typologies of virtual models obtained from them has expanded the range of verifications, research questions and outcomes.

3.1 Published surveys and 3D laser scanning.

The present investigation confirms that published plans and sections do not constitute reliable references for the design of geometrically accurate models. 3D laser scanning has allowed to observe for the first time that the outline of the apse curvature of S. Apollinare in Classe at the plan level is horseshoe-shaped and not semicircular, or that the dome of Agios Ioannis The- ologos at Adissarou is pointed and not hemispherical. These elements have a significant impact on the simu- lation of sound reflection.

3.2 Geometrical precision and acoustic parameters.

Highly precise models are unsuitable for exceptionally accurate acoustics simulations due to the long calculation times that they entail. Nonetheless, even standard simulations performed on them return relevant results. When precise virtual models are used, discrepancies between parameters obtained from acoustic simulations and measured on-site can be attributed with more confidence to incorrect sound properties – e.g. absorption coefficients or scattering coefficients – assigned to the surfaces rather than to geometrical inaccuracy. The sound parameters obtained for S. Apollinare in Classe and the reconstruction of Thirlings' Building A from the models directly derived from laser scanning data were extremely close to on-site measurements [17, 7]. This provided confidence in assigning the same sound absorption coefficients and scattering coefficients to simplified or modified versions of the models, allowing a more firmly grounded exploration of how acoustics change according to the different hypotheses on the configurations and materials of the building.

3.3 Sound reflection in detailed and simplified models.

Models derived from laser scanning and their conceptual simplifications can be significantly different as far as sound reflection is concerned. While their objective sound parameters usually do not show significant differences, the situation changes when sound reflection is visualised, as observed in the case of Agios Ioannis Theologos at Adissarou (Fig. 2). In the model obtained from 3D laser scanning, the dome of the building reflects sound in more directions than in the conceptual reconstruction. This is probably due to irregularities of the dome's inner surface, recorded by the scanner and practically impossible to be manually reproduced. It is therefore important to dispose of both detailed and simplified models for the validation of different typologies.

3.4 Intentionality in past acoustics design.

Precise surveys are a fundamental prerequisite to design reliable conceptual models, which are most appropriate to examine how acoustics would be if the building corresponded to the conceptual project of the designers with no irregularities or later changes. Thanks to the methods described in this paper, elements have been identified suggesting an intentional application of optics to sound reflection between Antiquity and the Middle Ages. This aspect can be exemplified by what has been observed for the acoustic relation between the apse and the nave of the investigated early churches and between the stage and the audience area of the grandstand at Yeavering. In all this cases, the geometry of the semi-circular surfaces generates a sound phenomenon that matches Vitruvius' description of a "circumsonant" place (*De arch*, V, VIII, 2). The voice of a person facing the semi-circular surfaces from a certain distance is reflected towards the focus of the curvature and then laterally dispersed. On the contrary, sound is reflected forward and significantly reinforced when emitted in close proximity of the curved surfaces. This creates a sharp hierarchical differentiation of space by means of acoustics: in the early churches considered here, differences exceeding JNDs in Ts, D_{50}, C_{80} and STI values indicate that an audience standing in the central nave would perceive a voice emitted from the inner limit of the apse – where the *cathedra* and *synthronon* were located – as more clear, loud and intelligible than a voice sounding from the area immediately in front of the apse. Finally, in the Yeavering grandstand, the presence of the semi-circular screening significantly increases the strength of sound inside the structure. These and other recently discussed examples from written sources [18] encourage new research to assess the extent to which acoustic notions were used to model the acoustics of spaces between Late Antiquity and the Middle Ages [15].

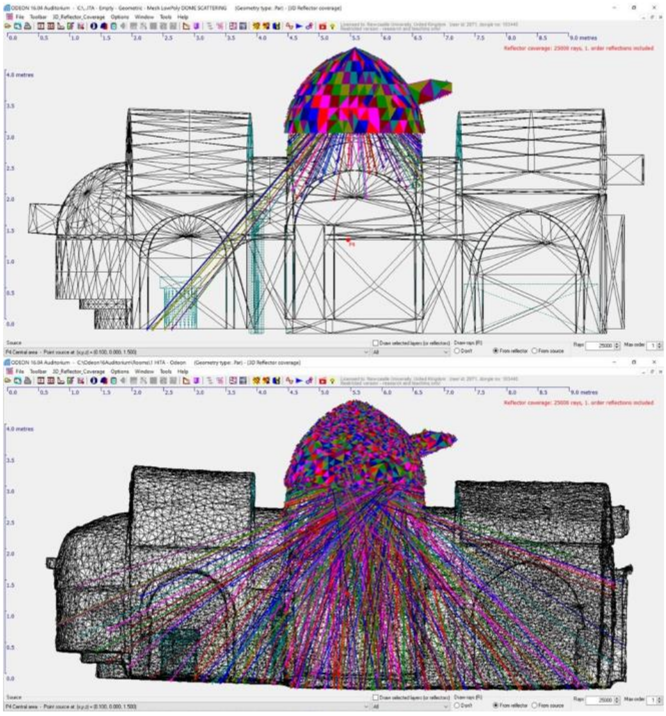

Figure 2 – Agios Ioannis Theologos at Adissarou. 3D Reflector coverage of the dome in ODEON Room Acoustics: conceptual reconstruction (above); model from 3D laser scanning (below) (G. Foschi).

4. CONCLUSIONS

Although highly simplified 3D models are generally used for digital acoustics simulations, the more a model is accurate, the wider is the range of research questions that can be addressed. A reliable geometry in a virtual model used for acoustic simulations favours the identification of sound absorption and scattering coefficients. Furthermore, simplified models producing acceptable results cannot be designed without exceptionally reliable 3D surveys. Only precise models provide correct visualisations of sound reflection, which are fundamental to investigate the application of optics in acoustics between Late Antiquity and the Middle Ages and, more in general, intentionality in historical acoustics.

Although this paper has been concerned with the technical side of modelling it should not be forgotten that sound perception is increasingly recognised as a social construct, subjective rather than objective, and largely dependent on individual backgrounds and historical factors [19, 20, 21, 22]. Its investigation requires a broad theoretical approach combining disciplines such as history, philosophy, sociology, psychology, biology, landscape archaeology, and engineering.

ACKNOWLEDGEMENTS

Agios Ioannis Theologos at Adissarou was surveyed in 2015 by Sam Turner and Alex Turner (Newcastle University, McCord Centre for Landscape) within the "Apalirou Environs Project, Naxos", in collaboration with the Ephorate of the Cyclades. S. Apollinare in Classe was surveyed in 2017 by Newcastle University's McCord Centre for Landscape (Sam Turner, Mark Jackson, Alex Turner, Gianluca Foschi), in collaboration with the Museo Nazionale di Ravenna (Emanuela Fiori, Paola Novara, Aurora Ancarani, Elisa Emaldi). The digital model of the Lateran basilica was designed in 2017 by Ian Haynes (Newcastle University), Iwan Peverett (New Visions Heritage Ltd), Lex Bosman (University of Amsterdam), and Paolo Liverani (Florence University) within the "Lateran Project", and is now under investigation for the "Rome Transformed Project". Laser scanning of the reconstruction of Building A from Thirlings at the "Jarrow Hall Anglo-Saxon Farm, Village and Bede Museum" was conducted by the author and Marco Romeo Pitone in 2020-1, and its impulse-response acoustic survey by Rebecca Romeo Pitone (Apex Acoustics Ltd) and the author in 2021. The 3D models and acoustic analyses of the buildings from Thirlings and Yeavering will be part of the Digital Collections of the Museum at Jarrow (project funded by Newcastle University and Groundwork South and North Tyneside). I wish to thank all the people I mentioned here, and also express my gratitude to Andrew Harvey for having proofread this paper with patience and dedication.

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Comparison of noise measurements and simulation on Siracusa Greek Theatre

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ABSTRACT

The paper describes the results of some noise measurements recently performed inside Siracusa Ancient Theatre, and the comparison with computerized model. More in details, the considered parameters are speech transmission index and clarity index C_{50}, measured in the field by means of MLS technique, and simulated on computer with numerical model.

Keywords: Model, STI, C_{50}

1. INTRODUCTION

The extraordinary Greek theater of Syracuse, presents itself, today, as a result of the expansion and of the reconstruction of the third century a.C. wanted by the tyrant Hieron II. What has come down to us, unfortunately, is reduces almost exclusively to part of the cavea cut into the limestone rock of the southern flank of the Temenite2 hill, a little elevated relief above sea level, which faces the Grand Port and the which you can see in the distance the opposite points of Ortigia and Plemmirio. Altogether disappeared are the highest part of the cavea and the scenic building, because the limestone blocks of both - steps for the one, wall structures for the second - between 1520 and 1530 were removed and transferred to Ortigia to be reused in the construction of the fortifications ordered by the sovereign Spanish Carlo V.

Today the Theatre is an important well known archaeological site, and it is used also for concerts and classical representations.

Figure 1 shows a picture of the Theatre captured form a drone.

In the period between summer 2021 and spring 2022, two measurement campaigns were carried out inside the Theatre. The first campaign was conducted when the theatre was covered with wooden benches and cushions, whereas the second campaign took place when benches were removed. The main idea of the research was to compare the results of measurements with the computer simulation of the theatre.

2. MEASUREMENT CAMPAIGNS

The measurements were performed by exciting the area of interest with MLS technique by means of a loudspeaker placed between proscenium and orchestra, and by detecting the response in 26 positions distributed inside the theatre, each of them placed 1 meter high from the seat.

Thanks to the acquired signals it was possible to calculate the impulse response for each pair of source-receiver point, and then compute all the classic acoustic parameters.

Figure 2 shows loudspeaker position (red colour) and receiving points position (green colour).

Figure 1 – Siracusa Theatre from a drone

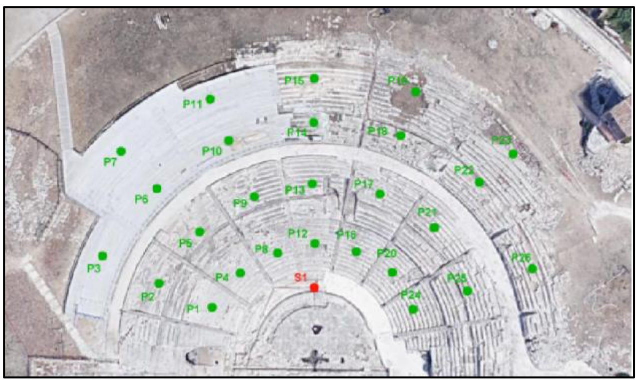

Figure 2 – Measurements points, © 2022 GoogleEatrh

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The MLS technique was implemented with a sequence length of 262144 points and a sampling rate of 48 kHz. The impulse responses were calculated by acquiring the signal coming from a microphone placed one meter from the loudspeaker and, sequentially, the signals coming from all the receiving points.

For the sake of brevity, in this paper only few results relating to the measurement campaign with wooden benches and cushions are reported.

3. MEASUREMENT RESULTS

The following chapters shows some results from the measurements. Results are presented as interpolated maps with 'multiquadric' interpolation algorithm.

3.1 Speech Transmission Index

As described above, starting from Impulse Response function it was possible to compute the Speech Transmission Index. A STI above 0.6 is considered good whereas a STI above 0.75 means that the intelligibility is excellent.

Figure 3 shows the Speech Transmission Index for the octave band of 125 Hz. The picture emphasizes a worse STI to the right-up part of the image where stones seats are still in place, unlike what happens to the left-up part where there are no stones anymore, and so STI is a little bit better.

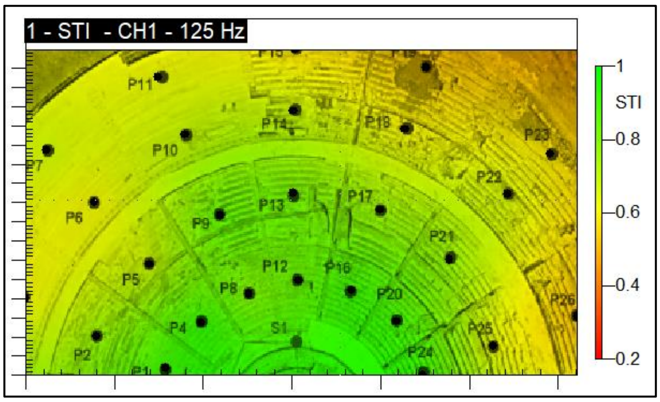

Figure 3 – Speech Transmission Index 125 Hz

In the same way, Figure 4 shows STI for the octave band of 250 Hz. For this frequency band it can be seen a more homogeneous behaviour.

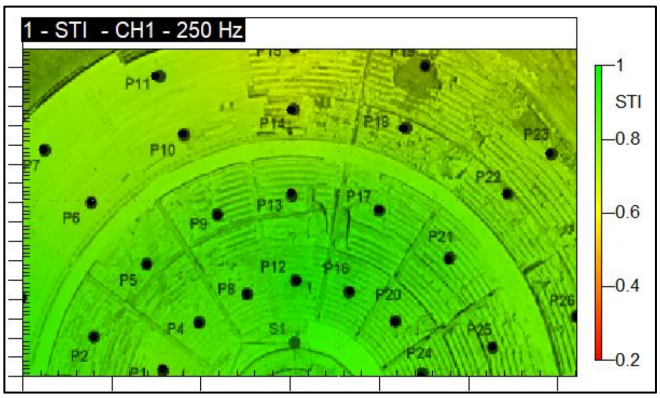

Figure 4 – Speech Transmission Index 250 Hz

Ones more, Figure 5 shows Speech Transmission Index for the octave band of 500 Hz. Even in this situation the map shows quite homogeneous values.

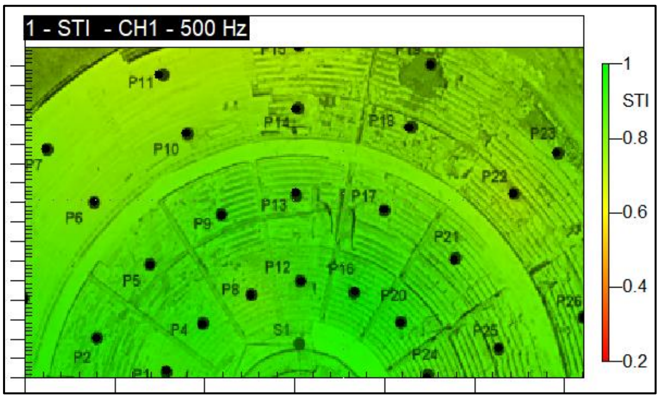

Figure 4 – Speech Transmission Index 500 Hz

In addition to the above, Figure 5 shows the spectrum representing the averaged Speech Transmission Index on all measuring points.

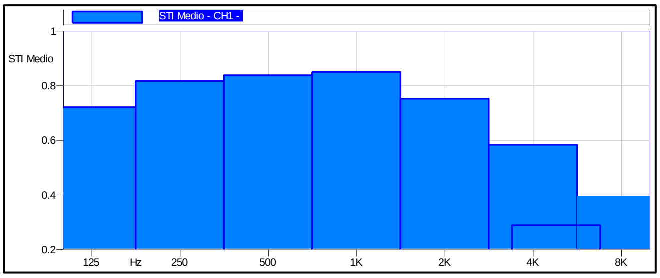

Figure 5 – Averaged Speech Transmission

Table 1 shows the standard deviation related of the STI averaged value. Smallest deviations are between 250 Hz and 1 kHz.

Table 1 – Standard deviation STI

Octave band	Standard deviation
125	0.13
250	0.08
500	0.08
1000	0.07
2000	0.12
4000	0.14
8000	0.12

3.2 Clarity indexes

Using Impulse Response function, also the Clarity Index C_{50} was computed. Generaaly an index above 3 is considered good for voice communication.

Figure 6 shows C50 for the octave band of 125 Hz. The image clearly shows some problems for all position that are far from the orchestra, especially on right-up part of the picture.

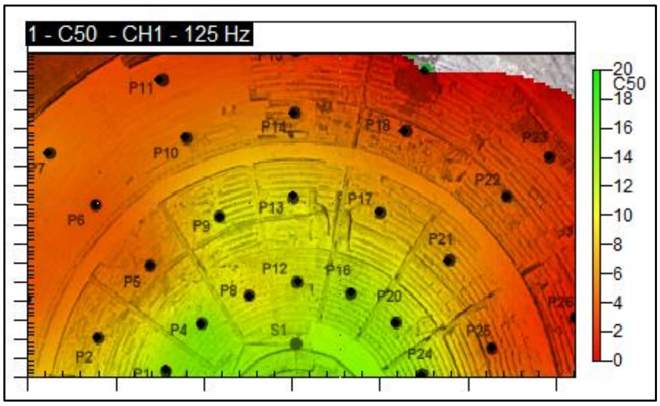

Figure 6 – C_{50} 125 Hz

Figure 7 shows C_{50} for the octave band of 250 Hz whereas Figure 8 is related to octave band of 500 Hz.

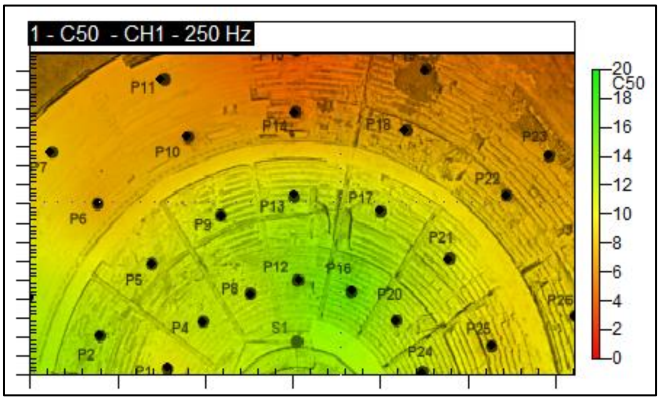

Figure 7 – C_{50} 250 Hz

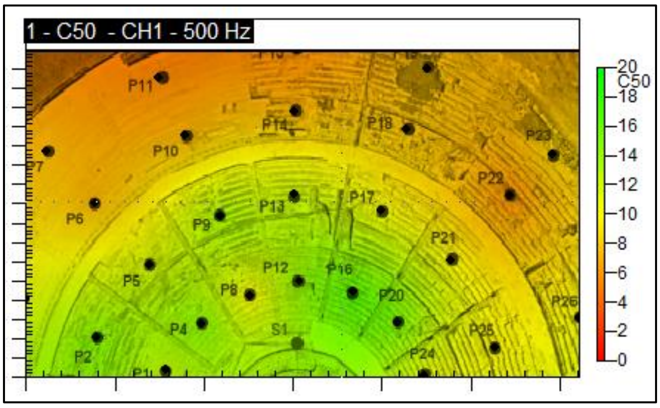

Figure 8 – C_{50} 500 Hz

Figure 9 shows the spectrum representing the averaged C_{50} on all the measuring points.

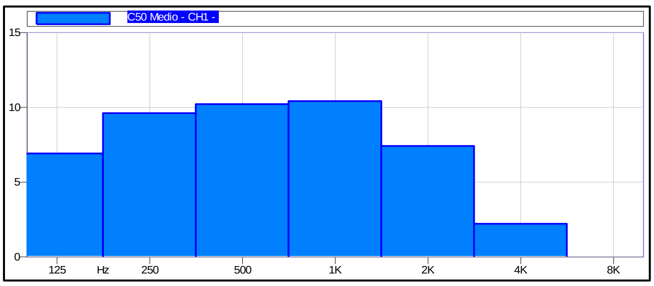

Figure 9 – Averaged C_{50}

Table 2 shows the standard deviation related to the average value (all positions). Smallest σ are between 250 Hz and 1 kHz, and for 8kHz band, where almost all the values are below zero, indicating a worse voice communication.

Table 2 – Standard deviation C_{50}

Octave band	Standard deviation
125	4.3
250	3.0
500	3.1
1000	2.5
2000	3.8
4000	4.2
8000	3.1

4. NUMERICAL MODEL

After the measurements, a simplified numerical model of theatre has been outsourced. Figure 10 shows the 3D model of the theatre which includes loudspeaker and receivers in the original positions for result comparison, plus others receivers in order to obtain more smooth maps.

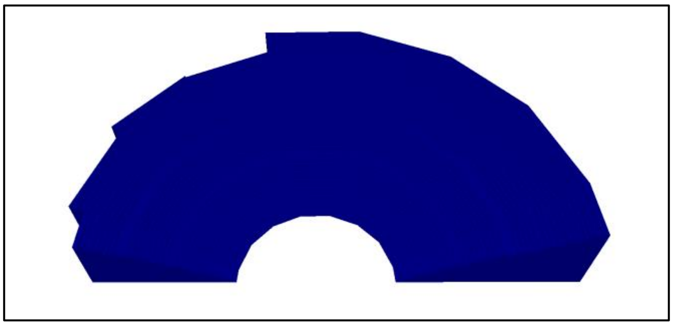

Figure 10 – Simplified numerical model

Thanks to the model it was possible to compute the impulse response function for each couple of loudspeaker-receiver positions, as well as all the other standard parameters, also collected in the field; then, after calculation, some comparison between measured and computed data were possible. Figure 11 shows an example of the computed Impulse Response function, in the example related to the octave band of 125 Hz. Using IRF is possible to compute parameters as reverberation time, EDT for each frequency band, and others, as well as is possible to make convolution with audio file and then auralization.

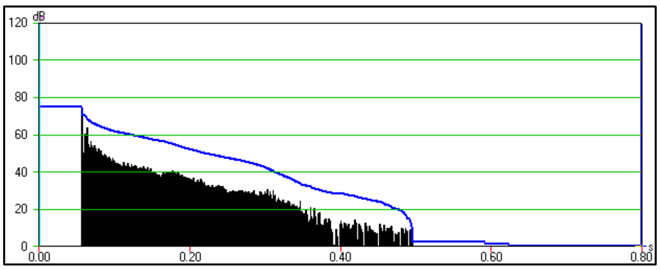

Figure 11 – Computed Impulse Response funcion

4.1 Sound mapping

Figure 12 shows the simulated A-weighted noise map due to an omnidirectional 110dB Lw loudspeaker, placed between proscenium and orchestra.

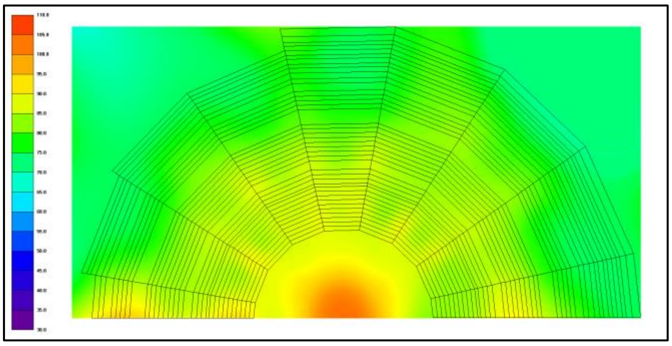

Figure 12 – A-weighted noise map

4.2 STI comparison

Figure 13 shows the computed STI map for the octave band of 125 Hz. Please note that the order of the colours in the picture is reversed respect to Figure 3, so the behaviour of the simulated STI for this band is practically similar to the experimental one. More in details there are low values in the upper right corner, and partially on the upper left corner.

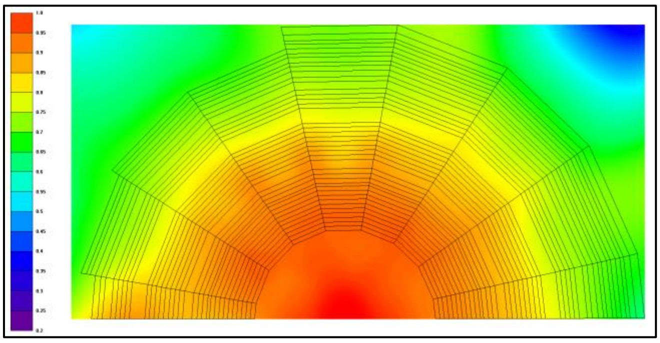

Figure 13 – 125Hz STI map

Figure 14shows the computed STI map for the octave band of 250 Hz. Also in this case the order of the colours in the picture is reversed respect to Figure 4, so the behaviour of the simulated STI for this band is again similar to the experimental one, that is more homogenous values.

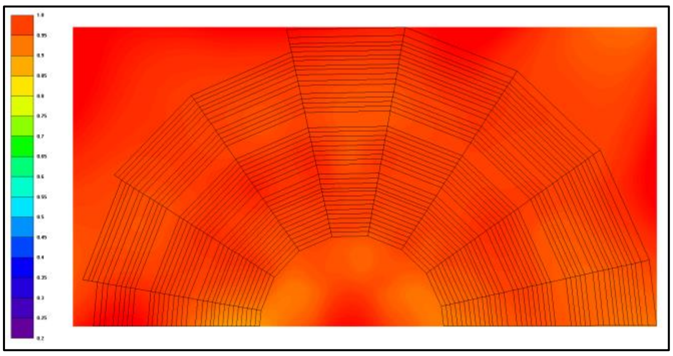

Figure 14 – 250Hz STI map

Similar behaviour is obtained for the 500 Hz octave band.

4.3 C_{50} comparison

C_{50} comparison showed an over estimation of the simulated parameter. Table 3 reports averaged measured and simulated values and, in the last column, the difference between values.

Table 3 – C_{50} comparison

Octave band	Meas.	Simul.	Diff
125	6.9	12.9	6.0
250	9.6	13.0	3.4
500	10.2	14.0	3.8
1000	10.4	16.0	5.6
2000	7.4	17.9	10.5
4000	2.2	19.3	17.1
8000	0	20.7	20.7

Data shows that differences are much higher at high frequencies. The reason for this mismatching is under investigation.

5. CONCLUSIONS

Measurement pointed some peculiarity of Siracusa Greek Theatre, which in any case demonstrate to have as very good acoustics. The comparison between experimental data and computer model, showed a good match of results for STI, whereas an overestimation of simulated C_{50} values, especially at high frequencies, emerged.

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Conservation, transformation and valorization of ancient theatres

The Acoustics of Ancient Theatres

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Architecture, Image, and Sound across history and time: conservation, transformation, and enhancement of Roman Theatres.

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ABSTRACT

The architectural heritage of the Classical age, present both in Italy and in the other Mediterranean countries, has been subject over the centuries to different phenomena that have caused either its abandonment or the continuation of its use, its transformation or the loss of its integrity. These processes have ensured the survival of these buildings through a continuous integration in urban and cultural activities. The paper presents the results of research aimed at the preservation of this heritage, suggesting strategies for its enhancement that proposes a project for tourist fruition according to the theatres and their cultural and geographical landscape.

Keywords: conservation, restoration, memory

1. COMMEMORATIVE VALUE AND PRESENT-DAY VALUE IN ANCIENT CLASSICAL THEATRES

The classical architectural heritage is a significant presence in Italy, Europe, and other Mediterranean countries. Over time, it has been subjected to strongly diverse phenomena, which have led to its abandonment, use continuity, transformation, or disintegration [1]. In particular, theatres, following destructive events or interruption of use, have reached a state of ruin after transformations, re-functionalization, repairs from several types of damages, restoration or structural reinforcement, and adaptations to new stylistic canons. On one hand, these processes hinder the analysis of the typological characteristics of their original configuration; on the other hand, they have allowed their survival by integrating them continuously in urban and territorial activities. The relationship between ancient buildings, new architecture, urban environments, or landscape contexts has lasted over centuries. Following changes in their in-use destination, theatres were used for handcrafting or agricultural activities or were converted into households. Aside from subsequent adaptations to modern urban fabrics, these functions stayed unchanged until – with the rediscovery of antiquity – archaeological excavations and restoration interventions compromised their secular stratifications [2].

Nowadays, these artifacts are an integral part of landscapes and cities; their continuous transformation dynamics, imposed by strategies aimed at the tourism requalification of these contexts, are inexorably producing drastic separation between these monuments and their urban-territorial contexts. Conversely, they had been built in the framework of an inseparable relationship between theatres and landscape; sometimes, the latter even represented a natural scene for theatrical representations [3].

Ancient theatrical architectures can be categorized according to three factors: the historical vicissitudes that have allowed their conservation, their use over history, and their appreciation in the past. Hence, they can be divided into four categories: buildings located in archaeological sites; formally recognizable buildings, located in urban areas; buildings that, despite being still present in cities and territories, can only be identified through small traces, or are incorporated into modern buildings or complex urban fabrics, through modifications that, while preserving archaeological monuments, have limited their architectural interest by hiding their classical typological features; finally, still poorly examined buildings that are located in landscape contexts. These latter have a variable conservation state, are often abandoned, and are rarely the object of cultural enhancement strategies [4]. This distinction is essential, as until now artifacts in archaeological areas, or in urban centers when evident and tourism-attractive, have received a much wider interest. The present and past cultural conditions have been suggesting – too often – recovery or (stylistic) restoration interventions to remove additions and revert to the original appearance of the monument: however, this has led to the loss of the historical traces accumulated on these buildings over time. The presence of stratified elements has not been subjected yet to a recognition process, especially because of the lack of suitable tools for the comprehension of the underlying secular stratification processes [5]. This framework is compounded by the execution of badly conceived works of 'functional actualization', which have mostly overlooked investigation actions and conservation practices, proposing valorization strategies exclusively aimed at immediate returns in terms of economic efficiency and tourism.

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The interest in the protection of the cultural heritage in Italy, Europe, and extra-European countries, and the launch of initiatives for the restoration of the archaeological heritage [6], require an improvement in the knowledge tools of this heritage, and strategies for conservation and cultural development for sustainable fruition project. This latter has been encouraged more than 50 years ago by the Franceschini Commission [7], and more recently reiterated by the Siracusa Charter in 2004 [8]. This also requires total respect for the transformation dynamics that have always guaranteed a close relationship between theatrical building, city, and landscape, in addition to the awareness that valorization could also be performed by letting nature 'use' the archaeological ruin for the sublimation of a specific urban or landscape context. Hence, this paper proposes some methodological reflections for the analysis of this archaeological heritage by suggesting tools for the analysis of the transformation processes and for the verification of their current conservation state, suggesting suitable strategies for culturally sustainable promotion [9].

Notably, in some areas in Italy, Europe, and Mediterranean countries some studies have been performed in recent years and have sometimes served as a starting point for valorization projects of the diffuse archaeological heritage, especially theatres of the Greek, Hellenistic, and Roman age [10]. Following a literature review, this research is aimed at knowledge deepening for the theatres whose history (transformations, re-functionalization, total or partial destruction, *ante litteram* safeguard actions, stylistic restorations) has not been studied with sufficient detail. They have been transformed by these events for about 2000 years since their construction until conservation and valorization policies [11]. This knowledge is indispensable, especially to their possible re-functionalization as cultural and musical venues.

2. FROM THE ABANDONMENT OF RUINS TO SUSTAINABLE REUSE

In the framework of interventions on archaeological artifacts, especially on theatrical structures from the Roman age, one of the key items is the full understanding of the intrinsic meaning of the ruins, of their symbolic and semiotic value, in addition to their tangible characteristics, which are the object of physical modifications. The re-functionalization of an archaeological ruin implies a new conceptual and interpretative paradigm, which is an integral part of a multi-disciplinary transformation project. As highlighted above, ruins recall void, absence, gap, silence, and have a deeply strong relationship with the Past [12].. Ruins must be intended as architectures on the theme of silence, and that is the reason why for scholars, researchers, and artists these contexts and remains have originated important reflections, which have influenced Western artistic, literary, and architectural culture in the last centuries. Probably for this characteristic and unicity, architectural ruins are a rich and invaluable heritage, whose conservation is frail and exposed to many threats: when transformed into a ruin, a building loses its function and shifts from being architecture to being a memory, a monument, and a simulacrum of the past [13]. The transition from an abandoned ruin to a restored building, with a new design, valid acoustic performance, and regulatory compliance cannot be implemented through the conversion of a single theatrical architecture; instead, it requires the semantic transformation of the surrounding landscape and context. In this perspective, the refunctionalization of the heritage can be performed only in a shared multi-disciplinarity and trans-disciplinarity, which allows a mutation of the historical context under careful supervision aimed at the conservation of archaeological and cultural ground [14]. Notably, some areas of the Italian, European and Mediterranean heritage have been the object of studies that served as a starting point for valorization projects on the diffuse archaeological heritage. However, this has been rarely supported by an interest in the landscape or urban context of the artifacts; instead, tourism-driven valorization projects have often led to landscape devastation and monument isolation, resulting in its desertification. Indeed, the study of a monument requires a complex knowledge process, starting from its origins and entailing all its historical stages, including the most recent ones, which have produced a surprising 'symbiosis' between human life and natural regeneration [15]. Hence, the main operations are: the individuation and cataloging of the heritage; the interpretation of the literary and epigraphic sources [16]; the consultation of cartographic, graphical, iconographic, and photographic records; the direct analysis of stratifications and the analysis of the conservation state of the buildings; the planning of interventions aimed at the conservation of the examined artifacts; the individuation of possible valorization strategies extended to the urban contexts and the landscape where the ancient places of performance are located [17].

In this perspective, the discipline of architectural restoration represents a potential coordination system for the activities aimed at the re-functionalization and valorization of the heritage. It can combine the fundamental study of archival and documental sources with the technique of building design and regulatory retrofit, hence coordinating transformations and ensuring a sustainable reconversion of the heritage. In fact, sustainability is not only related to the characteristics of the architectural work (soil consumption, material choices, programmed management criteria, …) but also to the cultural dimension, including social and communicational aspects. Transforming the ruins of Roman theatres into new, efficient places, yet preserving the historical value of the archaeological space and ground, appears to be the fundamental challenge of our time for the conscious conservation of the built heritage.

3. USING THEATRES: THE CHARTERS ON THE ANCIENT PLACES OF PERFORMANCE, ACROSS CONSERVATION AND RE-FUNCTIONALIZATION

In addition to the abovementioned feature, another peculiar characteristic of ancient places of performance is the specific focus received by the International Charters, where the general strategies for the conservation of the cultural heritage are intertwined with more the cogent guidelines for archaeological artifacts. The Segesta Declaration (1995), the

Verona Charter (1997), and the Siracusa Charter (2004), despite not having a doctrinal nature, have become the reference documents for the compatible and sustainable use of theatres and amphitheatres, and have influenced many European and Mediterranean cultural strategies in this field.
They follow the *European Convention on the Protection of the Archaeological Heritage* (Valletta, 1992), adopted by the European Council, which had a mainly socio-political purpose, that is to fortify European identity also through the development of the heritage [18]. The pursuit of this goal has triggered the activation of many knowledge projects on this theme, in relation to the acoustic performance or the geometric and material configuration of buildings [19]. Moreover, it supported the restoration of the original in-use destination of many theatres, opening them to events and performances. Safety requirements and the intention of clearly displaying the original layout of the theatrical spaces often led to quite massive interventions, where reintegration was prioritized to the persistence of stratified spaces shapes and materials. This hints at a contradiction in the three Charters: the importance of the "minimum intervention" is affirmed, yet the reuse of theatrical structures is strongly encouraged, as if it were the only available option for their conservation.
Since the use of a building clearly implies a maintenance activity, is it necessary to fully restore the efficiency of ancient theatres, so as to make them available for reuse? Since the three Charters pursue this goal, are they antithetical to the criteria of restoration? Definitely not. Indeed, they have deeply influenced the cultural climate, fostering an in-depth technical analysis of every aspect of ancient places of performance. In particular, the Siracusa Charter provides well-founded support to the whole methodology of data acquisition and improved comprehension of these architectural organisms and contains useful management suggestions. However, not all ancient places of performance should receive the application of these directives, simply because not all of them are compatible with transformation. Or rather, they could be, but they would be turned into mere simulacra of design hypotheses.
The fulfillment of the transversal validity of the Charter requires clarifying that use is not an absolute postulate, but only one of the possible paths: probably, this path can be chosen only for a limited number of buildings. Different scenarios should be envisaged for all the others, in compliance with the indicated procedure: these could range from simple structural reinforcement to partial reconstruction, making them understandable but not usable, or even to the conservation of their collapsed state, with simple safety interventions [20]. In all these cases, as suggested in the Valletta Convention, there could be a more intense focus on virtual reconstructions, through shared scientific modalities, using the results of research activities also for communicational purposes [21]. If this were not to occur, the undoubtable critical validity of the Siracusa Charter would keep being hindered. It would end up being a *checklist* for the achievement of good results, yet perceived as univocal. This should not happen, as restoration is, first of all, a philosophy [22], and its results – be they satisfying or not – derive from a cultural reflection that technique must merely put into practice [23]. For all these reasons we believe that, after almost twenty years, the Charter should be revised: not in its prescriptions – which are still functional and effective – but in its premises, freeing it from eminently political interests. This opinion is also motivated by the introduction of new documents, which are changing the approaches to the heritage, such as the Faro Convention [24]. However, these documents must also be contradicted when they give higher importance to identity and processes than to the constraining role of architectural material, for the definition of orientation principles and operational models in restoration [25]. These latter must be questioned even more than the postulate of use; at least, they must no longer be the base for reflections that produce effects on the authenticity of the cultural heritage [26].
In conclusion, we believe this to be the time to debate again the fate of ancient places of performance. However, the object of the debate must not be "how" to intervene to preserve and use them at best, but "why" doing that. Almost thirty years of Declarations and Charters-driven restorations have certainly produced food for thought, together with the results of research in this field. However, these latter must be critically interrelated, leading to a trans-disciplinary – not only multi-disciplinary – comparison, based on a complex, global, and, above all, inclusive vision of knowledge [27].

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The Colosseum: an iconic space

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ABSTRACT

The Colosseum is the greatest and most important Roman Amphitheatre, built by the Flavian dynasty. It is the most visited monument in Italy and has become an icon for its imposing architecture, for the memory of the popular shows performed in it and later for its Christian reuse.
The restoration works started at the beginning of the XIX century and never stopped until today, thus both to preserve the monument for the future generations and in order to assist contemporary visitors by introducing facilities such as elevators, a modern lighting system and the new arena floor.

Keywords: Colosseum; conservation; visitors

1. INTRODUCTION

The Colosseum is not only an icon, a must-see, visitors from all over the world come to Italy and to Rome attracted by the charm of a nation that has identified itself with its culture and art. The amphitheatre is also one of the most extraordinary monuments of antiquity, in terms of building technique, architecture, history and symbolic function; it is still capable of engaging visitors in an exciting journey, seducing the imagination, inspiring new stories that renew its fascination lasting since 2000 years.

This story begins at the time of Emperor Vespasian, in 71 AD, when the construction of the Colosseum began in the valley occupied by the immense lake around which Nero's *Domus Aurea* stood and where the colossal statue of the emperor was placed.

The inauguration took place under Emperor Titus in 80 AD, spectators accessed the monument passing through numbered archways each bearing a ticket to reach the assigned place in the *cavea*. Seats were strictly divided according to their social class. The performances attracted people from all over the empire, and the amphitheatre became a real melting pot. Noise and bustle characterised the stands, darkness and stench the underground levels where the "entertainment machine" was set up. This is where slaves, animals, those condemned to death and above all gladiators, waited to appear on the *arena* floor. During the first centuries of its use, earthquakes along with renovations requested by emperors, led to modifications, restorations and new installations, all designed to accommodate between 50,000 and 70,000 people.

The shows lasted till the 6th century, when new political demands and religious fervour, along with the Christian Emperors' aversion to bloody games, contributed to the progressive deterioration of the building. As a symbol of imperial power it reflected the city's decline: the building was turned into a place of conflict between Rome's most prominent families, a domestic space with stables and vegetable gardens, until it was lastly silenced and abandoned, and its ancient role forgotten.

From the Middle Ages and up to the 18th century, a combination of sacred and profane factors played an important role; it is in this time that the Colosseum became, unknowingly, the world icon it is today. In the interaction between secular and Christian usage, the symbolic function and identity of the monument are played out, recognized and admired by people from all over the world. Inscriptions, artifacts, paintings and traces left on its walls act as a guide on this journey of knowledge. A renewed awareness in conservation began in the 19th century and the same Popes who in the past centuries had tried to cover it up, chose now to implement it. It was the Popes who appointed, among others, the architect Raffaele Stern to build the eastern spur, also by fixing and "freezing" the state of collapse of the third order, and Giuseppe Valadier who built the western one [1-2].

In the meantime, excavations began in order to clear the monument of debris, which had been covering it, up to the corbels of the arches of the first tier. In 1899 the entrance ticket to the Colosseum, costing 2 lire, was instituted in order to increase the funds for archaeological excavations in Rome.

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It is the beginning of a new phase, approaching the recent times, which will see in the following decades the Colosseum supporting the fascist propaganda and the idea of urban modernity, as for the construction of the subway line B, which cut off the western foundations of the amphitheatre, definitely compromising the water outflow from the underground levels. It is for this reason that today the undergrounds undergo frequent floodings. In the 1970s, the area of the Colosseum was freed and it was tuned into to a traffic free island, in conjunction with a renewed season of excavations and restorations conducted with rigorous scientific method, still ongoing today.

In the last twenty years many initiatives have been carried out in the Colosseum, with a specific attention to the scientific investigations and care of the monument, as well as to the needs of visitors from all continents. This was done in a constant dialogue with the institutions and the civil society of Rome, in order to make the Central archaeological area more and more the beating heart of the city.

Despite its shape, articulated in archways, ambulatories, stairs, orders and levels, the Colosseum is,

Figure 1 – The Colosseum by drone

for the great majority of the areas, opened to the public and accessible to all. Soon it will also be possible to take advantage of further facilities to reach newly opened areas.

In ancient times the use and access to the amphitheatre did not give the chance to those with reduced mobility to reach the various levels of the *cavea*, but nowadays the Colosseum has become a place that allows everyone to admire the mastery of the Roman construction technique and the remains of an imposing entertainment machine.

Accessibility is an imperative act of civilisation; the challenge for those who have to match the conservation of the monument with the removal of architectural barriers is to insert such facilities in the existing structures, with no harm to the monument, making the most of the possibilities offered by the building itself.

Currently there are two kinds of accessibility: cultural and physical. Cultural accessibility concerns the opportunity for visitor to use applications and experiences such as video and light mapping to improve knowledge and enjoyment of heritage [3].

Concerning the physical accessibility, we can say that today access to the Colosseum does not reflect the ancient one; in the past, infact, the access took place radially, from each numbered archway and spectators were led to the path they had to follow in order to reach the assigned seat, which, as we said, was differentiated according to the social class.

Nowadays, for visiting needs, involving also security checks that have become necessary in the last 15 years due to the changed international condition, the access takes place through some selected gates and introduces visitors along the ambulatories, corridors that form the four concentric ovals of the Colosseum.

Three levels are currently open to visitors: what is conventionally called first order, which corresponds to the ground floor, is externally framed by Tuscan semi-columns; the second order, corresponding to the first level, so named for the arches bordered by half-columns with capitals of the Ionic order, and the underground level or hypogea, recently reopened to public after a long restoration campaign.

All areas of the first level are accessible by visitors; ramps have been built in case of differences of height and their visual impact was mitigated with a studied and contextualised insertion.

Access to the second order is possible through 4 steep stairs with two ramps, rebuilt around the 30s of the ‘900 on the footprints of the ancient ones, and, through two elevators built on the occasion of the Jubilee of 2000. The two elevators are inserted in a space where, due to the collapse of ancient structures, a section of the floor is missing, thus allowing an insertion that did not require any changes to the monument.

The entire first floor, so-called II order, is accessible and can be visited as it is, on the same level.

Between the second and the third tier, in the northern part of the monument, there is a section of the intermediate gallery: this corridor is extremely evocative for the alternation of views towards the arena that create panoramic glimpses towards the inside of the Colosseum. It also bears interesting traces of plaster and graffiti.

Access to this intermediate tunnel was of course via stairs, two of which have been adapted, in recent years. The construction of a panoramic lift is nearly completed, so to allow people with reduced mobility to access this area.

The latter has been designed starting from the second ambulatory, taking advantage of the lack of vaulted structures and allowing the insertion of a highly transparent structure. This will both permit to reach the intermediate gallery and will offer a spectacular view of the inside of the Colosseum during the ascent.

The underground levels are also accessible to everybody: in 2010, during the first restoration, a modern staircase and a freight elevator were inserted in a spot, already in used in ancient times to bring props and equipment down to the lower levels. Moreover, since 2021, the latest restoration work has made it possible to open to public the undergrounds in their entirety without any architectural barrier, while at the same time preserving the delicate *opus spicatum* floors.

Presently, to go back to the first order after the underground tour, visitors use an evocative and narrow staircase that retraces what in ancient times allowed workers to move from one level to another. For those who have reduced mobility, the route provides to go back along the walkway to the existing freight elevator; however, it is planned to build another lift with an extremely slender and transparent structure that will complete the path.

The accessibility for all also includes the reconstructed portion of the arena floor, allowing visitors to enjoy a 360° view of what remains of the incredible *cavea* and all its levels.

Figure 2 – The Colosseum and the arena

The arena floor currently has a surface area of approximately 700 m² and, since its construction in 2000, it has been the venue for numerous events, both contemporary and classical music concerts, plays, movies with live music, presentations, conferences, charitable initiatives, and shows with educational purposes.

2. CONCLUSIONS

The goal always pursued by the Administration was to link the image of the Colosseum to cultural initiatives or charitable purposes, connoting the contemporary civilization of different values from those for which the Flavian Amphitheatre was built.

From the summer of 2022 to the Jubilee of 2025, the protagonist will be the project for the complete reconstruction of the arena floor with an intervention that, by fully respecting the monument, will use the most advanced technologies to reproduce the dynamism that the arena floor had in ancient times with its numerous movable devices.

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Verona Charter on the Use of Ancient Places of Performance
The acoustics in the Verona Arena project with the central stage

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ABSTRACT
The Charter to be found below originated in the work of experts who met in the framework of the European Network of Ancient Places of Performance (theatres, amphitheatres and circuses), which has been fostered since 1993 at the initiative of the Council of Europe. Its purpose was to promote cooperation, centred on tangible examples, among professionals active in one area or another in the life and enhancement of a heritage widely established in many countries of Europe and around the Mediterranean. Archaeologists, architects, art historians, scenographs, performance organisers, representatives of local authorities, tourism experts, economists and specialists in local development exchanged their points of view in the course of a number of thematic encounters, giving expression to an intersectoral approach towards objectives for a better conservation and use of the cultural heritage.
The Charter on the Use of Ancient Places of Performance is the result of cooperation between the Council of Europe, the European Union and Unesco. It is the outcome of a series of stages. In the first place, there was a colloquy on conservation and use of ancient theatres held in Sicily in 1995, which resulted in the Segesta Declaration.
This achievement has been amplified and enlarged upon in the framework of the Minotec project, which was launched with the support of European Union in association with various institutions in France, Greece, Italy and Spain.
The colloquy on *New Technologies and the Enhancement of Ancient Places of Performance* of August 1997 (Verona), following upon seminars held in Messene (El) and Lyon (Fr). The text of the Charter was submitted to the Council of Europe Cultural Heritage Committee which recommended the dissemination of the charter during its March 1998 meeting.
The “European Network of Ancient Places of Performance” and the Minotec project were implemented by the European Foundation for Heritage Skills. The writer was part, as an acoustic expert, of the Minotec project and collaborated in the drafting of the paper.
Keywords: Amphitheater; Verona Arena; Verona Charter.

1. INTRODUCTION

The "Charter on the Use of Ancient Places of Performance" concerns the ancient places of entertainment, such as theaters, amphitheaters and circuses, which are among the very few monuments still used,. These places are a cultural heritage not only as monuments but also for their transformations, their subsequent uses and the cultures and traditions that have determined them.

2. MAIN POINTS AND OBJECTIVES OF THE CHARTER

The Charter aims to organize and protect a repository of scientific information on these places, to manage the monuments from a perspective of economic and cultural development and, where possible, to reuse once again these ancient sites as entertainment venues for artistic creations and shared emotions. The charter was divided into the following points:

2.1 I. Resource preservation

The ancient places of the show are a vulnerable resource threatened by time and by the improper uses to which they are sometimes assigned. It is up to the governments and authorities that own these sites to create appropriate conservation strategies for this heritage that fit into the general context of policies for the conservation of architectural and archaeological heritage. Any changes to the assets must comply with the reversibility principle.

2.2 II. Conveying accurate information

i. Many of the most well-known and popular ancient entertainment venues are not adequately studied and documented. New technologies represent sophisticated aids in the research of monuments and their history, and they can also help in conservation and restoration. It is very important to adequately inform public opinion, improve its knowledge and raise awareness of these issues.

ii. However, the development of digital and virtual technologies, in particular as regards images, require vigilance in terms of professional ethics and a clear distinction between scientific purposes and any dissemination purposes.

2.3 III. Facilitating comprehension by the public

i. The conservation of the entertainment venues only makes sense if it makes this heritage accessible to the general public and improves their knowledge in general.

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ii. Access to the ancient places of the show may be subject to restrictions due to safety or maintenance reasons, and in any case the entrance to these places must be designed with the aim of offering visitors help in their knowledge.

iii. A selective and low-cost scientific work should serve as a basis for providing information to the general public, either through traditional information tools of a tourist-cultural nature or through "social media".

iv. Raise awareness in young people of the existence of a category of cultural heritage that is widespread throughout Europe, the Middle East and North Africa; this fact should contribute to transmitting an ethical message based on common values deriving from a heritage due to a shared urban way of life.

2.4 IV. Enhancing the sites by using them

i. Considering that the monuments, due to their state of conservation, are not suitable for modern performances, the adaptation of the sites for performances will increase their significance.

ii. It is essential to take into account the vulnerability of the site when any type of event is organized, at the same time the shows must help to enhance the historical place.

iii. In using these sites for shows, it is necessary to find a balance between the need to protect the monuments and the expectations of the public, visitors and residents. For this purpose, there must be a collaboration between the municipalities that own the sites, those responsible for the conservation and the organizers of the shows.

iv. Correct use of the sites should reduce the risk of material damage to the ancient buildings during the performances. It will take into account both the needs of the "staging" during its planning, but also the maintenance and restoration of the monument,

v. With the realization of live performances and hi-tech shows, the history of the place will benefit from this through the use of new technologies for lighting, images and sound.

vi. Creations of contemporary representations should be encouraged, provided the artist is able to interpret the spirit of the site and use it for the benefit of both the show and the monument.

2.5 V. Managing places of ancient performance by contributing to development

i. Entertainment venues are both a resource and a hub for local development, they act as major tourist attractions, generating economic spin-offs for the cities and regions concerned.

ii. The sustainable management of these venues for the show will only be possible if there is a good agreement between the various partners regarding the conservation and use of the sites. This will involve the elaboration of a management plan defining the aims pursued and the responsibilities of the partners, as well as identifying a coordinator to reconcile the different interests on the site.

iii. Strategies must be adopted to promote the ancient places of entertainment in a more complex scheme of intersectoral development based on the combination of interregional and international cooperation initiatives and agreements.

iv. The development of ancient entertainment venues should be centered on a series of cultural projects that create jobs for local residents without causing undue inconvenience to them and their environment.

2.6 VI. Improving skills through networking

i. In order to improve skills, adequate information must be provided to companies, project-makers and all other partners on the development of techniques for the conservation and use of the sites. In addition to the initial training and further requests for specific professions for both conservation and entertainment, special training courses will have to be organized on how new technologies can be used effectively in entertainment venues.

ii. The international character and the similarity of the problems relating to the conservation and enhancement of the ancient places of entertainment require transnational professional cooperation. Networking should be developed to foster the exchange of scientific information between research groups and to organize advanced professional training courses for researchers, managers and professionals involved in the production of shows.

It is considered appropriate that a network system be adopted to pool and group the data on these sites, and to coordinate in synergy the initiatives to promote the ancient places of entertainment as part of the cultural heritage.

3. APPENDIX I TO THE CHARTER – *Technical details concerning the conditions of use of ancient places of performance*

The experts who took part in the activities of the European Network of Ancient Places of Performance and the Minotec project have drawn up a series of guidelines for the implementation of the Charter on the use of ancient places of performance.

3.1 I. Heritage resource preservation and data accuracy

i. Maintenance, consolidation and restoration work carried out on ancient spectacle places must be based on sufficient scientific documentation and in-depth archaeological analysis. In addition, they must:

– aim to implement the principles of the International Charter for the Conservation and Restoration of Monuments and Sites (Icomos, 1964);
– respect the aesthetic, historical and scientific integrity of the monument;
– leave some areas reserved or closed in view of the resumption of further research or scientific tests.

ii. If the venues are to be open to the public, the measures to be taken must be such as to minimize the risk of damage caused by the presence of too many visitors. These measures will consist of:

– informing the public of the vulnerability of the sites, through signage, documents, etc.;
– building attractive and interesting routes that distract the public from fragile areas. In some cases, it will be necessary to prohibit access to sensitive or dangerous areas;
– providing adequate facilities which reduce the risk of pollution and damage.

iii. The use of new computer technologies will facilitate the tasks of recording, analyzing, scheduling and monitoring the work carried out on the sites.

iv. In matters of dissemination of information and divulgation, interdisciplinary teams created to develop multimedia products should be able to minimize the risk of scientific data becoming irrelevant or distorted. Project leaders will need to define the level of their goal (e.g. scientific research, evocation or dissemination).

The professionals who will be involved in the projects for these places will have to adhere to the ethical and moral principles that will be adopted in the future at an international level regarding the use of new information technologies in the cultural sphere..

3.2 II. The quality of public access

Measures to improve the quality of public access should help ensure that sites are well preserved, while promoting public understanding of cultural heritage values.

A. Improving public understanding of the site

The necessary measures will include:

- designing circuits that follow the routes used in antiquity, so that the public is able to gradually discover the sites and can access the relative places;
- providing aids to understanding the remains, through brochures, audio guides and guides suitable for the various categories of visitors;
- opening an information center for visitors, strategically positioned at the main entrance to the site, to explain to visitors how to interpret the site, placing it in its historical context;
- creating dedicated "on-line" websites and "off-line" multimedia information sources can help the public prepare for the visit.

B. Promoting the site image by guaranteeing high standards for visitors and spectators

i. Due to their historical and architectural significance, some ancient venues open to the public are real cultural enterprises and a factor of local development. However, the strategies for public entry adopted for each site must set the maximum number of visitors compatible with the guarantee of its conservation and maintenance.

ii. Where possible, sites should be able to offer visitor-friendly services and equipment, such as credit card services, information displays, multilingual signage, queuing systems, cloakrooms, etc..

iii. Facilities for disabled people should be as similar as possible to those for other visitors, although special evacuation and safety procedures will be required.

iv. Whenever performances are organized at the ancient sites, the logistics regarding the needs of the performers will also have to be taken into consideration. The desire to provide maximum comfort to the staff must be reconciled with respect for the cultural heritage.

v. In order to ensure high standards for visitors, staff must receive continuous training and must be adapted to the public relations and language requirements of a highly image-conscious cultural enterprise.

C. Safety

i. Measures consistent with the layout of the monument or its position will be taken to address not only the effects of a fire or any other danger, but also, and above all, the panic that could arise in the crowd of visitors or spectators.

ii. Provisions must therefore be made to:

- define a safety zone around the monument that prevents random parking and allows the free movement of law enforcement and emergency services;
- develop specific safety rules for each site. These standards must define:
  - maximum capacity in terms of the number of visitors or spectators;
  - public safety measures, including risk prevention, medical treatment, and emergency facilities.

3.3 III. Use of sites as a means of enhancement

The equipment used for the exhibitions should be such that it affects as little as possible the legibility of the monument to the public and the understanding of its historical significance. This observation is particularly important in the case of festivals that take place at the times of the year that attract the majority of tourists.

i. Regardless of the wide range of different show productions that may be staged at the ancient sites, the shows must comply with the site's conservation and protection rules.

It is advisable to try to satisfy all users and all audiences, not only by integrating but also by smartly exploiting the stage devices and security measures to better show and better understand the site, by:

- restoring the stage to the original level and layout of antiquity;
- placing sets, backdrops, audio equipment and stage covers so that they coincide with the ancient stage walls, which have usually disappeared;
- using light as an aid to the scenography, in order to avoid excessively bulky scenographies;
- thinking virtual scenographies adaptable to different locations;
- using mini-equipment for lighting, projectors, wiring, control units, etc.;
- giving priority to the restoration of ancient stairways and corridors when public walkways and escape routes are to be built, so that the original structure of the monument is more evident.

ii. Virtual images will be useful for staging productions that do not cause damage to the site's structures, and can minimize wear and tear.

iii. Where necessary, computers can be used to develop acoustic models that can help design new ways of using space and scenery. The three-dimensional sound reproduction can be used to integrate the use of virtual images by recreating specific sounds of the place. The evocative quality of sound, when coupled with visuals, offers viewers a more in-depth analysis of the nature of ancient sites, as acoustics is also an integral part of cultural heritage.

3.4 IV. Adoption of negotiated codes of good practice for each site

The measures to be adopted in respect of the ancient places of entertainment will be based on general principles established by the Council of Europe and other international organizations. A set of specifications for use will have to be drawn up for each site:

- on the basis of negotiations between the local authorities that own the site and the conservation services;
- on the indication of the constraints connected to the site and the definition of the rules of use that must be observed by the organizers of shows and other events.

3.5 V. Networking

Professionals offering their services in relation to ancient entertainment venues will benefit from working together by developing a network approach.

An approach where information and initiatives are shared between European and Mediterranean countries will help to promote not only research, but also continuous training and raising awareness of a large audience.

For example, joint projects can be set up in the following areas:

- Scientific research and communication of research results;
- Promotion of cultural events inspired by this specific type of heritage;
- Promotion of lasting cultural tourism initiatives that recall the ancient heritage of the entertainment venues, as well as their past and present significance.

4. MINOTEC PROJECT

The European Network of Ancient Places of Performance was promoted in 1993 by the Council of Europe to focus attention on and protect the ancient entertainment venues, a heritage that Europeans share with the inhabitants of all the countries bordering the Mediterranean.

The Minotec Project was one of the activities of the European Foundation for Heritage Skills and was implemented with the help of the European Commission.

The project had the purpose of proposing the use of new technologies for the enhancement of ancient entertainment venues, and it involved the following places: Verona (Italy), Messene (Greece), Merida (Spain) and Lyon (France); and the ultimate goal was to organize an international conference in Verona in 1997, an international conference, where the countries interested in ancient entertainment venues and the managers of these sites could have exchanged experiences.

Therefore, the Minotec Project was concluded on 27-31 August 1997 in Verona by the international colloquy on "*New Technologies and the Enhancement of Ancient Places of Performance*".

4.1 The "Arena" Amphitheater of Verona and the central stage

The study group for acoustics, within the frame of the Minotec project, worked on the initiative for the Verona Arena with the central stage for public performances, the "Arena 2000" project drawn up by the Ente Lirico Arena of Verona.

The working group for acoustics in the Minotec project was composed of Prof. Pompoli Roberto, Prof. Farina Angelo, and Ing. Cognini Mario.

As part of the "Arena 2000" project, considering the central stage and the tiers around 360 degrees, the following activities were briefly carried out:

- Live study of the propagation in space of the singers' voice (a soprano and a baritone were used) at 360°, recording and measuring the sound levels every 5°;
- 3D modeling in CAD of the Verona Arena;
- Study, through simulations, of the propagation of the singers' voices and the sounds of the orchestra instruments within the amphitheater, considering them on the central stage and in different positions.

During the International Colloquy on "New Technologies and the Enhancement of Ancient Spectacular Places", the results of the acoustic study were presented, and through the *Auralization* process of the acoustic parameters, it was possible to make the participants feel virtually how the voices of the singers would have been heard on the central stage in the various positions of the audience on the bleachers.

5. CONCLUSIONS

It is believed that the Verona Charter has been an extremely important result for the conservation and enhancement of the ancient places of entertainment, both for the individual sites but also for the creation of a network that allows sharing of ideas, projects, scientific research and new technologies that can be used on these fundamental monuments that are part of the European and Mediterranean cultural heritage.

ACKNOWLEDGEMENTS

It should be emphasized the fundamental participation in the working group for acoustics in the MINOTEC project of Prof. Roberto Pompoli of the University of Ferrara (Italy) and Prof. Angelo Farina of the University of Parma (Italy).

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Discussion on acoustical parameters for ancient open-air theatres

Theatres from roman age to renaissance: on the meaning of reverberation time measurements

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ABSTRACT

In the mind of C.W. Sabine, reverberation time was thought as a numerical index of what was happening in a closed hall when a sound source acting within was suddenly stopped: the original idea was that sound rays where travelling in any direction reinforcing residual sound energy, but at the same time overlapping audible messages that these rays where carrying to the listener's brain. x

As well known, he stated a formula linking the R.T. value to the hall volume and to the capacity of the impinged surfaces of keep a fraction of the sound energy: from one hundred years to now, many authors researched in the field and stated the best R.T. values for the listener of different kinds of sound.

Surely Greeks and Romans did not know the possible existence of such a parameter, as they acted in open spaces, neither Vitruvius and, successively Alberti, Milizia, Poletti and so on, even if the tile cover utilized by the Romans to preserve from sun light and rain was avoiding that some sound energy dispersed in the sky.

Surely the modern computer assisted measurements techniques are able to keep some kind of sound decay even in an ancient theatre, but we are aware, as Greeks were, that they are derived only from reflections travelling quite horizontally, between vertical structures, or inclined between actors and spectators via orchestra floor, when not occupied from public.

Keywords: acoustical parameters, reverberation time, running strength

1. INTRODUCTION

In the last fifty years electronic instrumentation allowed us not only to memorize the signal received from a microphone but also to elaborate it quite in any possible way.

The first step of this "new age" was the automatic calculation of the reverberation time and this event signified the disappearance of protractor rule from our desk, soon after the availability of a reverberation time calculated on any possible temporary base, such as EDT, T20, T30, and so on.

A new step was to compare the amounts of energy received in different time intervals, so to have the various clearance indexes, like C50, C80, and so on.

A particular index was derived from the comparison of the really received sound level in a particular selected position to that hypothetically generated from the same omnidirectional source in an open field ten meters far, the strength G.

All these indexes are now well known to everybody involved in acoustical measurements in general and particularly within spaces devoted to theatrical performances and are really of strong interest for those involved in planning modern spaces like multipurpose auditoria or reuse of any other, like churches, sport arenas and, way not, Greeks and roman theatres.

They are of fundamental relevance also for those involved in restauration of ancient Opera Houses [1] so to save their original state, like for instance in rebuilding "La Fenice" theatre in Venice [2], or restoring "La Scala" theatre in Milan [3].

Many researchers involved in the history of ancient theatres utilized them trying to evaluate the acoustical ability of architects working in the past, from Greeks to the modern age, but in my really not short career I never found someone speaking of them. At the most, someone speaks of "reverberation" but not of "reverberation time", till the coming on the scene of W.C. Sabine [4].

2. STATE OF ART

It is possible to think that god-fearing is strictly linked with the man existence: so, even the need to involve others in our thoughts is originally linked with our existence and for theatrical expression may be the same.

We have proof of this when Egyptians began to leave some paper, at the time of the XVIII dynasty [5].

Looking to the archaeological remains, it seems possible to locate the beginning of the theatres building art in the VI century b.C. [see f.i. 6], with the transition in some century from the original squared shape to that best known semi circular one [7],[8].

We know that Greeks of the Pitagora's school, then Aristoxenus [9], were aware of many aspects of the generation and overlap of sounds, first of all the propagation spherical rule. So they probably found only on the field that some vertical surface or structure could generate reflected sound reinforcing the direct sound: for instance, the particular diffraction effect in the Hellenistic amphitheatre

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of Epidaurus generated by the nature of stone utilized for the seats was unexpected [10].

The first paper we found on the subject is the famous treatise by Vitruvius [11] where, it is well known, we can found many notes and geometrical details about the shape of a theatre either Greek or Latin, but quite nothing about natural reverberance: only some word is devoted to sound reflection, more is devoted to artificial reverberance dealing with sounding vessels.

The first appearance of reverberance derived by chance from the introduction of some kind of cover as sun or rain protection.

After a long period of silence about the buildings devoted to theatrical performances, in XVII-XVIII century the interest on these covered spaces raised, so we can find in Italian literature some writing speaking of them, like for instance Carini Motta [12]; in Europe Pierre Patte [13] was the first to announce in cover that his studies were placed upon "les principle de l'optique et de l'acoustique".

In particular, the declaration of Patte clearly confirms that, at least till the end of XVIII century, acoustical reasons were not the first problem for everyone involved in theatrical design.

Among the Italian architects involved in design of theatrical space during the XVIII century exploded a deep research about the best shape for the audience, but even in this case we found only visual reasons; may be there were also some acoustical reasons that each designer kept for himself or for his family, like in the case of Galli da Bibiena. We have the same impression reading [14] were the work of less famous architects who signed many proects in Italy, like Aleotti and Poletti, is taken into consideration.

In Europe, the situation is well represented, in my opinion, from the words of the famous architect C. Garnier at the opening of his Opéra in Paris, who declared that he afforded the big problem of the acoustical result like an acrobat launching himself in circus arena without any security net [15].

A very interesting book was written by F. Canac [16] in 1967, who put in clear evidence the very unique importance in an ancient theatre of reflections coming from the orchestra surface in the construction of some reverberated sound.

So, when W.C.Sabine [4] was charged to modify the agreeability of sound reception in the famous auditorium of Fogg Art Museum, nobody was able to measure what he called "reverberation time" and to link it to the sound absorption power of materials facing the sound source. It is of fundamental relevance that Sabine was acting within a closed space, in particular claiming for an uniform acoustical field, that is to say far away to what happens in an open space!

3. MODERN MEASUREMENTS

In the frame of the ERATO European project, many researchers were involved both in measurements and simulations in Greek and Roman theatres: 3 annual reports were published where in particular we can found reports about the results achieved. At the end a symposium was held in Istambul [17].

An unexpected result was the amount of RT, as stated also in [18]: RT was higher than expected while SPL was almost that of free field.

May be, it would be interesting to study the slope of the impulse response, slope that only some new instrument shows, while usually they give directly the numerical result evaluated on the base of a time interval selected from the same software: in these cases EDT, T20 or T30, parameters that practically take into consideration only the direct sound and some first reflections.

Rindel, who acted as Coordinator of ERATO research, analyses in [19] the results achieved in particular in acoustical simulations on Greeks theatres of the IV b.C.

About reverberation time, his conclusions are that "EDT is not a usable parameter" and that T20 "is highly unreliable".

Instead, "G … could be a usable parameter for open-air theatres".

At that point it seems relevant to debate on the meaning of the parameter G , originally proposed to quantify the amount of acoustical energy apported from the envelope to direct sound in a hall and usually related to a free field 10 meters far from an omnidirectional source.

In the case of an open space, like in general a Greek theatre, may be a comparison with the result achievable in the same place thought flat and free of any building. This new version of G was firstly presented in [20] as G_{re} relative strength and now ibetter presented as:

$$G_{re} = 10log_{10}\left[\int_0^T p^2\,(t,x)dt / \int_0^T p_{ff}^2(t,x)dt\right] \qquad (1)$$

4. CONCLUDING REMARKS

Reading the papers of Sabine [4], it is evident that it is out of discussion the possibility to apply his work to an open field: even if we have reflections. In the field fancied, the decay slope must be rather regular during the canonical 60 seconds. Nevertheless, it is possible to limit this time interval to put in evidence some particular effect like direct sound, early sound and so on [21].

When carrying out reverberation time measurements it is always recommended to catch as first element the full slope of the decay, from which it is possible to deduce many informations about the acoustic field generated from the impulse response.

It seems also more realistic to examine the strength of sound G better related to a real position in the field than to a fixed distance from the source, chiefly in the case of ancient Greeks and roman theatres.

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Meaningful acoustical parameters for open-air theatres

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ABSTRACT

The reverberation time and other acoustical parameters defined in ISO 3382-1 have been derived with closed spaces in mind, and it is not obvious that the same parameters are meaningful in an open-air theatre. Low reflection density and lack of late reflections mean that the reverberation parameters are unreliable. It is necessary to re-think the need for acoustical parameters. The most important acoustical features of a theatre are that speech is sufficiently loud and clear. In addition, an echo-parameter is needed.

Keywords: acoustical parameters, speech, echo.

1. INTRODUCTION

The acoustics of performance spaces are usually characterised by the reverberation time and a handful of other acoustical parameters defined in ISO 3382-1 [1]. The reverberation time has normally little spatial variation within a room and thus the position-averaged reverberation time works well as a global descriptor of the acoustics. Other parameters like EDT, sound strength and clarity are useful to describe the variation over the audience area of acoustical conditions.

However, these parameters have been derived with closed spaces in mind, and it is not obvious that the same parameters are meaningful in an open-air theatre. The acoustics of an open-air theatre are very different from those of a closed room, and for that reason it is necessary to re-think the need for acoustical parameters.

Since antiquity, the most important acoustical features of a theatre are loudness and clarity of speech, avoiding disturbing echoes, see Vitruvius [2, 5.3.7]. Echo problems are more likely to occur in an out-door environment where the reflection density is low. Another difference between an open-air theatre and a room is that in the former, the acoustics are much more dependent on the source position, see Vitruvius [2, 5.8.1-2].

2. PARAMETERS FOR SIMULATIONS

For simulating an actor performing in a reconstruction of an ancient theatre, a very loud voice with clear pronunciation can be assumed. Thus, for the acoustical simulations, the vocal effort should be between ‘loud’ and ‘shouted’ as defined in ANSI 3.5 [3]. Suggested source data are the A-weighted SPL (sound pressure level) equal to 80 dB at 1 m in front of the mouth and the spectrum as ‘shouted’. The directivity of the sound source can be modelled with the data from Chu & Warnock [4].

As an example, acoustical calculations are made for the reconstructed Greek theatre in Thorikos. A speech source as described above is used and the acoustical parameters are total A-weighted SPL and the Speech Transmission Index (STI) [5], calculated both with and without the sound absorption of an audience, see Table 1.

Table 1 – Average and standard deviation of acoustical speech parameters calculated in Thorikos theatre with or without audience. Source positions are on orchestra in front (A) middle (B) or back (C). Ten receiver positions cover first to last row in the centre of the theatre.

Parameter	Source pos. A		Source pos. B		Source pos. C	
	Avg.	S.d.	Avg.	S.d.	Avg.	S.d.
SPL(A), audience	60,0	4,9	59,3	3,3	57,6	2,7
SPL(A), empty	61,2	5,2	60,0	3,6	58,7	3,1
STI, audience	0,80	0,08	0,81	0,06	0,79	0,04
STI, empty	0,77	0,08	0,77	0,05	0,75	0,03

For the STI calculations, the background noise was set to 35 dB A-weighted (pink noise). The spatially averaged STI values are 0,75 or higher, which corresponds to ‘excellent’ speech perception. However, the STI results can be misleading, because echo problems are not included, see the discussion below.

The spatially averaged A-weighted SPLs are around 60 dB, a little higher with source in position A (front) and a little below with source in position C. For comparison, the preferred median SPL for listening to speech (in a conversation) is 52 dB for native language and 55 – 57 dB for second language with background noise around 40 dB [6].

3. PARAMETERS FOR MEASUREMENTS

Acoustical parameters suitable for measurements should preferably meet the principles in ISO 3382-1, which implies a sound source that is omni-directional and parameters derived from the impulse response in octave bands at least covering the six bands from 125 Hz to 4000 Hz.

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3.1 Impulse response

Again, the reconstructed Greek theatre in Thorikos is used as an example. The squared impulse response shown in Figure 1 is from source position B in the centre of the orchestra with a receiver on the last row. It is characteristic that there are very few early reflections, and there is a gap between the direct sound and sound reflections. Depending on source position, this time delay gap can be below or above 50 ms, and in the latter case the reflection may be detected as an echo.

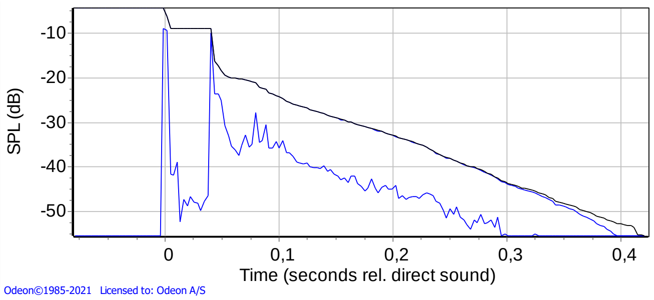

Figure 1 – Simulated squared impulse response (blue) and the integrated Schroeder curve (black) at 1 kHz octave band. This is from a reconstruction of the Thorikos theatre without audience, source position B in centre of the orchestra and receiver in the middle of last row.

Figure 1 also shows the integrated squared impulse response. This curve is very irregular over the initial 15 dB, due to the time delay gap. The consequence is that it makes no sense to derive the slope of the initial 10 dB, as needed for the EDT (early decay time). Other reverberation time parameters like T_{20} are also highly problematic, because the start of the evaluation range (5 dB below the maximum) is not well defined. It might be possible to derive a reverberation time for the late part of the decay curve, starting 15 dB or 20 dB below the maximum. But it is questionable what meaning such a late reverberation should have? During a performance, the late reverberation is not audible.

Results of several acoustical parameters derived from the impulse responses are shown in Table 2. Average and standard deviation are shown using ten receiver positions and three source positions. The echo parameter is from Dietsch & Kraak [7]. The efficiency E is defined below.

Table 2 – Average and standard deviation of acoustical parameters calculated in Thorikos theatre without audience. Source and receiver positions are as in Table 1. All results are for the 1 kHz octave band.

Parameter	Source pos. A		Source pos. B		Source pos. C	
	Avg.	S.d.	Avg.	S.d.	Avg.	S.d.
EDT (s)	0,88	0,33	0,57	0,13	0,36	0,25
T_{20} (s)	0,75	0,05	0,74	0,04	0,84	0,13
ξ (T_{20}) (‰)	28,0	8,8	17,6	9,7	29,0	19,9
T_S (ms)	24	7	23	2	22	4
G (dB)	1,4	5,0	0,6	3,5	-0,1	3,1
D_{50}	0,77	0,09	0,89	0,02	0,89	0,05
C_{50} (dB)	5,5	2,7	9,4	0,9	9,4	1,9
Echo - Dietsch	1,07	0,35	0,52	0,09	0,53	0,10
Efficiency E (dB)	2,8	0,7	4,9	0,4	6,3	0,4

3.2 Reverberation parameters

The EDT varies strongly over the positions, the standard deviation is high, see Table 2. This is as expected from the observation of the typical impulse response above. It is concluded that EDT is not a meaningful parameter for an open-air theatre. A similar observation was made by Farnetani et al. [8].

The spatial variation of the reverberation time T_{20} is more moderate. However, the ξ parameter gives a clear warning that something is wrong. This parameter is defined in annex B of ISO 3382-2 [9]. When $\xi > 10$ ‰, it means that the decay curve used for deriving the reverberation time is far from a straight line and the result should be used with caution. The results for the ξ parameter in Table 2 indicate that this condition is strongly violated in nearly all positions. It is concluded that T_{20} is not a meaningful parameter for an open-air theatre. A similar conclusion was made by Mo & Wang [10].

3.3 Sound strength

The sound strength G is a measure of the total sound pressure level L_p relative to the free field sound pressure level $L_{p,10}$ in a distance of 10 m. It is defined in [1, eq. (A.1)]:

$$G = L_p - L_{p,10} \quad \text{dB} \qquad (1)$$

In an open-air theatre, G will vary strongly with the distance from the sound source, just like the loudness from a talking person. The results in Table 2 show standard deviations of 5 dB with source position A and around 3 dB with source positions B and C. The great variation with position is expected and unavoidable in an open-air theatre. It is concluded that G is a meaningful parameter for acoustic conditions in a specific receiver position. This agrees with findings by other researchers [8, 10, 11].

3.4 Clarity parameters

Parameters related to perceived clarity of speech are clarity C_{50} in dB, definition D_{50}, and centre time T_S in ms [1, Annex A]. In addition, it is mentioned in a note [1, Annex A] that the speech transmission index (STI) can be used to determine the intelligibility of speech.

The definition D_{50} is the ratio of the early energy up to 50 ms and the total energy in the impulse response. It can take values between 0 and 1. In an outdoor scenario with few reflections after 50 ms, the results are typically close to 1.

The speech clarity C_{50} is similar to D_{50}, but expressed in dB and calculated as the balance between early and late energy in the impulse response. The two parameters are related by the equation:

$$C_{50} = 10 \lg \left(\frac{D_{50}}{1 - D_{50}} \right) \quad \text{dB} \qquad (2)$$

The problem with this parameter is, that the late energy can be very small or absent in an open-air theatre, and thus C_{50} can take very high dB-levels (approaching infinity), which is obviously not meaningful.

The centre time T_S is not specifically related to a speech signal, and the interpretation of the result is not obvious. It has the advantage of no sharp time limit, but it is rarely used.

The STI deviates from the other parameters discussed in this section, mainly by the sound source having a directivity similar to that of a speaking person. The parameter is intended for electroacoustic communication systems, not for room acoustics. Never the less it is often applied for room acoustical cases. The popularity among acousticians may be related to the easy interpretation of the results, using five classes: bad, poor, fair, good, excellent.

However, there are serious problems with the STI, especially when applied to a situation with low reflection density. Onaga et al. [12] have shown that STI responds to single reflections in the same way whether the time delay is positive or negative. Thus, a delayed reflection that causes a disturbing echo is not treated unfavourable in the STI. In most rooms this is not a big problem, but for an open-air theatre this is crucial and can give misleading results.

A very large amount of measured acoustical data from rooms (presumably without echo problems) were collected and analysed by Fürjes & Nagy [13]. They found quite high correlations between STI (average value minus standard deviation) and some other room acoustical parameters, especially the speech clarity parameters discussed here, see Table 3. Best correlation is for the D_{50} parameter (mid frequency average of 500 Hz and 1000 Hz octave bands). Thus, if for example D_{50} exceeds 0,55, it can be assumed with high certainty that STI will be in the range 'Good'. Similarly, the range 'Excellent' can be assumed when D_{50} exceeds 0,80 or C_{50} exceeds 8 dB.

Table 3 – Relationship between speech clarity parameters (mid frequencies) and the STI (average minus standard deviation) derived from measured data in rooms, Fürjes & Nagy [13].

Parameter	Quality: R^2	Poor STI ≥ 0,30	Fair STI ≥ 0,45	Good STI ≥ 0,60	Excellent STI ≥ 0,75
D_{50}	0,93	≥ 0,05	≥ 0,30	≥ 0,55	≥ 0,80
C_{50} (dB)	0,89	≥ -13	≥ -6	≥ 1	≥ 8
T_S (ms)	0,85	≤ 550	≤ 230	≤ 95	≤ 40

3.5 Acoustical efficiency

The efficiency E in dB is defined as the amplification of the sound provided by the theatre, calculated as the total SPL minus the SPL of the direct sound alone. A reflection from a single, perfectly rigid surface doubles the sound energy, which means an efficiency of 3 dB. In an open-air theatre this parameter can typically take values between 0 dB and 9 dB.

The efficiency can be measured or calculated with a calibrated omnidirectional sound source as for the measurement of sound strength G. Then it is possible to estimate and subtract the energy of the direct sound in any distance from the source:

$$E = L_p - L_{p,d} = G - 20\lg\left(\frac{d}{10}\right) \quad \text{dB} \qquad (3)$$

where d is the distance in metres from source to receiver. It is seen that E and G are closely related parameters. However, E does not vary so much across the audience area. While G is a measure of the sound level in a particular receiver position, E is a more global measure of how much the theatre supports and amplify the sound from a given position.

A similar approach was suggested by Farnetani et al. [8], who looked at the average difference between G_m in the theatre and in a free field using the mid-frequency octave bands (500 and 1000 Hz).

4. DISCUSSION

Figure 2 shows examples of calculated grid maps of some acoustical parameters in the reconstructed Thorikos Greek theatre and the well-preserved Aspendos Roman theatre. The architecture of the Roman theatre gives rise to a higher reflection density and more late reflections than found in the Greek theatre, but still some echo problems are noted.

As expected, the efficiency E is less dependent on distance from the source than G. Comparison of the results for the echo parameter with the STI results confirms the fact, that STI is unreliable in cases with echo problems. The D_{50} results are quite similar to the STI results, but the D_{50} behaves much better than STI in cases with echo problems.

5. CONCLUSION

In an open-air theatre, the reflection density is sparce and the energy of late reflections can be very low. It is found that reverberation time and EDT problematic and not meaningful in an open-air theatre.

The sound strength G and the definition D_{50} are found to be meaningful for characterizing the loudness and the clarity of speech, respectively, in an open-air theatre. The risk of a disturbing echo is much higher than in a closed room. In order to identify possible echo problems, the echo parameter suggested by Dietsch & Kraak [7] is found to be very useful.

A new parameter is suggested for the acoustical efficiency. This has a relatively small variation with position, and thus the spatial average efficiency is suggested as a global acoustical parameter that can be useful for comparison of different theatres or different stage conditions within a theatre.

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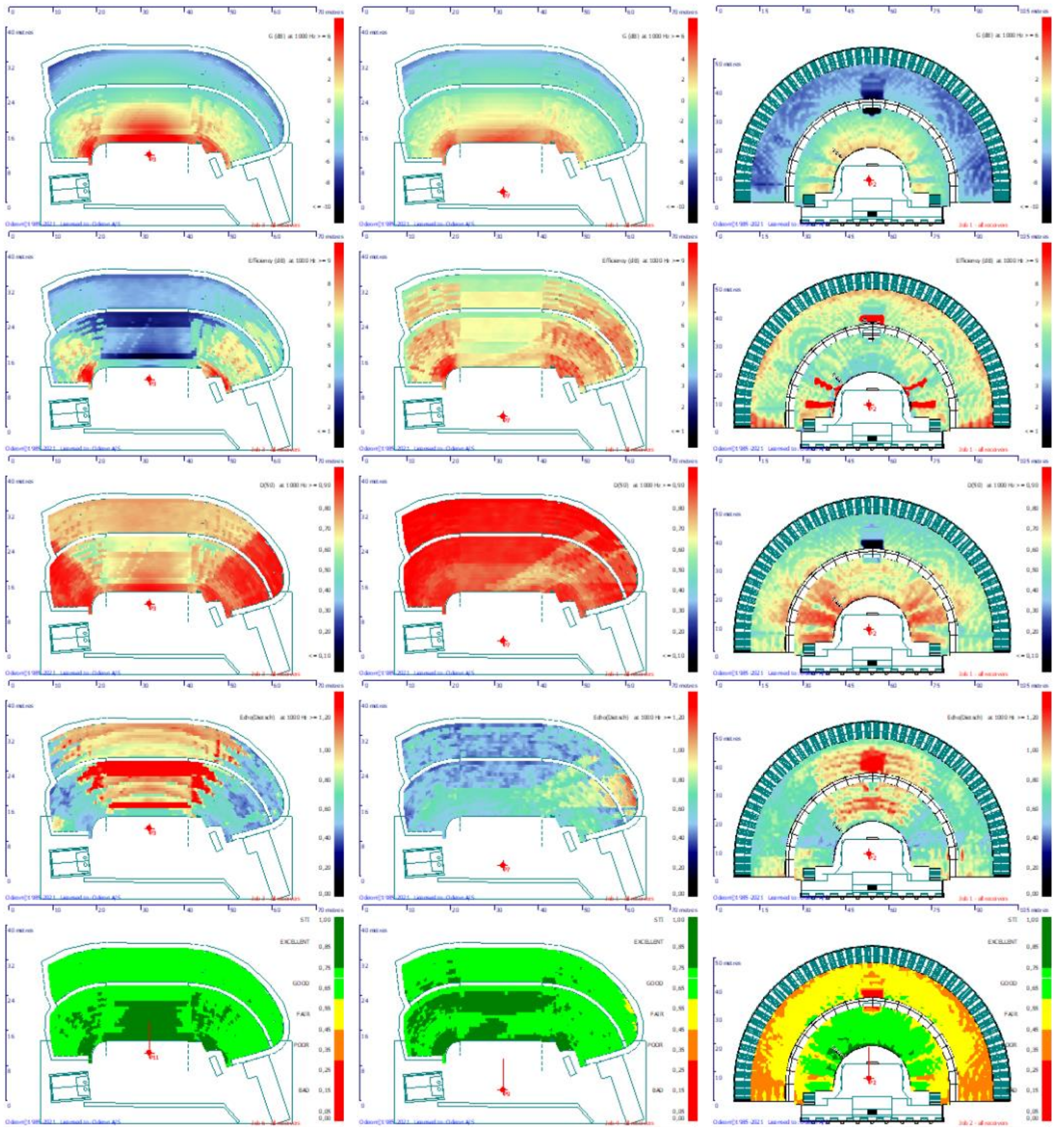

Figure 2 – Grid responses of calculated acoustical parameters from top to bottom: *G*, *E*, D_{50}, Echo (Dietsch), and STI (directional source). Left: Thorikos theatre with source position in front on orchestra. Middle: Thorikos Greek theatre with source position in back on orchestra. Right: Aspendos Roman theatre with source on a modern scene.

Modern use of ancient performance spaces

PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

The Teatro Colón in Buenos Aires. Preservation of acoustic quality during the latest restoration work.

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ABSTRACT
Between 2006 and 2010 an extensive restoration of the Teatro Colón in Buenos Aires was carried out. One of the main concerns related to the works was the preservation of the excellent acoustic quality of the theatre. To do so, a specific methodology was chosen that included acoustic measurements made at different stages of the works. This paper describes the applied methodology and some of the results of the measurements made.
Keywords: Teatro Colón in Buenos Aires, acoustic restauration.

1. INTRODUCTION
The construction of the Teatro Colón began in 1889 as an original project of the architect Francisco Tamburini, who died before finishing the work. He was succeeded by his collaborator Victor Meano and, on his death in 1904, the Belgian architect Jules Dormal completed the work. The Teatro Colón in Buenos Aires was finally inaugurated on May 25, 1908.

The hall meets the general characteristics of a classical Italian horseshoe-type theatre. It has a total capacity of 2,360 seats, with standing room for an additional 500 people. The stalls are 29.25 m wide and 32.65 m long, and the ceiling is 28 m high. The main floor, which has a gentle slope, is surrounded by seven levels: three levels of French-style open boxes and, above them, the levels of Cazuela, Tertulia, Galleria and Paradiso.

The stagehouse is 35.25 m wide, 34.50 m deep and 48 m high. Its floor has an inclination of three centimeters per meter and it has a rotating disc of 20.30 m that allows scenes to be changed quickly. The orchestra pit, framed by the boxes of the proscenium arch, has the capacity for 120 musicians.

Restoration work began in 2002, comprising three well-defined areas: the historic building, the main hall and the stagehouse. One of the main objectives of the works was to preserve the well-known acoustic quality of the Teatro Colón [1], [2]. Rafael Sánchez Quintana and the author acted as Acoustics Consultants for the Government of the City of Buenos Aires and Alberto Haedo for the companies contracted to carry out the work.

The purpose of this article is to describe the methodology developed to preserve the original acoustic quality of the Theatre.

2. PRELIMINARY DECISIONS
After an exhaustive analysis of many precedents of acoustic preservation works, it was concluded that none of the previous methodologies were suitable for the particular case of the Teatro Colón.

The acoustic parameters defined by ISO 3382:1997 were used as a starting point [3]. To overcome the limitations of the standard, it was decided to make broadband recordings using a large number of source-receiver pairs, in which the impulse responses were completely preserved. This database was used to calculate the ISO parameters, which are average values limited to the octave bands between 125 and 4000 Hz, and which would be used for future analysis.

The general approach adopted for the acoustic restauration was described by Javier Fazio, structural consultant of the works: "A building that is considered to have a high heritage value is subject to conservative restoration actions due to its uniqueness, which excludes it from the field of application of the standards" [4].

Taking into account the above statement, the technical objective was to keep the differences of the ISO 3382 standard's parameters, measured before and after the works, below the errors admitted by the standard, which correspond approximately to the acoustic limens of each parameter.

2.1 Acoustic model to preserve
Choosing the historic moment to use as a reference point presented certain problems. The Teatro Colón had undergone modifications throughout its history. For example, until the 1930s, when the final curtains were installed, its acoustics was considered from regular to poor, and in the late 1960s a new air conditioning system that reused the original ventilation ducts of the building was installed.

Another problem with the choice of the reference point is that previous measurements, at least until the 1990s, were scarce and limited. Those of Leo Beranek, mentioned in his 1962's book, and of Federico Malvarez, recorded in 1971, were incomplete and would not

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have served as a valid reference.

To solve this dilemma, we turned to heritage consultants, who suggested applying the principle that states that in the restoration of a historical monument, most recent significant historical event that occurred should be considered. If all the performances of operas and concerts are considered significant historical events, it is therefore possible to use the artistic performances and measurements of the year before the closure as valid reference points: it was decided that the "acoustic photograph" taken in 2006 should be replicated at the end of the restoration work.

2.2 Intervention criteria

The general principle that defined the intervention was that any modification that could affect the acoustics of the hall should be potentially reversible.

Four possible scenarios were foreseen:

1. It was technically possible to demonstrate that the change proposed by the team of architects would affect, if carried out, the acoustic quality of the hall. In those cases, the modification was rejected. Examples of this situation include the proposals to reduce two internal walls on the stage or the replacement of the ventilation grilles in the stall’s floor.

2. It was determined that the proposed change would not affect the acoustic quality of the hall. Therefore, it was accepted. For example, the installation of air conditioning through floor ducts in the upper levels

3. It was not possible to determine with certainty that the proposed change would be acoustically innocuous. In these cases, an extremely conservative approach was adopted and the proposals were rejected. This included the intention to create new access doors to the orchestra pit.

4. The last possible scenario was, perhaps, the most problematical: the modifications had the capacity to affect the acoustics of the hall, but they had to be made to increase the theatre’s resistance to fire. The example here is obvious: the complete textile material, responsible for much of the interior acoustic absorption and the spectral balance of the theatre, would be replaced.

3. IMPLEMENTED METHODOLOGY

The methodology adopted to achieve the goal of preserving the acoustic quality of the Teatro Colón can be divided into the following stages [5]:

1. Diagnosis of the acoustic state prior to the beginning of the restoration tasks. The measurements were made in 2006 based on the ISO-3382 standard.

2. Development of a digital acoustic model to control the hall’s disassembly-assembly process.

3. Acoustic measurements of the hall at specific stages in the disassembly.

4. Laboratory measurement of the acoustic characteristics of the components and materials removed from the hall.

5. Laboratory measurements of the acoustic characteristics of the components and materials to be incorporated into the restored hall.

6. Acoustic measurements of the hall at specific stages in the reassembly.

7. Final measurement with the hall restored and fully equipped. This was done in 2010 based on the ISO-3382 standard.

8. Comparison of the measurements mentioned in stage 1 (initial condition) and in stage 7 (final condition).

What follows will briefly describe what was done based on this methodology.

3.1 Acoustic measurements of the hall

The measurements in the hall were carried out by the Argentine Institute of Acoustics, Electroacoustics and Related Areas and certified by the Argentine Institute of Standardization and Certification IRAM -ISO representative in Argentina-. A normalized omnidirectional source (dodecahedron), excited with logarithmic sinusoidal sweeps of 5.5 s duration, was used. It was located in 8 different positions, half of them with the pit in the low position and the other half with the pit at the stage level. Measurement microphones were placed at 21 different positions around the hall. Broadband impulse responses were recorded on all emitter-receiver pairs and parameters defined by ISO-3382:1997 were measured.

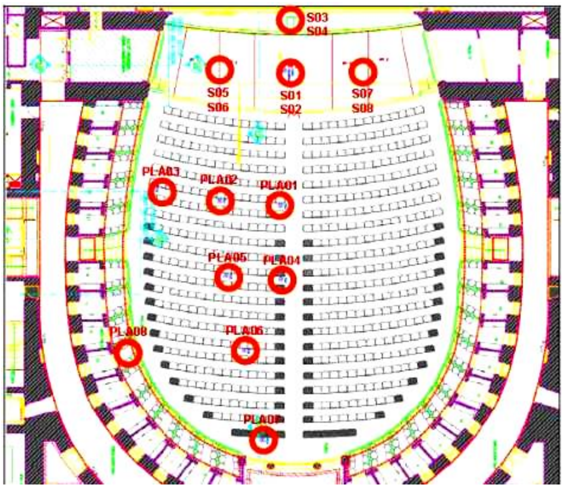

Figure 1 – Positions of the omnidirectional source, on the stage and in the pit, and measurement points in the stalls (After [6])

During the measurements prior to the works, carried out in November and December 2006, and during those carried out after its completion in March 2010, the textile curtain was used to decouple the main hall from the stagehouse. Throughout the intermediate measurements, the fire curtain made of iron was used for the same purpose.

Table 1 – Values of the ISO-3382 parameters measured in December 2006 [3], [6]

PARAM	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
EDT [s]	2,46	2,24	2,05	1,68	1,55	1,10
T10 [s]	2,37	2,24	2,02	1,81	1,61	1,32
T20 [s]	2,34	2,27	1,99	1,75	1,59	1,35
T30 [s]	2,37	2,25	1,99	1,75	1,61	1,37
C80 [dB]	-1,9	-1,5	0,8	2,9	2,6	5,3
G [dB]	1,1	1,7	3,5	3,7	3,1	2,8
Ts [ms]	167	159	113	80	81	53
LF	0,31	0,24	0,14	0,10	0,12	0,12

Intermediate measurements were made, during the staggered disassembly of the hall, in the following sequence:

- After the removal of the seats from the stalls
- After the removal of the stall's carpets
- After the removal of the upper-level seats
- After the removal of the chairs and stools from the boxes
- After the removal of the curtains from the boxes
- After the removal of the carpets from the boxes
- After the removal of the curtains covering the exits
- After the removal of the carpets from the Paradiso level

Figure 2 – Measurements in the hall after the removal of the stalls carpets

During the staggered reassembly of the hall, a reverse sequence was followed. Thus, the last measurement in the disassembling and the first measurement in the assembling were carried out with the hall completely devoid of textiles. In this way, the results of the equivalent stages -the ones with the original materials and the ones with the replacement materials- were able to be compared. The objective was to detect any deviation and correct it immediately if necessary.

Figure 3 – The hall before putting the seats on the main floor during its reassembly

3.2 Laboratory measurements

Samples of the original elements - curtains, seats, draperies, carpets, etc. - and their replacements were measured at the *Laboratorio de Acústica y Luminotecnia* (LAL-CIC) of the Province of Buenos Aires.

Figure 4 – Laboratory measurement of the hall curtains

Figure 5 – Kundt tube measurement of the carpets for the Paradiso level

In almost all cases, the acoustic absorption was measured in a reverberant chamber following the ISO-

354 standard. In some cases, the standing wave tube method -Kundt tube- was used to carry out preliminary measurements. By way of illustration, the replacement fabric for the upholstery of the seats was finally resolved having discarded the first seven samples that did not meet the required acoustic absorption values.

3.3 Development of a digital model

Simultaneously with the measurements in the hall, a digital acoustic model was developed using the *CATT-Acoustic* software. It was adjusted with the values of the on-site measurements until the errors were similar to those established by the ISO-3382 standard. The model was widely used throughout the process and was very useful for making critical decisions, such as extrapolating the measurements of the absorption of the seats made in the reverberant chamber to the particular acoustics of the theatre.

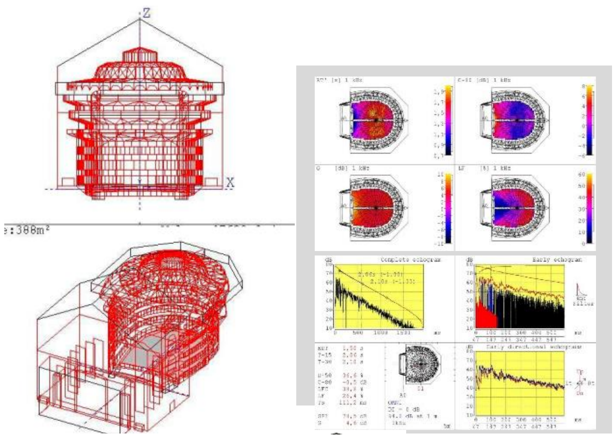

Figure 6 – Views and some predictions of the digital model of the Teatro Colón (*Catt- Acoustic* software)

4. RESULTS AND CONCLUSION

The comparison between the results of the measurements carried out before and after the restoration work showed that there were no deviations above the margin of error allowed by the standards. For example, Figure 7 shows the global T30 values, with the two curves practically superimposed. The rest of the global ISO-3382 parameters showed a similar agreement.

The methodology used proved to be effective in preserving the original acoustic quality of the hall. A methodology that, although designed *ad-hoc* for the specific case of the Teatro Colón, it would be possible to be adapted in the restoration of other halls of great heritage value

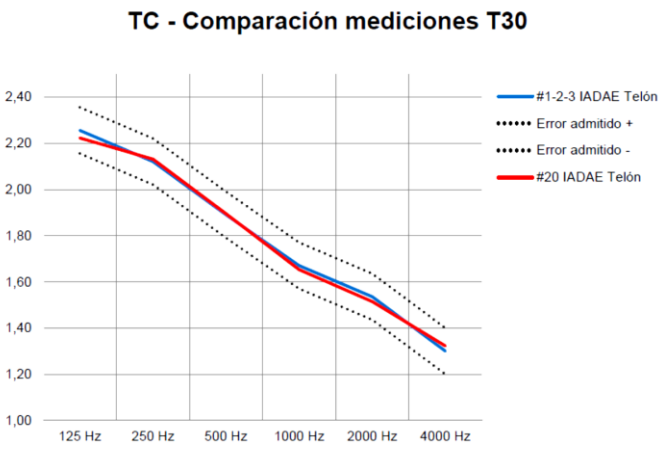

Figure 7 – Comparison of the initial (blue curve) and the final (red curve) T30 measurements in the empty hall. Dotted lines represent the error allowed [6]

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Preserving and Managing the Sonic Heritage of Performative Spaces of the Past.

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ABSTRACT

The ongoing SONIC HERITAGE project aims to develop a new multidisciplinary analytical approach that models the relationship between the intangible aspects and the spatial configuration of performative spaces of the past in order to assess the risk of sonic heritage of particular case studies in Italy and to contribute to the monitoring of present-day sound and noise for the future management and preservation of historical cultural heritage.
This project also concerns the risk assessment of sonic heritage in ancient theatrical spaces as well as the modern reuse of these theatrical structures and the relationship with their intangible aspects and environment. This paper will present some issues raised by the Sonic Heritage project concerning on how the study of the sonic fabric of extant buildings and their surrounding environment can allow us to investigate on sonic identities and spaces where sound - as a set of music, voices, ambient sounds and noises -, was produced and perceived and to speculate on how their sonic heritage can be preserved and managed in the future.
Keywords: Sonic Heritage; Modern Reuse of Ancient Theatres.

1. INTRODUCTION

Ancient theatres are spread in a large territory that embraces three continents. Their presence bears witness to belonging to common roots, contributing to promote mutual understanding and intercultural dialogue. Their preservation and their continued use as spaces for cultural activities allow us to promote the encounter of cultures, recovering the memory and awareness of a shared history through the arts and architecture [1].

International community has urged the commitment to preserve the ancient theatres from the ravages of time and the action of human beings, given that disastrous natural events, pollution or improper uses of these buildings and their related performative spaces are progressively damaging this cultural heritage, demonstrating urgency of an effective preservation planning policy based on the prevention and mitigation of vulnerabilities and dangers. Despite its relevance to this field, no study has focused on the risk assessment of acoustic features as sonic heritage of ancient theatres and the related performative spaces, some of which are now used as location for concerts and modern performances.

2. THE SONIC HERITAGE PROJECT

The ongoing project “Sonic Heritage. Risk Assessment and Sustainable Development of Acoustic Environments of Ancient Theatres” carried out at the Institute of Heritage Science, National Research Council of Italy aims to develop a new multidisciplinary analytical approach that models the relationship between the intangible aspects and the spatial configuration of ancient theatrical structures in order to contribute to the monitoring of present-day sound and noise for their future protection and preservation and their modern reuse. Despite significant past and current work on the acoustics of ancient theatres, no project up until now has approached these issues with a systematic and interdisciplinary effort. For the first time, all the results will be integrated into an innovative research method from which experimental interpretative 3D reconstructions integrating acoustic models can be created. As such, this research presents a model for future integrative scientific studies in the fields of digital heritage and of sound environment in sustainable theatrical spaces, and will provide a new approach to reconstruct sound phenomena and auditory experience in ancient performative spaces [5], stimulating the understanding of the role that sound plays in all aspects of society.

Moreover, this project aims to explore the risk assessment of sonic heritage in theatrical spaces of particular case studies in Italy (the theatres of Syracuse and Segesta) and the relationship with their intangible aspects. Indeed, as something that does not tend to leave direct material traces, sound is not often considered in archaeological work [5]. However, it was an important aspect of ancient life that can be investigated using a new approach to archaeological remains [5]. When taking this understanding of sound into account, it seems surprising that important public spaces in antiquity, such as, ancient theatres have been investigated in archaeological field almost exclusively with a focus on their visual function as performative spaces in which individuals or groups display and experience their collective or

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personal identities and status. Approaches such as these often fail to take into account the full range of sonic experiences in the performative spaces may have provided [5].

3. SONIC HERITAGE OF ANCIENT THEATRES

Preserving ancient theatres as an important part of cultural heritage, it is possible to hand down not only the developments of theatrical architecture in the ancient world, but also to interpret the signs that different cultures have brought to the original model. Investigations into the geometric design and sonic dimension of these structures may help us to understand the wide variety of uses and functions that sound fulfilled in ancient buildings and to enhance our knowledge on the links between the form and sonic function of ancient theatres and their transformation from generic or conventional built structures to buildings that can amplify the active sound properties of architecture.

Sonic dimension of theatrical structures involves these performative spaces as places for interaction and communication in the natural and human sonic environment. Indeed, architectural structures, decoration, and surrounding landscape created specific sonic features which influenced the soundscape of theatrical structures; these soundscapes consisted not only of music and recitations, but also natural elements, such as geophony and biophony [5]. The survey on these elements is useful to evaluate how sound in a landscape is a fundamental aspect of the complex relationship between spaces, social interactions, and the natural environment, as well as to assess how soundscape refers to human-environmental interactions and consists of all sounds present in any given environment, and how these sounds interact within that environment. This investigation provides critical information about sound in archaeological contexts and how sound is a valuable means of becoming better informed on the many different ways in which sound pervades spaces, architectural places, social interactions, and also human-animal relationships.

On the other hand, architecture reacted to musical developments as well as to vocal practices by designing and constructing new shapes for these buildings [5]. In this regard, it is necessary to take into account how the preservation of acoustics of ancient theatres as well a deeper knowledge of their original sonic features could be one of the most important issues to revive not only the ancient tragedies and comedies in these performative spaces, but also of musical and dance activities and modern performances in the theatrical locations. Moreover, it is crucial to identify risk factors related to their acoustics in order to minimise damage should they occur, thereby managing their future protection.

4. THE CASES OF SYRACUSE AND SEGESTA

In this debate, the theatres of Syracuse (5th c. BCE) (Figure 1) and Segesta (3rd c. BCE) (Figure 2) play a pivotal role due to the importance of performances related to modern concerts and festivals, in which sonic heritage of these buildings is subjected to high risk. The preservation of these monuments has urged institutions to host two important meetings on safeguarding of ancient theatres in the Mediterranean area. These two conferences aimed to the application of the "Convention for the Protection of the European Architectural Heritage" (Granada, 1985) and of the "European Convention for the Protection of the Archaeological Heritage" (Malta, 1992). The results of the first meeting (Segesta, Trapani, Palermo, 17-20 September, 1995) have been formulated in the "Declaration of Segesta" (1995) [5], where there is a generic reference to acoustic issues and to the need "to limit the number of decibels emitted in order to avoid harmful vibrations to the monuments and to respect the peace of the local people".

The second meeting "Ancient Theatres in the Mediterranean Area" took place in Syracuse (13-17 October, 2004). One of this conference's stated goals has been the approval of the Charter of Syracuse. This is a political declaration reiterating the international community's commitment to the preservation and enhancement of cultural heritage and of ancient theatres [5]. In this Charter, a short paragraph is devoted to the preservation of acoustic features of ancient theatres; however, no technical guidance has been provided as well as detailed references to the sonic characteristics of ancient theatres as heritage to be of safeguarding and protecting.

Figure 1 - The theatre of Syracuse (5th c. BCE)

Figure 2 - The theatre of Segesta (3rd c. BCE)

5. SOUND AS HERITAGE

Given its evocative potential of the original spatial configuration, acoustics of ancient theatres is a valuable cultural asset to be protected. In this regard, the "Sonic Heritage" project is developing a new approach to the knowledge of the acoustic design of theatre buildings obtained through 3D virtual reconstructions and the creation of acoustic models, taking in consideration the philological reading of the original system and the theoretical verification of available data. Performing analysis on the best sound effects in ancient theatres will help significantly in establishing more precisely the nexus sound-in-space in performative spaces, combining their acoustic model with a new method for generating 3D models and for exploring the sonic properties of any performative space in the future.

It is worth noting that, the application of new technologies to cultural heritage research has led to important methodological changes in the protection and enhancement of monuments. This new approach is stated in the objectives of the "International Council on Monuments and Sites" [5], an organisation which aims to restore meaning and preserve the memory of historic buildings, promoting the application of technology in the assessment of monuments: this is particularly interesting with regard to the recovery the evidence of sonic aspects in the archaeological heritage [5]. Within this context, new methods for the analysis of the historical sonic heritage of ancient theatres should be used, enabling the evaluation of their sound quality by using auralisation techniques [5] that allow cognitive and physical elements to be reproduced and combined.

Moreover, by combining the detection of acoustic emissions with computer processing, it should be assessed with particular attention the acoustic impact of electronic sound amplification instruments on the theatrical buildings, and the sonic stresses of these instruments on these ancient buildings [5],[5] . In this regard, it should be defined not only the acoustic parameters of sustainability of modern performative activities in ancient theatres through specific vibrometric analysis, but also it should be identified the critical issues of theatrical buildings [5], evaluating the data of vibrations produced by the acoustic sources in relation to the different types of performances.

6. FINAL REMARKS

The "Sonic Heritage" project will provide a new path of investigation in terms of the digital preservation of acoustic models of historical spaces and their sonic heritage. It will be, therefore, possible to critically explore the links between the propagation of sound and the shape evolution of the theatres as well as the role of the architectural elements configuration in featuring the sonic characteristics of these ancient buildings [5]; these data will be able to provide suitable suggestions to optimize the acoustic performance of the theatre architecture, or to define the most suitable solutions for modern performances. Moreover, acoustical measurements and models of ancient theatres offer a robust additional layer to their preservation, especially for locations that are at-risk, thereby managing their future protection and their modern reuse.

In summary, a rediscovery of the influence of sound on ancient theatres could help to increase the well-being of modern societies and protect the environment from noise pollution of human origin. The results of the "Sonic Heritage" project could provide the potential to better understand the current sonic environment and ecosystem and their meaning to human beings as well as the physiological responses to a sound environment.

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PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
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Acoustic modelling of the Veche Square in Veliky Novgorod, Russia

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ABSTRACT

Every year the awareness of the importance of architectural acoustics grows, its significance and popularity grows. So among the many interests of architectural acoustics, in recent years, "acoustic reconstruction" is gaining considerable popularity. This way we can study the evolution, culture and art, theater and architecture of ancient society by architectural acoustics. Thus, some papers have already been carried out on the acoustic reconstruction of the theaters of Ancient Rome and Ancient Greece. However, the "acoustic culture" of the Slavic countries is not still enough reconstructed and studied. Ancient Russian cities had their public spaces, which also used to be as local forums for gathering "veche". Veche is a popular assembly in ancient and medieval Slavic states. The veche was represented by various city classes. From an acoustical point of view, it was necessary to provide sufficient volume for the speakers and good intelligibility for the audience. Obviously, buildings around the square, fortress walls and other structures influenced the acoustic environment. The particular interest is that the squares are surrounded by a large number of churches and bell towers. Acoustic models were performed for squares to calculate the main acoustics parameters of the space. Full-scale acoustic measurements were carried out.

Architectural acoustics takes an extremely important place in architecture [1], it is impossible to imagine either theater design [2, 3], or city planning [4, 5], or a residential areas [6] without architectural acoustics. The result of acoustic design can lead to positive [7], negative health effects [8], and can also be subjected to serious architectural criticism [9].

Every year the awareness of the importance of architectural acoustics grows, its significance and popularity grows. So among the many interests of architectural acoustics, in recent years, "acoustic reconstruction" is gaining considerable popularity. This way we can study the evolution, culture and art, theater and architecture of ancient society by architectural acoustics. Thus, some papers have already been carried out on the acoustic reconstruction of the theaters of Ancient Rome and Ancient Greece [10 - 14].

However, the "acoustic culture" of the Slavic countries is not still enough reconstructed and studied [15]. First mobile theaters (Skomorokhs) appeared by the middle of the XI century in Russia, it is possible to say by the frescoes of the St. Sophia Cathedral in Kiev (1037) and by the leather masks of the actors of the XII-XIV centuries known from archaeological finds in Novgorod and Vladimir. The heyday of buffoonery fell on the XV-XVII centuries. Mobile theatres performed in the central squares of Ancient Russian cities, which also used to be as local forums for gathering "veche". Veche is a popular assembly in ancient and medieval Slavic states. In fact, it is a legislature with signs of democratic governance. In the Novgorod Republic, an independent proto-state that existed from 1136 to 1478 on the territory of the server-west of modern Russia, the veche was the highest legislature and judicial authority [16]. The veche was represented by various classes of society, but primarily citizens. Usually the meetings were quite numerous, so they were held in the city squares in the open air: on the square near the St. Sophia Cathedral, and in case of serious disagreements, some of the townspeople, dissatisfied with the decision, gathered in another place - at Yaroslav's Court [17]. From an acoustical point of view, it was necessary to provide sufficient volume for the speakers and good intelligibility for the audience. Obviously, buildings around the square, fortress walls and other structures influenced the acoustic environment. But the acoustic characteristics of such places have not been studied at all, like the entire acoustic culture in Russia. That is why this research of acoustic characteristics and acoustic reconstruction of the Veliky Novgorod veche square is so extremely relevant, important and necessary.

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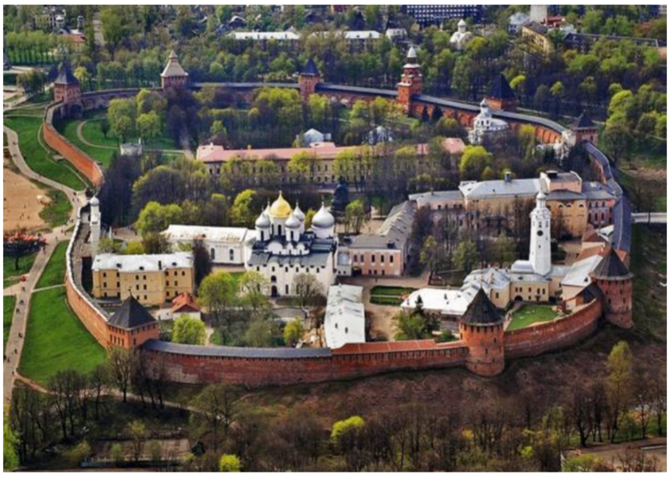
The spatial architecture of the two squares has been restored according to historical maps and archival documents: 1 - the square near the St. Sophia Cathedral, 2 - the Yaroslav's Court.

The particular interest is that the squares are surrounded by a large number of churches and bell towers. Acoustic models were performed for squares. The models were used to calculate the main parameters characterizing the acoustics of space. Full-scale measurements of acoustic characteristics were carried out. A description of the acoustic conditions in the area is given and the quality of acoustics and the level of acoustic comfort for the participants of the meeting are analyzed.



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Modern Use and Ancient Theatres: The Dilemma of Reconstruction of the Authentic Scientific Acoustical qualities

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ABSTRACT

The ancient theatre (Greek, Hellenistic and Roman) is one of the most critical and socio-cultural edutainment creative centres of human history that are still in use. Their cultural significance can be defined regarding their survival as ancient landmarks, impressive architecture, acoustic characteristics and qualities, and continuous reuse in modern socio-cultural edutainment performances and events. Eventually, the theatre became a global symbol of cultural sharing modernity. Reuse is now used as a means of conservation and justification for the enormous costs of restoration and conservation. Infusing ancient theatres with their full role, especially their authentic scientific acoustical qualities, as places of artistic creation, shared enjoyment and emotion, modem use should enhance their heritage and arouse the audience's interest in the present and future visions and needs of our digital age perspective and development. However, its environment to original or earlier settings should not be ignored. The question is whether it is only enough to preserve their authentic scientific information and improve sound volume by restoring and Anastylosis the stage wall and colonnade (portico) to their original level and layout in ancient times, or we should start to think about their physical in situ reconstruction in parallel to their virtual reconstruction? However, reviewing the main issues related to reconstruction in the international charters and conventions and those involved with conservation is mostly very conservative and reluctant to encourage any reconstruction for reuse. Therefore, this paper attempts to illustrate and discuss the abovementioned subjects and is-sues according to recent research and related worries, concerns, and opportunities for further modern use.

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Acoustics of Roman theatre of Salona.

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ABSTRACT

Salona was the capital of the Roman province of Dalmatia, and as all similar roman cities, had a theatre. Today, in Salona only scarce remains of an ancient Roman theatre exist, such as its foundations and low walls. To analyse the acoustical properties of Salona's theatre, we made a reconstruction of the theatre, according to data provided by the archaeologists and other similar preserved theatres. We then performed the acoustic simulation of the theatre to explore its acoustical properties. We performed the simulation using the geometrical simulation based on the hybrid ray tracing/image source method. In this paper we present the results of the simulation and discuss them. We analyse the influence of an audience and a stage wall on the acoustic performance of the theatre. The results suggest that the acoustics of this theatre was good for dramatic performance, which was its primary role.

Keywords: Acoustics, Geometrical Simulation, Ancient Theatre

1. INTRODUCTION

Although not as attractive as amphitheatres, Greek and Roman theatres present an important part of the architectural heritage in Western culture. Furthermore, many Greek and Roman theatres are preserved in such measure that they still serve their original purpose. A total of 744 structures of ancient theatres have been identified and documented [1], four of them in Croatia [2]. The theatre in Pula is best preserved, the theatre in Salona is preserved only in its foundations, while in the town of Vis the Franciscan monastery was built on the remains of *cavea* of ancient theatre. The remaining theatre of Zadar was identified only by architectural elements.

In this paper we concentrate on the theatre of Salona and present the reconstruction as well as the acoustical simulation of the reconstructed theatre.

2. THEATRES AND EXISTING MEASUREMENTS AND ANALYSIS

The literature review on ancient theatres must be started with Roman architect Vitruvius [3] who in his fifth book gives the principles of the design of theatres and their acoustics. Canac [4] in 1967. presented detailed study of ancient theatres, in which he used the method of image sources to analyse different geometries of ancient theatres. The evolution of ancient Greek and Roman theatres was researched by Chourmouziadou [5].

The ERATO project aimed at identification, virtual restoration, and revival of the acoustical heritage of ancient theatres and odea [6]. Reconstructed were theatres of Jerash, Aspendos and Syracusa, and virtual reconstruction and simulation was compared to measurement of present structures. Simulations were made with the room acoustic software Odeon [7]. The measurements and simulations were performed with and without audience. The reverberation time T_{30} with audience was 0.3-0.4 s less than without audience. Also, the simulation detected that presence of the colonnade on the top of *cavea* increased reverberation for about 0.6 s. C_{80} and STI were very good in all theatres due to the lack of reflections from the roof.

Alvares-Corbacho in [1] analysed three Roman theatres in Spain: theatre of Regina Turdulorum, theatre of Italica and Segobriga. Regarding the theatre of Regina Turdulorum they measured the impulse response of the existing theatre and simulated it with CATT software. They analysed the differences of acoustic parameters between simulated results and measured ones. T_{30} and T_s did not have significant difference at any frequency, while C_{50}, C_{80}, D_{50} and IACC showed significant differences, except on central frequencies. Similar results were presented for the theatre of Italica. For the theatre of Segobriga, authors analysed the measurements of three sources (2 on *proscenium,* and 1 in *orchestra*), and 19 receivers. Averaged reverberation time T_{30} was 0.45 s. When analysing different source-receiver combinations they discovered that their position influences the results, but in general no significant differences were detected, except in the aspect of spatiality.

Psarras [8] measured and analysed the theatre of Epidaurus, the best-preserved Greek theatre, with a capacity of 14500 seats. He noticed a dip of intensity level in the frequency range between 170-200 Hz, and

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the broad amplification region around 1000 Hz. These measurements are in accordance with Lokki [9] who used FDTD simulation along with beam tracing, and concluded that theatre's step size and backscattering generate the interference dip. This dip and amplification around 1000 Hz are responsible for good intelligibility and powerful sound of male actors who were performers in ancient times.

The measurements Psarras did are also in accordance with Declercq and Deskyser [5], who analysed the influence of diffraction on seats using numerical study and found out that it amplifies the frequencies above the 530 Hz. Psarras however did not confirm their findings of low frequency attenuation.

Works of Lokki and Declerq were performed for empty cavea, so it would be interesting to see to which extent such effect would be present in the case of full audience.

3. ROMAN THEATRE OF SALONA

3.1 Roman Colony of Salona

Colonia Martia Iulia Salona was the capital of the roman province of Dalmatia. It was situated at the end of a well-protected bay, beside the estuary of the river Salon [2]. Salona was founded in 3rd century BC by the Greeks and became Roman after their conquest of Dalmatia. In the peak of its expansion, it reached over 60 000 inhabitants.

3.2 Roman Theatre of Salona

F. Carrara started the research of the theatre of Salona in 1849. when a peasant ruined a part of the walls while building its house [10]. E. Dyggve in 1922. performed more detailed excavations revealing the theatre and an adjacent temple. The theatre was built in the middle of the Ist century AD and has been rebuilt several times later.

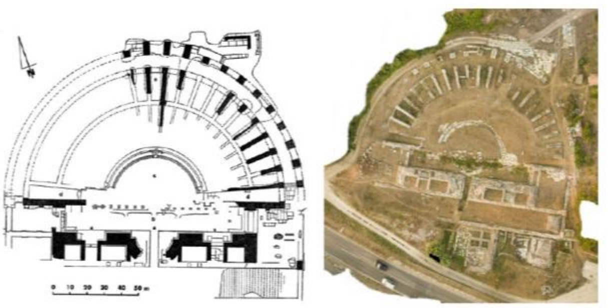

Figure 1 – Plan of theatre according to E. Dyggve, and aerial photo from the present time.

The theatre has 65 m in diameter, and the length, from rim of the *cavea* to the end of the *porticus* is 58 m. The theatre *cavea* is oriented towards south, but theatre's axis has an angular shift of 9° eastwards from pure north. *Imma cavea* is built using the natural slope of the terrain, while the *summa cavea* is supported on substructures comprised of walls and pillars. Besides this the foundations of *proscaenium*, *parascenios* - two buildings that flank the *proscaenium,* and front stage wall or *scenae frons* remain today. The *orchestra* is outlined between the *imma cavea* and *proscaenium,* but without the stone pavement.

4. RECONSTRUCTION AND SIMULATION OF THEATRE

4.1 Reconstruction of Theatre

Unfortunately, until the present time, archaeologists did not make the reconstruction of the theatre of Salona. However, some of them made assumptions about certain aspects of the theatre, like the number of rows in the *cavea*. So, to make the model for acoustic simulation, we had to make the reconstruction of our own.

As a starting point we used theatre plan according to Eynar Diggve (figure 1). Then, we georeferenced the plan to the aerial photo [11] in GIS system and extracted the following theatre dimensions: diameter of *cavea* 66.58m, diameter of *orchestra* 17.17 m, and the dimensions of *proscenium* 37.67m x 7.55m.

Besides this we analysed the list of 198 ancient theatres and odea from [12] and filtered 20 theatres that are similar to the theatre of Salona in its size and age. From this short list we selected the theatre of Dougga [14] and the south theatre of Jerash [15], as the most similar to the theatre of Salona. The criteria for selection were the similarity of footprints of *cavea*, *proscaenium* and *scenae frons*. Using those two theatres we reconstructed the features in the third dimension that is not present in the remains of the theatre of Salona. We have defined following dimensions: the seat height 0,41m, seat length 0.67m, *proscenium* height 1.05m, column height 5m, column width 0.62m, door height (*orchestra*) 2.6m, central door height (*scenae frons*) 4.5m and side door height (*scane frons*) 4.2m.

We also used the theatres of Dougga and Jerash to recreate the look of *scane frons* while respecting its footprint that is still preserved. We did not recreate the fine details of *scane frons* and its elements, but instead adjusted the scattering coefficient in the simulation. We created the 3D model using SketchUp Pro software.

4.2 Simulation of Theatre

The simulation of the theatre of Salona was carried out using Odeon software (v14.05). The 3D model of theatre of Salona was exported from SketchUp to Odeon using the SU2Odeon extension. In Odeon we assigned marble material for Scenae frons, empty cavea, orchestra, and other surfaces made of stone. We assigned the highest scattering coefficient of 0,8 to *scene frons* to simulate the decorations that were not modelled in detail. Other stone surfaces had the scattering coefficient of 0,6. To wooden *proscaenium* we assigned the floating wooden floor material, with 0,4 scattering. For the case when *cavea* was full of spectators, we used the Odeon's audience material with lowest absorption, because the seats were made of stone. To the virtual roof of the theatre and all doors we assigned the 100% absorption.

Air conditions were set according to ISO standard

3382-1:2009. The positions of sources and receivers are presented in figure 2. We placed three sources, at the height of 1,5m above the surface they were positioned on. The source S1 and S2 were positioned on the *proscaenium* one meter from the edge, the first one centred, and the second one moved to 7 m to the right. S3 was placed centred in the orchestra, 3,5 m from its edge. Ten receivers were scattered through the *cavea* in three rows: the first one was on central axis, the second one in the middle of the right quadrant, and the third one near the end of the *cavea*. The height of the receivers was 0,8 m above the seat.

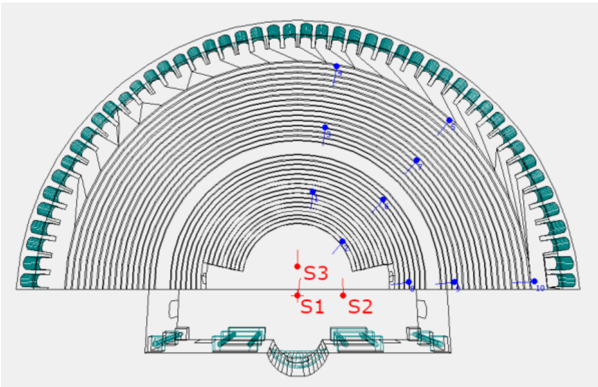

Figure 2 – Position of sources and receivers for the simulation of theatre of Salona.

To perform simulations, we set the "precision" parameters in Odeon simulation, with impulse response length of 1000 ms, approximately 145 984 late rays, max reflection order of 10 000, transition order of early reflection set to 2, 100 early scattered rays per image source, and screen diffraction on.

Simulations of theatre of Salona were carried out on three configurations: C1 *with empty audience,* C2 corresponds to the reconstructed configuration of theatre *with full audience*, and C3 - the reconstructed theatre *without the scene frons and with empty audience*

4.3 Results and Discussion

Figure 3 shows the simulation results for source S1, without the audience. Reverberation time T_{30} for empty audience (C1 – green line) is around 1,4 s, except for highest frequencies. When audience is added to the simulation (C2 – red line), reverberation time drops to 1 s on 1 kHz. This is consistent with results of ERATO project [6] where for south theatre of Jerash simulation produced T_{30} of 1,54 s (empty) and 1,06 s (full) respectively. It is also in accordance with the measurements of theater of Aspendos [13], which has completely preserved *scenae frons* and which has T_{30} of 1,7 s.

Clarity C_{80} in the theatre of Salona was rather low for empty theatre – 1,5 dB on 1 kHz, and good for full audience – 6,1 dB on 1 kHz. Results for definition show similar difference. D_{50} is relatively low without audience - 0,48 on 1 kHz, and good for full audience - 0,71 on 1 kHz.

We noticed that results we obtained are not as good (for dramatic performance) as those shown in [1,7,8] where simulations and measurements were performed for present state of various theatres. These theatres however do not have the *scenae frons* preserved or it is preserved only partially.

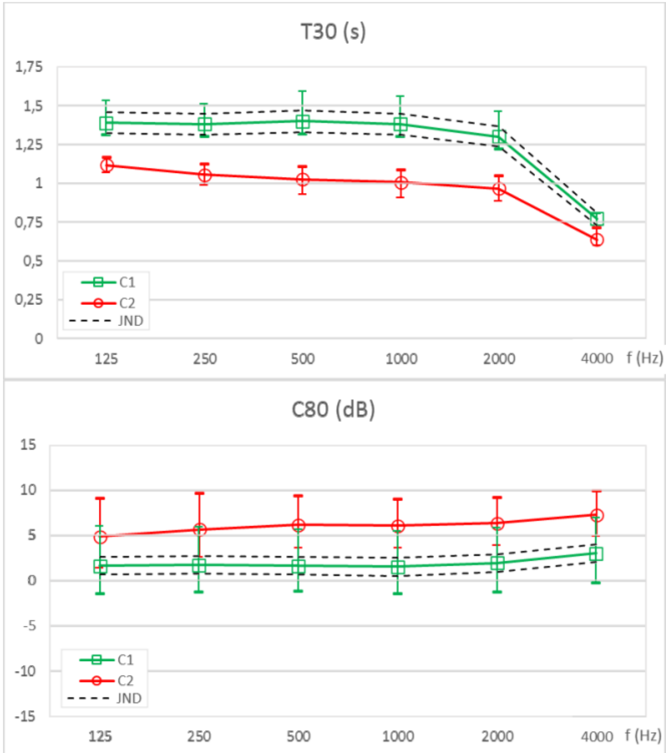

Figure 3 – Results of simulation for source S1: reverberation time T_{30} and clarity C_{80}. Green line shows simulation without audience (C1), and red line with audience (C2). Dashed line show ±1 JND region.

So, we performed simulation for the theatre of Salona without its *scenae frons* to compare it to the above-mentioned cases. Results are presented in Figure 4.

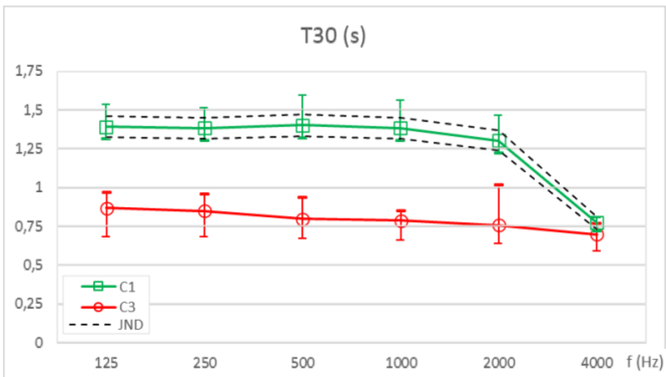

Figure 4 – Comparison of reverberation time T_{30} with (green line – C1) and without *scaene frons* (red line – C3) for source S1. Dashed line show ±1 JND region.

In this configuration, since there are no reflections from *scenae frons*, reverberation time is around 0,8 s. This is almost half than in configuration with *scenae* *frons*. Other parameters follow similar pattern, so on 1 kHz C_{80} is now 9,5 dB and D_{50} is 0,82. These values are now comparable with similar above-mentioned simulations – for example in [7] for 1 kHz T_{30} was 0,65 s, C_{80} was 12 dB and D_{50} was 0,86.

Next, we analysed the influence of different positions of the source on the simulation results, and found that the change in the position of the source does not induce a significant change in the reverberation time, as differences are bigger than 1 JND only for highest frequencies.

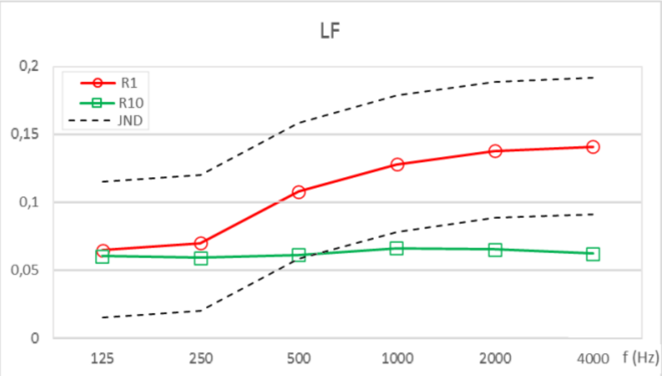

Figure 5 – Lateral fraction of received sound for source S1 and receivers R1 (red line) and R10 (green line) Dashed line show ±1 JND region.

Finally, we analysed the influence of the position of the receiver on the spatial parameters of the received sound. Figure 5 shows the lateral fraction coefficient LF of sound received by the receivers R1 and R10. Receiver R10 is positioned at the edge of the *cavea* and is partially occluded by the *scenae* buildings. LF is for receiver R1 equal to 0,13 (on 1kHz), while for R10 is only 0,07, or 46% less. The reverberation time T_{30} was only 7% lower for the same two sources. These results are consistent with Alayon in [7] and are caused by the screening of one side of receiver with building wall.

5. CONCLUSION

This paper presents the simulation of the theatre of Salona. Since this theatre is not well preserved, nor was it reconstructed, we made a reconstruction based on the remains and similar, existing, preserved theatres of Jerash and Dougga. The simulation results show good acoustical properties of the theatre for dramatic performances, with T_{30} equal to 1 s, C_{50} equal to 6,1 dB, and D_{50} 0,71 on 1 kHz for full audience. We found that different positions of sources produced similar acoustic results, and that position of receiver mainly influences the spatial properties like lateral fraction. We also made the simulation without the *scenae frons* to compare our simulation to simulations of existing theatres, that have well preserved *cavea*, but lack the scene. We got a significantly lower T_{30} and higher C_{50} and D_{50}.

The reconstruction of the theatre of Salona presented here gives valuable insight to the function of this important building of the ancient city of Salona and has confirmed that the theatre's acoustics was good, comparable to other great Greek and Roman theatres.

ACKNOWLEDGEMENTS

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Perception of speech and music in performance spaces

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The Egocentric Audio Perspective in Virtual Environments

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ABSTRACT

Although sound is an essential component of the grammar of digital immersion, relatively little compared to the visual domain has to be done to investigate the role of auditory space and environments. Nowadays, there is increasing consensus on the importance of spatial sound, especially in virtual reality (VR). Technologies for spatial audio rendering are now able to convey perceptually plausible simulations with stimuli that are reconstructed from real-life measurements or historical sites getting closer to a virtual experience indistinguishable from natural reality. This is made possible by a high level of personalization in acoustic transformations caused by the human body interacting with the sound field generated in room acoustic computer simulations. I believe it is time to tightly relate the real to the virtual listening experience from an egocentric audio perspective. The term audio identifies an auditory sensory component, implicitly recalling those technologies capable of immersive and interactive rendering. The term egocentric refers to the perceptual reference system for the acquisition of multi-sensory information in immersive VR technologies as well as the sense of subjectivity and perceptual/cognitive individuality.

Keywords: egocentric audio, virtual reality, sonic interaction design

1. INTRODUCTION

[1] A large body of research in computational acoustics focused on the technical challenges of quantitative accuracy characterizing engineering applications, simulations for acoustic design, and treatment in concert halls. Such simulations are very expensive in terms of computational resources and memory, so it is not surprising that the central role of perception in interactive and immersive rendering has gradually come into play. Nowadays, there is increasing consensus towards the essential contribution of spatial sound, also in virtual reality (VR) simulations. Technologies for spatial audio rendering are now able to convey perceptually plausible simulations with stimuli that are reconstructed from real-life recordings or historical archives, as for the Cathédrale Notre-Dame de Paris before and after the 2019 fire [2], getting closer to a virtual version indistin- guishable from the natural reality. This is made possible by a high level of personalization in modeling human body acoustics interacting with room acoustic computer simulations and non-acoustic factors such as familiarity and adaptability of listening.

At the terminological level, I would like to introduce a new perspective that relates the two listening experiences (i.e. real and virtual), called the egocentric audio perspective. In particular, I refer to the term audio to identify an auditory sensory component, implicitly recalling immersive audio technologies and auralization. The term egocentric refers to the perceptual reference system for the acquisition of multi-sensory information in immersive VR technologies as well as the sense of subjectivity and perceptual/cognitive individuality that shape the self, identity, or consciousness. In such a context, immersiveness is a dynamic relationship between physical and meaningful actions by the listener in virtual environments (VEs). Performing bodily practices such as walking, sitting, talking, grasping, etc. provide meaning to virtual places, objects, and avatars.

2. THE EGOCENTRIC AUDIO PERSPECTIVE

The search for lower bounds such as the "perceptually authentic" audio-visual renderings is an ongoing process. Continuous knowledge exchange between psychophysical research and interactive algorithms development allows to test new hypotheses and propose responsive VR solutions.

2.1 Spatial Centrality

Starting from an egocentric spatial perspective of immersive VR, the learning and transformation processes of the listeners occur when their attention is guided towards external virtual sounds, e.g. the "out-of-the-head" and externalized stimuli. The three-dimensionality of the action space is one of the founding characteristics of immersive VE. Considering such space of transmission, propagation, and reception of virtually

[1] Extracted from Ch.1 of [1], that covers the topic.

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simulated sounds, sonic experiences can assume different meanings and open up to many challenges [1].

Events in multisensory VEs are echoic, i.e., they produce auditory delays and resonances imprinted by the spatial arrangements of the avatar-VE configurations depending on the acoustical characteristics of the simulated space. Since the sound is received from the first-person point of view (generally referred to as 1PP), auralization has to take into account contextual information relating to spatial positions of sound events and self-produced sounds within the avatar's virtual body, creating a sense of proximity and meaningful relations for the listener. The concept of enaction, i.e. it is impossible to separate perception from action in a systematic way, shapes the VR experience by considering an embodied, environmentally situated perceiver with sensorimotor processes tightly connected with the exploratory action.

2.2 Binaural Hearing

Externalization can be considered a necessary condition for the place illusion, being immersed in that virtual acoustic space. From [3], one can learn that ambient reverberation and sensorimotor contingencies are key indicators for eliciting a sense of externalization, whereas head-related transfer function (HRTF) personalization and consistent visual information may reinforce the illusion. Accordingly, it is important to explore dynamic relations depending on specific links between evolving states of the listener-VE system during the VR experiences. Moreover, huge individual-based differences in the perception of externalization require an in-depth exploration of several individual factors such as monaural and binaural HRTF spectral features, and temporal processes of adaptation.

2.3 Quality of the Mediated Experience

There is still no adequately in-depth knowledge of the technical-psychological-cognitive relationship regarding spatial hearing and multisensory integration processes linked to plausibility and technological mediation. In particular, the sense of presence in VR is negatively affected if the experience is irrelevant to the listener. This means that the mediating action of the immersive technology might result in a break in presence that can hardly be restored after a pause [4]. These cognitive illusions depend, for example, on the level of hearing training, and familiarity with a stimulus/sound environment. All these aspects reinforce the term egocentric, grounding auditory information to a reference system that is naturally processed and interpreted in 1PP.

3. HUMAN-TECNOLOGY RELATIONS

Following the recent proposal of a post-phenomenological framework by Verbeek's concept of technological mediation and its extensions [5], one can identify mixed intentionality between humans and technology within VEs. We can describe the cooperation between human and technological intentionality to reveal a (virtual) reality that can only be experienced by technologies, by making accessible technological intentionality to human intentionality. The sonic information from intentional active listening is anchored to an egocentric perspective of spatiality that allows the understanding of an acoustic scene transformed by the listener's actions/movements. This process can be mathematically formalized with the active inference approach and its recent enactive interpretation [6]. Immersive audio technologies are quantitatively integrating prediction through probability and generative models as a function of the listener’s beliefs and expectations to contribute to the listener's internal representation in both spatial and semantic terms, eliciting a strong sense of presence in VR.

4. CONCLUSIONS

In the entanglement within the relational network of listener-reality-simulation, configurations and actors are dynamically defined in a situated and embodied manner. Exploring the evolution of such a configuration network might enable an active search for the egocentrically meaningful experience. However, the communication between the avatar and the listener, the virtual and the physical is challenging. Considering the avatar as part of a VE configuration, I can formulate one of the fundamental questions: if we might be able to handle mediation, where/who is in charge of that? I introduced a performative perspective questioning the a priori and fixed distinctions of certain representationalism between avatar and self, technology agency and listener, physical reality, and virtuality. These boundaries have to be drawn in situated and embodied actions, which makes them dynamic and temporary. The exploration of how, when, and why such boundaries trace identity, agency, and VEs is the core challenge of the proposed theoretical framework.

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Acoustic measurements of Ancient Greek Theatre Masks

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ABSTRACT

Theatrical masks were always used by the actors during ancient drama and comedy performances. However the acoustic function of the ancient Greek theatrical masks is a challenging topic for acousticians and theatrologists. From previous study by the authors, it is evident that such masks not only modify the natural sound of the actor's voice and the directivity of the human head, but also increase dramatically the level of the actor's self-perceived voice. It was found that the level of the actors voice received to his own ears via the enclosing mask could exceed 100 dB, which over the many hours of the ancient performances, would introduce significant hearing discomfort or even damage the actor's hearing.To verify such effects, this work provides a comprehensive set of acoustic measurements for the voice generated by a masked actor (transmit path, Tx) as well as the self-induced voice reaching his own ears (receive path, Rx). A set of mask templates was constructed using archeological data and the masks were set over a HATS dummy head system. The measurements were based on platforms and equipment used by the industry for speech and audio quality evaluation of current headsets, headphones and other telecommunication devices.

Keywords: theatre masks, acoustics, Greek theatre plays.

1. INTRODUCTION

Theatre masks were a fundamental element of the ancient Greek theatre tradition [1]. All theatrical forms that originally developed in Athens during the 6th and 5th centuries BC (tragedy, comedy or satyr plays) and eventually spread over the ancient world were forms of masked drama, i.e. the actors always were performing wearing such masks. A typical theatre mask allowed a transformation of the actor into a new visual and acoustic identity. Hence the function of such mask was crucial to the dramatic work and was more than just a typical theatrical gadget. Since the actor's voice was the most important theatrical element, the mask is considered as an instrument to enhance the voice presence over the entire theatre space and endow the voice with a decided directional delivery. However, up to now such assumption has not been verified. Ancient period vase paintings are illustrating masks before or after the performance and it is now accepted through the archeological evidence that classical masks had a head-enclosing (helmet) form and the mouth and eyes openings were rather small [1]. However, the method for their construction has not been identified, indicating that these masks were made of perishable materials. Note that such head-enclosing masks apart from transforming the actor's face, were also altering his voice and changed his self voice perception, especially if the ears were also fully enclosed [2]. However, prior to the earlier work by the authors [2], there was no study available in the literature providing acoustic measurements of reconstructed theatre masks. Although this early study provided acoustic measurements for such masks [2], it is still not fully understood how such acoustic properties of the masks were combined with the acoustic response of the theatre and how they affected the overall aural experience of the ancient drama. Such combined effects of measured mask directivity and response properties, combined with ancient theater simulations were examined by the authors in [3]. Nevertheless, these early measurements of masks were limited due the requirement of specialist equipment and controlled environment. Such measurements are now presented here.

2. MEASUREMENT METHOD

2.1 Procedure and standards

The measurements were conducted inside an audio measurement chamber (acoustically treated room with a background noise floor of 20dB(A)) following standards used by the industry for speech and audio quality evaluation as applied to modern head-related and wearable audio devices, such as headsets, headphones and smart speakers, especially during rather complex communication scenarios (e.g. multiple speakers to the near/far-end, background noise). The measurements were performed via multichannel microphones and dummy heads. Multiple measurements on the Rx and Tx paths assessed the on and off-axis / frequency response and Directivity for the masked actor. Thus, the measurements provide a set of Mask Impulse Response (MIR) filters, for different azimuth (θ) and median (elevation) angles (φ), i.e. $h_{\mathrm{MIR}\theta,\varphi}\,(n)$, n being the discrete time index.

The measurements were conducted using the HEAD Acoustics HMS head and torso simulator (HATS) [4] in the

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role of the “actor” and also the G.R.A.S. 45BM KEMAR HATS [5,6]. HATS were placed on a stand and at a height of 1.5 m from the ground, in the middle of the room (Fig. 1(a)). The sound source was calibrated at a level of 94dB at the mouth reference point (MRP). The masks were carefully fitted in the dummy head, in order to reassure that the dummy head mouth simulator coincides with the mask mouth (see Fig. 1(b))

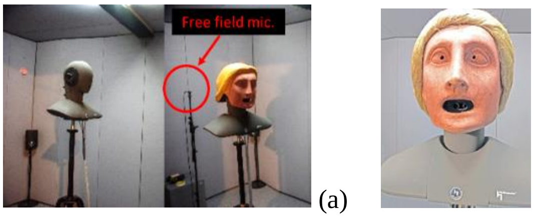


Figure 1 – Measurement of mask response: (a) HATS and HATS fitted with mask, (b) alignment of the artificial mouth to the mask mouth.

2.2 Time, frequency and polar response

For excitation, sweep signals (30 Hz to 16000 Hz range and 2.7 second duration) were transmitted through the built-in Mouth Simulator and recorded through a free field measurement microphone, placed at a distance of 1 m and at the same height as the manikin-mask mouth opening. A complete set of measurements without any mask on the HATS was also preformed and used as reference to all subsequent measured responses. Responses were measured on the horizontal plane for angles from 0^0 (on axis) to 180^0 with a step of 30^0 covering the half plane, assuming symmetrical response (Fig.2). Two additional measurements were made on axis in the vertical plane for +/- 45^0 using the measurement microphone. A total of 6 masks were measured, as shown in Table 1. The recordings were made at 48 kHz with a 24-bit precision using the APx555 and APx 4.6 software (available after registration with AP) [7].

Figure 2 – measurements for different orientation of the HATS plus mask.

Table 1 – List of measured masks.

mask code	ears	details
A1	Enclosed	-
A2	Enclosed	horn mouth
A3	Not enclosed	hairdo
B1	Not enclosed	-
B2	Not enclosed	-
B3	enclosed	hairdo

2.3 Binaural self-voice perception and isolation

For measuring the self-perception of the actor’s voice when he was wearing the mask, responses of the HATS were made both as a sound source and as a receiver. Additional measurements were also obtained using dumping inside the mask as shown in Fig 3. For the dumping regular wavy acoustic foam of 30mm thickness was used.

Figure 3 – A mask filled with dumping material.

3. RESULTS

3.1 Frequency response measurements

The spectral response of the masks exhibits response peaks at approx. 150Hz, 250Hz and 700Hz. Comparing the measured spectrum of the head (HATS) without the mask, it is evident that the on-axis amplification gain is approximately 5dB and is mostly for the ranges around 250 and 700Hz. For off-axis angles, the radiation above 500Hz is reduced by about 5 to 10dB (see typical example for mask A1 in Fig.5), as will be shown more clearly by the polar plots in the next paragraph.

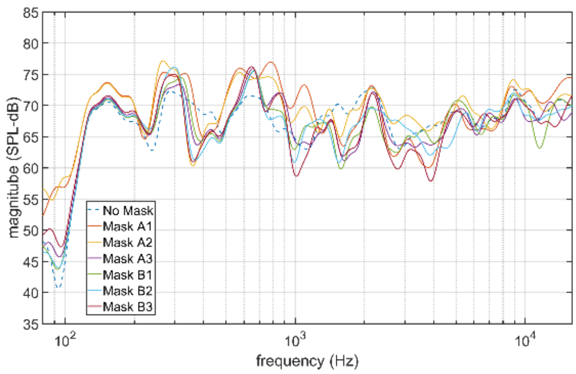


Figure 4 – On axis frequency responses for all masks compared to the HATS response (No Mask, dashed line).

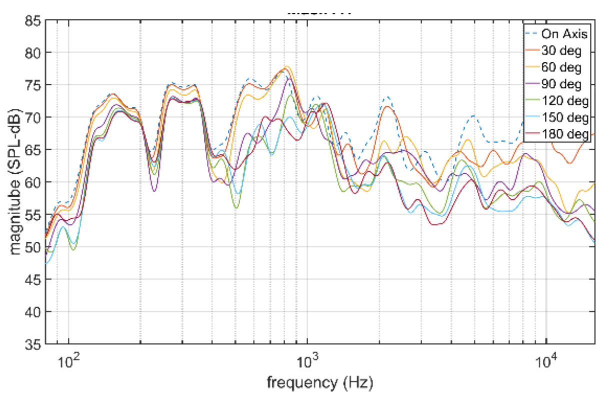
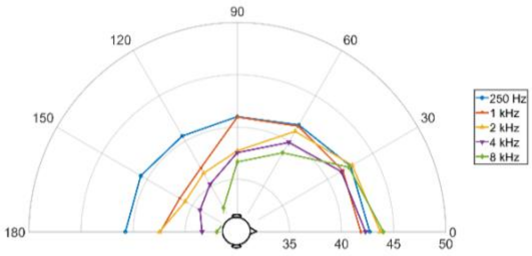


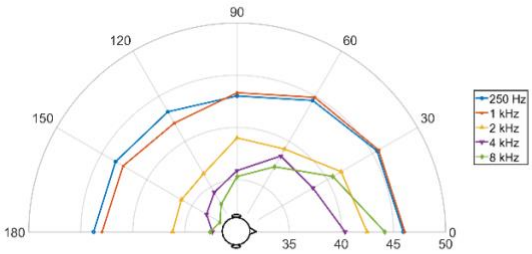
Figure 5 – Frequency response for different azimuth. Angles for mask A1.

3.2 Polar response measurements

Figure 7 shows the measured horizontal plane (azimuth) polar plots for the HATS with no mask (Fig. 7(a)) and with mask 1 (Fig. 7(b)), noting that similar results were obtained for the other masks. It is clear that the mask amplification gain is nearly 5dB for most angles up to 1KHz whilst above 2KHz it is mostly reduced mostly for angles close to the head axis. However, as was previously shown, the amplification gain at low and mid frequencies was for discrete bands of resonance.



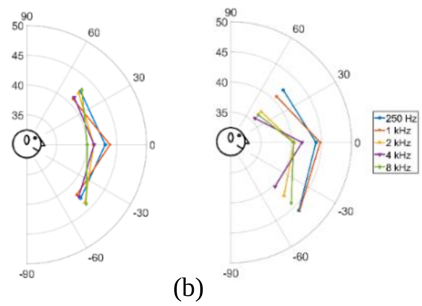
(a)



(b)

Figure 6 – Horizontal polar radiation of the HATS: (a) no mask and (b) fitted with mask A1.

Figure 8 shows the corresponding radiation plots for the median (elevation) plane and for on-axis azimuth measurements (for 3 angles). The comparison between the head (HATS) radiation without and with the mask, shows some small amplification gain for the -45^0 angle when the mask is used, especially for the mid-low frequency range can reach 5dB. The higher-frequency bands show a clear gain reduction of up to 10dB for the mask, for the off-axis angles.



(a) (b)

Figure 7 – On axis vertical polar radiation of the HATS: (a) no mask and (b) fitted with mask A1.

It is evident that the masks provide significant radiation gain for the actor's voice, at least below 2kHz, for broad azimuth angles and for the vertical angle that radiates the sound towards the floor (orchestra) for generating a reflection that is critical for speech perception especially at distant positions. Direct speech radiation via the mask (for the same frequency range) is also enhanced increasing the level at similar distant and elevated listener positions.

3.3 Self-voice perception

Previous work [2] has highlighted the potential extreme levels of the actor's voice reaching his ears due to the amplification by the mask. As can be observed by Fig.9 this finding is also verified here, noting that the results refer to on-axis sound pressure level of 80 dB/ 1m.

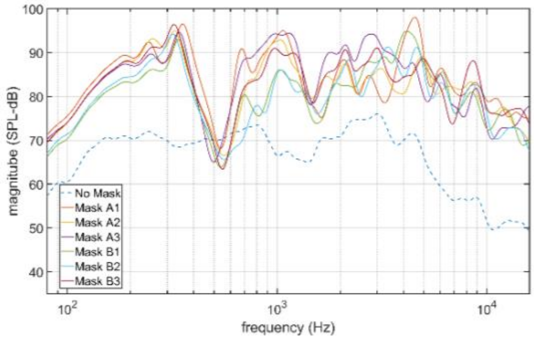


Figure 8 – Self-perception for HATS generated signal without a mask (dashed line) and when fitted with the tested masks (solid lines).

Figure 9 shows that for all masks, there is an approx. 15dB increase in the self-perceived voice level, thus for a normal voice level of 80dB /1m, the actors would receive up to 95dB, (level varying with the frequency). Therefore, for extremely loud voice delivery by the actor in period and for lengthy performances (the plays could last for many hours), the level of the self-perceived voice would be potentially deafening. There is no historic evidence for any solution for this problem. Perhaps the actors were wearing some form of ear protectors, which of course would eliminate reception of outside sounds, e.g. the voices from other actors. There is also a possibility that perishable absorptive materials could be used in period to reduce the internal sound level. To examine this possibility, as mentioned previously, absorptive damping was also used which as can be observed in Fig. 10, resulted to a sound level reduction between 5 and 10dB, thus still a significant loud voice level.

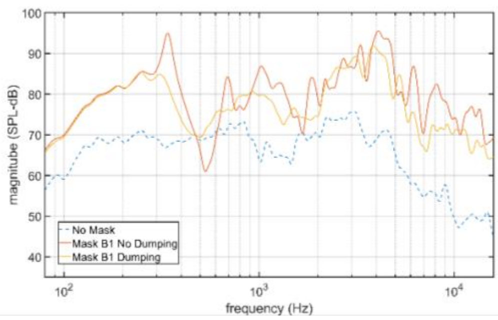


Figure 9 – The effect of the internal dumping for mask B1 at the self-perceived sound level by the actor.

3.4 Mask and amphitheatre acoustics

The effect of the mask acoustic response to the sound of the actor's voice within an amphitheatre (e.g. Epidaurus) has been studied in the past by the authors [3]. This can be described as a linear filtering process that for a specific receiver / listener position at various angles (θ_j) and distances (r_j) from a source located at the centre of the orchestra. For simplicity, we will only consider variation for azimuth, 'though in practice, the elevation angle must be considered.

Denoting by $h_{\mathrm{TIR\theta jrj}}\ (n)$ the discrete-time impulse responses of the "theatre-filter" (TIR) measured or numerically simulated for azimuth angles θj and distances rj. Then, the combined mask and theatre impulse response (CIR) $h_{\mathrm{CIR\theta ijrj}}\ (n)$ at any audience position, may be expressed as a discrete convolution of the corresponding responses, as is shown in Figure 11.

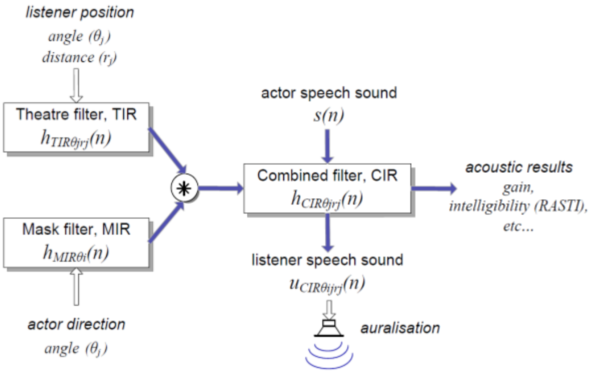


Figure 10 – Schematic diagram for acoustic reconstruction of masked actor performances in an ancient theatre.

4. CONCLUSIONS

This comprehensive acoustic measurement study of the ancient theatrical masks extends and validates previous results in tests previously carried out by the authors. With reference to a typical manikin head radiation, the spectral and spatial radiation gain added by the tested masks was established.

It is evident that the masks provide a nearly 5dB gain for the actor's voice, at least below 1kHz, for broad azimuth angles and for the vertical angle that radiates the sound towards the ground (e.g. the orchestra). This amplification gain is concentrated in distinct spectral regions, with peaks at approx. 150Hz, 250Hz and 700Hz, with progressive attenuation for high frequencies, properties which add percieved colouration to the sound of the voice. Furthermore, such spectral amplification may relate to male fndamental and formant peaks, provided that the actors delivered a rhapsodic style speech with constant or small pitch. However, there is no historic evidence on the way ancient greek language was pronounced and spoken, especially for theatrical speech delivery, so this aspect is open to speculation and may be partially verified by modern theatrical practices.

Another controversial aspect of these tests with respect to the ancient theatrical performances is the finding of extreme levels of self-perceived voice at the actror's ears, irrespective of the shape of the mask. It was verified that this amplification could exceed 15dB at some frequencies, with respect to the level without mask. Even if some internal absorption was used (assumed that the ancients were aware of the acoustic absorption properties of some materials, e.g. wool), then a reduction of approx. 5dB was measured, so still the voice level at the actor's ears would be highly uncomfortable during lengthy performances. If the actors wore hearing protectors, then they would not be able to receive any information from other actors.

Analyzing these combined mask-theatre responses, it was found that the masks amplified the spectral region up to 1000 Hz. This effect was found to be stronger around the male speech fundamental frequency. Given that the theatre responses present a significant peak around the mid 1000 Hz region, the "mask-filter" effect appears somehow to smooth the overall spectral profile of the "theatre-filter". Furthermore, the masks would alter the actor's voice by boosting the low-mid region of speech reaching the audience.

Preliminary tests for the combined effect of the masks and the theatre's acoustic indicate that the masks enhance directivity even for the side of the actor's head and hence amplify significantly such low-mid speech frequency region, for listeners located beyond the central positions and especially at the sides of the cavea. This radiation property of the masks would improve reception at these more problematic audience positions, especially under noisy conditions. Overall, the masks were not found to affect the excellent speech intelligibility of the Epidaurus theatre which has remained perfect for all listener positions.

ACKNOWLEDGEMENTS

The authors acknowledge the kind support of Dialog Semiconductor, a Renesas company, for providing the facilities and additional equipment for the measurements.

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PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

Reinforcement of binaural cues by floor and ceiling reflections

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ABSTRACT

Sound reflections occurring only on floor and ceiling usually have the same azimuthal angle as the direct sound. Their energy thus adds to the direct sound with binaural cues similar to those of the direct sound. The anticipated benefits are of improved source localization and, for a frontal target, of higher binaural coherence of the ear signals. This modelling study investigated these hypotheses using a shoebox room whose specular reflections were modelled with the room acoustic simulation of the Simulated Open Field Environment (SOFE). Adding floor and ceiling reflections decorrelated the binaural ear signals and added late reverberant energy – C50 was higher without a floor or a ceiling. Binaural cues for very low and very high elevation angles converge to zero, i.e. to more centered binaural cues compared to those of a lateral direct sound source. An analysis with mapping these reflections into the horizontal plane did not show consistent evidence for an increase of correlation or coherence due to floor or ceiling reflections.

Keywords*:* spatial hearing in rooms, speech intelligibility, effects of reverberation

1. INTRODUCTION

Sound reflections in (shoebox) rooms occur – for sources at the same height as the listener – mostly parallel to the main horizontal dimensions of the room, and from floor and ceiling along the direct path from the source to the listener. These floor and ceiling reflections thus come from the same azimuthal angle as the source and could be seen as emphasizing the source's binaural cues. Clapp and Seeber [1] demonstrated that misplaced floor reflections can substantially affect the localization of the source if the direct sound is attenuated, e.g., because the speaker turns away. This was attributed to floor and ceiling reflections emphasizing binaural cues of the source against the diffuse energy in other reflections. The present investigation builds on this idea and questions if floor and ceiling reflections can indeed emphasize the binaural cues of the source. The question arises from the fact that binaural cues become smaller with increasing elevation angle of the source. Figure 1 shows interaural level differences (ILDs; upper panel) and interaural time differences (ITDs; lower panel) for a source at 45° azimuth as a function of source elevation. ILDs and ITDs are largest for horizontal sources (elevation of 0°) and decline if the source comes from below or above the horizontal plane. For sources overhead (elevation of 90°), binaural cues become zero. This is equivalent to the binaural cues of a source in the front, which leads to interaurally correlated ear signals. Hence, floor and ceiling reflections will always have smaller binaural cues by magnitude than the source itself, cues that indicate a horizontal source more toward the front (see right-hand ordinate of Figure 1). The present study investigates the impact of floor and ceiling reflections on interaural parameters relevant for binaural unmasking. Room acoustic simulation is used to create specular reflections of a shoebox room. To test the contribution of floor and ceiling reflections, the binaural room impulse response is manipulated by either omitting floor and ceiling reflections or by mapping them to horizontal sources at the same azimuth.

2. METHODS

2.1 Room Acoustic Simulation

The room acoustic simulation and auralization software of the Simulated Open Field Environment [2] (Matlab code) was used to create binaural room impulse responses (BRIRs). The software uses the mirror-image source method for arbitrary geometries [3] to create a list of image sources. Visible sources are synthesized by spectrally modifying the head-related transfer functions of the KEMAR manikin [4] of the image source location with the wall transfer function and the distance-related attenuation, and placing the resulting impulse response into the BRIR at the time related to the image source distance. Specular reflections up to reflection order 200 were computed, resulting in BRIRs of ca. 12 sec duration. Reflections from order 5 were temporally jittered by up to 5% of their delay to reduce the strict periodicity in the reflection pattern of the rectangular room. No specific diffuse field simulation was used.

In "mapped" conditions, image sources below the horizontal plane (floor reflections) or above the horizontal plane (ceiling reflections) were mapped to the horizontal plane (elevation 0°), while the azimuth angle of the image source was kept the same.

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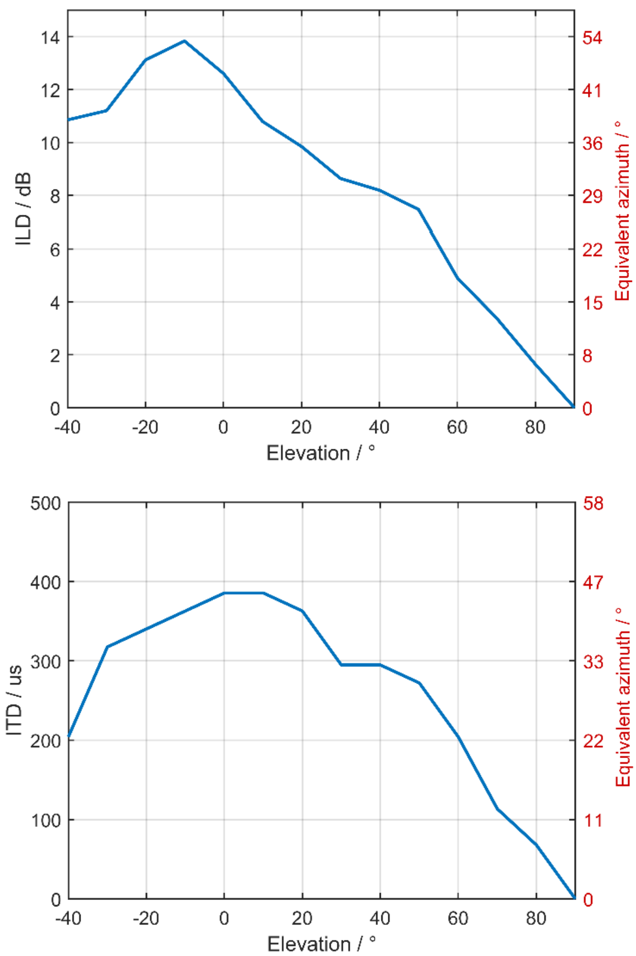

Figure 1 – Interaural level differences (ILD, top panel) and interaural time differences (ITD, bottom panel) as a function of the elevation of a source at 45° azimuth. ITDs and ILDs were extracted from the head-related transfer functions of a KEMAR manikin [4]. The right ordinate presents the azimuth angle of a source in the horizontal plane with the same magnitude of ILDs or ITDs. With increasing absolute source elevation, ITDs and ILDs tend toward zero, representing a horizontal source toward the front, which has interaurally correlated binaural cues.

2.2 Room conditions

BRIRs of an empty rectangular room with dimensions 20 m x12 m x 7 m were simulated. The source was positioned at (4.36 m, 17.64 m, 1.50 m) in 3.7 m distance to and at an angle of 10° left to the frontal direction of the receiver at (5.00 m, 14.00 m, 1.50 m). The directional characteristics of the source were those of a human speaker [5] in the direction of the receiver. Reflection coefficients of vertical walls were those of gypsum board, those of the floor mimicked wood parquet in asphalt on concrete and those of the ceiling stemmed from wood.

Seven room conditions were created to assess the impact of floor and ceiling reflections on binaural parameters:

6 walls, 3D – Simulation of the shoebox room with all 6 walls and “correct” 3D-mapping of the reflections. This room reflects the baseline condition. The top panel of Figure 2 depicts the reflection paths of the reflections in this condition up to reflection order two.

5 walls: No ceiling – The ceiling was omitted in this simulation, resulting in an shoebox room with 5 walls. This room represents an open-air theatre.

4 walls: No floor & ceiling – The floor and ceiling were omitted, resulting in a space made of only side-walls (i.e., perfectly absorbing floor and ceiling). This condition contrasts with the “6 walls, 3D”-condition in that the energy and binaural cues of floor and ceiling reflections are absent. The reflection paths for all reflections up to order two are shown in the lower panel of Figure 2.

6 walls: ceiling mapped horizontally – The above conditions are dominated by the energetic change of omitting floor and ceiling reflections. In order to specifically test the impact of reflection elevation angle on binaural parameters, in this condition reflections coming from above the horizontal plane were mapped to the horizontal plane while their azimuthal angle was kept identical and the number and the energy of all reflections was kept identical to “6 walls, 3D”.

6 walls: floor mapped – Reflections coming from below the horizontal plane were mapped to the horizontal plane while all other reflections were kept identical to the “6 walls, 3D” condition.

6 walls: floor & ceiling mapped – In this condition, both floor and ceiling reflections were mapped into the horizontal plane, i.e. all reflections were within the horizontal plane while the number of reflections and their energy was identical to the “6 walls, 3D” condition.

2.3 Room acoustic and binaural parameters

The ***direct-to-reverberant ratio (DRR)*** was computed as the ratio of the direct sound energy and the reverberant energy expressed in dB and averaged across both ears. To compute the reverberation-only BRIR, the BRIR of the direct sound was subtracted from the overall BRIR of the respective condition.

C50 expresses the ratio of the energy arriving within the first 50 ms (here: up to sample 2205 of the BRIR at a sampling frequency of 44.100 Hz) of the room impulse response and the energy arriving after 50 ms.

The ***interaural cross-correlation (IACC)*** is the normalized correlation coefficient of the two ear signals in the BRIR.

The ***coherence*** was computed as the maximum of the interaural cross-correlation function evaluated over a delay of ±1 ms. The coherence will compensate for the decorrelation caused by the azimuthal source offset of 10° and expresses the delay-independent similarity of the ear signals. Note that both IACC and coherence were computed from broadband signals.

The ***coherence ratio*** reflects the idea of useful source information arriving within the first 50 ms and detrimental cues arriving later (c.f. C50). Binaural unmasking is driven by a contrast in correlation. The ratio of the coherence of the first 50 ms of the BRIR and the coherence of the BRIR after 50 ms is computed.

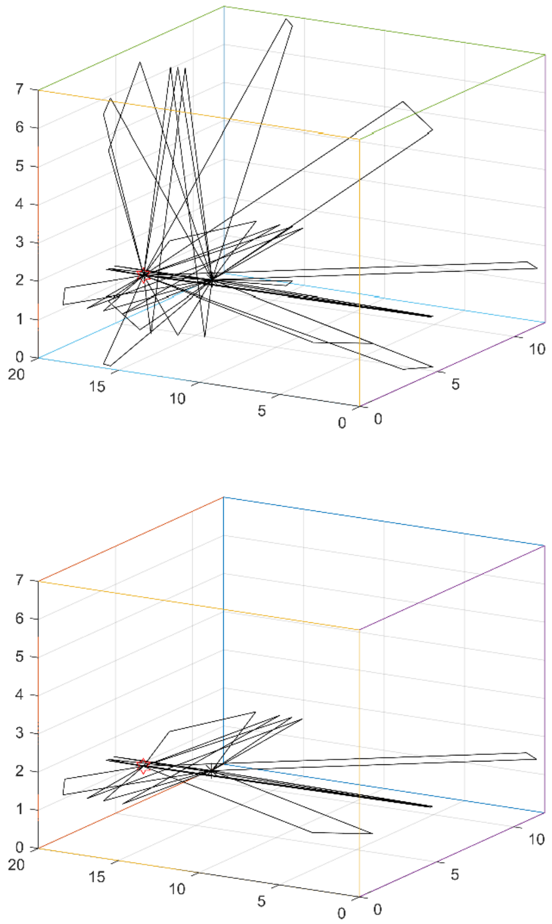

Figure 2 – Reflection paths up to the second reflection order in a simulated rectangular room with 6 walls (top panel) and in the same room without floor and ceiling (bottom panel). The source is at 350° azimuth relative to the receiver and depicted in red; the receiver is marked by a black asterisk.

3. RESULTS

Table 1 shows room acoustic parameters of the 7 room conditions. As one would expect, the DRR improves when omitting floor and ceiling reflections, indicating that an open-air arena should be beneficial in binaural terms. Mapping reflections to the horizontal plane does not affect the DRR since it is an energetic measure and the change was mostly binaural (though there is also a spectral change). C50 increases strongly when there is no floor or no ceiling. While some floor reflections arrive early, the majority of floor and ceiling reflections arrive in the late, “detrimental” part of the BRIR such that omitting those leads to an increase in C50.

Table 1 – Room acoustic parameters.

Room condition	DRR / dB	C50 / dB
6 walls, 3D	-4.3	2.4
5 walls: No ceiling	-1.4	8.1
5 walls: No floor	1.9	7.1
4 walls: No floor & ceiling	3.7	8.2
6 walls: ceiling mapped horizontally	-4.3	2.6
6 walls: floor mapped	-4.3	2.8
6 walls: floor & ceiling mapped horizontally	-4.6	2.6

Table 2 – Binaural parameters.

Room condition	IACC	Coherence	Coh ratio
6 walls, 3D	0.06	0.42	12.9
5 walls: No ceiling	0.03	0.62	5.0
5 walls: No floor	0.06	0.59	5.7
4 walls: No floor & ceiling	0.07	0.67	8.4
6 walls: ceiling mapped horizontally	0.03	0.45	14.7
6 walls: floor mapped	0.06	0.46	6.9
6 walls: floor & ceiling mapped	0.02	0.45	5.7

Table 2 shows results in terms of binaural parameters. For all room conditions, the IACC is close to zero, indicating highly decorrelated ear signals. The coherence, however, is considerably higher, suggesting that the 10° azimuthal offset of the source results in interaurally decorrelated, but still largely coherent ear signals. The anticipated effect of floor and ceiling reflections leading to higher correlation cannot be observed – it is more that their absence in the late reverberant tail leads to an increase in coherence.

The mapping of reflections from elevated angles to the horizontal plane increases coherence somewhat, in agreement with the hypothesis. The ratio of early and late coherence was another attempt to investigate the potential benefit of floor and ceiling reflections for emphasizing the source (correlation). However, the ratio increases when the ceiling reflections are mapped to the horizontal plane. A similar measure based on the correlation values decreases (from 2.22 for the 6 walls, 3D condition to 1.09 for the condition with horizontally mapped ceiling reflections), which could be supporting the hypothesis. An issue of useful-to-detrimental ratio analyses is that individual reflections might fall into or just out of the useful window, thereby changing computed parameters considerably [6]. Thus, these values appear too unreliable to draw formal conclusions from the present analysis – a more substantial modelling study using more rooms and a time and frequency dependent analysis of spatial unmasking would be needed to gain a better understanding.

4. CONCLUSIONS

This study investigated the question if the smaller binaural cues for sound reflections below and above the horizontal plane increase binaural correlation of a frontal target stimulus, which might be beneficial for localization and spatial unmasking. Analyses using manipulated reflections of a shoebox type room could not find consistent evidence – if a ceiling exists, the additional reflections decorrelate the target sound and they add late reverberant energy, while an open-air theatre configuration has increased C50. If floor reflections are mapped into the horizontal plane, the coherence slightly increases in favour of the hypothesis, but the ratio between coherence in the first 50 ms of the binaural room impulse response and coherence in the late part decreases, suggesting that the binaural contrast between both parts is reduced. A more detailed analysis using different rooms and additional temporal measures is needed to shed more light on the question.

ACKNOWLEDGEMENTS

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Does surface scattering improve speech perception compared to plain surfaces?

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ABSTRACT

Ancient theatres are characterized by a peculiar impulse response where, aside the very close floor reflection, all of the remaining components come from regularly profiled tiers of steps making up a scattered sound tail. Declerq and Dekeyser [J. Acoust. Soc. Am.,121 (2007), 2011-2022, https://doi.org/10.1121/1.2709842] have attributed good speech reception properties in ancient theatres to the phenomenon of back-scattering, whose ultimate effect is a filtering out of the unwanted low frequency noise and an enhancement of the speech-related frequency range. While the regular corrugation of the tiers of steps provides a time-lock to the scattered components, this property is mostly lost when surface scattering consists of phase grating diffusers. Hence the question arises whether and how the speech perception could be supported by conventional room acoustics diffusers. In this work, based on a set of experiments, it will be shown how turning one or more flat surfaces into diffusing ones modulates performance in speech perception and affects the perceived spatial features of the speech source. The effects of reverberation and of the spatial character of the noise (diffused or concentrated) will be outlined too.

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Architectural acoustics and parliamentary debate: Exploring the acoustics of the UK House of Commons Chamber.

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ABSTRACT

The United Kingdom's House of Commons chamber is a theatre for confrontational political performance, speech-making and Parliamentary debate. The space has been subject to considerable architectural change due to historic events such as the Reformation, the English Civil War, the fire in 1834, and destruction in the Second World War. Considering its importance in shaping the history of the UK, together with the political speeches, performances and decisions that have taken place within it, we explore and compare the acoustic characteristics of the House of Commons Chamber in different contexts. Acoustic results are obtained from measurements carried out in the modern House of Commons chamber, and the University of Oxford's Divinity School and Convocation House as alternative spaces used for Parliamentary debate in the 17th century. An overview of the acoustic parameters and a comparison between them is presented, with a specific focus on speech intelligibility and the perception of speech in the context of Parliamentary debate. Auralisation examples are provided as a listening experience of these spaces and the data will be used to inform further acoustic modelling work of the historic House of Commons chamber site within the Palace of Westminster.

Keywords: Speech intelligibility, House of Commons, Measurements

1. INTRODUCTION

The House of Commons of the United Kingdom has changed locations and buildings several times due to political changes and damage to the spaces over a number of centuries. St Stephen's chapel in the Palace of Westminster was dissolved during the Reformation of Edward VI, redesigned in 1692 with wooden panels covering the main structure, followed up by several stages of layout changes of the seats and gallery until 1834 when a fire in the Palace destroyed the building which was then demolished in 1837 [1]. The new building was then designed with the same architectural style which has been copied until the very modern House of Commons. Over the course of some of these changes, Parliament had met in several other locations including the Convocation House and the Divinity School at the University of Oxford.

The uniqueness of Parliamentary spaces is the fact that they require good speech intelligibility across all the members' positions. Each member of the parliament is not only the receiver of the speech taking place in the space but could potentially be the speaker. This is particularly challenging in a rectangularly shaped space, where the benches are arranged in parallel rows across the length of the room facing each other for debating.

This layout is influenced by the choir stall arrangements of the medieval St Stephen's Chapel where Parliament sat between the 16th-19th century. There have been several discussions over the years regarding the effectiveness of this layout and its impact on the meetings that took place.

There are studies discussing speech intelligibility parameters for spaces such as schools, churches, and theatres. As part of the Past Has Ears project [2], our aim is to reconstruct the acoustics of the historic St Stephen's Chapel as it was used before the fire in 1834 and explore the impact of its acoustics on Parliamentary debates. In this paper, we are interested in the investigation of the acoustics, and specifically the speech intelligibility of three existing spaces used for Parliamentary debates. The acoustic analysis and auralization results are based on impulse responses obtained from in situ measurements by a different scientific team (see acknowledgements).

2. PARLIAMENTARY SPACES

2.1 House of Commons chamber, Westminster

The current House of Commons in Westminster Palace (Figure 1) was designed by Sir Giles Gilbert Scott and completed in 1950, after the previous chamber was entirely destroyed by bombing during World War II in May 1941. It was deliberately rebuilt following the architectural style and political culture

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of the previous chambers. Members of the Parliament may speak from where they are seated, except for the floor area between the red lines, which traditionally is said to be two sword-lengths apart.

From the available acoustic measurements, two source locations have been chosen; one being at the Speaker of the House of Commons' Chair, and one to their left, where the Opposition Leader stands, as due to the symmetry of the space, similar results would have been obtained from a source at the dispatch box, where the Prime Minister usually stands. Measurements were taken with the following combinations of source/receiver positions; 1:S1-R1, 2:S1-R2, 3:S1-R5, 4:S1-R3, 5:S1-R4, 6:S2-R4, 7:S2-R5 and 8:S2-R6 (Figure 2).

Figure 1 – Chamber of House of Commons, in Westminster in its current condition [3]

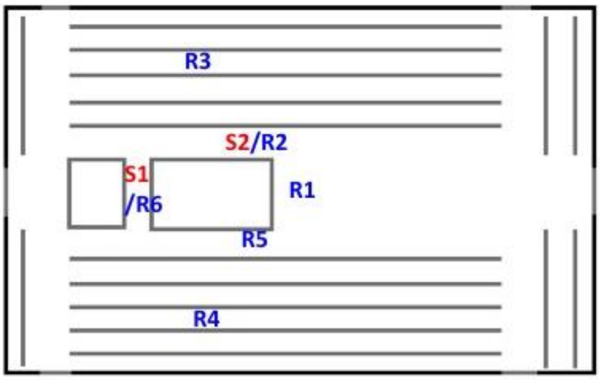

Figure 2 – Measured positions in House of Commons, Westminster, dimensions: 21m x 16m x 14.7m, Volume: without furnishing 4839m^3

2.2 Convocation House, University of Oxford

Convocation House is part of the University of Oxford's Bodleian Library (Figure 3), built in 1634. During the English Civil War and in 1665 and 1681 it was used for meetings of the House of Commons.

The measured positions for this study are shown in Figure 4. Three different sound source locations were considered; one at the Speaker's position (S1), S2/R2 and S3/R5 representing members of the Parliament who could have also been listeners/receivers in different source combinations. Additionally, four more receiver positions were spread symmetrically in the space (R1 - R6) resulting in the following combinations of source/receiver positions; 1:S1-R1, 2:S1-R2, 3:S1-R3, 4:S1-R4, 5:S1-R5, 6:S2-R1, 7:S2-R3, 8:S2-R4, 9:S2-R5, 10:S2-R6, 11:S3-R1, 12:S3-R2, 13:S3-R3, 14:S3-R4 and 15:S3-R6 (Figure 4).

Figure 3 – Convocation House, University of Oxford, Photo by DAVID ILIFF. License: CC BY-SA 3.0 [4]

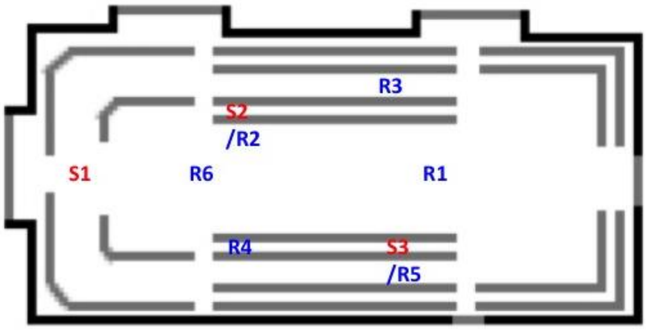

Figure 4 – Measured positions in the Convocation House, Oxford, dimensions: 18.55m x 8.4m x 7.63m, Volume: without furnishing 1177.9m^3

2.3 Divinity School, University of Oxford

Divinity School (Figure 5) is also part of the Bodleian Library at the University of Oxford and adjacent to Convocation House. In 1625 and during the English Civil War, the House of Commons had sat in Divinity School. One measurement was arranged here, with the source and receiver set in central positions (Figure 6).

Figure 5 – Divinity School, University of Oxford, Photo by DAVID ILIFF. License: CC BY-SA 3.0 [5]

3. RESULTS

The acoustic measurements were carried out with a Genelec 8030 as a sound source and a Soundfield

ST450 microphone as the receiver and using an exponential sine sweep of length 15s. For the analysis, MATLAB was used to post-process the recorded files, while Aurora plug-in was used for the traditional ISO3382 acoustic parameters such as T30, EDT and C50. The impulse responses were also imported into ODEON for the calculations of speech intelligibility parameters. The values of the background noise observed from the Aurora plug-in also were imported into ODEON for each individual octave band frequency for each of the impulse responses.

Figure 6 – Measured position in Divinity School, University of Oxford, dimensions: 27.6m x 10.3m x 7m, Volume: without furnishing 1989.9m^3

Three parameters are presented and analysed here. We start with reverberation time (T30) for an overall impression of the acoustics of the studied spaces. Clarity (C50) is analysed as it is associated with the perception of speech. It has also been considered that for this study Speech Transmission Index (STI) provides sufficient information regarding the speech intelligibility of the spaces across the different measured positions. For each space, we use the following abbreviations; HoC for House of Commons, CH for Convocation House and DS for Divinity School.

3.1 T30

Figure 7 shows the results of T30 calculations from the three spaces. For the HoC and CH, the curves show the octave band average values across all measured positions, with error bars to indicate the variance of the results for each frequency band, while the results for DS are based on the single available measurement. As expected, the variations between the multiple positions are minimum, while the curves of the HoC and CH follow a typical pattern for such spaces. Reverberation time is much shorter in the HoC, as this is a modern space compared to the CH or DS, and was built to fit the purpose of its use. Note that T30 is quite high for DS and for 500-4kHz octave bands for CH.

3.2 C50

Figure 8 shows the octave band averaged results for C50 for all 3 spaces with error bars across. It was observed that two locations, Position 7:R2-R5 from HoC and Position 8:S2-R4 from CH, were significantly different from the rest of the locations for each space.

Their values have been excluded from the average values, and have been represented here with no fill on markers in order to demonstrate their differences from the rest. Further detailed analysis of these locations showed that Position 7:R2-R5 from the HoC is in the near field of the sound source, and any acoustic measurements are not representative of the acoustic behaviour of the space. It is interesting to note that their distance is 3.3m, which is within the 2 swords' length (3.9m) that the tradition required. For the exceptional position in CH, the different acoustic behaviour could be a result of standing waves due to the parallel walls in that specific location, or comb filter effects from a wooden stand/table placed nearby as some possible frequency interference was observed in the frequency analysis. Overall, it was observed that the results of the modern HoC are above 0dB across all the frequency bands, indicating very good clarity for speech purposes. On the other hand, CH and DS have poor clarity, with C50 values below 0dB.

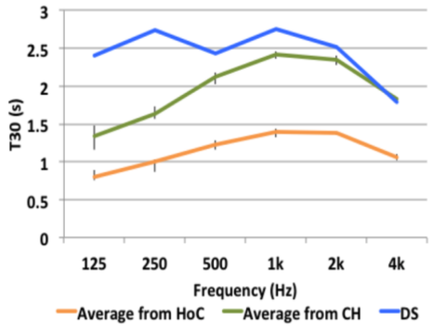

Figure 7 – T30 results from the three spaces

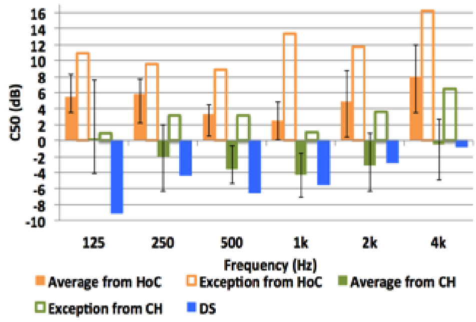

Figure 8 – C50 results from the three spaces. The solid lines represent the average values of the positions with standard deviation across the frequency bands. Particular locations for HoC and CH have been excluded from the average results, although being presented for reference

3.3 STI

The Speech Intelligibility Index is evaluated based on the STI label categories from ISO 9921. The range of measured outcomes is shown in Figure 9, as well as the results of the measured positions for each of the three spaces. Two points, as discussed above, for Position 7 of the HoC and Position 8 of the CH have been left with no fill on markers, indicating their differences from the rest of the results. The STI results from the HoC are *good* to *excellent*, from CH are *fair* while the single position in DS has *poor* speech intelligibility.

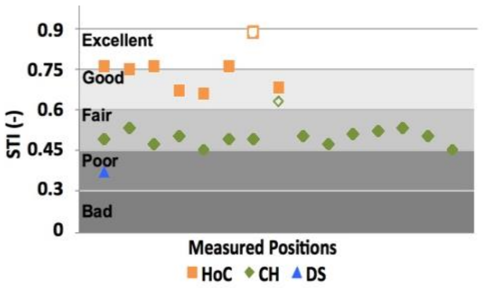

Figure 9 – STI results from the three spaces across the different measured positions

4. AURALIZATION RESULTS

An excerpt of an anechoic recording from the speech made by Henry Beaufoy to the HoC in 1792 on the slave trade was used for this purpose. The performer for this recording, one of the authors of this paper, is an English native speaker. The W channels of the ambisonic recordings have been convolved with the anechoic recordings and the MONO results are available at the Open AIR Library [6].

The objective results analysed above can be confirmed from the listening examples. The intelligibility of the speech in the HoC is significantly better than the auralization examples from CH and DS. In the last two spaces, the reverberance of the space has a negative impact on speech perception.

5. CONCLUSIONS

We have studied three spaces that have been used or are still used for meetings of the UK Parliament. The layout of the seats is of particular interest and is challenging due to the fact that all the receivers in the Parliamentary spaces are potential sound sources too.

Overall, the modern House of Commons has low values of T30 and high values of C50, representing an excellent space for its purpose. STI values have also confirmed this result, indicating good to excellent speech intelligibility. Note that there is a complex sound reinforcement system built into the benches of the House of Commons chamber that is used to enhance speech further for all listeners although this was turned off during the measurement process.

Convocation House and Divinity School have longer reverberation time, affecting C50 and STI values correspondingly. The spaces are rated between poor (for Divinity School) and fair (for the Convocation House) for their speech intelligibility. While their main use was for lectures and meetings of the University members, the acoustics are not appropriate for this purpose. The above results indicate that Parliamentary meetings in both these spaces would have been a challenge to comprehend and participate effectively in debates across the measured positions. Further source/receiver combinations, however, for these spaces would also support our investigation in this paper.

The current results will be used to inform and calibrate the reconstruction of the historic chamber model of the House of Commons as it was before the fire in 1834, as the main focus of the PHE project.

ACKNOWLEDGEMENTS

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Ritual spaces in ancient times: caves, temples, and early Christian churches

PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
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Acoustical measurements of Japanese Kagura ancient theatres

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ABSTRACT
The Kagura is a specific type of Shinto ritual ceremonial dance and drama offering to the Gods. The Shinto priests act mythological character and play traditional musical instruments on a stage, but the Kagura theatre does not arrange the audience area. I hypothesized that the audience are the Gods enshrined in the main hall and the acoustics is optimized to them. So, I measured impulse responses in the three different types of Kagura theatres and report the acoustical characteristics in the area between the theatre and main hall to identify who is the audience.
Keywords: Kagura ancient theatre, impulse response, absence of audience area, reverberation time

1. INTRODUCTION

The Kagura is a specific type of Shinto ritual ceremonial dance and drama offering to the Gods. Because the Kagura was described first in Kojiki (Japanese history book including myths) edited in the 8th century, the origin may not be later than the century [1]. Today, it is very much a living traditional especially in Shimane and Miyazaki prefectures of Japan, and the Shinto priests act mythological character and play Japanese traditional musical instruments on the stage [2]. To enjoy the performance, we sit on folding chairs lined up around the stage. So that means the Kagura theatre does not arrange the audience area. Who is the audience? I guess that the audience of the Kagura performance is the Gods of the shrine, because the Kagura theatre always locates closely to the main hall in which enshrines God. And I hypothesized that the acoustics of Kagura theatre was optimized to the main hall.

To verify the hypothesis, I measured impulse responses in the Kagura theatres in three shrines (Sata, Kumano and Miho shrines in Shimane) and report the acoustical characteristics in the area between the theatre and main hall to identify who is the audience.

2. ACOUSTICAL MEASUREMENTS

2.1 Kagura Theatres

The acoustical measurements were carried out in three shrines which Kagura theatre have different layouts and structures (Fig. 1). Generally, Japanese shrine is constructed by an entrance gate, worship hall and main hall. The worship hall is a place where we visit to pray, and the main hall is an inner building to enshrine the Gods.

The theatre in Sata shrine is located inside the

Figure 1 – Birds-eye-views and standing views of (a) Sata, (b) Kumano, and (c) Miho shrines

entrance gate and separated from the worship and main halls (Fig. 1a). The stage is opened in the three sides, and the openings are toward to the main hall. The theatre in Kumano shrine is also separated from the main hall, and the stage is opened in all the four sides. Differently from these shrines, the theatre in Miho shrine is not an independent building, but the stage is included in the worship hall. The worship hall is adjoining to the main hall.

2.2 Measurement positions

To examine the sound propagation from the theatre and the main hall, Figure 2 shows the measurement positions of impulse responses.

The sound source position was fixed in the area

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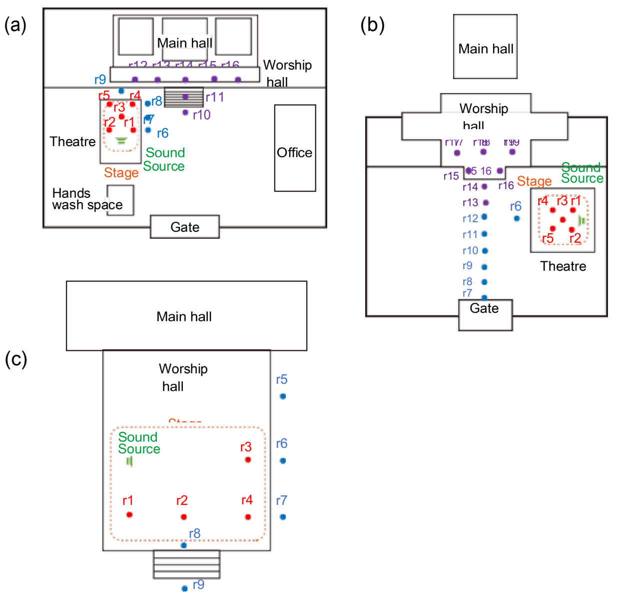

Figure 2 – Displacement of sound source and receiver positions: (a) Sata, (b) Kumano, and (c) Miho shrines

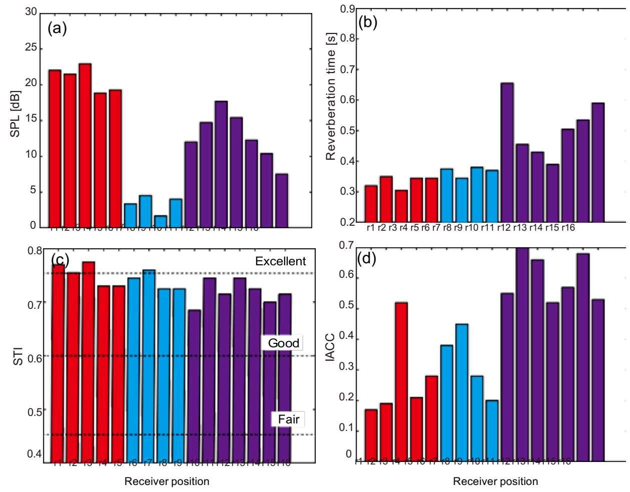

Figure 3 – (a) SPL, (b) reverberation time, (c) STI, and (d) IACC in the Sata shrine. The different colors indicate the receiver pisitions (red bar: on the stage, blue bar: around the stage, and purple bar: around the worship or main hall).

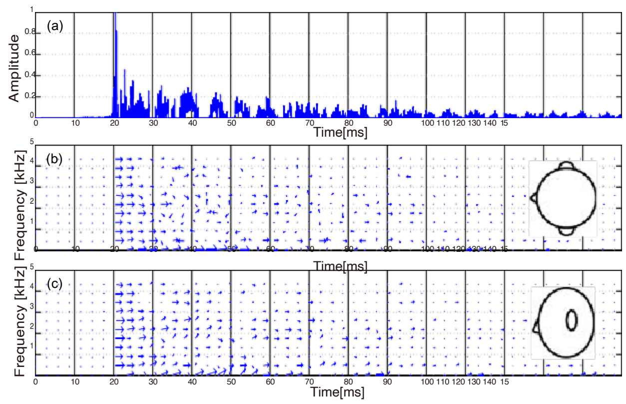

Figure 4 – (a) Relative amplitude, (b) DOA in horizontal plan, and (c) DOA in vertical plan in the receiver position r12 (Sata shrine)

where orchestra members are sitting during the performance. The receiver positions colored in red were on the stage to examine the sound arriving to the performers. The receiver positions colored in blue were around the stage to examine the sound arriving to the human audience. The receiver positions colored in purple were around the main hall and worship hall to examine the sound arriving to the Gods. In preparation for a religion ceremony, the receivers could not be put close to the main hall of the Miho shrines (Fig. 2c).

2.3 Measurement equipment

On the sound source position, a dodecahedral loudspeaker (Type4292, Brüel & Kjær) was put at 1.2 m height from the stage floor. On the receiver positions, an experimenter (body height: 1.65 m) stood wearing a binaural microphone (Type4101, Brüel & Kjær) on his both ears. He always looked toward to the sound source. And a 3D microphone (AMBEO VR MIC, Sennheiser) which outputs sound direction of arrival (DOA) was put next to him at 1.6 m height. The 3D microphone always faced to the gate and turned its back on the worship hall and main hall.

The sound played by the loudspeaker was a swept sine signal from 63 Hz to 16 kHz over 18 s. The left and right data from the binaural microphone and FLU, FRD, BLU, and BRD data (F: front, B: back, L: left, R: right, U: up, and D: down) from the 3D microphone were recorded by a PC (CF-SZ5, Panasonic) via an AD/DA converter (OCTA-CAPTURE, Roland). The sampling rate and size were 44100 Hz and 16-bit. Although the output levels of the signal were varied according to the receivers' positions, the sound pressure levels of the recorded signals were adjusted digitally according to the output levels.

3. RESULTS

From the binaural impulse responses, several acoustical parameters were calculated. And from the 3D impulse responses, the DOA was synthesized. Results shown in this report were limited in sound pressure level (SPL), reverberation time, speech transmission index (STI) [3], and interaural cross-correlation coefficient (IACC) calculated from the binaural impulse responses because of the page limitation.

3.1 Sata shrine

Fig. 3 shows these acoustical parameters obtained in the Sata shrine. The red, blue and purple bars indicate different receiver's zones: on the stage, around the stage, and near the main or worship hall, respectively. From the SPL data, it can be said that the sound on the stage did not arrive to the receiver positions around the stage (blue bars in Fig. 3a). The stage is too high from the ground (1 m), and the audience sitting a folding chair have to gaze up the stage. The stage in the too high position prevented propagating sound around the stage. On the other hand, the sound arrived effectively to the

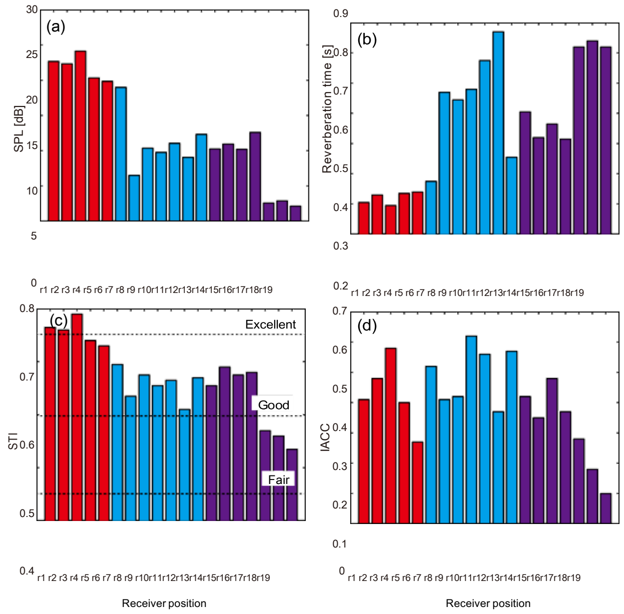

Figure 5 – (a) SPL, (b) reverberation time, (c) STI, and (d) IACC in the Kumano shrine. The different colors indicate the receiver pisitions like Figure 3.

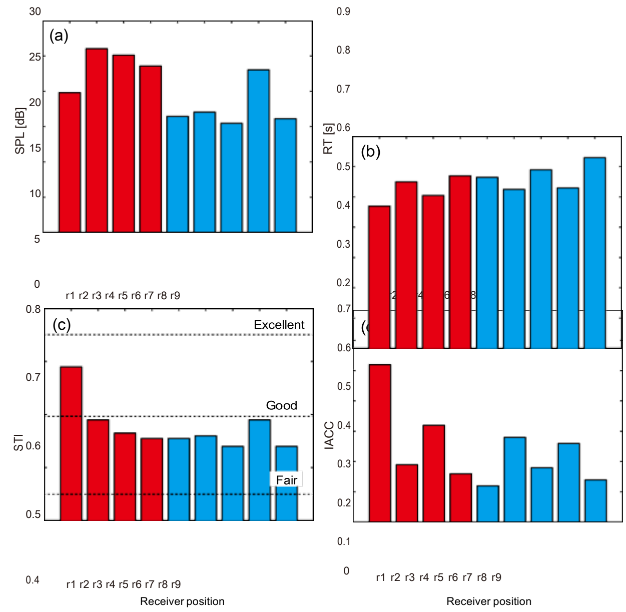

Figure 7 – (a) SPL, (b) reverberation time, (c) STI, and (d) IACC in the Miho shrine. The different colors indicate the receiver pisitions like Figure 3.

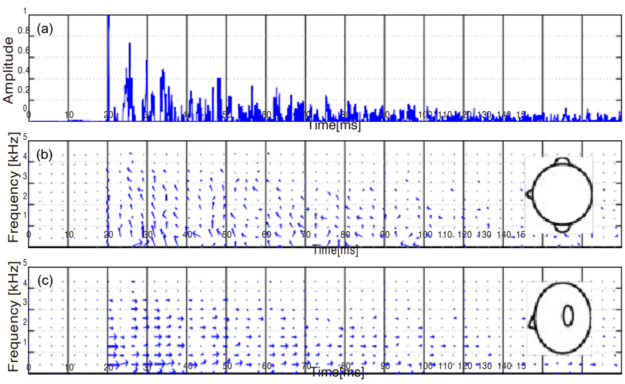

Figure 6 – (a) Relative amplitude, (b) DOA in horizontal plan, and (c) DOA in vertical plan in the receiver position r11 (Kumano shrine)

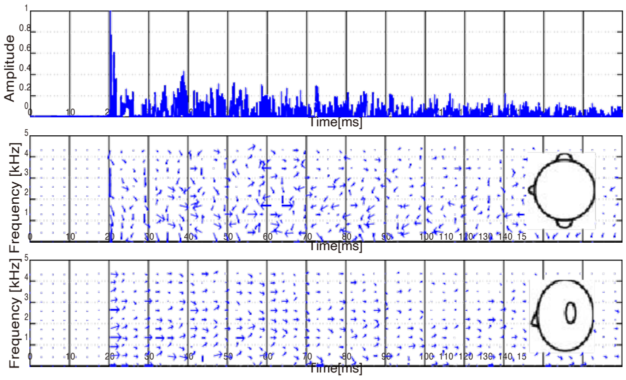

Figure 8 – (a) Relative amplitude, (b) DOA in horizontal plan, and (c) DOA in vertical plan in the receiver position r3 (Miho shrine)

receivers around the worship or main hall (purple bars in Fig. 3a), because the worship and main halls are located upper from the ground 1.57 m, and they are higher than the stage floor. Fig. 4 shows the DOA in receiver position r12 around the worship and main halls. The calculation method of the DOA should be referred to our previous work [4]. The DOA shows that the sound was coming from the bottom (Fig. 4c).

The reverberation times were longer in the receiver positions around the worship and main halls. The reflections from the eaves and walls of the worship hall prolonged the reverberation time. Regardless of the long reverberation times, the STIs were high enough to be rated as good intelligibility. The IACCs around the worship and main halls were higher than the other receiver positions. It means that one can recognize the DOA from the stage clearly.

3.2 Kumano shrine

Fig. 5 shows the acoustical parameters obtained in Kumano shrine. The SPL was decreased as the distance between source and receiver was longer. Because the stage in the Kumano shrine is opened in all the four sides (Fig 1b), the sound propagation behaved in much the same way as a free sound field. We consider that the Kagura theatre in Kumano shrine has varied the purpose from shrine ritual to popular entertainment in the history, and the stage design has been optimized for the human audience. The reverberation times were longer for the receiver positions (r17 – r19 in Fig. 5b) in the worship hall due to the reflections in the hall, and the speech transmission qualities were rated as fair intelligibility (Fig. 5c). The reflections in the worship hall decreased also the IACC (Fig. 5d).

Fig. 6 shows the DOA in the receiver position r11, which is the center of the shrine area, and the reverberation time of this position was the longest as shown in Fig. 5b. The direct sound around 20 ms was arrived from the source position (left side), and the subsequent reflections were arrived from the worship hall (left rear side). Since the halls and gate are scattered in the shrine area, the reflections reach partially.

3.3 Miho shrine

Fig. 7 shows the acoustical parameters obtained in Miho shrine. The sound field in Moho shrine was characterized by the long reverberation time (Fig. 7b). Because the stage for Kagura performance is embedded in the worship hall, the stage area is the largest in the three shrine and the large ceiling covers it. The complex reflections in the stage obscured the speech transmission quality (Fig. 7c) and decreased the IACC (Fig. 7d).

Fig. 8 shows the DOA in the receiver position r3, which is on the stage (Fig. 2c). The direct sound was arrived from the source position (right side), and the subsequent reflections were arrived from the various directions. This diffused sound field prolonged the reverberation time and decreased the IACC.

4. DISCUSSIONS

The three Kagura theatres measured in this study are quite different in terms of the current operations and styles. The Kagura performed in the Sata shrine keeps the dancing style and musical playing based on age-old belief and is registered as UNESCO Intangible Cultural Heritage (“Sada-shinnou,”) [5]. It means the Kagura theatre in Sato shrine is the most suitable for calling “ancient theatre.” The stage was optimized for viewing for the Gods in the main hall (e.g., openings in three sides toward to the main hall), and the sound was arrived effectively to the main hall, too (Fig. 3). Although the reverberation times were the longest around the worship and main halls, the speech intelligibility was kept in “Good.” The reason that the acoustics around the worship and main halls was excellent is the floor level. The floor level (1m) of the stage is too high to enjoy the performance sitting around the theatre; however, the floor level of the stage meets that of the worship and main halls, and then the sound propagates effectively to them.

Although Kumano shrine hosts the Kagura performance offering to Gods, the theatre is used often for the other events (e.g., soybeans scattering ceremony). It means that the role of theatre has been varied for a public space in the history. And the current theatre was relocated from the worship hall in 1978. The stage has the all four-side openings, and the sound propagation from the sound source on the stage was approximately the same manner in a free sound field.

The theatre in Miho shrine is covered by the large ceiling (height: 7m at a maximum), so that the sound in it propagates diffusely unlike the Sata and Kumano shrines. The reverberation time was the longest in the three shrines and is not suitable for the drama performance but the historical musical performance like a concert hall. The Miho shrine has enshrined the Gods of music, and many musical instruments have been devoted. Differently from the other two shrines, Kagura is not performed annually in the theatre, but female attendants dance to the music twice in every day (8:30 and 15:30). Due to the good acoustics, the theatre is used often for the other musical performances (e.g., classic and pop music).

5. CONCLUSIONS

Although I hypothesized that the acoustics of Kagura theatre was optimized to the main hall where the Gods exist, the hypothesis was not demonstrated for all the three theatres measured in this study. The role of Kagura theatre has been varied in response to the need of the times. In the three shrines, the Kagura performance in the Sata shrine preserves the style more closely to the original one, and the acoustics in the Kagura theatre is optimized to propagate sound effectively to the worship and main halls. The Kagura theater might be designed while assuming that the audience is the Gods.

ACKNOWLEDGEMENTS

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Review of sixteen Pskov churches equipped with acoustic vessels

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ABSTRACT

A lot of worship spaces with acoustic cavities of different sizes and forms are known today due to a number of reviews and studies published last decades. Pots, jars and other vessels were used in church architecture of the Middle Ages in many European countries. During this period the practice of using such devices was widespread in Russia as well, but the most impressive heritage was given by the Pskov architectural tradition. The churches built there from the 13th to 16th centuries were equipped with hundreds of the acoustic vessels. For various reasons, many churches have not survived to this day, but a significant number of them still exists. This paper reviews sixteen Orthodox churches in Pskov, which were built from 1243 till 1586 and have a lot of acoustic vessels. The biggest number of vessels is observed in the Peter and Paul Church. In spite of its small volume which is only about 1300 m^3, there are 326 vessels installed in the drum, pendentives and walls. Ten churches have more than 100 vessels, the smallest number is 42. Description of the churches and analysis of the location of the vessels on inner surfaces are presented.

Keywords: resonator, archaeoacoustics, medieval architecture

1. INTRODUCTION

The idea of using large vessels to influence the acoustics of rooms dates back to antiquity. Aristotle or another unknown author of the Problemata [1] states that buildings have more resonance if there are large jars, earthenware or bronze vessels and cisterns inside. Vitruvius [2] recommends to arrange bronze vases or clay jars in theatres. The use of the resonant cavities in the history of architectural acoustics is reviewed in the study [3]. Today we can meet the vessels primarily in worship places. Many churches distributed throughout Europe [4,5], mosques [6] and synagogues [7] are equipped by different types of pots, amphorae and hollow vessels.

In Russian architecture, the acoustic pots have been installed in the construction of churches since the Christianization in 988 [8]. Since then, a lot of churches were build following the Byzantine traditions, however national architecture styles were being developed as well. One of the most interesting is the Pskov school of architecture reached its peak in the 15th and 16th centuries. A feature of the school was the application of the built-in pots orderly arranged on inner surfaces [9]. This paper briefly describes the unique acoustic heritage of Pskov monuments.

Sixteen existing and functioning churches are surveyed here. Without being able to describe each of them in details, we review only one taking into account that all medieval Pskov churches have a lot in common. The church of Peter and Paul was chosen as an example because it has the biggest number of the acoustic pots. Then we provide and analyze data on the pots in other churches.

2. CHURCH OF PETER AND PAUL

2.1 History

The church of Peter and Paul s Buya (Figure 1) was built in 1540 in the place of an earlier church known since 1373. The name “s Buya” might mean that there used an old Russian burial mound nearby.

Figure 1 – Church of Peter and Paul s Buya

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By the beginning of the 17th century, the church was in a very bad state. The old clergy bulleting reported that in 1610 its walls were rebuilt, as well as vaults, iconostasis, roof and cupola. In 1713 and 1810 the roof and outer walls were renovated. In 1920-1930 the church was closed. During the occupation of Pskov in 1941-1944 the building was not damaged. In 1989-1995 a series of restoration works followed to make the church fit for service.

So, we can be sure that the original building including acoustic vessels has been almost completely preserved since 1540 or at least since 1610.

2.2 Interior description

Figure 2 shows the interior of the church. The inner volume is cubic with dimensions 11x11x11 m. There are three apses at the eastern wall and four piers with the rectangular cross-sections (1.7x1.5 m). The high drum is cut by eight slots of windows. In the western part there are two small chambers on the first floor. All surfaces except the floor are covered with plaster and painted.

The iconostasis is a solid screen of wood separating the sanctuary from the nave and decorated by icons. It is partially visible in Figure 2a. In all churches reviewed in this paper the iconostasis is located in the same place from the northern wall to the southern one without gaps, but their heights are different. In the church of Peter and Paul its height is 5 m or about half the room height. But in some other churches the iconostasis height is close to the room height, therefore the sanctuary and the nave are acoustically separated. Probably, this point should be taken into account in the further acoustic analysis.

2.3 Acoustic vessels

In Figure 2a we can see numerous holes which are necks of clay pots. There are several pots in the drum between the windows and in the pendentives, whereas most of the vessels are placed on the walls. All walls have two groups of the vessels, which are periodically arranged. The example of one group on the northern wall is in Figure 2b, this group has five rows with 8, 10, 11, 12 and 13 pots. So, the group contains 54 pots. The average distance between the pots is approx. 0.3 m; in other words, the density is 11 pots per 1m^2. Total number of vessels in the church is 326. It is the largest number among all Pskov churches.

As noted in [8] the regular positioning of the vessels could be applied for decoration. Usually, the Pskov churches had no murals or frescos and their surfaces were white, and the pot arrays provided a contrast pattern. However, some churches are known, where the murals and the pots are used together.

Unfortunately, we have no reliable information about the sizes of the pots. Based on the old review [10] we can assume that a diameter of the neck is about 10 cm and a volume of the pot is about 10 L. There is no any information about their resonant frequencies and Q-factors.

Figure 2 – The plans and interior of the Church of Peter and Paul s Buya. View of the eastern and southern walls (**a**); a fragment of the northern wall (**b**).

3. PSKOV CHURCHES

3.1 List of the churches

Table 1 contains the list of the churches ranked in decreasing order of the number of vessels. The period of their building is 1243-1582, but only one of them was built earlier than 1400. The volume of the main room including both the sanctuary and the nave is given as well. One can note that they are unusually small chambers, if they are compared with most of Russian or European churches. The reason is the small churches were one of features of the Pskov school. Ten monuments of the school were included in the World Heritage List of UNESCO in 2019 and seven of them are presented here.

Table 1 – Reviewed churches

No.	Name	Year	Volume, m^3
1	Peter and Paul	1540	1330
2	Nicholas (from the dry place)*	1536	1700
3	Zhen-Mironosits	1546	810
4	Pokrova ot Proloma*	1582	170/190
5	Theophany*	1496	1600
6	Assumption of the Virgin	1521	1750
7	Clement	~1500	370
8	Basil (on the hill)*	1413	680
9	Kozma and Damian*	1463	1370
10	Ascension	1467	620
11	Resurrection	~1586	860
12	John the Apostle	1547	370
13	Sergey	~1582	330
14	George*	1494	850
15	Varlaam	1495	750
16	John the Baptist*	1243	1200

* included in the World Heritage List of UNESCO

The smallest church should be noted especially, because in spite of its size it contains two small churches connected together. As shown in Figure 3 the church of Pokrova ot Proloma has two chambers, which are the church of Intercession of the Virgin (a) with a volume of 170 m^3 and the church of Nativity of the Virgin (b) with a volume of 190 m^3. Both of them have arrays of the vessels on the western and eastern walls as well as some vessels in the drums. Further we will consider these churches separately, however the rank in the Table 1 is defined by the total number of vessels, since they form the single building.

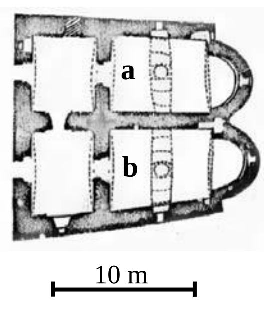

Figure 3 – Church of Pokrova ot Proloma.

Also, some details about the church of St. Nicholas from the dry place and the church of Theophany (No. 2 and 5 in Table 1) with their pictures can be found in [9].

3.2 Acoustic vessel

The acoustic pots are distributed on upper parts of the inner surfaces like in Figure 2. To characterize this distribution Table 2 shows the numbers of pots placed on different parts of the churches as well as their total number. Most churches have the vessels in the drum and pendentives. The church of Theophany has the extremely large number in the drum. There are the pots on the walls in all churches, in most cases the eastern wall has the largest number.

It is interesting that only two churches have the pots on the apses. If the iconostasis is not very high, they can be seen and create a peculiar interior solution. To demonstrate it the eastern wall of the Clement church (No. 7 in Tables 1 and 2) is shown in Figure 4. We can see large numbers of pots in the drum and pendentives as well.

Figure 4 – The Clement church.

In all churches except the church of John the Baptist the pots form the regular pattern like in Figures 2 and 4. The exception is the oldest building in the list in Table 2. The vessels are chaotically distributed on the surfaces, moreover some vessels are built in the columns. This church was built much earlier than the others and probably the Pskov style was not yet fully formed at that time. The churches equipped with the vessels and build during the period 1250-1400 have not been preserved today. So, it is impossible to trace the development of the style at this period. We can assume that architects were transforming their approaches on the design of the acoustic vessels.

Table 2 – Distribution of the vessels

No.	Drum	Pend.	Apse	Walls East	Walls South	Walls West	Walls North	Total
1	3	4	0	91	73	62	93	326
2	0	29	36	84	63	20	74	306
3	0	0	0	70	79	65	71	285
4a	19	0	0	58	0	43	0	120
4b	15	0	0	52	0	38	0	105
5	95	39	0	27	26	5	33	225
6	0	0	0	18	81	36	52	187
7	76	13	42	30	0	19	0	180
8	0	0	0	43	47	25	44	159
9	8	4	0	29	35	25	35	136
10	0	0	0	39	40	19	28	126
11	0	39	0	15	15	15	15	99
12	0	0	0	27	23	11	31	92
13	8	12	0	0	22	5	19	66
14	0	4	0	0	14	16	14	48
15	0	0	0	45	0	0	0	45
16	0	13	0	0	3	0	8	42*

*includes 18 vessels built in the columns

3.3 Originality of the vessels

A quick glance at Table 2 shows the variety of the patterns created by means of the pots. The architects might apply different distributions of the vessels to design a unique pattern. On the other hand, several reconstructions and repairs have taken place over the long history of the buildings. The vessels could be covered with layers of plaster applied to the ceilings and walls. Furthermore, some churches were partially destroyed and restored after decades. The recovery could miss some vessels. So, we can not be sure that the current interior corresponds to the original one. For example, only one wall in the Varlaam church has the pots. Highly likely the pots on other surfaces are closed.

The oldest detailed description of the vessels in six Pskov churches can be found in [10], which contains the sketches with the vessel distribution on the walls. Comparing data from 1861 with current information we can conclude that there is no difference for the George church and the church of Theophany. The slight difference in the number of pots is for the church Pokrova ot Proloma and the church of Kozma and Damian. Today we can see more vessels in the church of Bazil and in the church of Assumption of the Virgin. It seems that the pots were closed by plaster in 1861 and opened later.

3.4 Comparison with French churches

A similar number of churches in France is analysed in [4], that makes it possible to compare the Pskov and French experience. The mean number of pots by church is about 150 for the considered Pskov churches. The same value for French churches given in [4] is about 25.

Figure 5 shows no trend in dependence of the number of vessels on the church volume, the distribution of points seems to be chaotic. Analytical law found in [4] for French churches is shown by the red line. All points are much higher than the line, and no correlation between the points and line can be suspected. We can state that the Pskov and French churches are very different.

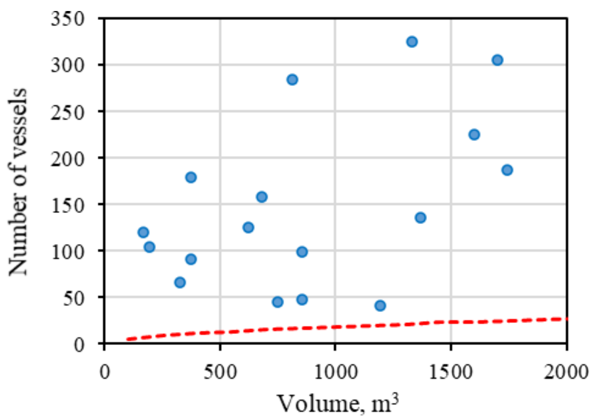

Figure 5 – Number of acoustic vessels in Pskov (points) and French (line) churches.

4. SUMMARY

A unique feature of the Pskov school of architecture is the use of numerous acoustic vessels in the churches. It is demonstrated by means of sixteen buildings of the 13th to 16th centuries that have survived to the present day. The vessels are clay pots, and they are places in upper parts of the churches. The number of pots is extremely high in comparison with other known buildings around the world [3-7]. So, the Pskov monuments are very important for archaeoacoustics.

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Acoustics measurements, analysis and comparative study for caves used for Pan and Nymphs' ancient rituals.

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ABSTRACT
This project investigates the possibility that caves dedicated to the worship of the goat-legged god Pan and the Nymphs in Classical Greece had unique acoustics that were suitable for such rituals. Two such caves in Attica, Greece known for their ancient ritual use were measured acoustically and were compared to the acoustics of another cave not associated with ancient ceremonies whatsoever. The ancient worship of Pan and the Nymphs have special connections to sound and resonance and hence it is important to examine a reciprocal potential relationship between their ritual performances and the sonic qualities of grottos. The acoustics measurements were taken in two sacred caves (cave of the Nympholept Archedimos in Vari, Lychnospilia cave on Mt. Parnitha) and for comparison, in a third cave with no evidence of ritual use (Korakovouni I on Mt. Hymettus).The measurements were taken using: (a) an omnidirectional mic to derive the acoustics parameters of caves and (b) with a binaural dummy head to calculate binaural parameters and allow subsequent virtual soundscape auralizations. The thorough analysis examines the acoustic suitability of these sacred underground.

Keywords: cave acoustics, Greek god Pan, acoustics measurements

1. INTRODUCTION

In the past few decades there has been a turn towards the acoustical and sensual properties of the material past. Especially within sensual archaeology, increasing research has been done on the aural perspectives of ancient sacred grottos and other rural sacred places, offering the potential to enrich interpretations of how ancient buildings or natural spaces were used, and proclaiming the importance of sound as one of the determinants in their identification as places of divine presence and worship [1,2,3].

Caves are understood as complicated enclosed spaces composed of numerous surfaces, objects, and geometries, creating an acoustic arena which behaves differently from analogous open-air spaces [4]. Likewise, the underground sanctuaries dedicated to the Nymphs and Pan in ancient Greece should not only be perceived as landscapes with certain visual characteristics, but also as soundscapes with important auditory features [5]. As a result, an acoustic survey of these caves and an appropriate analysis of their aural characteristics, combined with archaeological and musical methods is necessary, in order to understand whether sound was a determining factor in the selection of caves as appropriate sacred sites to host the combined cult of Pan and the Nymphs in antiquity.

2. HISTORICAL AND ARCHAEOLOGICAL DATA

The principal seat of Pan's worship was Arcadia and from thence his name and cult spread over other parts of Greece [6] . The Athenians were the first who established his cult inside a cave after his cult was transferred to Attica in the first quarter of the 5th century BC (Herodotus, Histories, VI, 105–106). The presence of water sources, evidence of previous use, closed entrances, high altitude and liminality, made caves particularly attractive as homes and sanctuaries of the Nymphs and Pan [7].

Pan is a deity connected with natural sounds, echoes and loud noise; sound is an important component of his cult. For the sake of Pan's love of noise the ritual protocol involved the production of various sounds and the resulting resonating and echoing effects of caves would have been regarded as signs of his divine presence. During a Pan ritual, the participants, through their noise-making, dancing, music, and feasting, were creating a system of ritual action, in which they themselves became agents of the god's epiphany.

Within the geographical region of Attica, fourteen underground cult sites have been identified so far dedicated to Pan and the Nymphs (Acropolis, Marathon, Dafni, Mt Hymettus, Mt Penteli etc). However, here only two caves were selected for archaeoacoustic research, the "Cave of the Nympholept" at Vari and Cave "Lychnospilia" on Mt. Parnitha.

3. THE CAVES

The places of the three caves under investigation are shown in Fig. 1. They are all placed in Attica, and with the exception of Cave Lychnospilia, the other two are surrounded by the urban web of the city of Athens.

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3.1 The "Lychnospilia" Cave

Cave "Lychnospilia" is located at the southwest foothills of Parnitha, at a height of 35m. from the left bank of the Goura stream at an altitude of 773m above sea level. The cave is accessed relatively difficult through road that has been opened since the antiquity leading from the medieval settlement "Roumani" to the north side of the cave's terrace. The cave was partly excavated by Andreas Skias in 1900-1901 revealing extensive evidence of the worship of Pan and the Nymphs especially in the 5th - 4th centuries BC [8].

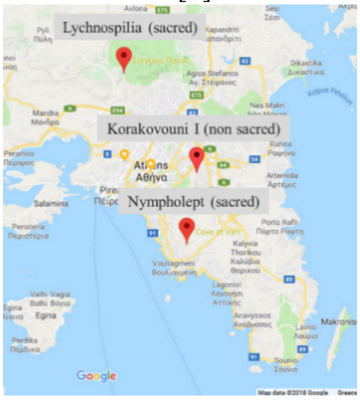

Figure 1 – The location of the three caves [9]

The triangular mouth of the cave located at the southern part of the plateau is 1.05m wide. The opening is surrounded by rough carvings and niches for the placement of votive offerings, as well as Late Roman inscriptions. The grotto is 62m long and extends from east to west, while its width ranges between 3.00-14.40m. After the entrance lies a large plateau (9.00x8.00m), while deeper in the interior the ground elevates especially near the southern wall (Fig. 2).

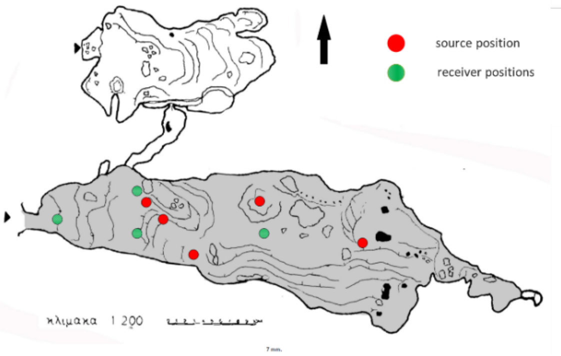

Figure 2 – Ground plan of Lychnospilia cave.

3.2 The "Nympholept" Cave

The Cave of the Nympholept or Nympholyptos Cave at Vari is located at the southern foot of Mt. Hymettus at an altitude of 290m above sea level. It is preserved in a very good condition and access to it must have been relatively difficult in antiquity. First traces of habitation date back to the 6th centu-ry BC, while in the third quarter of the 5th century BC Archedimos the Nympholept, seized by divine inspiration established there the cult of Pan and the Nymphs

The cave's oval mouth is vertical (4.00x2.00m), while a roughly carved staircase leads to the interior (21.00x23.75m, height 2.50m, depth 15.00m). A massive calcite formation separates the cave into two chambers: the southern is large and fairly bright (17.5x11.5m). The northern chamber is narrower, much darker, with no any special configurations and decorated with rich stalactite formations (18.5x8.00m). The shape of the interior facilitates the anticlockwise movement of the visitor, first through the steep, narrow and dark space to a much larger and brighter chamber. The latter is identified with the main sanctuary as most configurations are located there, such as the statue of a seated figure, altars, desks and niches for the placement of votive reliefs or other offerings, as well as scattered inscriptions from both ancient and modern visitors.

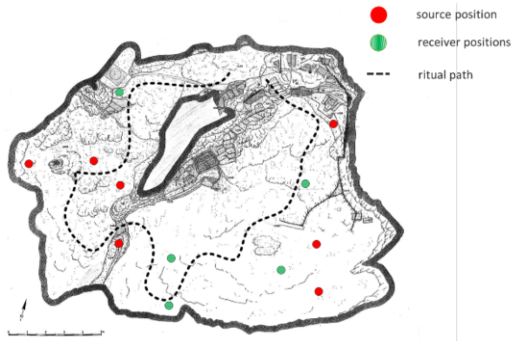

Figure 3 – Ground plan of the Cave of the Nympholept.

3.3 The "Korakovouni I" Cave

Cave "Korakovouni I" " is located at the relatively even northwest slope of Mt Hymmetus at a height of 691m above sea level and 500m West of the Cave "of the Lion", which was dedicated to the worship of Pan. Ceramic finds confirm the use of the cave since the Neolithic era, but also later during the Late Helladic, Archaic, Classical, Hellenistic and Late Roman periods (3rd - 6th century). The absence of finds with possible worship use indicates the cave was used as a place of residence or seasonal overnight.

The cave is in the form of a long relatively narrow smooth corridor with a total length of 90m and in a NE-NE direction, which widens to a depth of up to 6m. The width in its largest area is circa 2.00m, while height varies from 2.00 to 8.00m Approximately 25m from the entrance there is a narrow opening 0.40x0.50m., which divides the elongated part of the cave into two parts (Fig. 4). Along the first 25m extends to the NW a parallel corridor to a higher level with difficult access. After 60m the cave widens forming a fairly large space, while in its deepest part it is divided into two smaller narrow and long sections.

Its walls are relatively smooth, while in places, especially after the narrow opening in the middle, there is abundant stalactite material, part of which has been cut off by visitors. The highest concentration of stalactites occurs near the widest part of the cave, where steady drips have formed a large stalagmite volume, which dominates the center of the area.

3.4 Acoustical measurements

The caves, as mentioned before are far from any access road, being isolated and difficult to reach. Lychnospilia cave is reached after half an hour walk, then having to descend a 10m slope. The Nympholyptos and Korakovouni I Caves can only be reached with off-road vehicles and after special permission to use mountain roads usually closed to public. The heavy equipment for the measurements (Table 1) was carried by the research team and workers of the Greek Ephorate of Palaeoanthropol-ogy and Speleology.

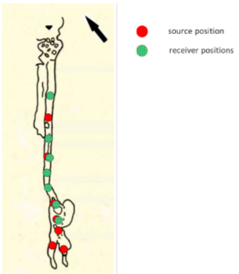

Figure 4 – Ground plan of Korakovouni I cave.

The measurement stimulus signal was a logarithmic sine sweep [10] of T=10 sec duration at Fs = 44100Hz and an SPL=88.5 dB /1m with a bandwidth covering 40Hz to 20kHz. The ears of the dummy head were at a height of 1.2m, which represents the mean height of Greeks of the period and the omni mic was positioned 15cm above the dummy head at 45^{o} angle vertically.

The source and receiver measurement positions for the caves are shown in Figures 2-4. The source positions were chosen based on archaeological assumptions for the potential locations of an ancient musician during performance, and the receivers were located at the possible positions where participants of the ancient rite would probably have stranded or danced. Especially in the cave of Nympholept, there is an obvious dark path that the believers followed entering the cave in order to reach the main hall. There were 9 measurement positions selected inside Cave Lychnospilia, 12 in Cave Nympholyp-tos and 13 in Cave Korakovouni I. In the Cave of the Nympholept an additional set of 14 binaural measurements were taken following the descending path (Fig. 3 black dashed line followed counter clockwise).

Given that there was no access to electric mains power in the caves, a portable gas-powered generator was used positioned about ca. 50m away from the entrance of the caves. The background noise level measured is shown in Table 2 and is very low to allow measurements with good SNR. The temperature and humidity levels were very stable: in Lychnospilia it was $8^{o}C$ with 55% relative humidity, in the cave of Nympholeptos it was $17^{o}C$ with 80% relative humidity and in Korakovouni I it was $12^{o}C$ with 70% relative humidity.

Table 1 – List of equipment used for the measurements

Model	Description
EV SXa100	12” 200W active Loudspeaker
MOTU 828x	audio interface
G.R.A.S. - KEMAR	Binaural dummy head
G.R.A.S. – 26AS	Miniature preamps
G.R.A.S. – 12AA	Power module
PCB 377A40	Free field microphones
SVANTEK SV 01A	1/2“ preamp
SVAN955	Sound Pressure Level Meter
CEL 284/2	Calibrator

Table 2 – Background noise levels

Cave	Background noise dB(A)
Lychnospilia	26.6
Nympholeptos	22.8
Korakovouni I	20.7

4. RESULTS

From the omnidirectional microphone impulse response measurements at the above positions, the acoustical parameters of T30, D50, C80, C50, and STI were calculated in 1/3 octave bands, according to ISO3382[12] using the Audacity 2.0.5 [12] with Aurora plug in software [13]. The IACC parameter was calculated from the corresponding binaural impulse response measurements.

The reverberation time of the caves is almost identical and ideal for speech (Fig.6). The slight rise at the low frequencies gives warmth to the sound and the value of 0.9s to 1.3s at the mid frequencies gives clarity to speech. In comparison, the non-sacred Cave of Korakovouni I introduces a slightly lower RT with more than 10% deviation in the whole frequency spectrum.

The **clarity** index for speech C50 (Fig.7) and music C80 (Fig. 8) for the caves has acceptable values (above 0 dB) from almost 200Hz.

The **STI** (Fig 9) values of the caves indicate good to excellent speech intelligibility.

With respect to the binaurally accessed spatial qualities of the measured spaces, the **IACC** (interaural cross-correlation coefficient, Fig 10.) was derived from the corresponding binaural impulse response (BRIR) measurements. The results for the caves exhibit the expected nearly perfect diffuse and spaciousness character for frequencies above approx. 400Hz. Hence, the caves provide an increased sense of spaciousness to the listeners.

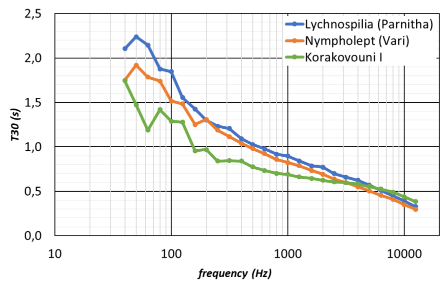

Figure 6 – Reverberation time for the three caves.

5. CONCLUSIONS

Overcoming the inaccessibility of the caves with well-established historical links to ancient rituals of Pan and the Nymphs in ancient Greece, a set of acoustical measurements has been obtained and analysed. Apart from the quietness and isolation offered in such spaces, the results indicate that these caves had low reverberation time for their volume, exceptional clarity for speech and music and generate increased feeling of

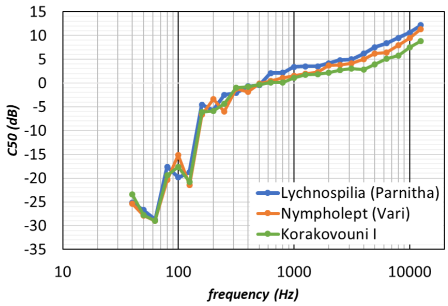

Figure 7 – Clarity index for speech

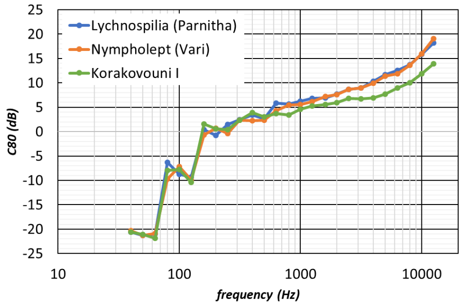

Figure 8 – Clarity index for music.

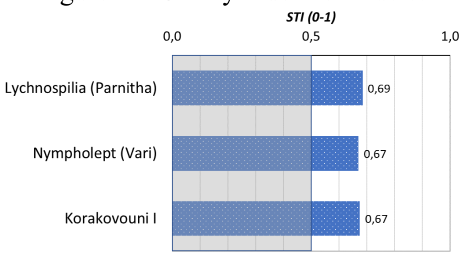

Figure 9 – The Speech Transmission Index (STI).

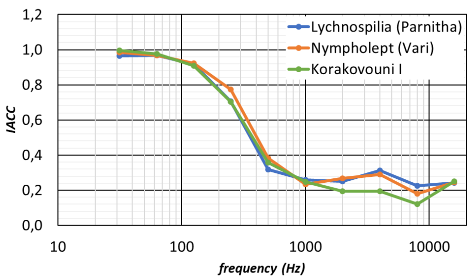

Figure 10 – Comparison of the IACC index.

spaciousness to the listeners, achieving also very good speech intelligibility within the range of positions where the ceremonies were performed. The comparison between sacred and non-sacred caves showed a potential of utilizing special acoustic characteristics for rituals but further investigation is needed to obtain more statistically valid results (measurement in more sacred and non-sacred caves).

As future work, the measurements obtained in the current work, will become available in public databases [14] and will be compared to other ancient places of worship [15]. Virtual auralizations of ancient musical instruments and speech along with perceptual tests will compare the listener preference for such ancient and modern spaces of worship.

ACKNOWLEDGEMENTS

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The Acoustics of Ancient Theatres

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FVTD simulation of the acoustics of the Phonocamptic Cave in Noyon.

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ABSTRACT

Starting from new measurements of the acoustical pots and room geometry in the phonocamptic cave at the Cathedral of Noyon, a numerical study was undertaken to understand the acoustical effects at the boundaries, and to provide an auralization of the space. An implementation of the finite volume time domain (FVTD) method was used to model the cave, including fitting the impedance presented by the acoustical pots on certain boundaries. The individual impedances of the pots were estimated from impulse responses collected pot-by-pot and parameterized in terms of a Helmholtz resonator model. Then, using the electroacoustic analogy, the sum effect of the pots was modeled as an equivalent spatial distribution in the FVTD boundary conditions. Additionally, the space was discretized with an unstructured mesh in order to capture the complex geometry, minimize dispersion error, and to check the accuracy of the FVTD implementation. **Keywords**: acoustical pots, cave acoustics, simulation.

1. INTRODUCTION

The phonocamptic cave (or *caveau phonocamptique*) at the Cathedral of Noyon is a unique acoustic location, studied for its use of acoustical pots. While acoustical pots have been found in many ancient churches, the phonocamptic cave in Noyon has unique characteristics, as 64 pots are embedded in a room below the ground floor, under the cathedral's choir, as opposed to being placed in the high parts of the church's walls, which is the case for most churches.

Figure 1 – Acoustical pots in the West wall of the phonocamptic cave at Noyon

In many cases, it is believed that the introduction of pots into existing churches was an acoustical intervention intended to amplify the voices of singers, either for aesthetic or economic reasons [1]. This belief may have been based on the common observation that singing into a pot at a particular pitch, thus exciting its resonant frequency, can result in the pot "singing back" at the user. While we understand now that passive terminations cannot amplify sound in large spaces, the practical effect of these resonators in the phonocamptic cave is to increase resonant frequencies, so that the pots have a meaningful effect on the perceived acoustics of a space [2].

In this paper, we expand upon previous acoustical analyses of this space with new characterizations of individual pots and their collective boundary impedance, and integrate these findings into a numerical acoustical model intended to provide a basis for future studies of the space.

2. BACKGROUND

2.1 Previous Acoustical Studies

The cave has been the subject of previous studies that have aimed to characterize the space acoustically as well as ascertain the practical effect the pots induce on a group of singers [3].

This study collected measurements of the frequency-dependent reverberation time within the space, with pots open and closed, and at a variety of locations, serving as a ground truth for the overall

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acoustic behavior. This confirmed the impact of the pots within the cave itself, especially within the regions nearest particular groups of pots.

The study concluded with a performance within the space whose results suggested an improvement in the acoustics when transitioning from closed to open pots.

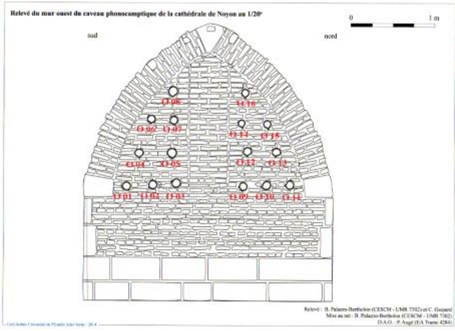

Figure 2 – Mapping of West wall with acoustical pots' positions

2.2 Numerical Models

In this study, we utilize two numerical models, the first being a characterization of the impedance of the acoustical pots (and other boundary surfaces of the cave), and the second a finite volume time domain (FVTD) model of acoustical wave motion within the space. Each of these individual models was the subject of a Master's internship undertaken by the primary authors [4, 5]. The goal of the study was to enable virtual auralization of the space and confirmation of the modal effects detected in the previous analysis of the space. Both models are well-known, but the nature of the space as well as the challenge of matching specific geometry and materials introduce new views onto each technique.

3. ACOUSTICAL POT MODEL

The first investigation was modeling the acoustical effects of the pots in the cave. In [1], the approximate resonant frequency of the pots was determined by clapping a hand over the mouth of each resonator and then singing into the pot to confirm the pitch. More recent measurements have enabled a more precise characterization of the individual pots in order to better model their combined effect [2, 3].

3.1 Measurements

Impulse responses of example pots on the North face of the cave were collected in order to understand the relationship of pot size to acoustical impedance using white noise as an excitation source. Additionally, the pot dimensions were measured with a laser rangefinder. The spectrum of the impulse response was used to find the width and peak of the resonant frequency, and the decay of the response was used to estimate the absorption of the pot [2, 3].

3.2 Acoustical Model

From these measurements, the impedance of a given pot could be calculated using a Helmholtz resonator as a model to fit, and a RLC circuit describing the damped oscillation of the air in and out of the opening could be defined using electroacoustical analogy.

For a given RLC circuit, the characteristic differential equation is:

$$L\ddot{u} + R\dot{u} + \frac{1}{C}u = 0 \tag{1}$$

for a given inductance L, resistance R, and capacitance C. Similarly, the pots' resistance can be found using the system's damping ratio ζ, stiffness k and mass m.

Thus, with:

$$R = 2\zeta\sqrt{km}, \quad L = m, \quad C = \frac{1}{k} \tag{2}$$

we can write the characteristic damped oscillator differential equation:

$$\ddot{x} + 2\zeta\omega_0\dot{x} + \omega_0^2 = 0 \tag{3}$$

Calculating the coefficients for a given pot was performed by matching the response of this idealized model to the aforementioned resonant frequencies and decays. Then the impedance boundary conditions for various surfaces within the cave could be estimated by creating an equivalent spatial distribution of the averaged impedances of the pots. Additionally, the relationship between the opening diameter of the pots and their absorption as well as their resonant frequency and absorption could be estimated and compared with the theoretical model.

4. FVTD SIMULATION

A second investigation was undertaken to integrate the previously calculated impedance boundary conditions into a FVTD simulation of the space. The model is detailed in [6], but we give an overview of the method, which produces an energy-stable simulation with arbitrary impedances on the boundaries.

Beginning with the linearized Navier Stokes equations, we notate:

$$\frac{1}{c^2}\partial_{tt}\Psi - \Delta\Psi = 0 \tag{4}$$

where Ψ, the velocity potential of the field, is defined in terms of the particle velocity vector $\boldsymbol{v} = -\nabla\Psi$ and the sound pressure $p = \rho\partial_t\Psi$, where ∇ is the gradient operator, Δ the Laplacian operator, ρ the air density, c the speed of sound, and the first and second partial derivatives according to coordinate i are notated as ∂_i and ∂_{ii}, respectively. Gauss' theorem shows that any change in the energy stored in the acoustic field must be balanced with an equivalent change in energy at the domain boundaries.

At the boundary, we expect the energy stored and dissipated to depend on the pressure and normal velocity incident on a particular element of the surface. Bilbao et al. [6] utilize a parallel structure of

M one-port circuits to characterize the impedance relationship between the pressure and incident velocity, which is given as:

$$\hat{v}_{inc}(\boldsymbol{x}, s) = Y\hat{p}(\boldsymbol{x}, s) \quad (5)$$

in the Laplace domain (with s as the transform variable) and where the impedance Y is given by:

$$Y(\boldsymbol{x}, s) = \sum_{m=1}^{M} \frac{s}{L^m(\boldsymbol{x})s^2 + R^m(\boldsymbol{x})s + \frac{1}{C^m(\boldsymbol{x})}} \quad (6)$$

This is a convenient representation as the coefficients representing the pots in the Helmholtz resonator formalism may be directly translated into terms in the circuit model by means of electromechanical analogy.

The FVTD approach results in a two-step update equation for the velocity potential Ψ given by:

$$\delta_+\delta_-\Psi_j + \frac{c^2}{V_j}\sum_{k=1}^{N} \frac{\beta_{jk}S_{jk}}{h_{jk}}(\Psi_j - \Psi_k) + \frac{c^2}{V_j}\sum_{l=1}^{N_b} \gamma_{jl}S_l v_l = 0 \quad (7)$$

for a collection of N cells, each of which with volume V, intercellular distances to each of its neighbors h, and intercellular or cell-boundary surface areas S; where δ_+ and δ_- are forward and backward temporal difference operators, respectively, β and γ are indicator functions selecting only neighboring cells or boundaries, and v_l is the velocity incident upon a given boundary, computed from the local reactivity impedance boundary conditions. Our implementation of this scheme is available online [7].

4.1 Modeling and Meshing

From measurements, a wireframe model of the space was created in the 3D modeling package *Blender*. It was created from pictures in [1] and [3].

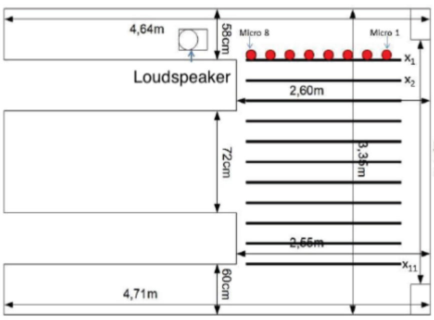

Figure 3 – Map with dimensions of the phonocamptic cave and positions of measurements performed in [3]

Because of the curvature of the cave, we decided to pursue an irregular meshing of the space in order to ensure excellent fit at the edges of the problem domain. Often, finite difference schemes use a cubic mesh for simplicity and computational efficiency, but such a meshing leads to error in the surface area modeled, which affects the resulting reverberation time. This "staircase effect" justifies the use of FVTD in modeling spaces with curved features. Ideally, we should use a hybrid meshing approach where most of the interior is modeled with regular elements and special elements are fit at the problem boundaries. But in the absence of specialized tools, a purely irregular meshing using tetrahedrons was undertaken using the *gmsh* package [8].

Irregular meshes also benefit from mitigation of dispersion error; however, in comparison to regular meshes, they can be challenging to parameterize and analyze.

4.2 Simulation Parameters

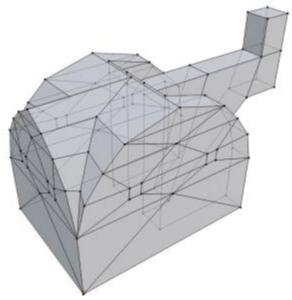

Figure 4 – Wireframe of cave geometry

For this study, the highest frequency simulated was 397 Hz. The mesh was ensured to only contain elements that satisfied the stability criteria for the FVTD scheme, where T_S is the sampling time interval:

$$\frac{1}{V_j}\sum_{k=1}^{N} \frac{\beta_{jk}c^2T_s^2S_{jk}}{2h_{jk}} \leq 1 \quad (8)$$

A spatial and temporal Gaussian was used as initial conditions. Its position is defined by the loudspeaker in Figure 3.

All walls were defined as either purely resistive, or using the model of acoustical pots. The resistive model was based on Sabine's formula, and the coefficients were computed according to the reverberation times with blocked pots [3]. The computed T_{60} was 0.58 seconds, the room volume was 28m^3, and the total surface area was 65m^2. The resulting absorption was applied to all of the non-pot surfaces.

As the highest frequency simulated was quite low, the meshed used in this study has been kept coarse, with a mesh size of approximately 40cm. Each zone of 12 pots was simplified into one square zone of side 36.47cm. Instead of 64 pots of 8.4cm of average diameter, the model has 6 square zones keeping the same total area, but with the equivalent impedance of the given group of pots.

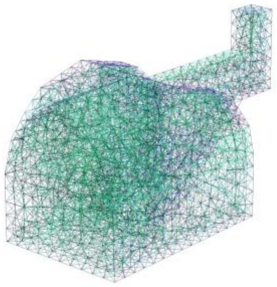

Figure 5 – Resulting nonuniform tetrahedral mesh

5. RESULTS

5.1 Acoustical Pots

After computing the RLC coefficients for each pot, they were compared with the physical dimensions and measured resonances to confirm the validity of the model.

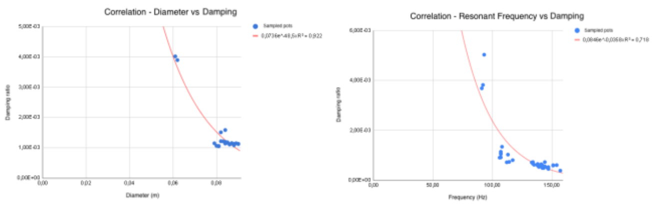

Figure 6 – Exponential relationship between: opening diameter and damping ratio (left); resonant frequency and damping ratio (right)

As can be seen, the expected exponential relationships were observed. This suggests that the model is well suited to modeling the pots and could be used in the acoustic simulation.

5.2 FVTD Simulation

Simulations were performed to compare with the known acoustical parameters of the space and better understand the impact of the tetrahedral meshing. The temporal evolution of a Gaussian impulse from the default loudspeaker position is shown in Figure 7.

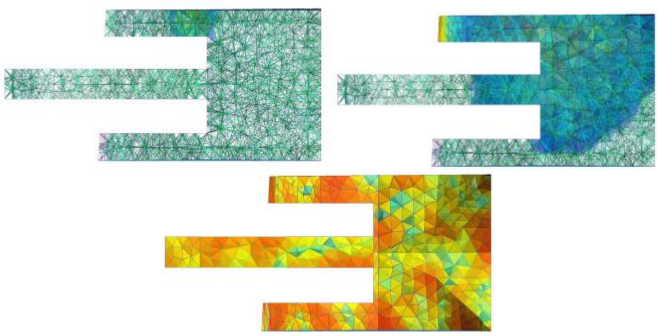

Figure 7 – Time evolution of simulated pressure field from initial impulse to diffuse field, viewed from above. Top left: after 1ms; top right: after 8ms; bottom: after 1.5s

One important observation is that all of the energy stored in the internal acoustic fields as well as in the boundary impedances (here, the capacitance of the pots) may be computed. It proved conservative to machine precision, confirming that the stability criterion was fulfilled.

The initial analysis of the simulations suggests that the overall room characteristics are matched. Further work is required to confirm the equivalent spatial distribution of pot impedances. But it is difficult to auralize the results yet. In the future, finer meshes and higher sample rates should make simulation of the wideband acoustics of the space possible.

6. CONCLUSIONS

In this paper, we have described an approach to modeling an acoustically and architecturally unique space with a combination of acoustic models for boundary conditions and acoustic wave motion. By using the model of a Helmholtz resonator to match physical pots embedded in the walls of the phonocamptic cave at the Cathedral of Noyon and computing the equivalent electroacoustic analogy impedance, the effect of these unique absorbers could be implemented in a wave-based acoustic simulation, well-suited for the expected modal effects in the range of frequencies under study.

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The Development of the Early Acoustics of the Chancel in Notre-Dame de Paris: 1160–1230

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ABSTRACT

The primary construction of the Cathédrale Notre-Dame de Paris began in the spring of 1163 CE and continued into the mid-14th century. Two decades after construction efforts commenced, the pre-existing liturgical community in Paris began its occupancy inside the incomplete building. To better understand the interrelationship between the occupants and the cathedral, the acoustical characteristics of key moments in the cathedral's early development in the 12th and 13th centuries are examined using geometric acoustic modeling. Room acoustic parameters of the sacred regions of the cathedral are examined with attention to the experiences of active participants within the chancel of the cathedral.

Keywords: room acoustics, cultural heritage acoustics, Notre-Dame de Paris

1. INTRODUCTION

The Cathédrale Notre-Dame de Paris is a building of great cultural significance with a rich heritage that began in its earliest years of existence. Since construction began in 1163 CE, the cathedral has hosted over 850 years of religious, musical, and French national history. While it is easy to conceptualize the heritage of the cathedral as a single and undivided abstraction, the continuous occupancy of the cathedral has led to structural and decorative modifications over time. As a part of the ongoing study of the acoustical heritage of Notre-Dame, this study focuses on the acoustic conditions of Notre-Dame's earliest decades.

2. ARCHITECTURAL DEVELOPMENT

Notre-Dame de Paris was among the first new constructions in France to fully realize a Gothic architectural sensibility, which began to emerge around the Île-de-France region in the preceding decades [1]. Development began in the spring of 1163 under the aegis of bishop Maurice de Sully when construction began on the eastern termination of the cathedral's ambulatory [2]. At this time, demolition began on extant church buildings to clear the site for the growing cathedral, including a small chapel dedicated to Mary under the present-day transept and a large basilica located underneath the present-day *parvis* of Notre-Dame [3][4, §*Cathédrale*]. In 1182, the first phase of construction (the full completion of the chancel) concluded with the consecration of the grand altar in the apse [5].

In this period, a large retaining wall was built to separate the consecrated chancel from the rest of the work-site. This wall allowed the liturgical community to begin religious activities within the completed structure after 1182, uninhibited by the ongoing construction. At this time, work continued west across the transept crossing, reaching the western rose window and grand facade by the 1230s [6]. From then, the cathedral was expanded, first at the transept, and later as chantry chapels granted to patrons of the chapter were built between the foundations of the flying buttresses [7]. Construction of lateral chapels concluded by the 1330s, and the external structure remained largely unchanged until the renovations of Viollet-le-Duc in the 19th century.

During his excavations and renovations, Viollet-le-Duc found evidence of an early design change in the clerestory of the cathedral (the location of the modern stained glass windows). In an effort to reduce the weight of the monumental walls, circular voids (termed here *oculi*, $\varnothing \approx 2$ m) were built into the walls below smaller versions of the windows we see today. If these oculi had been filled with glass, they would have resembled miniature rose windows, but since they were left open, they coupled the main acoustic volume with attics located above the triforium arcades. According to Viollet-le-Duc, the oculi were present from the beginning of construction until around 1230, when the windows above the oculi were extended down to create the longer windows seen today [4, §*Rose*]. Visual representations of the oculi can be found in [6, 8], which were used to inform the creation of the acoustic models containing the attics and oculi.

This study examines the effect of the retaining wall and oculi on the acoustics of Notre-Dame's early decades and compares the impact of these features to the acoustic behavior of a speculative model of the early basilica replaced by Notre-Dame. In this study, the cathedral has been modeled at points of partial architectural completion in the time period from ca. 1160 to ca. 1225, and the models have been been named after the years roughly corresponding to these architectural way-points. Historians and archaeologists, however, agree that construction on the structure was continuous and likely simultaneous [9, 10]. Consequently, the dates assigned to these models should be considered as temporal approximations rather than prescriptive claims re-

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garding the cathedral's state in that year. This approach is necessitated by continuous construction onsite and the contemporaneous documentation available, but more significantly reflects a desire on the authors' part to examine and quantify the acoustic effect of certain architectural changes in isolation from others.

3. MATERIALS AND METHODS

This study follows the methodology set out in [11], where a geometric acoustic (GA) model is calibrated to room impulse responses of the existing building. Four total GA models were created (see Table 1), with the speculative ca. 1163 model based on an extant building and the ca. 1182, ca. 1220, and ca. 1225 models based on the GA model reported in [12], subsequently modified to match the historical states as discussed in [13].

3.1 Geometric Acoustic Models

The oldest building modeled is the largest of the church buildings associated with the religious community on Île de la Cité in 1163. It is likely that this large building fulfilled a similar role for high feasts and holy days as Notre-Dame eventually would, and it is generally accepted that the building was built in the basilica-style [3, 8, 5, 14]. Traces of its foundation have been discovered underneath the parvis in front of Notre-Dame, outlining a rectilinear building ≈ 35 m wide, ≈ 70 m long [3, 5], with two sets of side aisles flanking the main aisle. Based on similar basilica-style churches, it is likely that a semicircular apse was appended in the liturgical east, framing the altar and providing a focal point for ceremonies held within the church. There is no record of the height of the ancient structure.

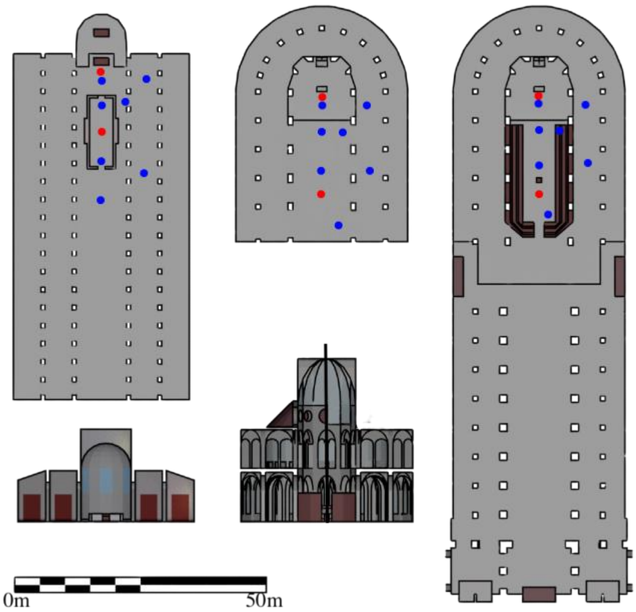

Figure 1 – Plans and elevations of ca. 1163, ca. 1182, andca. 1220, with sources (red) and receivers (blue) under con- sideration indicated.

To aid in the development of a speculative model of the early building, a well-preserved, contemporaneous basilica-style church was identified and selected to stand-in as a possible representation of the building. The Basilica of *Santa Sabina all'Aventino* is a basilica-style church located on Aventine Hill in Rome. Originally built in the 5th century, the interior of the basilica has survived largely unmodified to the modern era, maintaining the characteristic semicircular apse and flat, wood-paneled ceiling common to basilicas of the early Middle Ages. The acoustics of Santa Sabina were measured and reported in [15], and the base model was created and calibrated to the measurements following the procedures outlined in Section 3. Since materials from the demolished buildings were reused for the construction of Notre-Dame, the same acoustical material properties were used to ensure continuity between the models. After verifying the Santa Sabina model calibration with measurements, the model was morphed to match the dimensions of the pre-Gothic building, maintaining the calibrated material properties as well as key design elements from Santa Sabina. Without knowing the height of the historic basilica, surviving contemporaneous basilicas of similar or larger size were consulted to maintain a consistent proportion of width and height for the center and side-aisles. In addition to Santa Sabina, these include the basilicas of *San Paolo fuori le Mura* (Rome), *Sant'Apollinare in Classe* (Ravenna), and the *Church of the Nativity* (Bethlehem).

The ca. 1182, ca. 1220, and ca. 1225 models were based on the 2015 calibrated model of Notre-Dame [16]. Oculi were modeled as circular voids in the clerestory walls and the windows were shortened. The materials of the attics were chosen to represent the masonry, dust, and wooden bracing likely found in such a space. The interior geometry was altered to reflect the commonly-held view of the construction timeline, with attention paid to changes in furnishings and decorations. Changes from the 2015 model [11] include the closing of the lateral chapels, the inclusion of the clôture, reshaping the choir stalls, altering the ground floor of the chancel, positioning of the grand altar, and other local adornments.

3.2 Simulation Settings

All models were generated using CATT-Acoustic (v9.1e, TUCT v2.0e) [17]. As the goal of these simulations was an exploration of the acoustics of the buildings under consideration, simulations were generated using algorithm 1 (split order $N = 1$), with a 350,000 rays. The length of the impulse response duration was determined by an initial test run and then rounded up to the next integer second. For the ca. 1163 and ca. 1182 models, this procedure resulted in a 7 s impulse response, and for all other models a 10 s impulse response. Impulse responses were calculated for the

Table 1 – Approximate dates modeled in this study with volume (V) and surface area (S).

Year	V (m^3)	S (m^2)	Notes
ca. 1163	29,640	11,785	basilica
ca. 1182	27,935	12,900	apse only, + attics
ca. 1220	82,365	32,235	full length, + attics
ca. 1225	79,430	28,805	full length, - attics

sources and receivers noted in Fig. 1. For the purposes of addressing run-to-run variation, reported acoustic parameters are averaged over five repetitions.

Source and receiver positions were chosen to reflect the liturgical use of the space, with omnidirectional sources located where priests and lay members would speak or sing as a part of mass. Receivers were positioned to examine local variations in the acoustics in and around the consecrated portions of the chancel.

4. RESULTS

The change from the basilica to the Gothic style was a significant change in the architectural massing of the two buildings. Although the internal volumes were likely similar in magnitude (see Table 1), the Gothic building rearranges the internal volume vertically, creating a large ceremonial space, reinforced in later years by the inclusion of the clôture and the high-backed choir stalls. This reordering of the massing within the cathedral can be seen in the elevations of Fig. 1, and the effect of this rearrangement can be seen in Fig. 2, which compares the center time (T_S)[1] within the ca. 1163, ca. 1182 models and ca. 1120 models. Fig. 2 showcases the effect of the Gothic chancel on the temporal energy balance. Notably, while T_S clearly increases as a function of distance within the basilica model, the chancel maintains a steady and low T_S value for a larger area within the Gothic models. Furthermore, the lower ceilings and the corridors of the ambulatory maintain a relatively even energy balance after the installation of choir stalls and clôture in the ca. 1220 model. These mappings hint at the existence of acoustic sub-spaces from the earliest of the Gothic cathedrals (reported in the 21st century cathedral in [18, 19]), coupled by the volume overhead. Fig. 3 reports the global average of reverberation time (T_{30}) using the sources in the chancel as indicated in Fig. 1 and the receivers distributed throughout the apse. The reduction in T_{30} between ca. 1163 and ca. 1182 is significant, with a maximum difference of −0.8 s at 1000 Hz. While the removal of the attics between ca. 1220 and ca. 1225 represents a change of only 3% of the internal volume of the model, the closing of this coupled volume represents an increase of 7–13 % in T_{30}. For all octave bands, this increase of reverberation time falls outside

[1] T_S is measured in ms and is the balance point of early and late energy within the IR. Higher values of T_S indicate an IR with a large amount of late energy, correlating with low intelligibility and clarity.

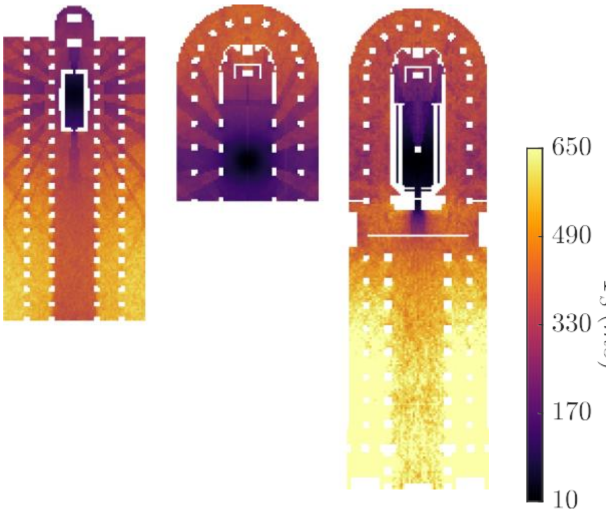

Figure 2 – Comparison of T_S in the ca. 1163, ca. 1182, and ca. 1220 models for a source in the center of the choir.

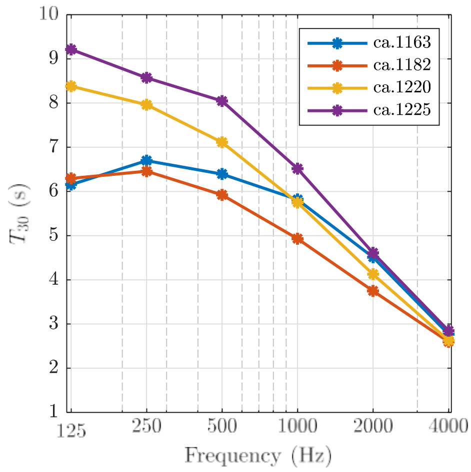

Figure 3 – Global average T_{30} values in the four modeled statesfor two chancel sources.

both computational run-to-run variation and the just noticeable difference for T_{30}. In general, the changes in T_s and T_{30} between these modeled states surpass the minimum requirements of the just noticeable difference(±40 ms for T_s [20] and ±5% for T_{30} [21]).

5. DISCUSSION AND CONCLUSIONS

These results demonstrate the acoustical evolution that occurred over the course of a few generations. The rearrangement of reflective structures and increased height of the new cathedral exaggerated the acoustical behavior of the basilica style model from ca. 1163. As can be observed in Fig. 2, T_s within the basilica increases linearly with distance from the choir source. In the Gothic buildings, this behavior does not occur at the same scale, with T_s remaining relatively stable in the apse. However, the T_s increases dramatically and to a greater extreme in the nave, creating a clear distinction between sacred and profane sections of the cathedral. In general, the acoustical changes between ca. 1163 to ca. 1182 and ca. 1182 to ca. 1220 pass the threshold of perception and likely would not have gone unnoticed by the community. Furthermore, the decrease in volume from ca. 1220 to ca. 1225 and the subsequent increase in reverberation time indicates that the high, flat walls of the clerestory play a significant role in the acoustic behavior of the cathedral.

Future work will deal with the acoustic sub-spaces and coupled volumes revealed in this preliminary examination and will expand to cover the entirety of the cathedral's 850-year history, including connecting the present work to recent contributions [22].

ACKNOWLEDGEMENTS

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Acoustic Characterization of the Rupestrian Pilgrimage Church of St. Michael's in Gravina in Puglia

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ABSTRACT
Rupestrian churches are very special semi-open acoustic spaces. Their acoustic features are strongly characterized by stone materials that (in the present stage) define their boundaries, and by more or less large openings. Consequently, strong frequency dependent effects are observed. The pilgrimage rupestrian church of St. Michael's in Gravina is one of the largest in Apulia and characterized by large flat surfaces. Acoustic measurements were carried out with a portable equipment. Results are discussed in the paper, pointing out that the combination of geometry and surface finishing determined a reverberant but yet clear acoustics, with a significant frequency imbalance which emphasizes bass sound (where modal behaviour also appears), and finally an impressive spacious and enveloping sound.
Keywords: rupestrian churches, acoustical measurements, 3D acoustic mapping

1. INTRODUCTION
Rupestrian churches and, more generally, rupestrian settlements represent an invaluable cultural heritage which is typical of Southern Italy and, in particular, of Apulia, representing an almost unique feature among Western European countries. Such settlements were built using natural caverns, generally due to karstic activity, or deliberately excavated in stone. They resulted, in most cases, from the spreading of Greek monks following the iconoclastic prosecution in the Eastern regions.

However, in many cases rupestrian settlements were established after assaults to cities that induced the population to find a refuge in caverns, forests, and along the slopes of hills where they built their houses and their worship places. The main difference compared to other examples of caverns [1-3] is that where natural caverns did not fit their needs, they created new ones (as it generally happened for churches) by excavating the stone and trying to imitate the shape and the architectural characteristics of "normal" churches.

The case of the Church of St. Michael's (Figure 1) exemplifies this approach to excavating spaces that resembled ordinary worship buildings. Its origin could date back to the destruction of the ancient city in 456 AD. However, since many of the places dedicated to St. Michael the Archangel were originally dedicated to pagan divinities, it cannot be excluded that the site has origins much further back in time.

When the natural cave welcomed the Michaelic cult it was modeled to become a real temple, probably in an era between the 8th and 10th centuries. Today the cave-church has five intercommunicating naves perpendicularly, marked by 14 quadrangular pillars. Round arches branch off from these and divide the interior space into naves and bays. The five naves end in apses with three altars in a central position; they are separated from the bema by a step on which once rested balustrades with barriers or wooden elements of the iconostasis.

The first nave, entering on the left, has remained similar to its original state: in the apse it preserves a triptych of frescoes with Christ Pantocrator in the center, St. Paul on the right, St. Michael on the left, datable to the 12th-13th century. Although the current liturgical layout of the presbytery denotes the use of the church according to the Western rite, as well as the absence of decorative or architectural elements that suggest the use of Eastern worship practices, it is not possible to exclude that, at least at its origins, the church was used for the Byzantine rite.

An acoustic analysis of the space was carried out in order to better understand how the peculiar geometry


Figure 1 – Panoramic image of the interior of the church

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and the surface finishing (in its current and in its original state) influenced the awe-inspiring nature of this place, and its attitude to host worship rituals.

2. MATERIALS AND METHODS

2.1 Main characteristics of the room

Among the Apulian rupestrian churches, St. Michael's is one of the largest (Table 1), with a volume of 640 m^3, a floor surface of about 200 m^2 and about 12 m^2 openings. On the material level, the church has few frescoed surfaces but most of the flat stone surfaces show a layer of whitewash in a fairly good state of conservation. No furniture was in the church during the measurements which were carried out under unoccupied conditions.

Table 1 – Summary of main geometric features

Property	
Floor surface	190 m^2
Overall surface	730 m^2
Volume	640 m^3
Average height	3.5 m

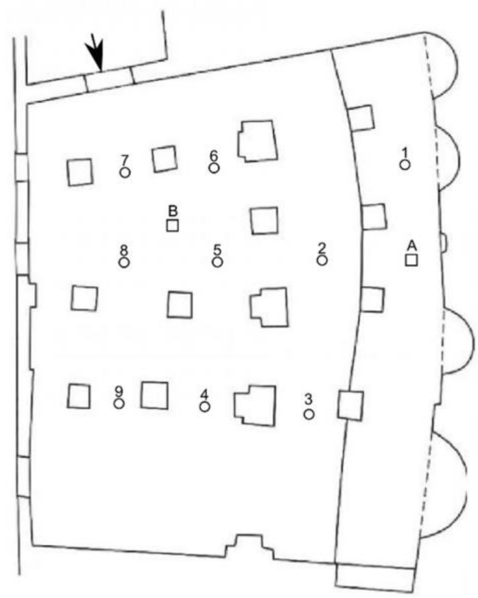

Figure 2 – Plan of the church with location of source (A,B) and receiver (1-9) positions

2.2 Measurement techniques

All the measurements were carried out with portable instruments. An omni-directional sound source (Lookline D301) located in front of the altar (Position A) and in the congregation area (Position B) was used to simulate sound emission from the priest and from the congregation (Figure 2). The source was fed by an equalized sine sweep played back by a smartphone and generated using MATLAB according to Müller and Massarani[4] so that the spectrum of the radiated sound was substantially flat from 50 Hz to 16 kHz. The duration of the sweep was kept short (about 8 s) in order to prevent negative effects due to lack of doors, determining significant air circulation which may compromise the time-invariant hypothesis, preserving at the same time frescoes and soft stone from any mechanical stress due to long lasting loud sounds. Impulse responses were collected using a portable B-format microphone (Soundfield ST-350) connected to a multi-channel recorder (Tascam DR-680) and a pair of binaural microphones (Soundman OKM II) worn by one of the authors and connected to a second recorder (Tascam DR-07). The measurement chain was previously tested in the lab to ensure that the "open loop" settings did not create any sync problem.

All the measurements were carried out complying with ISO 3382[5] standard, and, despite the small dimensions of the churches, at least two sound source position and an average of 9 receivers were used. Microphones were placed at a height of 1.7 m from the floor to take into account that the congregation was standing during the celebration. Given the small dimension of the churches only one person stayed in the room during the measurements. Impulse responses (IR) were calculated by deconvolving the signal used to fed the sound source and, despite a significant background noise due to birds and other natural sounds, provided an average S/N ratio of about 55 dB. The measured IRs were then processed in order to calculate the most important acoustic parameters and to investigate room resonances

3. RESULTS

3.1 Reverberation parameters

The observed reverberation time (Fig. 3) is very similar to those observed in smaller rupestrian churches, with a strong emphasis on low frequencies, while medium and high frequencies are influenced by the porous nature of the stone. From this point of view it should be noted that in rock churches, the need to have numerous vertical support elements determines an increase in the exposed surface as the volume increases, therefore this leads to a corresponding increase in the obtainable acoustic absorption.

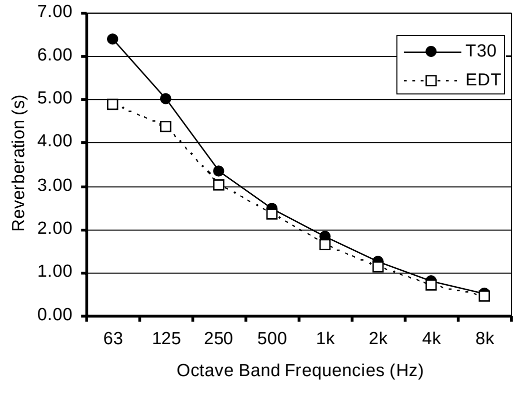

Figure 3 – Reverberation time (T30) and early decay time (EDT) as a function of frequency

A significant difference appears between EDT and T30 at low frequencies, potentially attributable to the presence of resonances (Figure 4) in the vertical direction (where the height is on average between 3 and 3.5 m, with consequent fundamentals between 50 and 60 Hz). To support the interpretation of the long low frequency T30, it is interesting to observe the spectrum of one of the measured IRs, showing clear modal behavior with four peaks located respectively at 59 Hz, 65 Hz, 72 Hz and 89 Hz, the first one being in agreement with the first vertical mode for a space with a height of 2.8 m.

Point-by-point variations can be observed but being visible at all frequencies they are therefore attributable only to the different relationship between source and receivers, mostly as a consequence of the masking effect produced by the many pillars.

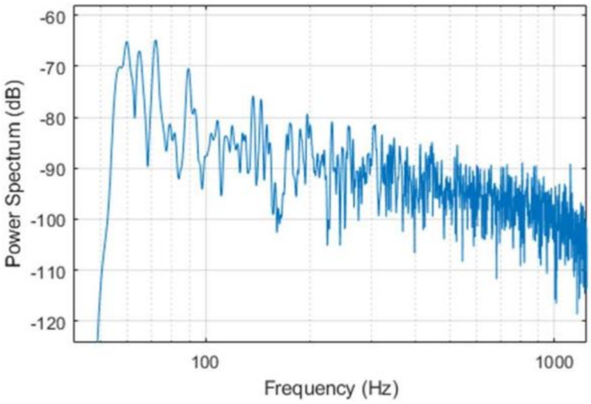

Figure 4 – Spectrum measured for combination A_01

3.2 Clarity and speech intelligbility

The relatively low medium and high frequency reverberation time determines an average value of STI equal to 0.57, with a maximum of 0.63 at receivers close to the source, and minimum values never lower than 0.5, therefore corresponding to a sufficient intelligibility which, however, could considerably increase considering the capacity of the church. and the consequent possible reduction of the reverberation time in the presence of a full occupation.

Given the larger dimensions of this church, it is also interesting to observe the trend of the parameters of clarity as a function of distance (Fig. 5). To provide a comparison with values expected for a space with comparable volume and T30, values derived from Barron theory [6] and from the revised version using increased control of early reflections [7,8] are shown. In the second case, the additional parameters were chosen assuming a source located close to hard reflecting surfaces (corresponding to a scattering coefficient s = 0.2), and a space with large reflecting surfaces (corresponding to parameter k = 0.7).

A decrease in measured values can be observed as a function of distance with a slope that is steeper than the expected one (whatever the model used to calculate). This results from measured values that are 4-5 dB higher than prediction at receivers within 8 m from the source. The explanation for this behavior is that strong early reflections (comparable with direct sound) come from the hard and reflective surfaces that surround both source and receivers.

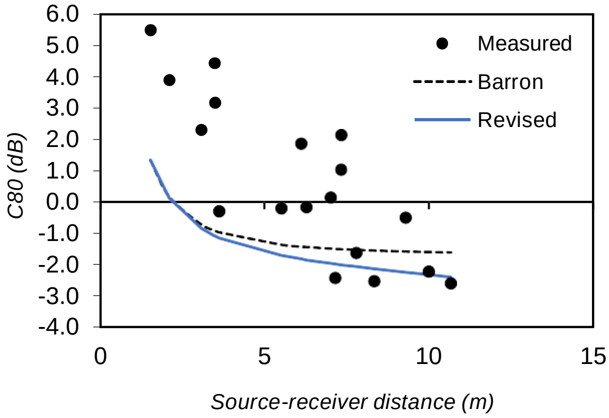

Figure 5 – Plot of C80 (averaged among 500-2000 Hz octave bands) as a function of source receiver distance

3.3 Spaciousness

As for the spatial parameters, the extension of the church, especially in width, combined with the many obstacles, induces lateral energy fraction values that are, on average, equal to 0.28 when the source is in A (Fig. 6). For the same reason, 1-IACC should also be affected. However, the presence of a "forest of pillars" [9] determines a partial compensation of this effect. In fact, when the source is in A, the average of 1 – IACC is 0.74 (quite close to values observed in other smaller rupestrian churches [10]), while when the source is in B the average value stands at 0.68 largely due to the lower measured values at points 5, 6 and 7 which are very close to the source.

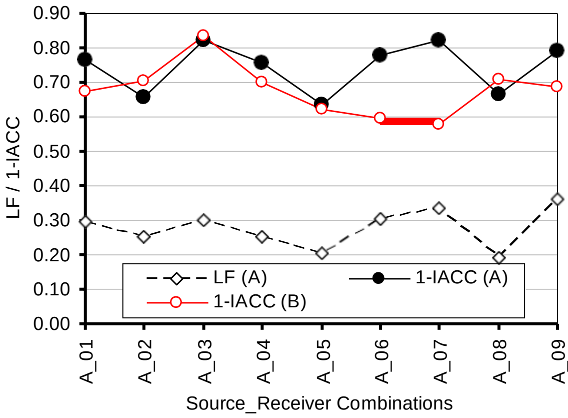

Figure 6 – Plot of Lateral Fraction (LF) and 1-IACC as a function of source and receiver combinations

3.4 Spatial distribution of early reflections

In order to finally explain some of the observed results, with particular reference to high clarity, STI, and strong lateral reflections, a directional map of the early reflections was obtained from the B-format recordings, taking advantage of the procedure discussed in Ref. 11.

As shown in Figure 7, the early part of the IR is characterized by strong reflections coming from the horizontal surfaces as well as from the side walls (particularly from the left side) where sound is reflected despite the presence of the large pillars.

Similar results were found at different source-receiver combinations, emphasizing the role of strong reflections bouncing between the floor and the ceiling and contributing to keep high clarity.

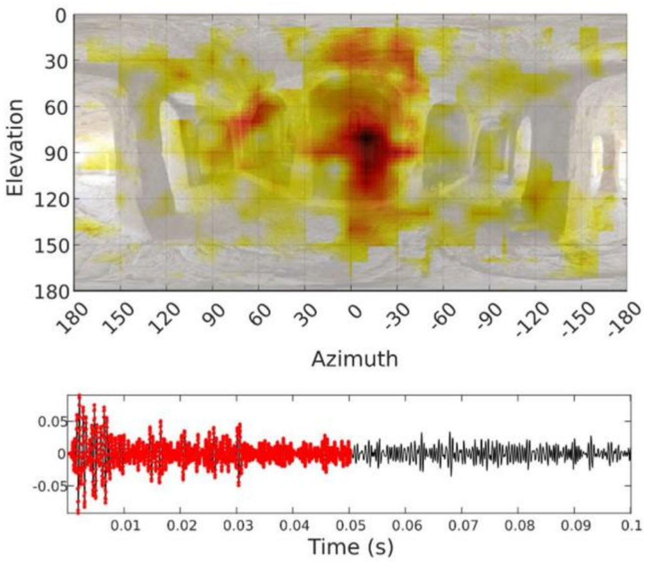

Figure 7 – Directional map at receiver 02 when source was in position A, time interval from 0 to 50 ms, at 2 kHz octave band frequency

4. DISCUSSION AND CONCLUSIONS

The paper investigated one of the largest rupestrian churches found in Apulia and dedicated to Michaelic cult. This ritual space, characterized by large flat horizontal surfaces made of stone, is characterized by a strongly unbalanced acoustic where low frequencies are resonant and reverberant, while medium and high frequencies are characterized by much lower reverberation times and high clarity, suitable for speech even under unoccupied conditions. Analysis of spatial distribution of reflections confirmed the role of flat horizontal surfaces in combination with some strong lateral reflections that also contributed to keep lateral fraction and inter-aural cross correlation coefficients at reasonable levels suggesting a fully enveloping sound.

Such results suggest that under fully occupied conditions acoustics might become even clearer and appropriate for preaching and ritual ceremonies, while keeping a very long low frequency reverberation that emphasized ritual singing. In fact, analyses of typical Byzantine chants have demonstrated the role of low frequencies that are used to produce almost continuous notes that interact very well with the resonant qualities of the investigated spaces.

In addition, the current state of the surface finishes (i.e. flat stone surfaces with thin layer of whitewash that is crumbling in large areas), is likely to return an absorption coefficient of about 0.05 at mid frequencies. As found in other rupestrian churches, plaster (with frescoes) was likely to cover the surfaces in the origin, thus realistically reducing absorption coefficients. Thus, it is reasonable to assume that a more reverberant acoustics, although equally characterized by much slower low frequency decay, would have characterized the space in its origin. However, the occupants are also likely to dramatically change acoustic conditions, making it even more unbalanced.

Further investigations are under way to properly analyse this condition by means of simulation tools.

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Acoustic analysis of a well-preserved Renaissance music space: the Odeo Cornaro in Padua.

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ABSTRACT

The Odeo Cornaro (1534) in Padua is a Renaissance music space designed by the architect Falconetto for the private palace of the Venetian entrepreneur Alvise Cornaro. Inspired by the classicism of Roman "villae" described in Cicero's letters, this octangular hall may be included in the "loci consonantes" Vitruvius' category, where the sound propagation isaccentuated, and the voice supported. In order to analyse these acoustic features through a contemporary approach, a campaign of in situ acoustic measurements allowed an accurate analysis of such a well-preserved space through objectiveroom criteria. Moreover, the acoustic role of the umbrella vault and the niches in the sidewalls has been evaluated througha numerical model tuned on the measurements' outcomes. The main results show that the neat modal behaviour of the symmetrical environment is also accentuated by the moderate volume and the lack of furniture. This effect contributes to supporting the voice of the singers without losing the intimacy of the music performance, proving the Odeo to be an outstanding music place of the past.

Keywords: Renaissance music space, well-preserved octangular hall, central-planned architectures, acoustic heritage.

1. INTRODUCTION

Central-plan buildings assumed a predominant role in the High Renaissance philosophical and artistic framework. The most leading architects, such as Bramante, Leonardo, Brunelleschi, Alberti, used to glimpse the idea of the divine perfection behind symmetrical shapes, also according to Aristotle and Plato's views and the *De Architectura* by Vitruvius [1,2]. Indeed, the geometrical features of centrally planned halls significantly affect the acoustics of the environments [3,4].

The aim of the present work is investigating the acoustic properties of a well-preserved Renaissance music space: the Odeo Cornaro in Padua (Italy). The Odeo Cornaro belongs to one of the most interesting Venetian architectures dating back to the XVI Century [5]. Designed by the architect Falconetto for the patron of arts Alvise Cornaro, the *ottangulo* (from latin "octangular" place) was probably conceived as a music space for the nobleman's villa (Figure 1), while the surrounding communicating rooms were intended for erudite symposia [6,7]. The presence of instruments and a choir is explicitly mentioned by the writers of the same period (1537-1542). However, the moderate volume of the *ottangulo* suggests that it was a hall reserved to small groups of erudite people [8,9,10]. What is also mentioned in historical evidence is the support given by the hall to the human voice, which was attributed to the niches and the shape of the hall [11]. During the study historical references have been useful not only to know the intended use of the distinct parts of the architecture but also for the comprehension of the materials employed during the construction [12].

Figure 1 – Interior view of the Odeo Cornaro (Padua).

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2. ACOUSTIC MEASUREMENTS

In February 2022 the authors carried out a geometrical and an acoustic survey of the Odeo Cornaro. The aim was, respectively, to create a reliable 3D virtual model of the hall and to investigate the acoustics of such a unique well-preserved place. Main geometrical features of the octangular hall are provided in Table 1.

Table 1 – Main geometrical features of the octangular hall.

Feature	Quantity
Volume [m^3]	220
h_{max} [m]	6
h_{mean} [m]	5.5
Floor [m^2]	40
Niches [n°]	4

The most significant room criteria have been collected by in situ measurements in compliance with ISO 3382. Acoustic measurements were performed within the central hall and the surrounding rooms. Two points were selected for the location of the omnidirectional sound source (dodecahedron); twelve receiver points (monoaural receivers) were employed: nine within the octangular hall and three in the main communicating room. Experimental results are reported in Table 2.

3. NUMERICAL MODELS

Since the Schroeder frequency of the Odeo is around 225 Hz (V = 220 m^3, $T_{500\text{-}1k}$ = 2.8 s) two distinct simulation approaches are required [14]. A ray-tracing time dependent approach was adopted for the analysis of acoustic coupling effects and the free path distribution (ODEON Room Acoustics). A wave-based approach was applied for the steady state response under a sinusoidal monopole source distribution at low frequencies (COMSOL Multiphysics).

3.1 Geometrical Acoustics (GA)

The 3D virtual model of the *ottangulo* and the adjacent room was created according to the geometrical acoustics (GA) state-of-the-art (see Figure 2) [13]. The calibration of the model was achieved by considering a single material for all the surfaces involved: the marble. The α coefficient in octave bands are provided in Table 2, along with the comparison between measured and simulated T_{20}. The scattering value was set equal to 0.3 for the upper part of the niches, and equal to 0.02 for the remaining surfaces. A transition order equal to 2, an impulse response length of 4 s, and 40 k rays were used during the simulation.

Table 2 – Measured and simulated T20 values along with the absorption coefficient of the marble.

	125	250	500	1k	2k	4k
T_{20} (Meas.)	3.49	3.23	2.92	2.70	2.36	1.69
T_{20} (Sim.)	3.32	3.20	3.02	2.69	2.31	1.61
α_{marble}	0.013	0.014	0.014	0.015	0.015	0.016

The calibrated model was employed to investigate the potential multi-slope decay curves between the coupled rooms [15]. The Bayesian analysis was carried out on the measured and the simulated room impulse responses (RIRs): mono-decay curves were detected for the receivers located in the octangular hall whilst dou- ble-decay curves were detected for the points located in the adjacent room (Figure 3).

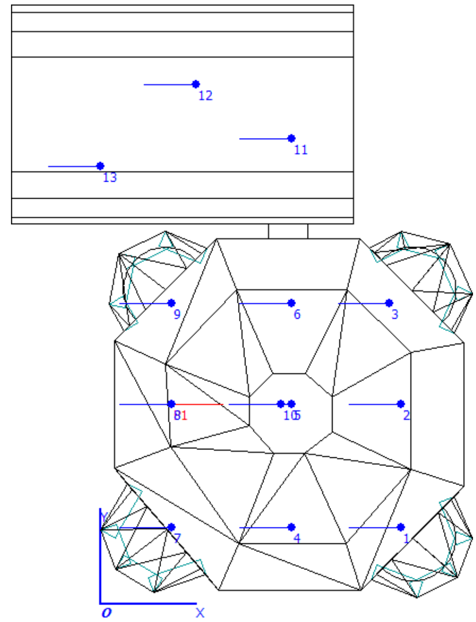

Figure 2– 3D model of the Odeo Cornaro (ODEON).

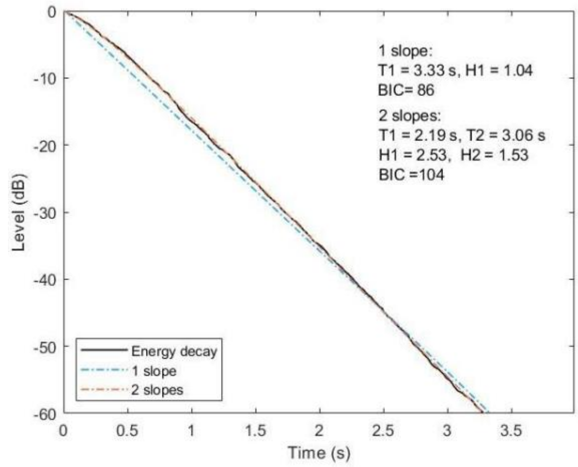

Figure 3–. Multi-decay analysis of measured IR at 1000 Hz with the sound source in the octangular hall and the re- ceiver in the adjacent room [16].

Figure 3 shows the results for the sound source in the *ottangulo* and the receiver in the adjacent room. According to the following expression [16]:

$$H_s(\mathbf{H},\mathbf{T},tk) = \sum_{S=1}^{2} H_s e^{-13.8tk/T_s}$$

where H_s is the Schroeder curve, **T**= T_1, T_2, and **H** = H_1, H_2 are the decay parameters, the combination of two slopes proves to be more accurate (higher BIC value for T_1, T_2, H_1, H_2) than the single slope (lower BIC value for T_1, H_1).

Moreover, the coupling factor *kc* was calculated according to the Cremer and Muller theory [17] considering the coupling surface, S_c, and the equivalent absorption area of the receiving space (A_2 when the sound source is in the octangular hall, A_1 when the sound source is in the adjacent room):

$$k_{c12} = \frac{S_c}{S_c + A_2} \approx 0.44; \;\; k_{c21} = \frac{S_c}{S_c + A_1} \approx 0.33 \qquad (1)$$

where Sc = 1.33 m2, A2 = 2.69 m2 A2 = 1.68 m2. Such values indicate that coupling effects between the *ottangulo* and the adjacent room are not neglectable.

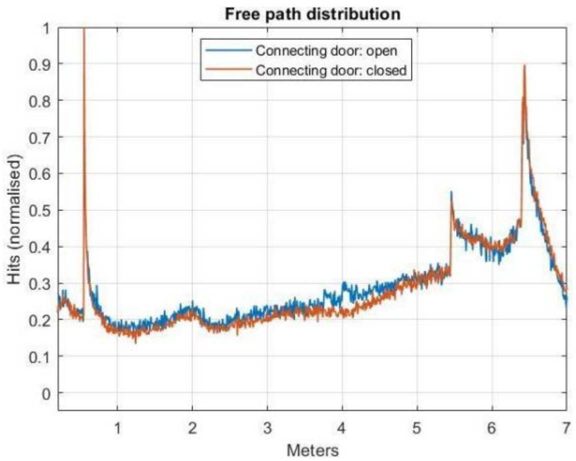

Figure 4 – Free path distribution in two configurations depending on the connecting door: open and closed.

A further analysis concerns the free path distribution in two distinct configurations depending on the connecting room (open or closed). Figure 4 provides the results in terms of normalised frequency of surface hits versus the distance of free paths in meters. It is possible to notice that no significant discrepancies are detected suggesting that the free path distribution in the main octangular hall is independent from the configuration of the door and the presence of the adjacent hall.

3.2 Finite Element Method

The sound energy behaviour at low frequencies has been assessed through COMSOL Multiphysics, in which the 3D model of only the octangular hall was built from the scratch. The *Pressure Acoustics, Frequency Domain* module embedded in the software was used to explore the effects of eigenfrequencies of the hall on the signal emitted by an omnidirectional sound source (*Monopole point source* placed at 1.5 meters above the floor). A single *air* domain was defined for the whole geometry by employing the linear elastic model. As a first approximation, no specific boundary conditions were set except for the *Sound Hard Boundary Wall* condition on all the surfaces involved. The mesh of the geometry has been set according to the rule of thumb of 6 elements for the minimum wavelength of interest (considering f_{max} = 400 Hz in FE analysis).

Figure 5 shows the steady state response under a monopole source distribution (P_{rms} = 1 W) in terms of total acoustic pressure distribution at f = 110 Hz, f = 130 Hz, f =150 Hz. These results confirm that the voice – which is here preliminarily approximated as omnidirectional and has the first energy contribution in the 125 Hz octave band – is effectively supported by the hall. Moreover, such kind of study also suggests that the behaviour of the *ottangulo*'s response at low frequencies is moderately affected by the presence of the niches, in contrast with the historical statements. Therefore, in the first place it is possible to consider the steady state response of the octangular hall similar to that one of cylindrical halls [11].

4. CONCLUSIONS

The present work investigates the acoustics of a well-preserved Renaissance music space in Padua (It- aly). A campaign of acoustic measurements allowed for the collection of the ISO 3382 room criteria, while two different numerical models have been used for a contemporary approach to the acoustic analysis of such unique hall.

The preliminary results clarify the relationship between the central octangular hall and the surrounding rooms (GA software) and show the response under a monopole source at low frequencies (FE software). The multi-decay analysis on measured and GA impulse responses proved that the adjacent halls work with acoustic coupling effects (double-decay curves) when the sound source is in the octangular hall and the receiving points are in the adjacent room. Furthermore, the FE results show the considerable sound reinforcement obtained with a source located where singers were supposed to be (at one side of the *ottangulo*). Finally, the present study proposes a method to exploit the advantages of different simulation approaches to investigate specific acoustic aspects in well-preserved historical music spaces.

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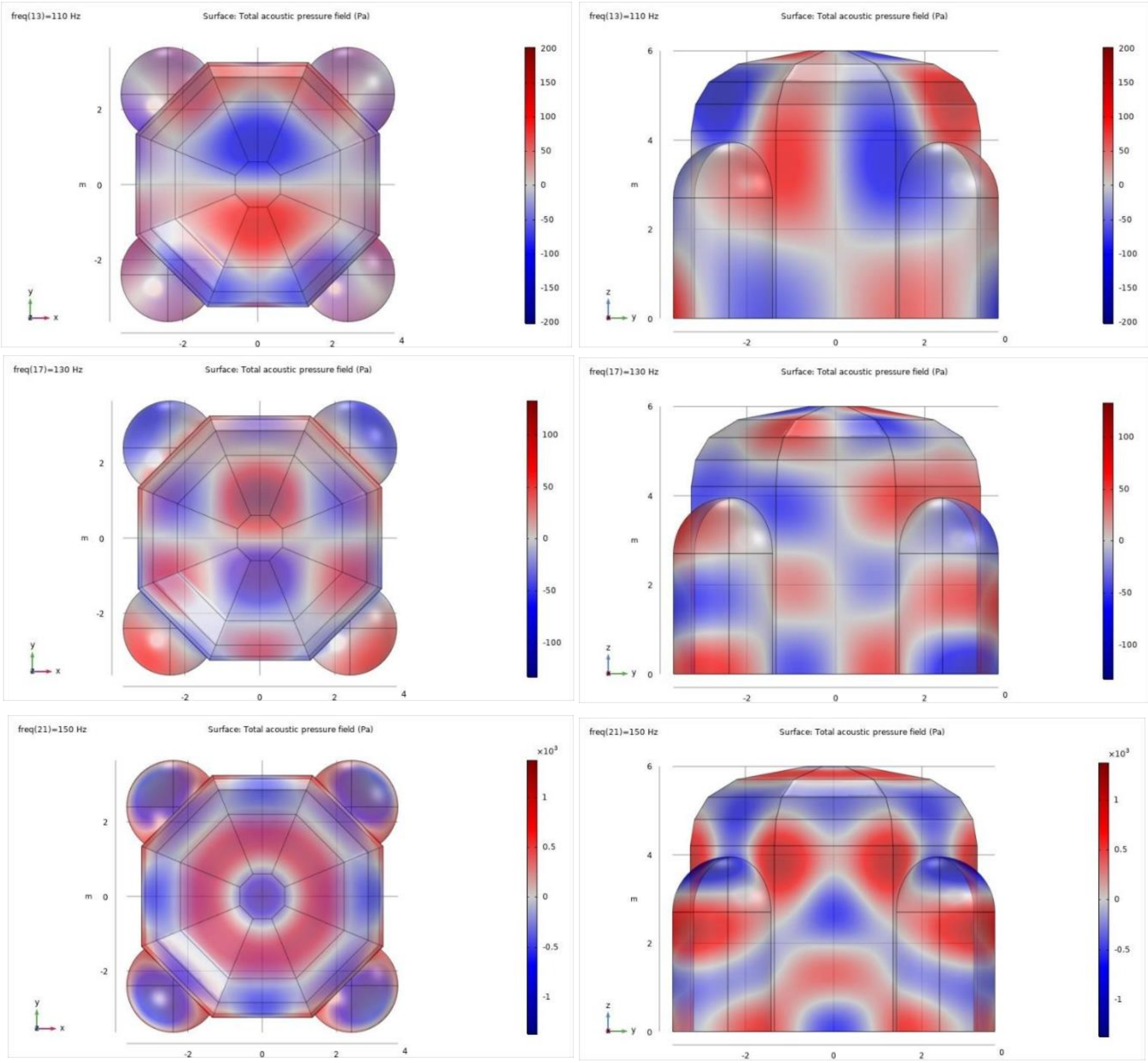

Figure 5– Steady state response under a sinusoidal monopole source distribution located at (x=0, y=2, z=1.5) with input frequency as indicated in each panel (COMSOL).

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SIPARIO - Spatial audio techniques for 3D measurements and recordings in ancient theatres

PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

Deepening the studies of the Roman theatre of Verona: acoustic effects from the installation of a barrier shielding the break-in of road traffic noise.

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ABSTRACT

The Roman theatre of Verona has always been subject to great interest under an acoustic perspective due to the continuous development of technologies that allow scholars to study monuments with more accuracy. Acoustic measurements have been carried out across the *cavea* to understand the existing conditions of the Roman theatre, been used for live musical events especially during summer seasons. The archaeological site is bounded to south-west by a road called Rigaste Redentore, which is an important arterial for the vehicular traffic crossing the city centre along the south-north direction. On this basis, the authors propose the installation of an acoustic barrier to protect the artistical performance from the road traffic noise. A deep analysis has been carried out by highlighting any difference in terms of acoustic parameters between the existing conditions, measured on site, and a digitally simulated condition with the insertion of a barrier.

Keywords: Acoustic measurements, Roman theatre, acoustic simulations, cultural heritage

1. INTRODUCTION

Recent research studies have been focused on the reconstruction of the original shape of the Roman theatre of Verona based on historical documents and archaeological excavations [1]. Furthermore, the employment of new technologies has contributed to complete the knowledge with respect to the early and late reflections hitting the architectural components of the Roman theatre [2].

This paper deal with the acoustic simulation of a barrier planned to be on the border line between the roadside and the archaeological site. The barrier has been designed to be 6 m high from the road level, considered in the model to be composed of a solid material (wood) capable of shielding the road traffic noise from Rigaste Redentore. The simulated results related to the main acoustic parameters have been compared with the measurements undertaken across the *cavea* of the Roman theatre. Differences and similarities have been widely commented.

2. SOME FEATURES OF THE THEATRE

The Roman theatre of Verona has been built along the slope of St Peter's hill by covering a surface area of 150 m wide and 100 m deep. The scenic building, realised on the edge of the river Adige, was composed of three doors, and the dimensions of this structure are 6 × 72 × 27 (W, L, H). The diameter of the orchestra is about 30 m and the proscenium is 1.4 m above the orchestra level. The original capacity should be of 3000 seats.

3. SITE CONDITIONS OF THE ROMAN THEATRE

The existing conditions of the Roman theatre have been developed since the first century AC, when the theatre fell in disuse and has been destroyed by Germans [3]. Further damage has been provoked by posthumous constructions that invaded the *cavea*, as visible by the prominence of the staircase of St Siro & Libera's church (built in 913), although other residential constructions have been removed during the archaeological excavations of the 20th century.

Another structure that is considered part of the site is the convent of St Jerome, developed during the 15th century due to expansion of the religious congregation [4].

3.1 Design Improvements

Since the Roman theatre of Verona has been restored to be one of the performing arts spaces to be active especially during the summer season due to the productive live musical events, the existing conditions of the road traffic noise breaking in the archaeological site is a main concern for the overall result of a peaceful listening condition. During summer season, a temporary wooden barrier is built for shielding the performance running outdoor from the road traffic noise, as shown in Figure 1.

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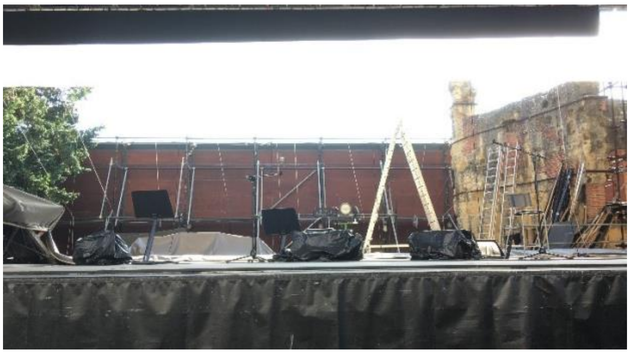

Figure 1 – View of a temporary acoustic barrier mounted behind the stage.

Different could be the solutions that can be adopted for reducing the extraneous noise levels of the road during the artistic performance, but this paper takes in consideration the solution proposed by the local authority. On this basis, a design of a barrier to be 6 m high from the level of Rigaste Redentore road has been used for the acoustic simulations. The barrier would be composed of smooth wooden planks to be installed vertically behind the partially erected scenic building.

The simulated results of this configuration have been compared with the measured values reflecting the existing conditions.

4. DIGITAL MODEL

A digital model has been realised in AutoCAD software package where all the layers have been grouped based on the existing finish materials. Thereafter it has been exported in dxf format, ready to be used for the acoustic simulation carried out with Ramsete 3.02.

The model represents the existing conditions of the Roman theatre of Verona, whose results have been compared with the simulated values obtained by adding the acoustic barrier designed to be at the edge of Rigaste Redentore road.

The absorption coefficients assigned to the entities of the model have been tuned based on the acoustic measurements undertaken in situ [5]. Figure 2 shows the digital model representing the existing conditions of the theatre with the barrier highlighted behind the scenic building.

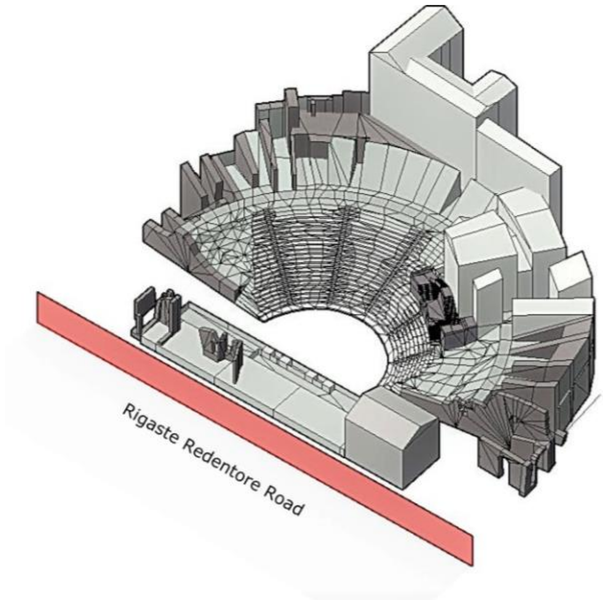

Figure 2 – View of the 3D model.

5. RESULTS IN COMPARISON

The main acoustic parameters have been analysed by comparing the measured values with the simulated ones representing the existing conditions with the addition of the barrier. The acoustic parameters have been analysed between 125 Hz and 8 kHz, to considered as the averaged values of all the receiver positions.

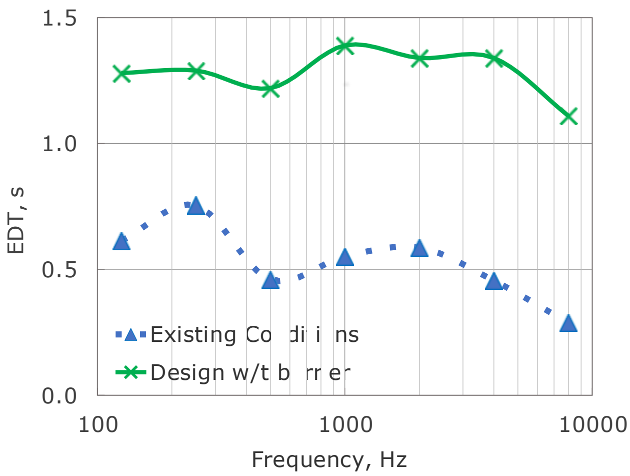

Figure 3 – Values of EDT.

Figure 3 shows that the EDT values have been found to be more suitable for music with the presence of a barrier behind the stage. The simulated results are up to 0.8 s more than the measured ones at each octave [6].

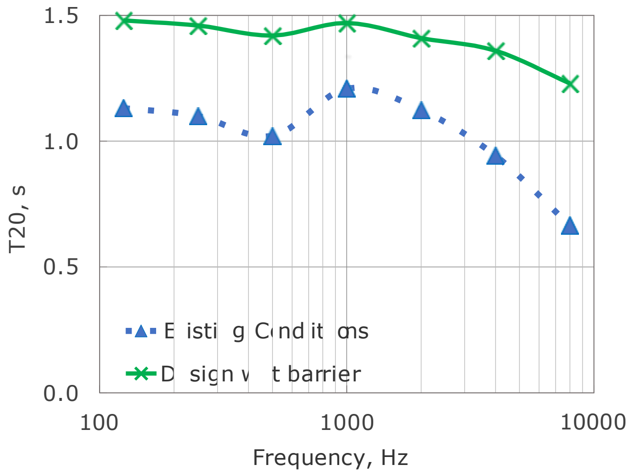

Figure 4 – Values of T_{20}.

Figure 4 indicates that the existing conditions of T_{20} are around 1.0 s and the insertion of the barrier will increase the results of up to 0.5 s. Given the volume size of the theatre, to be composed of the *ima cavea* mainly, the T_{20} will be more compatible with the musical shows that are usually performed [7].

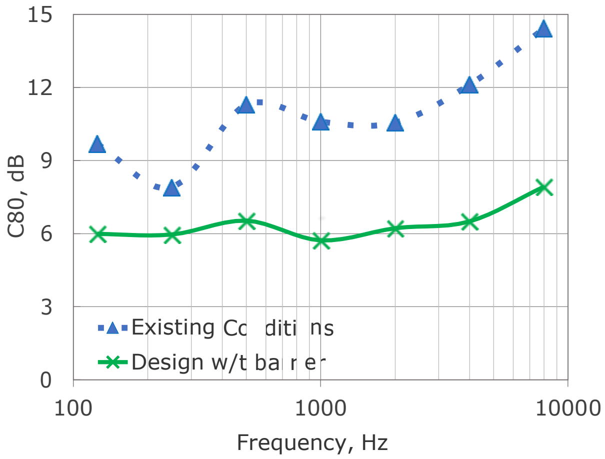

Figure 5 – Values of C_{80}.

Figure 5 indicates that the C_{80} values related to the existing conditions are clear in terms of music [8]. The addition of the barrier makes the values clearer across all the spectrum, to be up to 6 dB more than the measured on site.

Figure 6 indicates that the values related to definition are comparable between both scenarios. The values fluctuating around 0.85 indicate that the speech definition is very good [9].

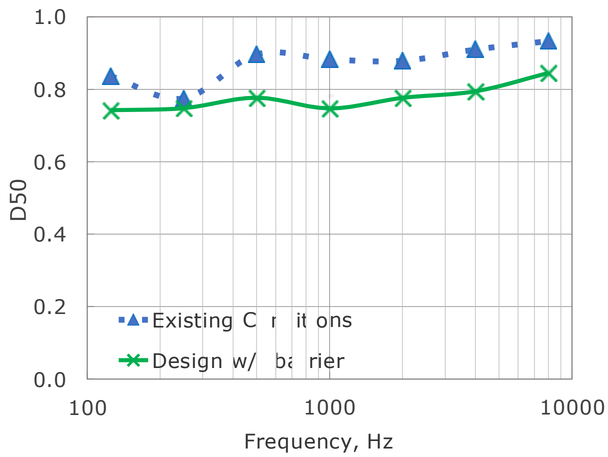

Figure 6 – Values of D_{50}.

6. CONCLUSIONS

This paper assessed the acoustic conditions of the Roman theatre of Verona by comparing the existing conditions with the addition of an acoustic barrier that contributes to limit the ingress of the road traffic noise, potential cause of a disrupting listening conditions during live performance inside the archaeological site.

The simulated values indicate that the insertion of a 6 m high barrier, placed behind the stage, will help to improving the acoustics of the theatre, by emulating the function of the scenic building that was covered by marble sheets. The addition of the barrier represents also a meaning of redirecting the sound towards the sitting area other than shielding the noise from the road.

Future research studies will be focused on the details of the barrier, in terms of texture and thickness, other than different options that could suggest the local authority to be considered for alteratives.

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Acoustics of the Teatro dell'Accademia delle Arti in Tirana (Albania) - spatial sound analysis

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ABSTRACT

The Theatre of the University of Arts of Tirana was realized in the early 20th Century in Tirana based on the design of the Italian architect Bosio. It was almost abandoned in the last 20 years and only recently has undertaken a complete restoration, including the design of a new orchestra pit. Acoustic measurements (monoaural and bin-aural IRs) were conducted to calibrate the 3D model and to elaborate the new acoustic design of the theatre. The paper briefly reports the story of the theatre and the most important outcomes of measurements and simulations.

Keywords: Theatre, Reverberation Time, Acoustic design.

1. INTRODUCTION

The Theatre of the University of Arts of Tirana has been involved recently by a project for the restoration and renovation that has been carried out by the Department of Architecture of the University of Florence together with the engineering study Atelier4 of Tirana. The supporter of the study was Trans Adriatic Pipeline, TAP, with the agree of the Ministery of Culture of Albania.

In this paper some of the acoustical investigations performed on the hall are shown, in order to ensure optimal room acoustics after the restoration works.

2. THE CONCERT HALL AT THE UNIVERITY OF TIRANA

2.1 About the history

The origin of the Opera Dopolavoro Albanese in Tirana dates back to the period between 1939 and 1943. During these years, the city underwent a building and territorial transformation that changed Tirana landscape from a small original city, with a prevalently residential layout, into an urban complex that better reflected the image of a capital city.

As part of this political, social and urban planning project that affected the whole of Albania, some Italian architects, mainly from Florence, guided by Gherardo Bosio, were called upon to contribute actively to the transformation of the city of Tirana.

The Theatre, designed by Bosio and developed by collaborators after his suddenly death, reflects that language of classical matrix, made of regular geometries, rhythmic repetitions, and functional expressions, which belong to the Italian architecture of Rationalism and that constantly characterize the work of the author.

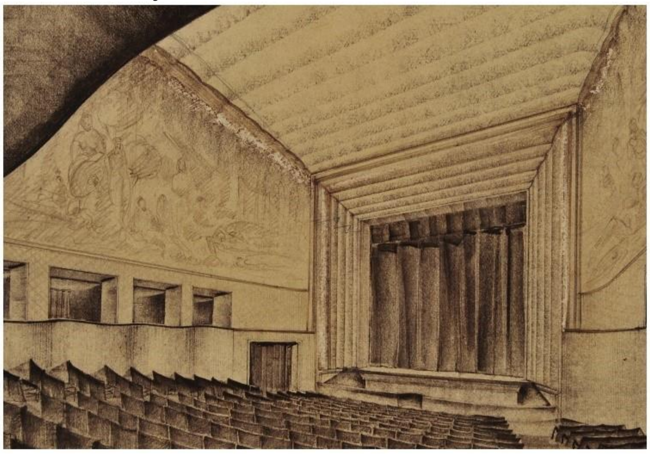

Figure 1 – Original drawing of the theatre.

Even though the settlement of the city has changed over time, as well as the surrounding area of the theatre, where today we find many other architectures close to the building which have lost the original linguistic strength, the Opera Dopolavoro Albanese, inside which we find the Concert Hall of the University of Arts, and

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the other architecture and boulevards of the same years are still a fundamental part of the historical identity of the city of Tirana. In fact, the building is currently considered as part of the Historical Heritage of Monumental Axis of Tirana: it's located in the historic centre of the city, within an area of national importance, declared protected since 2017, as architectural, cultural, heritage of XXth Century.

2.2 About the theatre

The hall of the theatre has a volume of about 5000 m^3 and is characterized by the presence of a platea surmounted by a gallery, both flanked by an order of double lodges. Both platea and gallery have a similar number of seats.

The scenic tower is composed of superimposed orders of rooms and technical rooms and the stage, with orchestra pit below.

Considering the volume of the hall, the optimal reverberation time should be between 1.3 s (for operas and theatrical performances) and 2.4 s (for classical music).

2.3 The aims of restoration project

The main aim of the feasibility study led by the Department of Architecture of the University of Florence was to define a line of restoration and refurbishment of the Theatre to identify, bring to light and protect the constructive and language characteristics of Bosio's project, and at the same time to guarantee an optimal and safe use of the building, in terms of technological and legislative adaptation, usability and accessibility, minimizing as much as possible the alteration of the original identity of the theatre (figure 2).

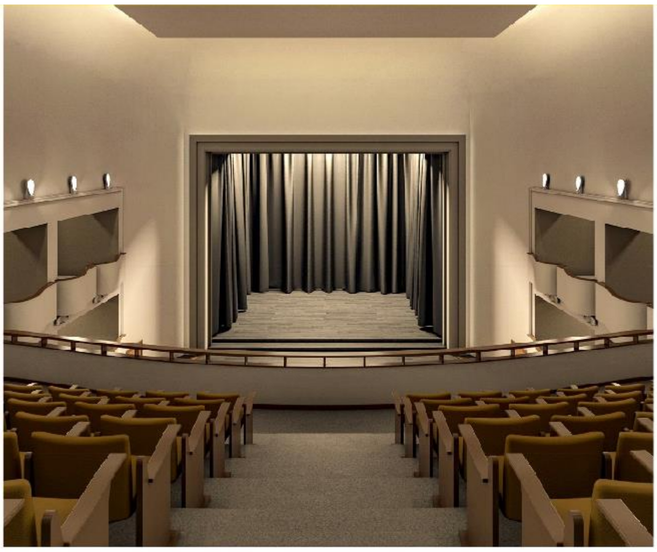

Figure 2 – rendering of the restored theatre

The main specifications for the acoustic project of the restoration of the theatre concern the reduction and restoration of armchairs, the replacement of curtains and the restoration and enlargement of the orchestra pit. To achieve this increase of the size of the pit, the floor plan was significantly modified from its original dimensions. It was also foreseen the installation of a mobile platform in order to vary the height of the orchestra pit according to the needs of the performances.

3. MESUREMENTS PROCEDURE

The impulse response measurements were carried out in the theatre on February 2020 in accordance with the requirements given by the standard ISO 3382-2. Both a single omnidirectional microphone moved from one position to the next (for monoaural measurements) and a pair of headset microphones (for binaural measurements) were used.

Two different types of fixed sound sources were used for sound emission:

- the theatre's loudspeakers for the reproduction of the "sine sweep" audio signal generated by the PC and reproduced by the theatre's amplification system; in this case, the measurement procedure used is that of the generation of a "sine sweep", then convolved by means of the plugin "Aurora" for Audacity® into a corresponding impulse response; the position of the two loudspeakers was that envisaged by the theatre (frontal, lateral to the stage, figure 3, S2 a and b);
- an impulse source consisting of the bursting of balloons with a diameter of 40 - 45 cm; the balloons were all burst from the stage at the position shown in figure 1 (figure 3, S1).

Care was taken to maintain a random and non-symmetrical distribution of microphone positions during the measurements (figure 3).

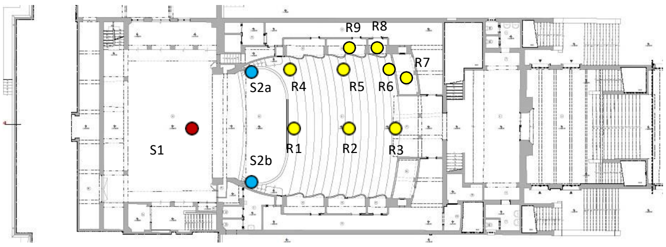

Figure 3 - Source positions and measurement positions in the platea (R1 - R6), in the central stage (R7) and in the lower side lodges (R8 and R9); S1 = position of the impulse source; S2a,b = positions of the two loudspeakers. Measurement positions R10-R12 were placed in the galleria and in the lateral lodges.

4. MESUREMENTS RESULTS

Using the two measurement methods described (impulsive noise and sine sweep), the impulse responses were obtained at the different locations and in both omnidirectional monaural and binaural modes. The following parameters were then analyzed (12 measurements x 2 methodologies = 24 measurements):

- Reverberation time T_{30};
- Clarity C_{50};
- Clarity C_{80};
- Barycentric instant ts;

- Early Decay Time EDT.

Moreover, also Speech Transmission Index measurements were carried out.

The results referred to the 12 measuring points of T_{30} and C_{80}, measured with the sine sweep technique and the omnidirectional microphone, are shown below.

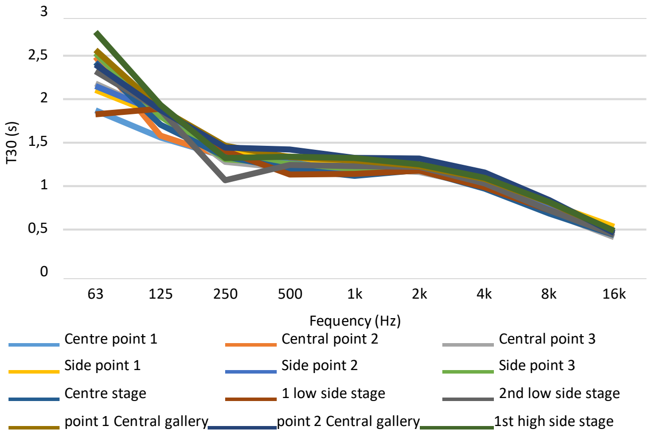

Figure 4 - Reverberation time T30 in octave frequency bands at the 12 measurement locations.

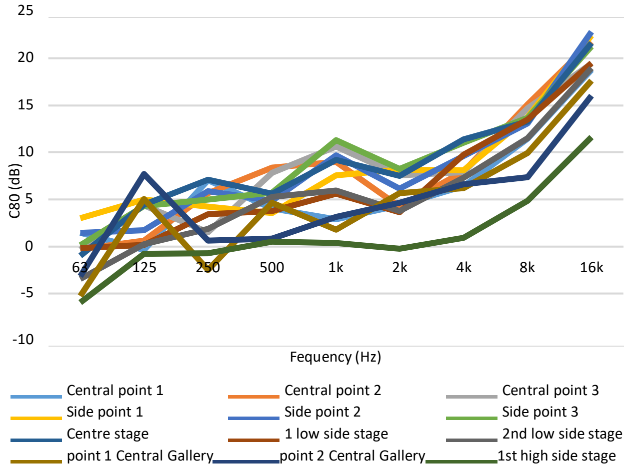

Figure 5 - C80 clarity in octave frequency bands at the 12 measurement locations.

5. DISCUSSIONS

Figure 6 shows a comparison between the average values of the reverberation time at the 12 measuring points obtained with the two techniques.

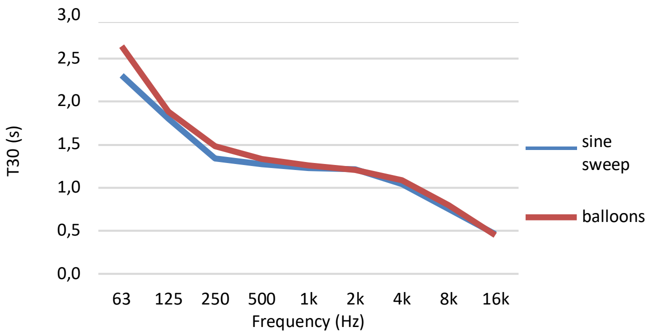

Figure 6 - Comparison of average T30 results with the two measurement techniques adopted.

A good repeatability of the measurement results obtained with the two signal techniques can be observed.

Moreover, the average values of T_{30} obtained at the different locations are quite repeatable and therefore "stable". Figure 7 shows the values of the average reverberation time, T_{30}, in the six platea positions, the two galleria positions and the lodges.

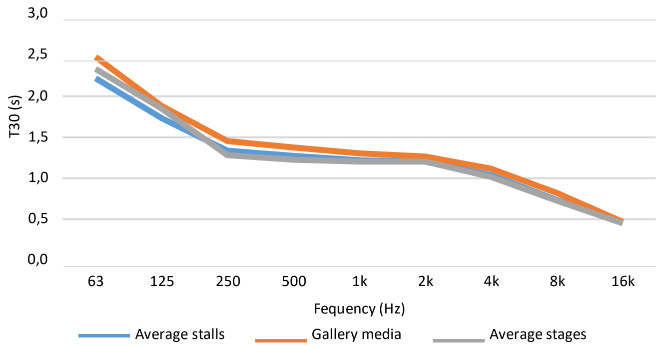

Figure 7 - Average value of the reverberation time T_{30} in the platea, galleria and lodges.

Considering the theatre's volume of approximately 5000 m^3 and referring to the value assumed by the reverberation time at 500 Hz it can be considered that the theatre has a rather "dry" acoustics, i.e. it has a low reverberation that is well suited to theatrical performances and listening to speech.

With regard to listening to music, for which a greater contribution of reverberation is normally required, the theatre is probably a little "dull" at high frequencies, i.e. it has a slightly too low reverberation time.

6. CONCLUSIONS AND INDICATIONS FOR THE RESTORATION PROJECT

The most relevant acoustic changes connected with the renovation project of the theatre were:

- restoration and reopening of the orchestra pit;
- reduction of seats in the platea by about 35%;
- reduction of seats in the galleria by about 30%;
- refurbishment of all plants and of all interior finishes of the theatre (plasters, stuccos, etc.);
- elimination of the carpets of the galleria;
- elimination of the curtains of the lodges.

The main aim of the restoration project was the conservation of the actual acoustics of the theatre that is considered one of the best in Albania, in terms of acoustic response. At this purpose, in agreement with the design team, the main acoustics issue of the project were:

- the design of the new orchestral pit;
- the design of the new rehearsal open space under the stage;
- the selection of the new theatre armchairs;
- the selection of the new curtains;
- the description of the acoustic requirements of windows and doors.

The main acoustic design efforts concerned the renovation of the orchestra pit that was closed and not used during the last decades. The following indications emerged from the analysis of the measurements results and from the simulations: the side wall of the orchestra pit must be lined in wood, as currently; also the floor of both the platform and the covered part of the pit must be in wood; moreover it was necessary to apply sound-absorbing material in the ceiling of the covered part of the pit, for the increase in the sound pressure level that could characterize this space. It was provided a solution of a panel with three different configurations to modify the acoustic response inside the orchestra pit according to the requirements given by the orchestra director (figure 8).

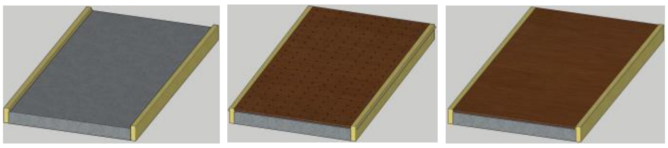

Figure 8 – Left: high frequency sound absorbing panel (not covered by the wood panel); center: low frequency sound absorbing panel (covered by the drilled wood panel); right: sound reflecting panel (when covered by the smooth wood panel).

Also the parapet, that separates the orchestra pit from the platea, has a very important acoustic function, to reflect the sound rays coming from the stage and the pit (figure 9). For this reason, it’s advisable to pay attention to its structure, inclination and material.

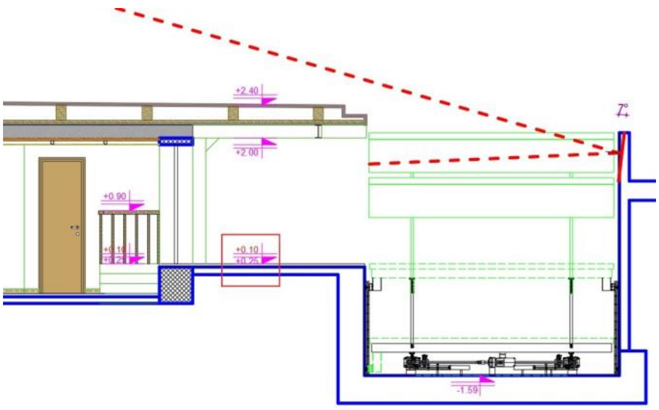

Figure 9 – Design of the parapet of the orchestra pit to improve the propagation of sound from the orchestra pit toward the stage and vice versa.

All existing armchairs will be replaced with others, made on the model of the currently ones present in the gallery, in accordance with Bosio’s original project. New armchairs must not have an equivalent acoustic absorption area (A) lower than the current ones (0.44 m^2 at 500 Hz frequency).

In order to maintain an acoustic response similar to the current one in the lodges, where the curtains will be removed, it was also necessary to insert sound-absorbing panels on the lateral walls inside them.

According to the results of the simulations based on the measurements results described in previous paragraph, the acoustic response of the room was slightly more reverberating at the medium frequencies (figure 10). However, this modification falls within the limits of tolerance and uncertainty of the calculation method and in any case should not alter the acoustic perception in the theatre compared to the current condition.

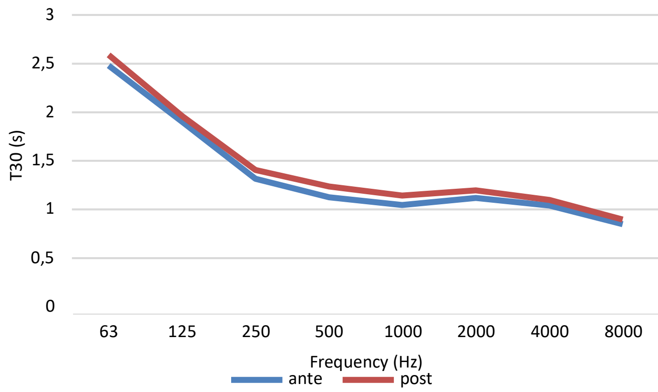

Figure 10 - Comparison of average T30 results before and after the restoration project (simulations).

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The Acoustics of Ancient Theatres

PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

Design of a multichannel audio system based on A²B architecture

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ABSTRACT

The main constraints when designing a multichannel audio system are management and routing of the great amount of data, cabling, and cost. This paper presents the design of an electronic board based on the Automotive Audio Bus (A²B), aimed to realize multichannel audio digital systems. The proposed architecture guarantees a latency of 2 samples, and supports hundreds of channels, making it suitable for any spatial audio rendering technique, such as Wave Field Synthesis (WFS) or Ambisonics.

Keywords – A2B bus; Multichannel Audio Systems; Wave Field Synthesis

1. INTRODUCTION

Spatial audio techniques are gaining popularity thanks to the improvement of signal processing algorithms and availazbility of powerful electronic devices, which are more and more affordable. Spatial audio reproduction systems typically require a high number of loudspeakers to improve spatial accuracy [1], [2], usually at the price of higher electronics cost and bulky wirings, particularly in case of analogue systems. The employment of digital solutions and audio-over-IP technologies [3] simplify the cabling, but it requires expensive devices (such as FPGAs or processors) that contribute to increase the system cost, also from a development point of view. In addition, audio-over-IP protocols typically introduce latency (usually in the order of few milliseconds) which can limit the application field of the system.

This paper introduces an architecture for multichannel audio distribution systems based on the Automotive Audio Bus (A²B) [4]. A²B allows reducing the cost of the system, since the protocol is managed by dedicated low-cost transceivers that do not require software management, but only an initial configuration. In addition, A²B guarantees a deterministic latency of just 2 samples (less than 50 µs at 48 kHz), as well as synchronization between devices.

2. CAPABILITIES OF A²B SYSTEM

A²B is a technology developed by Analog Devices for the automotive field. It is based on a digital bus capable of supporting up to 32 channels (32-bit wide) at 48 kHz, as well as power delivery (up to 2.7 W for each bus) and control over-distance (GPIO and I²C commands). A²B is multi-node: a single bus can be composed by one main node and up to ten subordinate nodes. The maximum distance between two nodes is 15 m, while the total bus length is 40 m. Nodes communicate over an Unshielded Twisted Pair (UTP), which is a low-cost cable. Since the system will be used in the professional audio field, it was chosen to adopt XLR connectors and AES/EBU cables due to their large adoption.

A²B allows reducing the system design effort since the access to the bus is completely managed by a dedicated transceivers developed by Analog Devices. The only required operation at the start-up of the system is a configuration of the transceivers on the bus, which can be performed by a simple and low-cost microcontroller. Even if redundancy is not supported natively by A²B, the technology offers fault diagnostic, by which is possible to identify, localize, and isolate faults, while other nodes continue working. A²B nodes are synchronized on the main node clock, and each node reconstructs its clock from the *superframe* (namely the data packet transmitted on the bus) transmission rate, that is the sampling frequency. Since each node reconstructs its clock from the main node clock, it is important that the clock source is jitter free [5].

For some applications A²B may present limitations, such as a limited cable length and a limited number of channels. Our system overcome these limitations by converting A²B data to other common audio protocols (e.g., MADI, AVB, Dante, Ravenna, AES67 or USB UAC-2) [6], [7]. A block diagram of the system architecture is shown in Figure 1.

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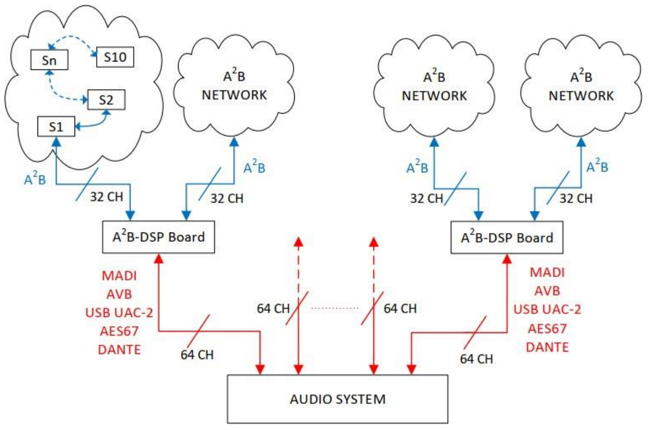

Figure 1 – Block diagram of the system architecture.

The system architecture is composed by three main parts:

- Audio system, such as a mixer or an audio interface.
- Conversion and processing board, namely the purpose-built A^{2}B-DSP in Figure 1.
- A^{2}B networks: each network is composed by subordinate nodes that communicate with different type of devices depending on the application. Some examples are amplifiers, processing units, pre-amplifiers, and microphone arrays.

The A^{2}B-DSP board has two main functions: protocol conversion and signal processing. The board provides the connection to two A^{2}B networks, for a total number of 64 signals, as well as other auxiliary input/output, as shown in Figure 2 and Figure 3.

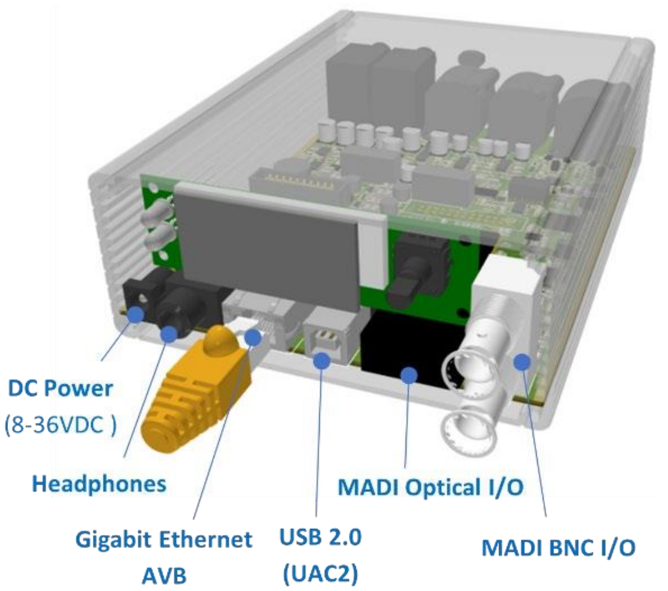

Figure 2 – A^{2}B-DSP connectivity, front view.

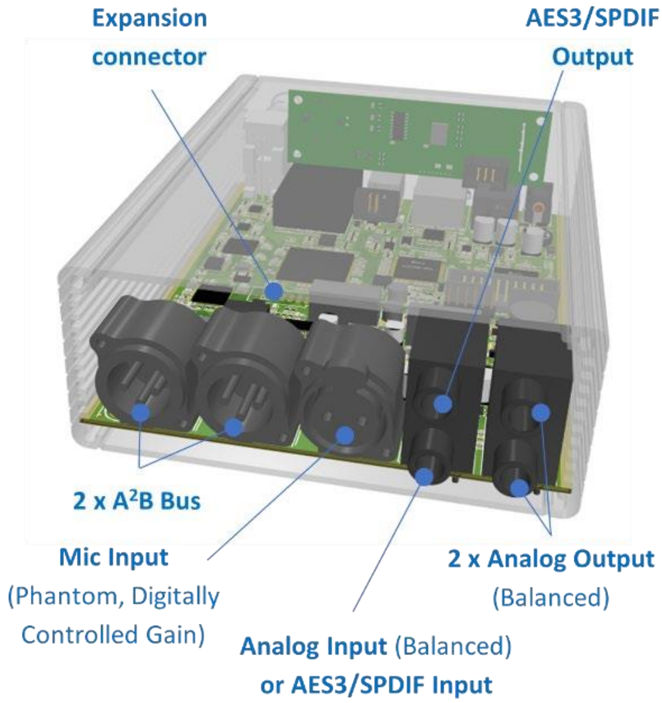

Figure 3 – A^{2}B-DSP connectivity, rear view.

3. FEATURES OF THE NEW A^{2}B-DSP BOARD

The board, shown in Figure 2 and Figure 3, is the core of the proposed A^{2}B system. It allows controlling the system through any general-purpose Audio over IP network, such as Dante, Ravenna, Madi, AVB. An USB interface is also available, even if limited to 32 channels. Additional features of the A^{2}B-DSP board are listed below:

- Two Sigma-DSP processing units, which can be programmed for providing various types of processing.
- An FPGA, which can be used for implementing different communication protocols.
- Two analogue inputs (one Mic, one Line) for performing acoustical measurements.
- Two analogue outputs, for driving loudspeakers.
- Digital AES3/SPDIF input and output.
- Madi Coaxial and Optical bidirectional interface.
- A Giga-Ethernet socket to be used for Dante, Ravenna or AVB digital audio bidirectional connection.
- A robust input power socket, which can accept a wide range of voltages.

The A^{2}B-DSP board was designed from scratch and built in a small pre-series, for being used in several research projects involving the University of Parma, such as PHE – Past Has Ears [8]. A commercial version is planned for 2023 [9].

4. EXAMPLE OF A MULTICHANNEL AUDIO SYSTEM

The presented architecture is particularly suitable for realizing signal distribution in Wave Field Synthesis (WFS) listening rooms. This kind of system requires a huge number of loudspeakers, typically hundreds, that encircle the room. Thanks to the modularity of the proposed architecture, it is possible to build systems of different sizes, which can be adapted to any listening room, from very small ones (e.g., 2×2 m, 64 channels, one seat) to very large one (e.g., 6×6 m, 192 channels, 40 seats). This is achieved just by increasing the number of A^2B-DSP boards, each of which provides 64 additional channels over two A^2B networks.

5. CONCLUSIONS

This paper has shown the benefits of the proposed architecture when employed for audio distribution in multichannel listening rooms. Research on spatial audio reproduction techniques gained popularity, but such systems are still expensive. The presented architecture aims to make them more affordable than other traditional technologies. In addition, it offers a low, deterministic latency and the possibility to develop modular, expandable, and adaptable solutions.

ACKNOWLEDGMENTS

This work was financially supported by Regione Emilia Romagna under EU Commission, project SIPARIO, CUP E91B18000440007, POR-FESR Azione 1.1.2, 2014-20, n. PG/2018/632038.

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Application of a Wave Field Synthesis (WFS) AudioSystem based on A²B protocol: a case study

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ABSTRACT

Wave Field Synthesis systems have been developed with the aim of controlling the sound field in a large area rather than in a small sweet spot, as it happens for traditional solutions. This capability comes at the price of a much greater number of loudspeakers, thus making them suitable for fixed installations only. This paper presents a WFS system based on A²B 8-channel soundbars, resulting in a flexible, portable, and re-configurable solution, thus solving the previously described problem.

Keywords – A2B bus; Spatial Audio Listening Room; Wave Field Synthesis

1. INTRODUCTION

In recent decades, spatial audio playback systems have been extensively studied due to the interest of increasing the immersivity of a variety of experiences, such as teleconferencing, video games for eSports, driving simulators, theme parks and movies and home entertainment. Traditional solutions, such as stereo, Stereo Dipole or Ambisonics, deliver an immersive audio experience in a single position, namely sweet spot.

This paper deals with the design and the installation of a WFS system [1], which overcomes the above limitation. The system is composed by 20 soundbars, each 1 m long and equipped with 8 loudspeakers, for a total number of 160 loudspeakers. Each soundbar is provided with its own power supply and an 8-ch, class-D power amplifier. The audio signals are delivered to the power amplifiers through a digital bus developed by Analog Devices, the Automotive Audio Bus (A²B) [2], which provides optimal features for multichannel audio systems [3]. Such solution has several advantages: a huge dynamic range (thanks to the 24-bits resolution), a latency of just 2 samples (50 µs at 48 kHz), 32 synchronized signals on a single bus line with very small jitter [4]. Furthermore, thanks to the low cost of the A²B chips and the capability of carrying the signals over Unshielded Twisted Pairs (UTP), the cost of electronics and cabling is significantly reduced, especially if compared to analogue solutions, which require digital-to-analogue converters (DAC) and long power cables or audio-over-IP solutions.

2. A²B SOUNDBARS FOR A WFS SYSTEM

A computer feeds the soundtracks of the WFS system through an RME MADIFace XT interface, capable of supporting up to 192 channels at 48 kHz on a USB3 connection. This audio interface provides three MADI connections, two optical and one coaxial. Each MADI connection carries 64 channels, and it is connected to a custom electronic board, named A²B-DSP, which delivers the audio signals to the power amplifiers over A²B bus. Each A²B-DSP board receives one MADI stream and feeds two A²B networks, carrying 32 signals each, which is currently the maximum number of channels supported on a single A²B bus. Finally, on every A²B bus four 8-channels active soundbars are connected in daisy-chain [5]. Since 20 soundbars have been built for this system, it will be possible in the future to expand the system with 4 additional soundbars, reaching the maximum capability of 192 channels.

The soundbars (Figures 1, 2, 3) are made of a birch wood frame and an aluminium plate on the back, for housing the power amplifier (based on the chip TAS3251), power supply (200 W) and connectors. Each soundbar has dimensions 100×19×14 cm (L×W×H) and a total weight of 10.5 Kg. Each of the 8 loudspeakers has its own separate volume of 1.2 litres. With the aim of reducing the standing waves inside the enclosures, they are partially filled with polyester fibre and the rear side of the frame is tilted by an angle of 10° for making the cavity not rectangular. The loudspeakers have an inter-axis distance of 125 mm, resulting in an aliasing frequency of 2.7 kHz (on-axis) and approximately 1.8 kHz

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at 30˚ [6]. The transducers are 4” full-range woofers by RCF, having a nominal impedance of 8 ohm and a sensitivity of 92 dB @ 1 W, 1 m. In Figure 3, it is possible to note the “pass-through” power supply and A^{2}B lines, allowing the soundbars to be easily daisy-chained with short patch cables.

Figure 1 – Front view of a WFS soundbar.

Figure 2 – Rear view of a WFS soundbar.

Figure 3 – Interiors of the electronics compartment.

A stress test was carried out to define the temperature profile of the soundbar (Figure 4). A white noise signal was played through a soundbar continuously for four hours at 100 W_{rms}. The temperature raised up to 62 °C against a room temperature of 26 °C. Then, the rear fan mounted in the electronics housing was switched on, and the temperature dropped to 42 °C in 1h 30’.

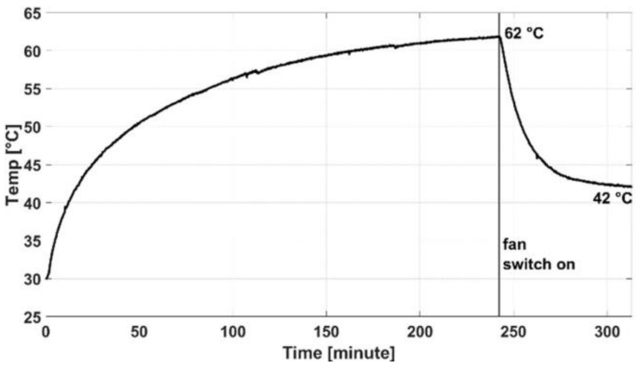

Figure 4 – Temperature profile of a soundbar as a function of time.

A test on the directivity was performed. The soundbar was mounted on a turntable controlled by a PC, in front of an omnidirectional measurement microphone (Bruel&Kjaer, type 4189) located at 1 m distance (Figure 5). An Exponential Sine Sweep (ESS) [7], was played through each loudspeaker, one at a time, for each measurement direction. A total number of 72 directions were measured, by rotating the soundbar with an angular resolution of 5˚, from 0˚ to 355˚. Finally, the impulse responses (IRs) were obtained, by means of the deconvolution with the inverse-ESS. One of the eight resulting sets of polar patterns is shown in Figure 6.

Using an advanced signal processing algorithm, namely Kirkeby matrix inversion, it is possible to calculate speaker equalization filters or synthesize a target directivity [8]. The digital equalization filter allows for a reasonably flat on-axis frequency response, as shown in Figure 7, and it is implemented in real time by FIR filters operated by the DSP units embedded in the A^{2}B-DSP interface.

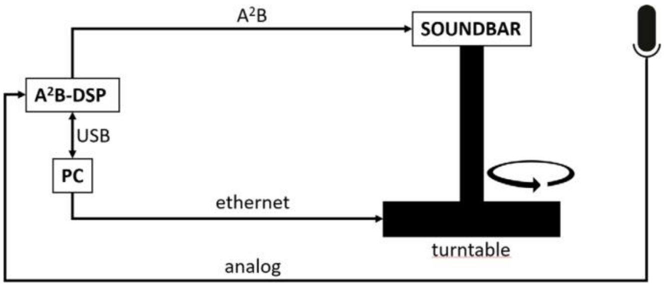

Figure 5 – Scheme of the directivity measurement.

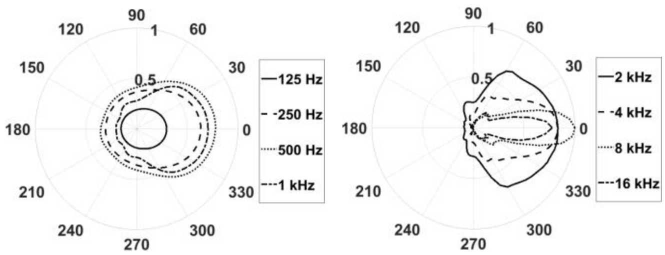

Figure 6 – Polar patterns of a single loudspeaker.

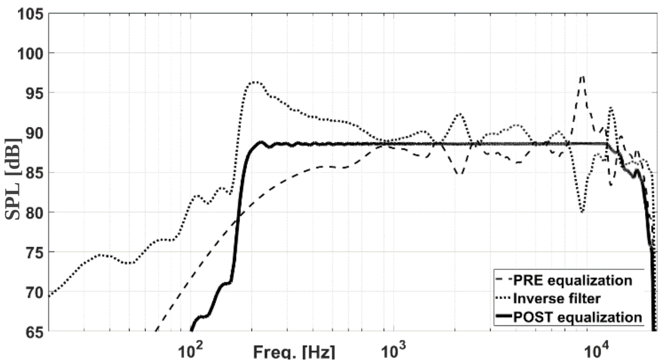

Figure 7 – On-axis anechoic frequency response of anot-equalized loudspeaker (dashed line), a FIR equali-zation filter (dotted line) and the equalized loudspea- ker (solid line).

Finally, the maximum sound pressure level (SPL) produced by a soundbar was measured with an omnidirectional microphone (B&K 4189), located on-axis at 1 m distance. A value of 108 dB(A) was obtained, with all the 8 loudspeakers playing a 1 kHz pure tone at the maximum power.

3. GEOMETRICAL CONFIGURATION

The WFS system was assembled in a square configuration. By exploiting the modularity of the solution, corners have been tilted by 45°, thus significantly reducing the edge effects. The inner area of the system in its maximum configuration is 5.4×5.4 m, for a capacity up to 28 seats, as shown in Figure 8.

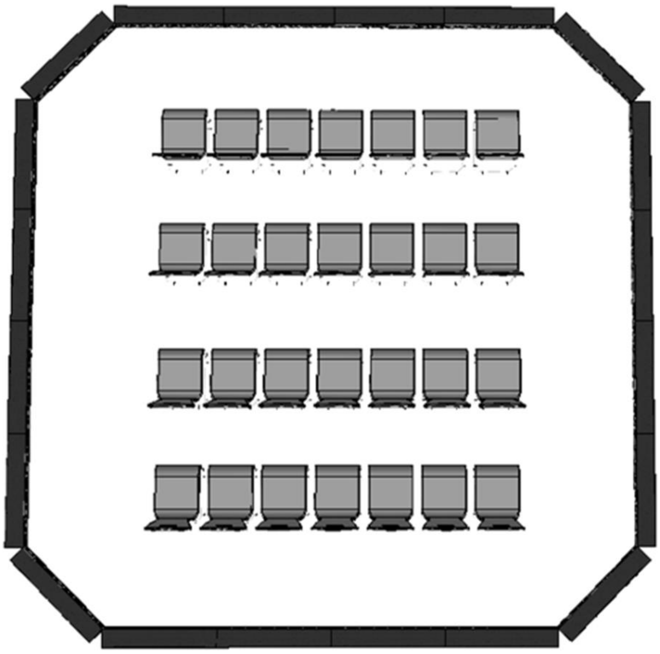

Figure 8 – Soundbars disposition for this case study.

In the facility of the Bologna Creative Hub, Italy, 18 of the 20 soundbars have been installed. A panoramic picture of the system, taken with a 360° camera, is shown in Figure 9.

Figure 9 – 360° view of the WFS system installed at Bologna Creative Hub.

4. SOFTWARE

For generating in real-time the large number of signals necessary for feeding the WFS system, a novel software tool has been developed. It is a VST plugin, called WFSmixer, which allows rendering in real time up to 32 virtual sound sources. Each source can be placed in an arbitrary position, or it can be "animated" with a combination of translational and rotational motion units.

The plugin, developed using Juce application framework, has been built for both Windows-64 and Mac OS systems, and runs smoothly under multichannel host programs capable of high channel counts, such as Plogue Bidule or MaxMSP. The geometry of the loudspeaker array is loaded from a spreadsheet file, containing the XY coordinates of the loudspeakers. Figure 10 shows the Graphical User Interface (GUI) of the WFSmixer plugin.

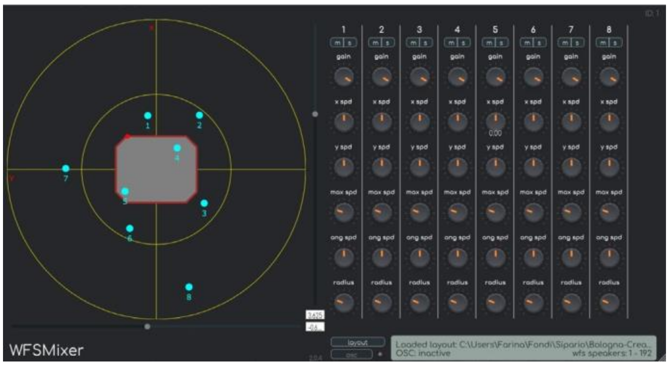

Figure 10 – GUI of the WFSmixer plugin.

5. CONCLUSIONS

This paper deals with the implementation of a modular, reconfigurable, and portable WFS system. Such characteristics have been reached by developing 8-channel active soundbars and adopting the A²B bus, which allows connecting the soundbars in daisy-chain. Moreover, an A²B, full-digital solution allowed for a considerably cost reduction.

The final installation was carried out in the facility of the Bologna Creative Hub, where the presented WFS system is now operating and available to composers and artists.

ACKNOWLEDGMENTS

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Comparison of the 3D acoustics of the Roman performing arts spaces in Pompeii

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ABSTRACT

Within the SIPARIO Project, a project founded by the European Community and lead by the Region Emilia Romagna, a specific acoustic survey has been carried out in the archaeological site of Pompeii. The ancient city includes three different Roman performing arts places: the theatre, the Odeon and the amphitheatre. The surveys have been conducted with different types of equipment: monoaural and binaural microphones, B-Format (4 channels) microphones and 32-channels probe (EigenMike EM32). This paper reports the most important outcomes obtained from the measurements, by including 360° acoustic maps that allow a study and the visualization of the early and late reflections. The panoramic acoustic maps have been compared among the above cited sites, and analyzed with reference to the standard requirements outlined by ISO 3382.

Keywords: SIPARIO Project, Pompeii Roman theatres, Intangible cultural heritage

1. INTRODUCTION

The development of the measuring technologies represents a great help for the researchers who actively attend deep studies on the ancient architectural patrimony. Especially for outdoor environments, the possibility of studying the direction of arrival of the sound rays during the IR is now possible to be achieved as experimented in the archaeological site of Pompeii. Scope of this paper is to compare the acoustic characterization of the Roman theatre, Odeon and amphitheatre of Pompeii based on 360° acoustic maps.

2. HISTORICAL DISCOVERIES OF THE ANCIENT POMPEII

The city of the ancient Pompeii has been taken under the attention of researchers especially after the excavations started during the 17th century [1]. The city has been buried since 79 AC under the lava of the volcano Vesuvius, but the archaeological discoveries allow the appreciation of the treasures of the Hellenistic style influenced by the previous Samnites [1].

Among the performing arts places, in Pompei it is possible to find the Roman theatre, located nearby the Odeon, considered the places for playing musical and prose events, and the amphitheatre located in the opposite side of the city, dedicated to the spectacles performed by gladiators and wild aggressive animals [2].

The Roman theatre of Pompeii had an original capacity of 5000 spectators, distributed across the *ima* and *summa cavea*, separated from the scenic building during the Hellenistic period and unified only by the Romans with the construction of corridors that link both structures, as shown in Figure 1.

Figure 1 – Roman theatre of Pompeii.

The Odeon built on the eastern side of the theatre had the function of playing proses (*odea*). This is the reason why the Odeon was provided with a contained volumetric space to be covered by a roof realised with a limited length of the wooden trusses [3]. The Odeon of Pompeii has a squared plan layout with a *cavea* not divided by horizontal corridors, as shown in Figure 2.

A different shape of a place dedicated for gladiators' spectacles is represented by the amphitheatre, built during 70 BC inside the *Regio II*. The dimensions of the axes are 131 m and 102 m, respectively related to major and minor [4]. The vertical division of the *cavea* in *ima*, *media* and *summa* follows the horizontal subdivision in

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wedged sectors, for a total capacity equal to 20000 spectators, as should be during the Roman Age, as shown in Figure 3.

Figure 2 – Odeon of Pompeii.

Figure 3 – Amphitheatre of Pompeii.

3. ACOUSTIC MAPS

Different campaigns of measurements were undertaken inside the theatre, the Odeon and the amphitheatre to understand the acoustic behaviour of the sound waves inside these specific volumes. The acoustic survey was carried out with the following equipment:

- Equalised omnidirectional loudspeaker (Look Line);
- Binaural dummy head (Neumann KU-100);
- B-Format (Sennheiser Ambeo);
- 32-channel spherical array (Mh Acoustic em32 Eigenmike®);
- Omnidirectional microphone (Bruel&Kjaer)

The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) having a duration of 15 s in a uniform sound pressure level for the range between 40 Hz and 20 kHz.

The employment of a spherical array microphone allows the elaboration of 360° sound maps where it is possible to recognise the interaction of the surfaces with the sound waves, including early and late reflections [5]. The videos have been elaborated based on the receiver position across the *cavea*. The different sound energy has been represented by contour levels of a range of colors going between red tinge and blue-violet shades, representing a high and a poor energy, respectively, which might also depend on the external thermo-hygrometric conditions [6], in a global building analytics perspective [7].

Figure 4 to 6 show the direct sound inside the three case studies above described hitting the probe of the microphone. Whereas the shape of the wavefront is not perfectly round, the presence of wind was the main cause.

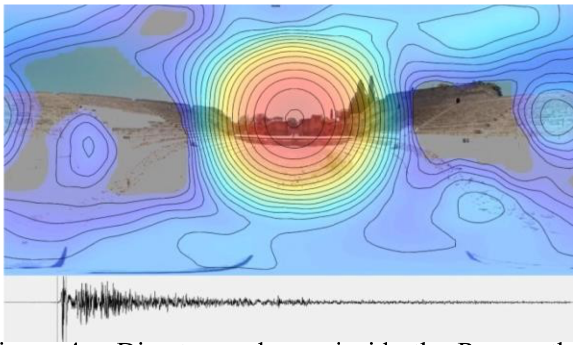

Figure 4 – Direct soundwave inside the Roman theatre of Pompei.

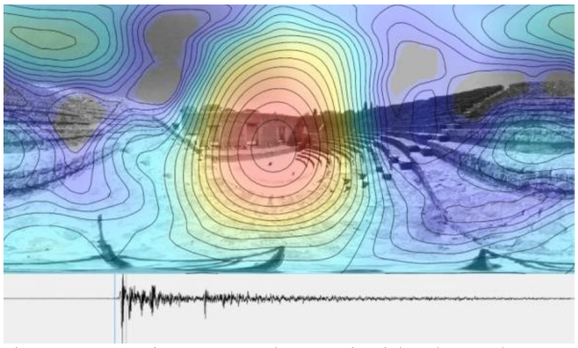

Figure 5 – Direct soundwave inside the Odeon of Pompei.

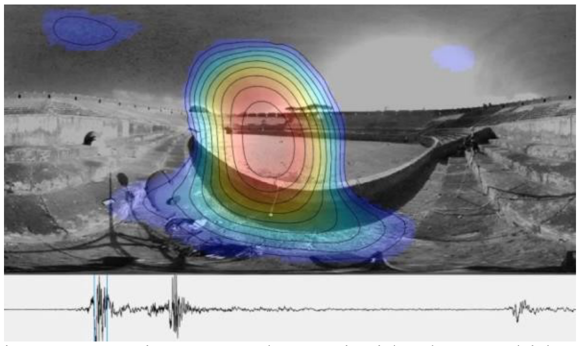

Figure 6 – Direct soundwave inside the amphitheatre of Pompei.

The sound intensity has been processed as contour levels based on a range of colours comprised between red and blue shades, representing a high and a poor sound energy, respectively.

Figure 7 to 9 show the reflection of the soundwaves, bouncing on the marble steps of the *cavea*.

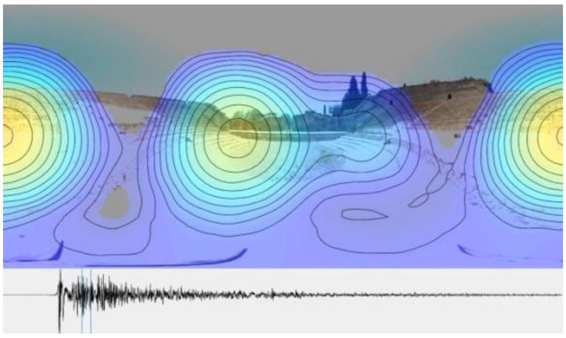

Figure 7 – Reflections inside the Roman theatre of Pompei.

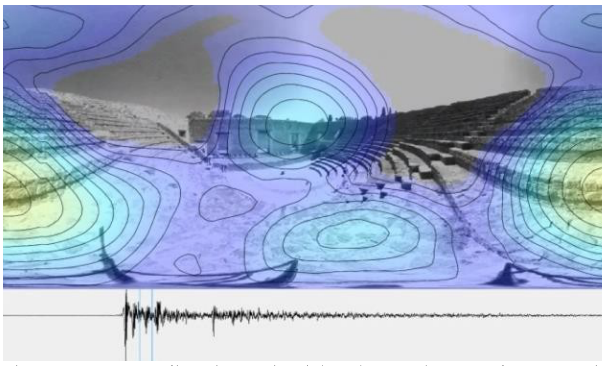

Figure 8 – Reflections inside the Odeon of Pompei.

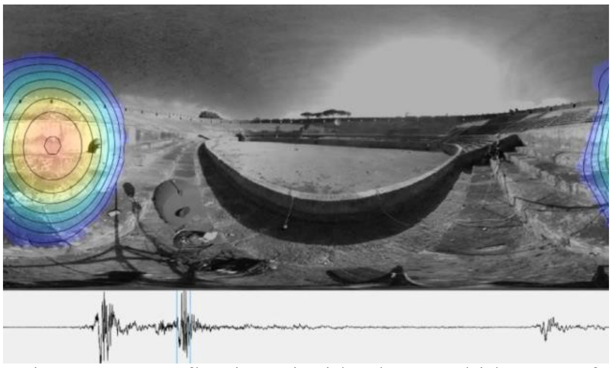

Figure 9 – Reflections inside the amphitheatre of Pompei.

4. CONCLUSIONS

This paper has shown that the innovative technology can help in deeply understanding the acoustics of spaces. The cases indicated in this manuscript are related to open-air performing arts spaces, located in the ancient city of Pompeii. Based on the position of the receiver across the *cavea*, it has been shown that specific architectural components of the room volume can contribute to detect the directivity of the soundwaves due to the uniform distribution of the capsules on the spherical front of the microphone [8].

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The acoustics of the current conditions of the Roman amphitheatre of Avella in Italy

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ABSTRACT
In the ancient Rome, the shows entertained by gladiators were very numerous, due to the always growing request from the spectators. After the disuse of the amphitheaters, a wide number of philosophers, writers and poets have described the shows performed in these arenas. Nowadays, this type of shows represents a source of inspiration for books and movies. The Roman amphitheaters had an elliptical plan, which allow to enlarge the capacity of seats and to improve the view along the steps of the *cavea*. The development of Christianism established the immorality of the theatrical shows, while the barbaric invasions contributed to convert these places into military barracks, whenever they were not demolished. This study described the acoustic study of the amphitheater of Avella, found only a few decades ago by archaeologists. The geometrical characteristics of this amphitheatre are typical of other Roman ones built in Campania during the Imperial age. An acoustic survey is described to understand better the acoustic parameters and discuss its current possible usages.

Keywords: acoustic measurements; amphitheatre; Avella; arena; elliptical plan.

1. INTRODUCTION

The word "amphitheatre" refers to a specific place elected to undertake events, where the spectators could assist in any position, meaning that they could stay all around the action. This is one of the reasons why the amphitheatre has an elliptical shape, enlarged from the circular geometry to increase the audience capacity.

Due to the importance of the gladiators' shows during the Classic age, Romans attributed a specific building type to these performances. The amphitheaters were erected mainly in the areas most prosperous of the Roman Empire, such as the Province of Campania in Southern Italy. The most elegant amphitheaters of this region have been built in Capua and Pozzuoli, to be second to the Coliseum in Rome for capacity and dimensions.

Based on archaeological excavations, Capua, Liternum and Cuma, all in Campania, are considered the first three amphitheaters, erected in stone during the 2nd century BC, in order to replace the previous temporary construction in wood [1].

Few decades later, during the 1st century BC, the amphitheater of Avella was built on top of structural walls belonging to the residential properties of Samnites. Nowadays, this amphitheater is located within a green belt of 300 m distant from the current town of Avella, and will be the object of this study.

2. HISTORY OF THE OLDEST AMPHITHEATER

The amphitheater of Avella has been used for the gladiators' shows other than for the hunting of fears, although it is believed that sometimes the arena was filled with water, allowing the sportive races by boats.

The amphitheater of Avella has a typical elliptical geometry, having dimensions comparable with the amphitheater of Pompeii. The arena was covered by sand and was surrounded by the steps of the *cavea*, subdivided in wedged sectors. The existing ruins consist of structures made of a technique called *opus reticulatum*, and of tuff cover sheets preserved in the *ima cavea*, as shown in Figure 1. Historical sources document the presence of an ambulatory (*ambulacrum*) above the whole cavea, but unfortunately this structure has been lost [2].

The dimensions of the main axes of the arena are equal to 62 m and 35 m, smaller than the amphitheaters of Rome and Capua. Avella was located on the road connecting Naples with Brindisi, two important ports placed respectively on the west and east coast of the Italian peninsula.

Figure 2 shows the view of the amphitheater of Avella, with main dimensions.

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Figure 1 – View of the amphitheater of Avella.

Figure 2 – View of the amphitheater of Avella, with main dimensions.

Figure 3 – Amphitheater in present state during the acoustic measurements

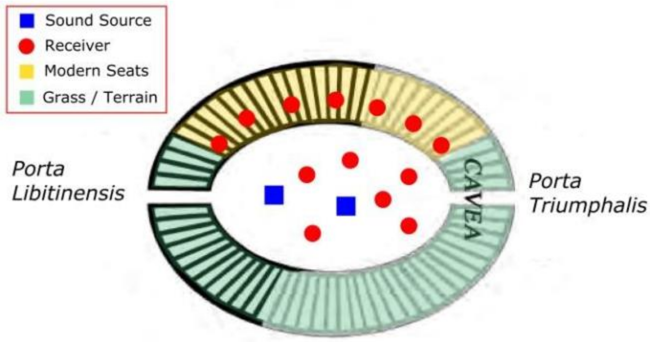

Figure 4 – Measurement positions.

3. ACOUSTIC MEASUREMENTS

Acoustic measurements have been carried out inside the amphitheater of Avella by using firecrackers as impulsive sound source, which is provided with a good signal to noise ratio (S/N) to be outdoor. A Brahma microphone has been used as a receiver. Figure 3 shows the amphitheater during the acoustic measurements.

The sound source was placed in two positions in the arena, while the microphone was moved in the *cavea*, specifically across the modern seats, and also in the arena, as shown in Figure 4. The choice of taking the survey in the *cavea* only where the modern seats are installed is due to safety reasons established for this archaeological site.

The calibration process of a digital model consists of a loop procedure of room acoustic modelling to increase the accuracy of the simulated results. As such, the absorption coefficients have been tuned based on the measurements undertaken in situ [3-5].

By analyzing the recorded impulse responses (IRs) with Dirac software package, a strong late reflection can be detected as an echo. This phenomenon is due to the geometry of the amphitheater and to the length of its axes that determine the temporal delay of the echoes.

4. ACOUSTIC RESULTS

The results of the main acoustic parameters have been assessed in accordance with ISO 3382-1 and compared with the measured values of the amphitheater of Pompeii, having similar dimensions. Figure 5 to 8 show the values of EDT, T_{30}, C_{80} and D_{50} in the octave bands between 125 Hz and 4 kHz. Figure 5 shows that the value of EDT related to Avella are more uniform across the spectrum than in Pompeii, where a down deep at 500 Hz has been recorded. Over the other octaves, the values are very comparable between the two amphitheaters, fluctuating around 1.5 s, which is good considered to be unroofed spaces and like other Roman amphitheaters [6, 7].

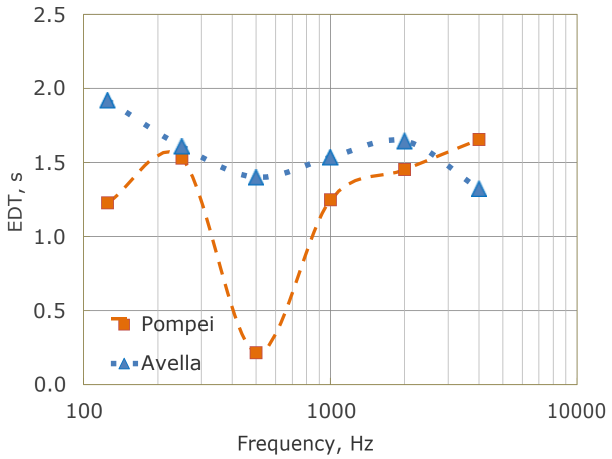

Figure 5 – Measured values of EDT.

Figure 6 shows also the values of T_{20}, which have been found to be around 1.5 s across all the spectrum in relation to Avella, while the measurements in Pompeii recorded T_{20} values to be around 2.1 s at 125 Hz and fluctuating around 1.4 s at mid-high frequency bands [8].

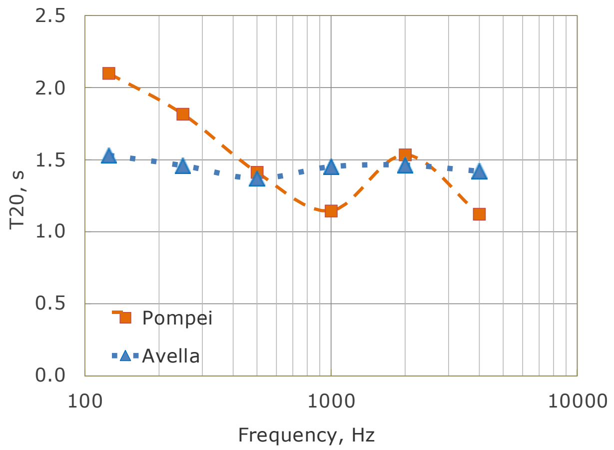

Figure 6 – Measured values of T_{20}.

Figure 7 shows that the values of D_{50} are very similar between Pompeii and Avella, especially at 125 Hz and 4 kHz, fluctuating around 0.75 if considered averaged across all the spectrum and having a soft peak at 500 Hz. This means that the definition of speech is good in both amphitheaters [9,10].

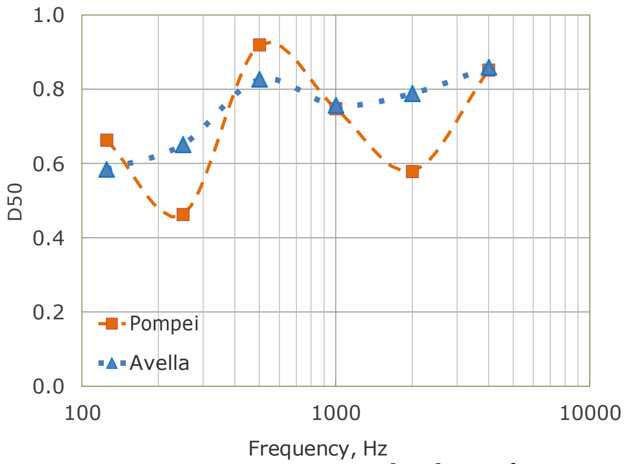

Figure 7 – Measured values of D_{50}.

Figure 8 indicates that the measured values of C_{80} are all more than 0 dB but above the upper range limit set for a good music listening (i.e. +2 dB), although these results have been found to have similar characteristics in other Roman theaters and amphitheaters. It shall be noticed the similar curve trend in both spaces, showing a soft peak at 500 Hz to be equal to 9 dB in Avella and 11 dB in Pompeii.

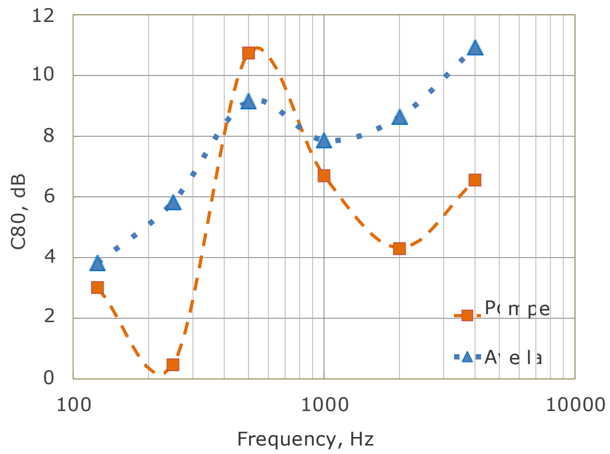

Figure 8 – Measured values of C_{80}.

5. CONCLUSIONS

The archaeological sites have always been investigated under an architectural perspective throughout the centuries. It was only during the second half of the 20th century that the amphitheatre of Avella has been discovered. This paper presents the acoustic measurements undertaken inside the amphitheatre of Avella.

The analysis of the measured results highlights a good reverberation time, suitable for potential acoustic shell that would be inserted for live musical events.

The clarity index has been found to be above the threshold limits but comparable with the results of other Roman theatres and amphitheatres.

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Soundscape of historical sites

Design retrofitting on an ancient amphitheater by combined room acoustics and soundscape methodologies

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ABSTRACT

Several charters of renovations propose methodologies of rigorous restorations on archaeological sites. in Greece, the legal framework results in interventions of minimum footprint. The present study was carried out in the Ancient Greek amphitheatre of Dimitriada (294-292 BCE) of Volos, Greece. Regarding the stated condition, the selected site was comprehensively evaluated by combining two main studies: (1)An in-situ room acoustic analysis was performed to calibrate the acoustic response of the three-dimensional model. The reverberation time durations and intelligibility of speech criteria are evaluated as these emerged from the suggested spatial interventions (Scene, Proscenium, Kilo, Epitheatron) of the rehabilitation scenario. (2)A soundscape analysis of the site presents how the traffic noise from a road adjacent to the site is regularly masking the voice signal within the amphitheatre area but also masking sound signals and sound markers from the surrounding suburbia. Correspondingly, the soundscape analysis interacts with the architectural rehabilitation decisions concerning the introduction of new spatial interventions at the Kilon and the Epitheatron. The assessed results show that a multidisciplinary study of the acoustic qualities of an amphitheatre site with the combination of the soundscape notion and the room acoustic analysis is capable of providing more precise rehabilitation scenarios for architects.

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The acoustics of the recently excavated Larissa Theatre A

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ABSTRACT

The work describes the acoustic properties of one of the two ancient theatres that existed n the city of Larissa, in Thessaly in central Greece. The first was initially excavated in 1910; since 1977, a more systematic project has been initiated to expose and preserve this monument. This theatre was initially built in the first half of the 3rd century B.C., within the ancient city at the foot of the fortified ancient acropolis. The theatre consists of the orchestra having a diameter of 25.5m (compared to 20m for Epidaurus), the cavea is divided in 11 sectors each with 25 tiers of seats and a partially preserved stage building is also in existence.

The work, presents a first record of the acoustics of this monument based on in-situ measurements based on: (a) an omni-directional microphone to derive the acoustics parameters of the Theatre and (b) with a binaural dummy head to derive the binaural responses and allow subsequent virtual soundscape auralizations. The results of these measurements are also compared to other ancient Theatres.

Keywords: ancient theatre acoustics, acoustic measurements, excavations

1. INTRODUCTION

The First Ancient Theatre of Larissa is the largest Theatre in Thessaly, having a capacity of 10,000 people. It is located in the city centre of the modern city of Larissa, in central Greece and was constructed in the first half of the 3rd century BC. In period, it was located at the southern foothills of the hill "Fortress", where the ancient city's fortified Acropolis stood. An earthquake in the late 2nd century or early in the 3rd century AD destroyed the second floor of the scene, the Doric entablature and a part of the transcendent epitheatre. Almost its total destruction was induced by a second strong earthquake that occurred in 7th century AD[1].

According to long-time head of the Ephorate of Antiquities and the monument's excavator, the archaeologist Athanasios Tziafalias, [2,3] the theatre had a lifespan of six centuries, from the early 3rd century BC until the late 3rd or early 4th century AD. During the first centuries, apart from theatrical performances, the assemblies of the senior regional authority were hosted, the so called "Koinon" of the Thessalians. In the 2nd c. BC the Romans converted it into an arena, reserved for the official celebrations. Subsequently, the theatre was gradually buried, notably so after the 1868 earthquake.

In the early 20th century, the then Ephor of Antiquities Apostolos Arvanitopoulos began excavations that revealed part of the scene ("skene"). After the Second World War blocks of flats constructed directly on the theatre's surface, which during the 1980's were compulsory demolished so that a gradual unearthing began that lasted until the mid-2000s.

Several monuments from different eras were found in close proximity to the Theatre, such as the smaller second ancient Theatre, the basilica of St. Achilles, etc, evidence to the city's continuous habitation throughout the centuries.

Today, the First Ancient Theatre of Larissa (Fig. 1) has been unearthed almost in its entirety. Its cavea ("koilon") is built on a natural hill side and is divided by the diazoma, a 2 m wide corridor, into the main theatre and the "epitheatron", the cavea's lower and upper section respectively. The main theatre was divided by 10 staircases ("klimakes") into 11 cunei, where each cuneus ("kerkida") consists of 25 rows of seats ("edolia"). When the theatre was converted to an arena, the three first rows where removed and their marble seats where repurposed to retain the upper rows. To this day, only a small part of the epitheatron is preserved. The orchestra has an estimated diameter of 25m and is surrounded by a closed conduit, the "evripos" that runs under the foundations of the eastern and western rooms of the scene building. The retaining walls ("analLimata") are maintained in excellent condition, although still not fully unearthed.

The Scene building ("Skene") is one of the best preserved and perhaps the most luxurious of the few examples of this category of Hellenistic buildings that survive. It is pre-served in situ, retaining numerous architectural elements of the colonnade that forms the Proskenion, and the

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drystone masonry that forms the side rooms. The Proskenion is made of marble and the rooms are made of limestone and marble blocks without the use of mortar. The stones' origins are traced in the ancient marble quarry of Kastri (Melfos V., 2010) and limestone quarry of Tirnavos (Melfos V., 2011). Throughout the centuries several architectural elements, especially limestone blocks were removed and used as building materials, and can now be found in nearby historic buildings of the early Byzantine and Ottoman eras [1].

2. MEASUREMENTS

2.1 Measurements

The first set of acoustic measurements followed the approach of previous work in the ancient theatre of Epidaurus [5]. The measurements' positions are placed in three different rows and in three different angles 5^0, 45^0 and 85^0. An additional set of 5 measurements was conducted on cunei D since this section retains the most well preserved seatsthough those measurements are not presented and analysed in the current work. A list of the positions is given in Table 1 and in Fig. 1. In Fig. 2 there it is shown the measurement equipment during the preparation of the measurements.

These measurements should be considered as preliminary, as the restoration of the main theatre - by means of repositioning ancient and installing new seats - is not yet finished and in front of the skene, there was an obstacle (a crane truck of 8x2.5x1.6m used for lifting the marble seats, in the scope of the restoration works). Although this crane was placed about 4m from the skene façade and the sound source was about 8m far from the truck, another set of measurements is scheduled after the restoration is finished.

Three types of measurements were conducted: (i) via an omni free field microphone for calculating the acoustical parameters (ii) via a binaural head for calculating IACC and for further virtual auralizations and (iii) via a Sound Pressure Level meter for direct measurement of the sound pressure level differences and the ambient noise. The sound source was producing white noise signal of 100dBA at 1m. Table 2 gives a list of the equipment used for the measurements.

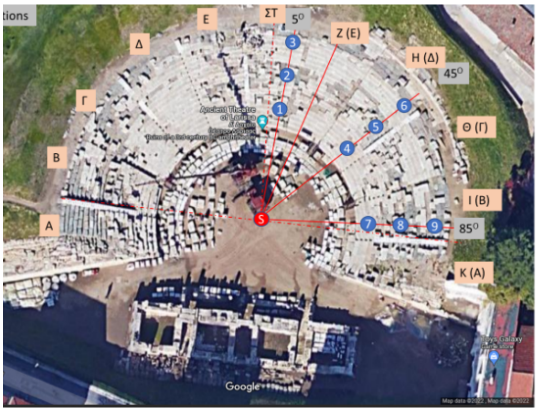

Figure 1 – Top view of the theatre showing the measurement positions (blue dots) and the sound source position as the red dot [6]

2.2 Ambient Noise

Since the theatre is located in the centre of the city of Larissa and behind the skene which is below the ground level, there are many taverns and cafeterias which were closed at the time of the measurements. However, noises were present from passers-by and wind, affecting mostly measurements at the upper positions, near the hills' top. The wind gusts mostly affected the binaural measurements since as the rest of the microphones were equipped with wind shields. In general, the SNR of the measurements is greater than 30dB.

Table 1 – Measurement positions

Position	Distance (m)	Angle (deg)	Row (number)
R1	20	5	5th
R2	25	5	12th
R3	30	5	17th
R4	20	45	5th
R5	25	45	12th
R6	30	45	17th
R7	20	85	5th
R8	23.5	85	11th
R9	27	85	15th

Figure 2 – Preparation of the measurement setup. It consists of the KEMAR binaural dummy head, the omnidirectional microphone and the SPL meter.

Table 2 – Measurement equipment

Item	model
Sound card	RME Babyface
Free Field mic.	PCB 377A40
Binaural mic.	G.R.A.S. KEMAR
SPL meter	NTi Audio XL2
SPL Meter mic.	M2210
Sound Source	Mackie Thumb 15BST
Calibrator	G.R.A.S. Type 42AB

3. DATA ANALYSIS & ACOUSTIC INDICES

3.1 Single channel responses

The free field measurements were performend using REW [7] software and a log sin. sweep signal of 10sec duration [8]. The sound source was set at 100dB at 1m for a 1kHz sinewave. The recordings were at 44.100Hz and subsequently the responses were exported using a Half Hanning window of 3 seconds. The measured impulse responses (IR) *h(t)* were imported to Audacity [9] for analysis and calculation of the Acoustics Parameters, using Aurora Acoustical Parameters available in Aurora plug-ins package [10].

The acoustical parameters calculated are, D50 (%), C80 (dB), STI/RaSTI and frequency response, as presented in the following sections.

3.2 Calculation of the acoustical parameters

The Acoustical Parameters are calculated in accordance to ISO3382 [11] as also mentioned in [10].

The Definition index for speech signals (D50%) is defined as:

$$D50(\%) = \frac{\int_0^{50ms} h^2(\tau)d\tau}{\int_0^{\infty} h^2(\tau)d\tau} 100 \qquad (1)$$

The Clarity for music C80 (dB) is defined as

$$C80(dB) = 10\log\frac{\int_0^{80ms} h^2(\tau)d\tau}{\int_{80ms}^{\infty} h^2(\tau)d\tau} \qquad (2)$$

The RaSTI index is defined as:

$$RaSTI = [S/N + 15]/30 \qquad (3a)$$

Where S/N is the signal to noise ratio defined as:

$$S/N = 10\log\frac{\int_0^{95ms} a(t)p^2(t)dt}{\int_{95ms}^{\infty} p^2(t)dt} \qquad (3b)$$

Where *α(t)* is the contribution of the signal to the measured sound pressure level and *p(t)* is the measured sound pressure level.

The STI is calculated using the Modulation Transfer Functions method described in [12].

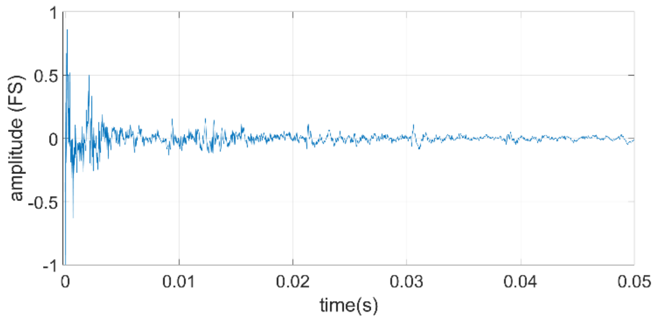

Figure 3 – Typical IR for position R1(first 50ms)

3.3 Binaural responses

The Binaural impulse responses were recorded using Audacity [6] and processed using the Aurora plug-ins utilizing the Binaural dummy head option for the analysis [7]. The excitation signal is a sign sweep of 10s duration at a sampling frequency of 44.100 Hz.

From the binaurally recorded impulse responses $h_L(t)$ and $h_R(t)$ the normalized Interaural Cross Correlation (IACC) was evaluated as:

$$\Psi_{yl,r}(\tau) = \frac{\int_{t=-\infty}^{+\infty} y_l(t) * y_r(t+\tau)dt}{\sqrt{\int_{t=-\infty}^{+\infty} y_l{}^2(t) * \int_{t=-\infty}^{+\infty} y_r{}^2(t)\,dt}}$$

with the internal delay τ, and left and right sound pressure signals, $y_l(t)$ and $y_r(t)$[13].

4. RESULTS

4.1 SPL vs distance

Figure 4 presents the measured SPL reduction with distance. The variation of SPL with distance is comparable to that measured for Epidaurus [5], noting that here the measurements were restricted to the maximum distance of 30m as opposed to the longer distances for Epidaurus (almost 60m to the far position).

4.2 Acoustic Indices

4.2.1 Clarity and Definition

As can be observed from Figs.5 and 6, both Clarity and Definition were found to be exceptional and independent of distance and angle.

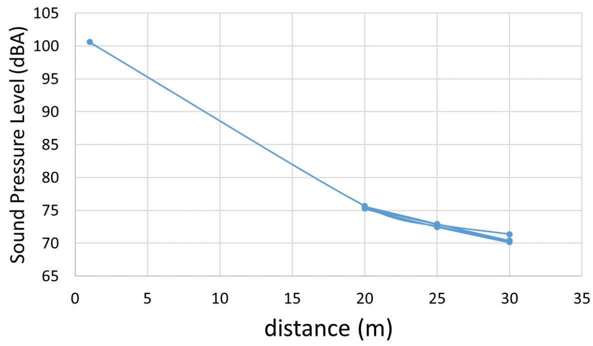

Figure 4 – SPL vs distance measurement

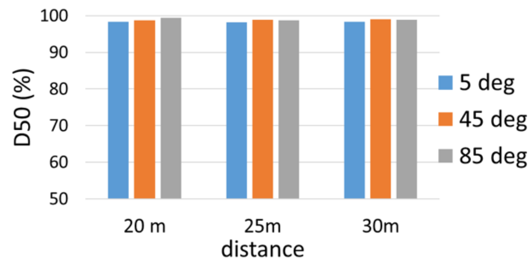

Figure 5 – D50 (%) for the measurement positions.

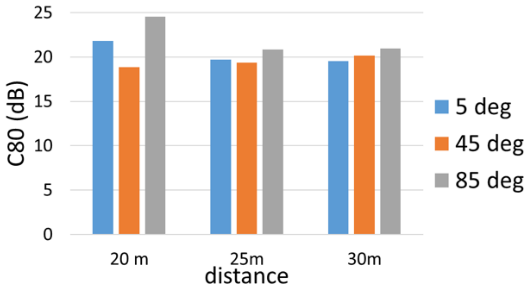

Figure 6 – C80 (dB) for the different measurement positions.

4.2.2 Speech Intelligibility

Speech intelligibility is predicted to be excellent and largely independent of distance or angle. For the longest measured distance, intelligibility is even slightly improved, a result of the higher contribution from reflection / diffraction from the lower tiers.

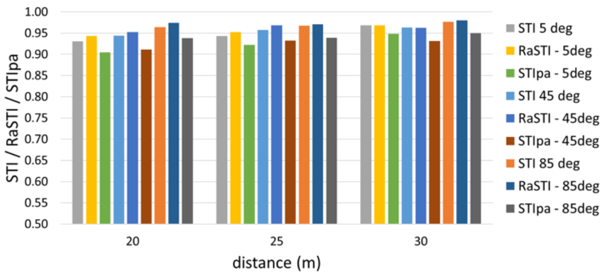

Figure 7 – The various Speech Intelligibility Indexes for the different measurement positions.

4.3 Frequency domain analysis

4.3.1 Response spectra

The response in Fig. 8 shows a rather more even characteristics than other measured theatres. The typical dip around 180Hz (due to the orchestra floor reflection) is present but the dominant peak around 1KHz is still present but rather less prominent than the spectra measured in Epidaurus [5].

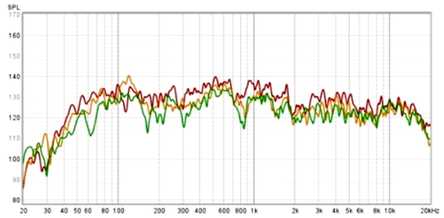

Figure 8 – Frequency responses for the 3 different angles and the nearest positions (R1-R4-R7).

4.3.2 Clarity for speech vs frequency

Figure 10 shows the mean clarity for speech (C50) over frequency for three different distances from the sound source. It is obvious that this parameter does not vary significantly with the position and even for the far away positions, the clarity of speech is expected to be at very good level

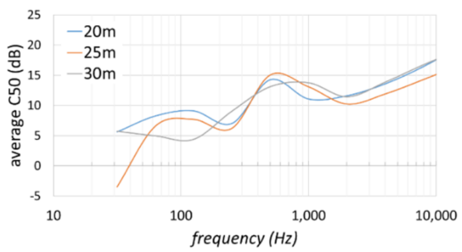

Figure 10 – Mean C50(dB) versus frequency for the same angles and for the different distances

5. CONCLUSIONS

The Ancient theatre of Larisa A, after its recent unearthing and ongoing restoration was thoroughly measured here and provides evidence for brilliant acoustics for speech transmission. Although the theatre is placed in the centre of a modern city, the background noise did not affect the acoustic performance of the theatre.

This first measurement session produced data from free field microphone and a binaural dummy head, able to fully characterize the acoustics of the theatre and create virtual auralizations. Measurements are also planned for a latter stage of the on-going restoration to record the acoustics of a fully restored cuneus and scene of the theatre.

ACKNOWLEDGEMENTS

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Digital Humanities in the Historical Soundscape Research: Sound of 18th Century Naples

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ABSTRACT

The historical soundscape is a timely research topic and arouses interest in the fields like history, architectural acoustics and urban musicology. While the approaches in these disciplines are diversified in themselves, the latest phenomenon of digital humanities suggests more holistic attitudes to the subject. Can these novel digital methods help us to give a satisfying answer to the popular questions of sound history? How might the past have sounded, or is it possible to hear past sounds? This study tries to show that problems like lack of adequate historical evidence or poor quality of digital reconstructions are likely to be solved at a certain level with the advancing digital humanities technologies. A brief review of the available digital humanities methods that can be applied to the historic soundscape research is provided. It uses natural language processing, digital mapping, acoustic modelling, and extended reality techniques to trace the soundscape of 18th century Naples.

Keywords: historical soundscape, digital humanities, virtual acoustics

1. INTRODUCTION

This paper describes the steps of a digital reconstruction study on the historical soundscape of 18th century Naples. It is based on a series of digital humanities methods dedicated to each step of the reconstruction work and includes a sound source seeking game on an interactive 2D map to encourage users to experience the 3D spatial sound reproduction.
Since the advent of computational acoustic modelling techniques [1], it has been applied to historical buildings in architecture, and in a number of studies, their acoustic features have been the subject of study [2-5]. This resulted in raising awareness on the cultural value of acoustics of the historical spaces and led to the born of the "acoustic heritage" notion [6] unless it has been assessed as a part of "intangible" heritage in the current literature [7]. On the other hand, the developments in the last two decades in computation technology which is reflected in physically-based rendering and acoustic modelling approaches in the meantime, have provided the possibility to calculate dynamic acoustic scenarios. Contrary to former static calculation softwares, this novel approach of Virtual Acoustics, which can include multiple mobile sound sources and give the receiver the possibility of moving in 6DoF [8], opened new ways of working with acoustic heritage. Henceforth, not only the ceremonies held in sumptuous palaces, or the masses in parish churches, soundscapes of the public events or acoustics of urban squares can also be studied with the digital methods [9].

2. METHODOLOGY

Inherently, working with the historical soundscape and study of building acoustics differs on several accounts. Since the only way of hearing past sounds is passing from the reconstruction studies, digital recreation of historical soundscapes necessitates more grounded strategies. We embrace it in four main stages; acquiring historical data, sampling, auralization/reproduction and representation. This approach of historically informed soundscape, which was detailed in [10], can be applied to the several cases. All the steps can be accelerated by applying the latest digital humanities methods. Earlier applications of text analysis on historical data acquisition, 3D spatial sound design for auralization and virtual reality for representation were applied to the case of 18th century Naples in this study. The daily soundscape of Naples's historic centre was reconstructed on a 2D interactive map as a sound sources seeking game.

The flowchart, seen in Figure 1, was followed starting from a sample archive composed of a limited number of historical sources from/about the period. A summary of this application is presented in the following sections.

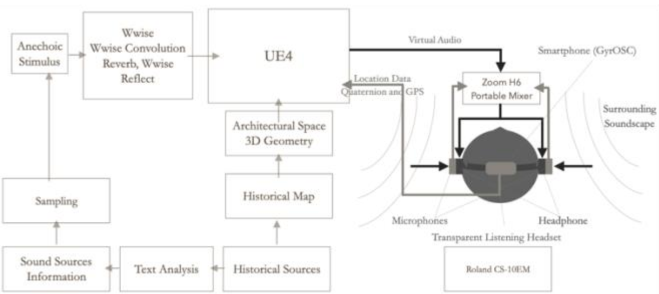

Figure 1. Application flowchart

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3. HISTORICAL SOUNDSCAPE RECONSTRUCTION

3.1 Historical Data Acquisition / Text Processing

Gathering evidence for historical soundscape has always been a complex and labouring process. The earwitness accounts have become one of the featured sources for historical soundscape studies over the years [11, p. 8]. The traveller accounts, diaries, guidebooks, royal, vice-regal diaries, ceremony records, notarial archives, music books, journals, and a few used the visual sources as well. Among this large number of archival sources, the difficulty and slow data acquisition are the humanities' common and major research challenges.

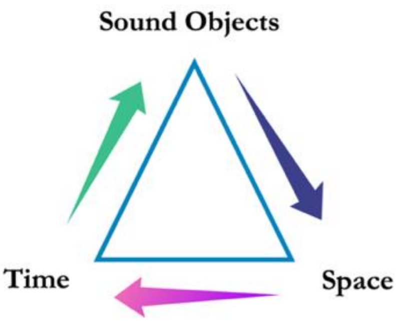

Figure 2. Historical Soundscape Elements

Historical soundscape data acquisition comprises three major parts; (1) Time, (2) Space and (3) Sound Object-Event. Three parts of this triangle seen in Figure 2 must be scrupulously scrutinized to lead reliable soundscape reconstructions. Linking the historical sources to crosscheck is of capital importance. In such cases, some interpretive steps can be taken as well. The information for the sampling and the architectural plans, sketches and images must be collected and then provided for the auralization process. Not just the type and properties of sound, the entire scenario of the sound event, artistic directives, guides, and instructions for the performances are also required for the voicing-sampling process [10,12].

This study's approach to historical soundscape suggests using text processing methods to determine sound sources of the case period. This way of investigating all historical records entails working with not only a straightforward case book or books; it requires extensive databases constituted by hundreds of books from several libraries and collections [13]. Only by this way can more reliable results be obtained by discovering interconnectedness of several sources, and only this way each part of the historical soundscape triangle (time, space and sound objects) can be discovered deservedly. Considering that creating such a database is out of this project's scope, the application was applied to a selection of historical records for 18th century Naples as a case study. Some of the primary visual sources were also analyzed with these textual sources. GATE, a Natural Language Processing (NLP) toolkit, is used for text analysis. It is an open-source toolkit for text processing and allows to write a simple keyword-based information retrieval application for historical soundscape instead of struggling with the major challenges in NLP like machine learning or natural language understanding. One of the most effective solutions for information extraction is to use keyword-based gazetteers by considering ontologies and helpful classifications. We took advantage of the source-oriented structure of historic soundscape research. We generated a gazetteer, a very basic and popular approach used to find the occurrences of entities such as cities, countries, geographic names of places, organizations, companies, through a list containing names of these entities. The application for historical soundscape research was prepared in GATE with its other ready-to-use components/processing resources oriented to complete different tasks at each phase of the analysis.

As a result of the application, some of the most cited sound sources were determined. As expected and in line with the analysis on visual sources, vendors, horse carriages, horses, and dogs are shown up as most mentioned urban sound sources in textual sources too (see. Figure 3).

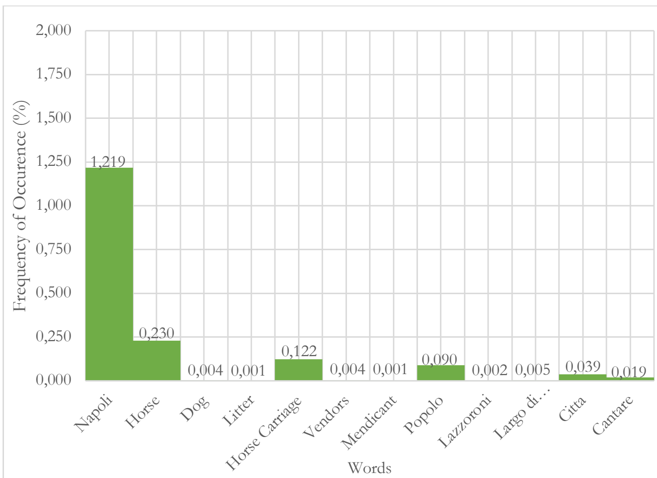

Figure 3. Frequency of word occurrences analysis for some of the soundscape elements

The analysis here was focused on the sound sources of the entire period instead of a more detailed focus which could have been place and time specific. But that analysis was left to the future works. Besides, even it is not mentioned in this short paper, the sampling process, especially recording human sounds of the period, is of significant importance for having authentic sound reproductions. We had the support of stage actors and singers in this stage where we tried the follow the tendencies in the early music.

3.2 Spatialization / 3D Spatial Sound

After having unearthed all necessary information on sound sources and providing necessary directives for the performation, human sounds were recorded in anechoic chamber and environmental sounds were recorded in the situ or recordings from online sound databases were used when needed. Later on 3D architectural space was modelled in the game engine (UE4) based on a historical map of the period, and sound sources were placed according to the created scenario.

Basically, some market points were determined to place vendor cries, and the churches were identified to locate church bell as sample sounds to create 3D sonic environment. Vendors, horses and dogs scattered around the square and horse carriages were directed to the palace. A group of singing people were placed at the corner of a street connected to via Toledo. Eventually, auralization was done through an audio middleware (Wwise) designed to provide 3D spatial audio for game engines. The used sound engine for this sound reproduction includes several calculation methods. The details of these methods and the performance of analysis of the middleware are provided in [14].

3.2.1 Sound Reproduction System and Head-tracking

The auralization can be presented to the users in various ways. The conventional listening practices with the headphones isolate the listener from his/her acoustic environment. In addition, sounds are traditionally produced for a fixed source and specific receiver positions specifically in the music industry. This way of virtual audio listening created its own aesthetic norms with the stereo, and the music production sector strongly promoted it because it is easy to mix translation across all stereo systems. However, contrary to standard stereo based audio production, virtual (binaural) audio provides the listener with 6 DoF movement, namely all basic ways of a rigid object can move through 3D space. This approach promises a more natural mode of listening and give a chance to the audience to discover acoustic space freely.

In the case of using HMDs, motion tracking is done by the sensors of HMD, but when the traditional DAWs are used, or the concept of augmented audio is followed, motion tracking has to be provided with some external sensors. In this study, thanks to the OSC networking protocol, the location and rotation info were gathered from an OSC messaging application (GyrOSC) which is developed to work on any smartphone running IOS operating system, but applications developed for Android mobile operating system or any device/sensor that can send OSC messages can also be used. The information gathered from the sensor is transmitted to the game engine, and auralization is calculated in real-time regarding user position in the 3D environment for each frame.

3.3 Representation / Interactive Map

The map used to represent 3D spatial audio was the Zannoni's map of Naples, as it existed in 1790. It is designed as an interactive map to serve as a useful guide helping users find their way in the 3D space of a historic environment.

Figure 4. Giovanni A. Rizzi Zannoni "Pianta della Città di Napoli Come Esiste nel Presenta Anno 1790"

The user's movement and head orientation were represented on the map with a player icon, as seen in Figure 5. The motion on the map was restricted with bodily movement, which is a key to finding one's way and to get closely acquainted with the acoustic space. Whether digital or real, the bodily movement contributes to the sense of being there. As Niall Atkinson emphasized, "way-finding" is a fundamental way to "knowing one's self in relation to others and to a common identity." [15, p. 178]

Figure 5. Graphical User Interface of the Application

Originally, the game engines's first person template was used to create 3D environment and to place sound sources. Then the historical map was generated with the help of widget blueprints, which serves to create GUIs. The minimap concept, which has been used in most of first-person games, was used to create the map to represent all game objects over by marks. The point of player and the point of interests (sound sources in this case) were added to GUI as an overlay. The options for users to choose whether they want to use the application with or without GPS, rotation sensors, and background sound were presented in the game intro. A profiling survey was added to the game intro as well.

The application is designed to work for different scenarios in-situ, remote, with or without sensors. The users can walk around the virtual environment by using W-A-S-D on the keyboard to walk for a specific direction, mouse to change head orientation and mouse scroll wheel to zoom in and out. At the end, the application was formed as a full screen, and a sound seeking game was included. During the game, users try to find the location of the historical sound sources by following their ears. If they press the "F" while thinking that they are in the 8 meters range, the sound source appears on the map and becomes visible as found sources and player-source distance is saved to calculate user game points. The success of sound localization of the system will also be assessed in future through the controlled tests with the help of total wasted time and average user game points.

As mentioned, the quaternion data flow for head orientation and the GPS data flow for user's location were included in the game. But then the preliminary test showed up used smartphone's GPS sensor accuracy (2-5m in best conditions) was not at the expected level to conduct this kind of study successfully. Therefore, GPS is provided as an option. The user can set the right condition for the game play through settings tab in the game intro GUI. It is possible to choose one sensor only, as using the map with head rotation sensors to change game character's head direction, W-A-S-D keys can be used for bodily movements.

A video record of the game play was provided in the [16], and a study on the perceptual assessment of the application was also planned as future steps.

4. CONCLUSIONS

The early approach here to the text processing method within the historical soundscape concept is promising, thanks to the research's object-based target. Similar research on olfactory references is under investigation in the project of Odeuropa [17].

The study showed that we might reconsider our approaches to digital audio design techniques that have changed fundamentally in the last two decades. The traditional channel-based, static stereo sound will give way to object-based 3D spatial audio entirely in the not too distant future. To place the sound sources into three-dimensional Euclidean space not just helping to create physically based environments, it is also more appropriate for the presentation of non-spatialized sound samples.

As a result of this application, it is possible to say that interactive HIS maps are an effective way to study historical soundscapes. Using historical maps increases the perception of the reconstruction as historical, and as conceived by Tim Ingold "they resemble storytelling than map-using". They are considered condensed histories. Not just sound sources, other related historical information can be considered in the same way rather than using static GIS. The high integration capacity of VR with its standard or graphical coding features brings an infinite number of possibilities to light.

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Ancient theatres as part of the soundscape of contemporary urban fabrics: The A' Theatre of Larisa.

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ABSTRACT
During the process of urban development in Greece a part of the A' ancient theatre of Larisa was revealed. Today, after several expropriations and support frameworks, the theatre is fully excavated and partly reconstructed. Recently, an International Open Ideas Competition was launched for the urban regeneration of the surrounding area and the enhancement of the theatre's value and function. This paper discusses the contemporary soundscape, competition axes and urban design approaches.

Keywords: ancient, theatre, soundscape.

1. INTRODUCTION

During the process of urban development of Greek cities in the mid- 20th century, the construction procedure revealed a palimpsest of the cities' history, a layering of materials and structures. In Larisa, a part of the A' Ancient Theatre of the city was revealed during the construction of new residential buildings. Today, after several expropriations, two Community Support Frameworks and research sub-projects, the theatre is fully excavated and partly reconstructed.

Aiming to introduce the theatre to the public, not only as a monument but also as an active cultural landmark, an International Open Ideas Competition was launched in 2021, to reconsider its reflection on its surroundings and the wider central area. The objectives of the competition included monument connections, enhancement and enrichment of the theatre's value, functional issues for its operation and landscape design.

This paper presents the A' Ancient Theatre of Larisa, it discusses the contemporary soundscape by overlaying noise maps, sound sources that rely on land uses, urban design approaches, as part of an overall investigation in the fields of soundscape planning, urban design, architecture and noise control that could be considered in similar cases, establishing the cultural significance of the monument, incorporating it in the city's contemporary social life and facilitating its use for performances.

2. ESTABLISHING THE CASE STUDY

2.1 Background information

In many Greek cities that date back to the ancient times construction procedures in the last century provided information of previous eras, a palimpsest of their history translated into a layering of materials that led the researchers back to the classic - Roman times. The palimpsest of Thessaloniki is widely discussed, especially in relation to the present construction of the underground. Similarly, in Larisa, the fourth largest city in Greece, a part of the A' ancient theatre of the city was revealed - namely a part of the koilon- during the construction of a new residential building in 1968. The new building was erected, despite the Ephorate of Antiquities' opposition and, after several years of discussion, the expropriation was completed in 1979, and the building was demolished in 1981. Today, after two Community Support Frameworks and several research sub-projects the theatre is fully revealed. Recent studies have investigated its potential regarding the cultural and financial development of the city and school education and it is important for the authorities to consider all parameters for its optimum use.

However, its position in the city center, next to high rise buildings can result in inappropriate for its use acoustic conditions, while commercial activity and nightlife of the area increase background noise.

How can the theatre be used for performances again while all city functions remain untouched; Is it possible to limit background noise and allow for optimum conditions of speech intelligibility?

In an attempt to open the theatre to the public, not only as a monument but also as an active cultural landmark, an International Open Ideas Competition was launched in 2021, to "reconsider the theatre's reflection to its surroundings and the larger central area" [1]. The objectives of the competition include carving the city's character to establish a fresh identity, con-

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nections between the theatre and other important landmarks, establishing a new attraction, landscape design, enhancement and enrichment of the theatre's value as a landmark and functional issues for the theatre's operation - namely organisation of paths, entrances / exits and supporting spaces. The competition participants were provided with a considerable number of maps, plans, elevations and technical reports. However, no mention has been made to the function of the theatre that should take into consideration the acoustic conditions, the land uses of the surrounding area, existing noise maps and future noise control, the evolving city's soundscape that continuously changes during the day and night.

2.2 The palimpsest of the A' Ancient Theatre of Larisa

The A' Ancient Theatre of Larissa, at the north-eastern part of the Thessalian plain, near the banks of river Penaeus (Pinios), was inhabited, developed and reconstructed at the same location for many centuries. The reuse of the constructing material during the reconstruction phases was common. As an immediate consequence, public buildings, markets, temples and the city walls were dismantled. Only a few monuments have survived, including the two ancient theatres [2].

The A' Ancient Theatre of Larissa lies on the slope of Frourio hill (or "Fortress" hill) coinciding with the fortified citadel of the ancient city, and one of the prehistoric Neolithic settlements on which the oncoming city was based on and evolved. The ancient city being surrounded by Pinios developed only towards the south and east of the citadel, since the north and west sides were restricted by the river. The A' ancient theatre's construction is chronologically placed in the 1st half of the 3rd century BC. It is one of the largest ancient theatres in Greece, with a 10.000 audience capacity, and it is suggested that it also served as a public place of gathering of the Thessalians.

The theatre accommodated events until the 4th century A.D. Following the construction methods of that period, the koilon was initially formed on the hillside, later covered by marble. It was divided by the diazoma to the main theatre, consisting of 24 rows of seats and the epitheatre, consisting of 11 rows [3]. The orchestra, measuring 25,50m in diameter, was initially covered by marble and later by soil to accommodate Roman fights. The stage building, which is relatively well preserved, can be associated with four construction periods during the ancient times.

The theatre underwent various design stages and modifications, due to earthquake activity (3rd and 7th century A.D.). The lowest part had already been buried until the Byzantine years. In the late years of the Ottoman Empire, a large building or a complex of buildings had been erected on the theatre's territory. Seats of the ancient theatre were used as a building material for its construction. Up to 1985 the theatral area was covered by contemporary constructions and was essentially bisected by two main streets, Al. Papanastasiou str., north to south, and Venizelou str., east to west.

After 17 centuries of the city's development in layers above the theatre (residential buildings and roads), in 1910 and 1968 preparations for the foundations of new buildings revealed parts of the skene and the koilon respectively. By 1985 the NE part of the theatre had been revealed, whereas the south and west remained under other constructions. Between 1977 and 2008, after several expropriations, private and public building demolitions and street abolishment, the epitheatre's area (traces of which no more exist), the skene, the western and eastern entrances (parodoi), the latest leading through a pathway to the B' Ancient Theatre, were found [4]. Marble seats used in their infrastructure were discovered and transferred to appropriate places. Recently, the Central Board of Antiquities of Greece approved the restoration of the theatre – initially the koilon to its later architectural phase (arena), and later the retaining walls, the stage building, which is the best preserved part of the monument, and the accessibility [5]. Figure 1 illustrates the plan and section of the theatre in its present condition, compared to the initial.

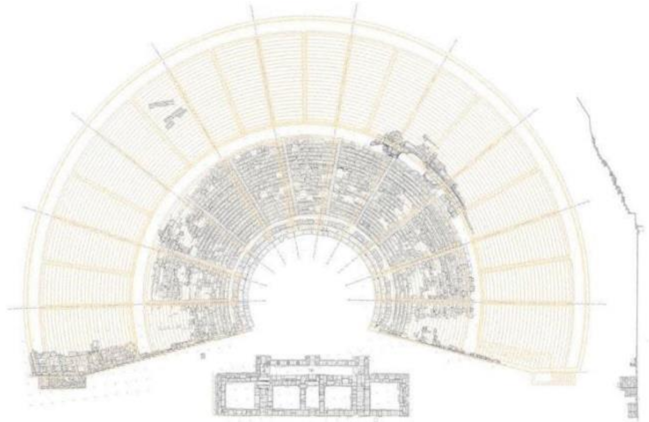

Figure 1 – Plan & Section of the A' Theatre of Larissa.

3. CONTEMPORARY USE OF THE THEATRE

3.1 Fields of research on ancient theatres

Building heritage is a multidisciplinary field of study, involving history, social science, architecture and engineering.

Since the revival of ancient drama in the 20th century many ancient theatres have been excavated, investigated and restored. Research has revealed the effectiveness of their architectural evolution on the acoustics [6]. The process of the skene's evolution enabled conventional use during the dramatic performance and changed the focal point from the orchestra to the stage, allowing for further enhancement of the actors' voices due to relative source-receiver heights. In some cases, the theatre's restoration was accompanied by appropriate architectural and acoustic interventions to ensure optimum visual and acoustic conditions during their contemporary use. Studies have indicated the contribution of ephemeral scenery, designed and applied to the theatres for performance purposes to replace missing stage buildings, to the soundscape of ancient theatres, either positively or negatively [7], [8], and [9].

However, although scenery application can activate the acoustic capabilities of an open-air theatre, an important factor for the acoustic quality of many ancient theatres was low background noise, important for the unassisted speech to be audible. Contemporary conditions – theatres situated in Greek cities or nearby busy roads – imply the necessity of an acoustic treatment to ensure optimum conditions during performances [10]. Recent research on European cities has indicated the significance of the soundscape approach for the preservation and promotion of cultural heritage [11], where appropriate architectural and urban design can contribute to the overall experience and comfort, depending on the uniqueness of each theatre, its position, construction characteristics and background noise.

Regarding the A' ancient theatre of Larisa, apart from the architectural quality, evolution and restoration process, it is important to discuss its position within the urban fabric, mainly in terms of the acoustic environment; and consequently, to develop guidance for its contemporary use.

3.2 Soundscape analysis

The city is a place of coexistence of many different social groups, a synthesis of architectural forms, deriving from different sociopolitical circumstances over the centuries. Identifying and studying the independent elements that form the collage of urban space can lead to understanding the development and function of the city [12], based on the context, background, prior experiences, familiarity with the place, so that each person constructs a different image of the city. According to Lynch [13], grouping these images reveals common elements that emerge as characteristics of the city. He distinguishes five types of elements that constitute its structural features (paths, edges, districts, nodes and landmarks), the interrelations of which determine the clarity of the city's 'imageability'. Similarly, as previous research has indicated [14], one can identify such elements of the urban fabric associated with auditory perception.

The acoustic environment of the urban fabric surrounding the theatre was investigated through the collection of the latest noise maps [15] and the use of the sound map technique, as a research tool from Amphoux's 1st approach, sound memory [16]. Figures 2 and 3 present the overlapping of the two illustrations, namely the noise maps that present the Lden and Ln and the sound map that focuses on the land use that characteristically provides different sound sources for day and night. As expected, linear sources act as boundaries / axes and omni-directional sources provide distinct features to the sound environment. Size of symbols reflects intensity of phenomena. Traffic noise prevails (Lden>70dB that exceeds 75 at crossroads - Ln>60-65 dB), forming strict boundaries at the perimeter, intruding the area where no building boundaries exist. At this end, an important decision by the municipality to demolish the two building blocks marked with black at the south will increase the impact of traffic noise at the area. Some of the competition design proposals include new city tower landmarks (1st prize) or sheds replacing these blocks, that would reduce traffic noise propagation but at the same time create visual obstacles for the view of the theatre.

Figure 2 –Lden map with overlapping sound sources.

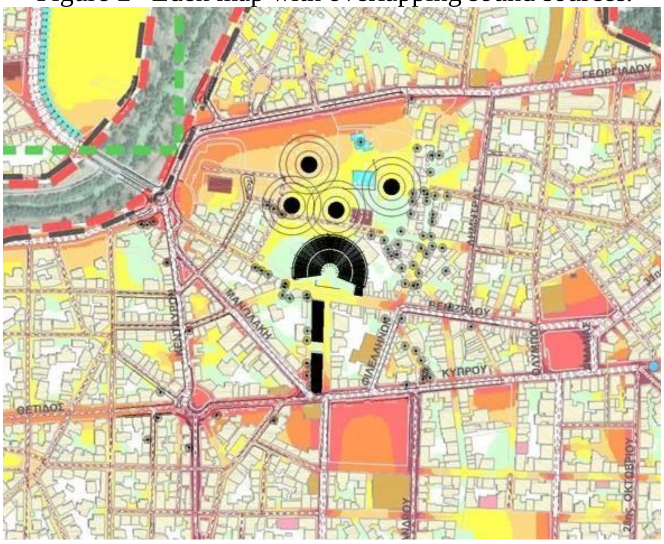

Figure 3 –Ln map with overlapping sound sources.

Pedestrian roads surrounding the theatre present lower values in Lden and Ln (56-60 and 45-55 dB respectively), while the Lden and Ln at the theatre is above 50-55dBA and 40-45dBA respectively. It needs to be mentioned that these noise maps (created in 2014) present residence as the prevalent land use surrounding the theatre. Since then, the city has evolved and, apart from its commercial life, the recreational quarter (cafes, restaurants, bars etc.) has moved from the city centre to the eastern and northern parts of the theatre, as indicated by the omnidirectional source symbols. In total, 69 bars and restaurants are located in this area, out of 82 that can be found at this part of the city, all of which mostly use their outdoor space. Additionally, as can be seen in Figure 3, the area at the top of the Frourio hill is the new “meeting point” (symbolised by the large sources), mostly occupied by traffic noise during the day (Lden>60dB – since there is a difference in level from the main road), but also characterized by natural sounds of birds due to the thick tree foliage), accommodating several thousands of young people between 7pm and after midnight during the summer. A recent urban installation created a promenade and resting points at the linear pathway at the tangent of the epitheatre area.

Another important factor that controls the soundscape of the area of the theatre and its surroundings are the building shells that function as sound reflectors. This could be altered by the architectural treatment of building surfaces [11]. The analysis presented in this paper will be further investigated through future soundwalks and the application of the Swedish Soundscape Quality Protocol (SSQP) [17].

4. CONCLUSIONS

Considering the wider theatre area as surrounded by road axes, one can easily distinguish three areas: the high density building area at the east, where commercial uses and leisure are mostly concentrated, the open area at the top of the Frourio hill that provides a vibrant and rich soundscape at the north, fluctuating in level and sound source categories, according to the season and time, and an urban environment, concentrating commercial, leisure, administrative, educational and similar functions at the south and west. The distinction coincides with the spatial distribution of existing land uses.

Overall, establishing the cultural significance of theatre as a monument and ensuring its operation, requires an interdisciplinary study that will reconsider the impact of the surrounding land use on the soundscape, apply urban design decisions for monument connections and architectural design for building treatments. Only when the basis of its functionality is set, the acoustic simulation of its current condition and the layout of its restoration can be carried out to suggest further improvements and scenery design applications.

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The effect of lightscape on soundscape perception in historical sites.

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ABSTRACT
A combined protocol for lightscape and soundscape assessment was tested in four historical locations along Via dei Fori Imperiali (Rome) to identify whether changes in lighting conditions influence the acoustic perception of urban settings with historic value. Objective data were collected at each location while participants filled the questionnaire for both acoustics and lighting. Although acoustic parameters showed little variation between lighting conditions, perceptual changes were observed.

Keywords*:* soundscape, lightscape, perception

1. INTRODUCTION

The way people experience an environment is affected by external inputs at a physical (e.g., acoustic, visual, thermal) and perceptual (e.g., the feeling of belonging to it, of being happy in it) level at the same time. A main drawback related to the studies conducted so far, especially as far as the physical environmental factors are concerned, is that they are not considered and evaluated in combination. Focusing on the acoustic and lighting domains, much has been done so far, but separately[1]–[5], particularly with the approach of lightwalks and soundwalks to analyse key points or landmarks of the environment quantitatively. However, assessing the acoustic and lighting appropriateness of a place in such a way may fail to recognize the importance of perceptual implications. To this aim, Radicchi & Henckel [6]proposed a method to combines lightwalks and soundwalks for the evaluation of the perception of cities in the night-time. Calleri et al. [7] investigated on the influence of acoustics and lighting on the perception of safety and social presence, which resulted to be improved particularly in presence of background music.

With this shift to a multi-domain approach, a few recent studies [6], [8] explored the use of acoustics and lighting in the environment to the aim of protecting and enhancing the cultural landscape, which is intended as the combination of cultural heritage and territorial context. The perception of cultural landscape in the daytime and in the night-time was shown to be profoundly different. Therefore, this work tests a combined protocol for lightscape and soundscape assessment focusing on the premises of the cultural landscape. A light- and soundwalk was carried out in the area of Colosseum and Fori Imperiali in Rome, where subjects were askedto fill-in a survey on acoustics and lighting perception.

2. METHOD

The study aims to define and test a first draft of a procedure to identify subjective and objective correlation among the acoustic and lighting aspects that influence how people perceive a specific environment.
Over the last few years, several studies have demonstrated how the same environment can induce different perceptions if the surrounding conditions change, in terms of sound and light[6].

2.1 Site Description

The Colosseum area was chosen to test the procedure proposed. The site could induce a wide variation of visual sensations, due to its relevance on rich cultural and historical context and its change of surrounding conditions, such as the designed lighting for night-time. This well-known archaeological site is located in the city centre of Rome. It is situated within a restricted traffic zone (Fori Imperiali area) at its southern border.

Figure 1 shows the route followed during the walk and the locations where the measurements were taken for the sound/lightwalk. In the area under investigation and its proximity, traffic is limited to public transport and emergency services, as well as non-motorized vehicles and pedestrians. The locations were visited twice, under day and night conditions from CL2 to Pven. Subsequently, for each location, there are two sets of questionnaires and measurements data available. Only Pven location was investigated at sunset time therefore these data were not included in the analysis.

2.2 Participants

Forty-six students aged between 19 and 52 years (M=24.9; SD=7.2) voluntarily participated in the study (26 women and 20 men). All participants provided informed consent and research was carried out in

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accordance with the ethical requirements approved by BSEER Ethics Committee at University College London (UK).

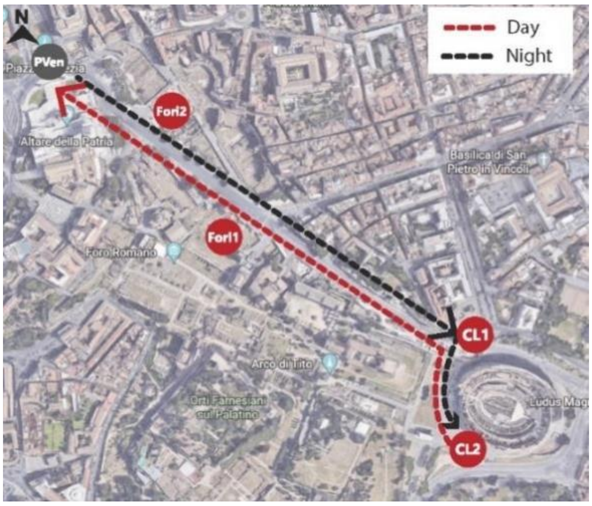

Figure 1- Colosseum archaeological area. Dashed lines show the sound/lightwalk path, red line shows the starting direction (from CL1 to PVen) and the black line the return path (PVen to CL1).

Participants were recruited through an introductory webinar to address the main issues and the whole procedure in a group discussion. During the webinar, key concepts in soundscape and lightscape theory were addressed, as well as the protocol of the walk to be conducted on site. Items of the questionnaire were discussed to have a common understanding of their meaning and provide consistent perceptual data. This approach was already proved to be viable[4].

2.3 Data Collection

The binaural recordings and lighting measurements were carried out in April 2021, between 18:30 and 21:00 hours. Due to the COVID-19 pandemic, there was a lockdown policy in Rome with some restrictions for public activities. However, sound/light walk was still allowed to take place. The sites of the case study are usually quite crowded, but the lockdown implemented at the time of data collection provided an opportunity for a relatively controlled experimental setting less influenced by people's presence Social presence in a given area has indeed been suggested to affect several perceptual constructs, such as soundscape, visual quality and perceived safety[7], [9], [10].

2.3.1 Questionnaire

The questionnaire protocol was developed based on the instruments from literature, and internal discussion among the authors. Most soundscape-related items were taken from Method A of the ISO/TS 12913-2018 on soundscape [3]. The Soundscape descriptors for the "Historical settings" category were adapted from different sources in literature, with a focus on soundscapes of cultural heritage value [11], [12]. Similarly, the Lightscape descriptors, Light sources and Lightscape quality categories were adapted from previous sources in literature [1], [7], while the items of Lights for colours and materials category were defined during a workshop session in the context of the project of this study. The questionnaire was translated in Italian before the sound/lightwalk.

2.3.2 Sound and Lighting

During the data collection campaign on site, a non-participant operator performed binaural recordings wearing a head-mounted kit. In order to assess how humans experience the acoustic environment, binaural acoustic measurements (2 mins each) were carried out, as per the Annex D of ISO/TS 12913-2:2018[3], using a Head Acoustics SQobold with BHS II. Simultaneously, photometric measurements were taken at each location at 1.6 m of height (only illuminance was taken at floor level). Participants were guided to the scene where the photometric measurements were taken.

3. RESULTS

The analysis of the data was completed for each location using the total number of responses from participants. Data was grouped by location and by day/night periods. Incomplete data was eliminated from the analysis. The resulting dataset was processed in IBM SPSS Statistics Version 27 (statistical significance at $p < 0.05$). Differences between lighting conditions were tested via Mann-Whitney tests. The lighting analysis of subjective and objective parameters will be reported in separate publications.

3.1 Objective Parameters

The difference (difference=daytime measurement - night-time measurement) of the psychoacoustic objective parameters measured in each location for both lighting conditions (daytime and night-time) did not change significantly over time. If the difference in SPL was around and/or lower than 3 dB, it was considered constant as that difference is usually barely perceptible [13]. The only location which had greater changes in dBA psychoacoustic value was Fori 1 (ΔdBA = 6.43).

3.2 Effects of light on soundscape perception

The aim of the study was to investigate the effect of lighting conditions in soundscape attributes perception at historic locations. Mean values of soundscape descriptors were calculated and used for the statistical analysis. Table 1 shows statistical significance in differences of perceptual soundscape attributes between daytime and night-time for each location.

The "Meaningless" attribute from the proposed historical settings had significant differences in three of the four locations, and also changes are positive meaning that responses tend to change from disagree to agree during night-time as can show in Figure 2.

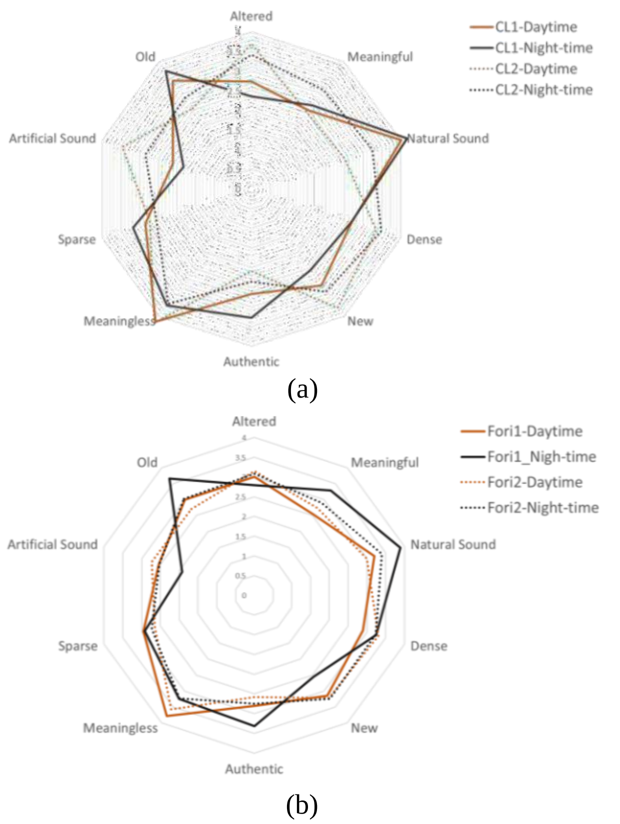

Figure 2. Mean changes in soundscape attributes perception: CL1 (a) and Fori1 (b) are shown in continuous lines; CL2 (a) and Fori2 (b) are shown in dashed lines. Orange lines refer to the daytime while darker lines refer to the night-time.

The distribution of "monotonous" perception scores at CL1 and CL2 between day and night was not similar, as shown in Table 1. For example, scores for CL1-day (mean rank=49.78) were statistically higher than CL1-night (mean rank=38.87), U = 736, z = -2.05, p =.040; while scores for CL2-day (mean rank= 45.64) were higher than CL2-night (mean rank= 33.54), U = 545.5, z = -2.42, p = .015. This may be read to mean that more people thought these two places were more "monotonous" during the day. Similarly, CL1 is considered to be more "meaningless" (p =.027), "newer" (p=.019), and "altered" (p=.011) at night, whereas CL1 is perceived to be more "authentic" (p=.008) during the day.

During the day, location CL2 was rated as "calmer" (p=.008) and "pleasant" (p=.001) than during the night walk. Also, between walks, the counter characteristics "natural (p=.008)-artificial (p=.028)" and "meaningful (p=.008) -meaningless (p=.028)" were significantly different, with CL2 being perceived as more artificial and meaningless during the night. Furthermore, Fori1 results revealed more significant variations in most historic attributes. It was perceived as more "authentic" (p =.050), having more "natural sound" (p =.003), "meaningful" (p =.003), and "old" (p =.030) during the day, and considerably less "meaningless" (p =.023), "new" (p =.025), and "artificial sound" (p =.003) at night.

Table 1. Mann-Whitney U results of soundscapes attributes between two lighting conditions.

Mann-Whitney U test

	Attribute	CL1	CL2	Fori1	Fori2
		p-value			
ISO	Chaotic	0.335	0.082	0.39	0.057
	Annoying	0.827	0.136	0.717	**<.05**
	Monotonous	**<.05**	**<.05**	0.059	0.609
	Uneventful	0.709	0.664	0.236	0.852
	Calm	0.748	**<.05**	0.074	**<.05**
	Pleasant	0.249	**<.05**	0.71	**<.05**
	Exciting	0.172	0.098	**<.05**	0.636
	Eventful	0.363	0.216	**<.05**	0.479
Historical Settings	Altered	**<.05**	0.144	0.347	0.77
	Authentic	**<.05**	0.185	**<.05**	0.405
	Natural	0.499	**<.05**	**<.05**	0.085
	Artificial	0.196	**<.05**	**<.05**	0.338
	Dense	0.979	0.674	0.141	0.791
	Sparse	0.065	0.681	0.941	0.58
	Meaningful	0.622	**<.05**	**<.05**	0.528
	Meaningless	**<.05**	**<.05**	**<.05**	0.199
	Old	0.368	0.287	**<.05**	0.184
	New	**<.05**	0.081	**<.05**	0.804

4. DISCUSSION

This study evaluated the effects that two lighting conditions have on the perceived soundscapes of historical outdoor spaces along with lightscape attributes. A combined set of methods was used for five different locations in the daytime and in the night-time, where participants were asked to rate their sound and lighting perception while parametric measurements were taken. However, only four locations were analysed since location five was only visited during sunset.

The attribute of "monotonous" was reduced in most locations at night, which could indicate that the lighting in these historical locations modified people's perception of sound to be more dynamic or that people are more aware of their surroundings at night.[14]. The sites in the Colosseum, on the other hand, were viewed as more "meaningless" at night. Overall, we were unable to detect a clear influence of changes in lighting conditions on sound perceptions in our investigation, which supports previous laboratory findings[15]. Although, to the authors' knowledge, past research has merged soundscape and lightscape assessments [9], [14], there is still no consensus on the optimum methodology to utilise, and few methodologies have been used. Also, the attributes proposed for the historical context are yet to be supported and tested in more similar environments; considering that past studies[11] have suggested that historical locations could bring additional meaning and values regardless of the designed surveys.

4.1 Future work

To observe whether lighting conditions have an impact on sound perception, future studies should investigate historical environments in exceptionally differentiating lighting conditions (morning vs evening) and soundscapes conditions. Additionally, would be relevant to test whether perception of historical attributes on both light and soundscape change due to personal experiences and/or background.

5. CONCLUSIONS

A combined sound/lightwalk assessment was carried out in order to test whether different lighting conditions affect sound perception in historical environments. To assess both soundscape and lightscape we created and tested a new instrument, where results showed to be a good first approach to record how people perceive a heritage environment. These preliminary findings draw attention to the relation between sound and light in historical locations as these could not only have an impact on people's experience and perception but understanding the relation between these two could be used during planning stages of the surroundings areas of the historical sites, specifically those located in metropolitan areas.

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Research of the Historical Soundscape of the Ancient City of Side in The Light of Small Findings and Architectural Elements

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ABSTRACT

Side is an ancient city located in the Pamphylia region in the Eastern Mediterranean. Due to its location, it has been an important stop for maritime trade and transportation between Greece, Cyprus, Syria, Aegean Islands, Phoenicia and Egypt. The city, which has developed commercial activities, is an important visiting point visited by many tourists today. The revitalization studies on the region mostly focus on the architectural elements in the area. It is seen that there is no study on "sound", which is an important part of understanding past. The historical soundscape of Side, which was an important port city in the past, will be evaluated using archaeological finds. Urban life and sounds of the city were investigated in the light of small finds like those that ceramics, sculpture, etc. and architectural remains. In this study, which aims to create an acoustic base to improve today's tourist experience, academic studies on the region were examined and supported by view of the archaeologists. Within the scope of the study, the soundscape of today's experience route of the ancient city was also evaluated, and determinations and evaluations were made on how it could be improved.

Keywords: Historical Soundscape, Ancient City Side, Small findings

1. INTRODUCTION

Side is one of the important ancient cities in the Pamphylia region in the Eastern Mediterranean. It is also an important port city with connections to many regions such as Greece, Cyprus, Syria, Aegean Islands, Egypt and Phoenicia. Today, this ancient city, which is within the provincial borders of Antalya in Turkey, is an area visited by many tourists every year. The revitalization studies on the field are focused on visual expression. It has been seen that there is no study on "sound", which is an important part of understanding the past.

Sounds are powerful elements tshat give a certain atmosphere. Recreating the historical soundscape is a popular presentation technique. There are many studies in ancient cities and museums where sound is used as an element to augment the experience.[1]–[3] The enrichment of the experience positively affects the visitors opinion who coming to these areas.[2] The use of sound as an element that enhances and enriches the experience is also important in this sense.

In recent years, there have been many studies investigating the acoustic characters of historical areas. Especially the number of historical soundscape studies is increasing day by day. These studies, carried out in historical urban areas, focus on the identification of sounds, which are part of intangible cultural heritage in these areas, and how they are evaluated by the citizens.[4]–[7] In these studies, sources such as interviews with earwitnesses, field archive research, audio and video recordings are used to determine the historical soundscape. Although earwitnesses are the main data source for historical areas[8], but it is not possible to reach earwitnesses for ancient areas. In the ancient period areas, all the data reached are important. The challenge of such areas is the analysis of all soundscapes, from a number of separate discipline like architecture, archaeology, history, urban planning, landscape design etc.[9] The sources provided by all these disciplines should be well identified and evaluated.

In this study aims to find a holistic approach that can be followed in the historical soundscape determination of archaeological sites and to offer a proposal for applications that will enrich the experience in these areas. The ancient city of Side was chosen as the study area. In order to evaluate the area, academic studies on the region were examined and supported by view of the archaeologists. In the study, in which ceramics, sculpture and architecture were evaluated holistically. Within the scope of the study, the soundscape of today's experience route of the ancient city was also evaluated, and determinations and evaluations were made on how it could be improved.

2. METHODOLOGY

2.1 The study Area –Side Ancient City

Side ancient city is an important city of Pamphylia region. Pamphylia is the ancient name of the wide coastal plain that follows the seashore for more than 80 km from around Manavgat to Antalya. The region is surrounded by the Taurus Mountains in the north, the Mediterranean in the south, Lycia in the west, and Kilikia Trakheia, in the east. Due to its location in the Eastern

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Mediterranean, the Pamphylia Region has been an important part of maritime transportation and trade between Greece, Aegean Islands, Cyprus, Syria, Phoenicia and Egypt since early times. Side, a port city, has become one of the most important trade centers in its region thanks to its export goods and slave trade. [10] It is not certain when the rich and crowded city was abandoned. Sources and new research indicate that the city got smaller after the third quarter of the 7th century AD. [11] Greek, Hellenistic, Roman and Byzantine art can be seen together in Side.

Figure 1 – Side Peninsula (URL1)

The city of Side, where many building types and various piece of art can be found, is an area where acoustically different characters and many sounds can coexist.

2.2 Study Aim

The study is a method experiment for determining the historical soundscape in the ancient city. In the study, the importance of a holistic assessment of the historical soundscape is emphasized. Suggestions that will enrich the visitor experience have been researched.

2.3 Highlights in Detecting the Historical Soundscape

There are settlements in the region during the ancient Greek, Hellenistic and Roman periods. First of all, all data should be collected under these periods for easy categorization and understanding. In the studies on historical soundscape detection, first, the sources that we can call objective and subjective about the area were grouped and examined. [12]

The sources that can be considered as an objective source vary for ancient cities. It is not possible to record any sound on the past of ancient cities, information on sound sources is interpreted through the findings. **Objective data sources for ancient cities** include written sources, maps, inscriptions, and all the findings in the city. The structures, statues and small findings related to urban life in the city should be identified.

Small archaeological finds are important data for our understanding of past life. These findings give important information about the functions of the buildings, the life in them and the people who lived there. The material, construction technique and density of the findings provide important information.Small archaeological findings can also provide insight into the soundscape of the region.

Another important issue to be taken into account in the determination of historical soundscape is today's field measurements that will enable us to make inferences from the past. A soundscape of today indeed, it can convey information about the past.[13] The city walls, structures and their features can be the elements that change the acoustics.

Subjective data sources, on the other hand, are mostly people who have ear witnessed the field. It could not discuss such a data source for ancient sites. Although, data about the sound environment of the area and the satisfaction of the people can be deduced from by the ancient authors. Books are used as a source in determining the historical soundscapes.[12], [14] Schafer used novels and sound descriptions in these novels in many chapters in her book.[8]

All these data collection methods mentioned are important sources for historical soundscape detection. In addition, historıcal soundscape studies are done to better understand the past and narrate it to the present. For this reason, today's acoustic environment determinations of these areas are also important. Sounds and situations that may negatively affect the relationship with the history of the area should be identified.

2.4 Highlights in Evaluation the Historical Soundscape

Conceptual framework of Soundscape in the ISO 12913-1 explained under these headings; context, sound sources, acoustic environment, auditory sensation, interpretation of auditory sensation, responses and outcomes.[15] In historical soundscape determinations, these definitions can be used and the findings can be evaluated. Especially the implications about context, sound sources and acoustic environment come to the fore. The **context** includes the interrelationships between person and activity and place, in space and time. For example, agora areas are the areas where people's shopping activities take place. Inferences on context also lead us to information on **sound sources**. From the agora example, these areas are human voices are dominant. After the predictions about the **sound sources** and **context,** analyses of the **acoustic environment** should also be made. Acoustic environment is the sound from all sound sources as modified by the environment. Modification by the environment includes effects on sound propagation, absorption, diffraction, reverberation and reflection [15]. The physical properties of the environment, materials and spatial relationships must be determined with the help of archaeologists.

After the determinations made on the context, sound sources and acoustic environment, it is important for these areas to consider the classification proposed by Schafer in order to understand the acoustic character of the area. According to Schafer, soundscape perception occurs in three main categories. These categories, also known as; **keynotes**, **Signals** and 'Symbol sounds' (**soundmarks**) [8]. **Keynotes** are not sounds that we consciously listen to, but the sounds we cannot ignore. **'Signals'** are conscious listen. These are informative and attention-oriented sounds. **Soundmarks** is a recognized and shared sound in the sound field of the social group. It can be relatively unique or specific to a particular community. It has features that make it special or noticeable by people such as identity and belonging. In particular, soundmarks are important sounds that show the character of the field. For this reason, it is important to make these groupings in historical soundscape assessment in terms of understanding the sound environment.

3. FIELD STUDY

In this study, determinations and evaluations were made on the historical soundscape of the ancient city of Side, which experienced many different periods.

3.1 Data Findings and Evaluations

The studies on the historical soundscape of the area are dividing it into five different parts.

The First part is about establishing the timeline of the area, determining the periods. This timeline, in which important events such as the wars, drought, etc. that the region has gone through, are handled, will be a base. The region experienced Goth attack, Persian raids.

The second part is the evaluation of architectural and small archaeological findings belonging to the periods, starting from the first part.

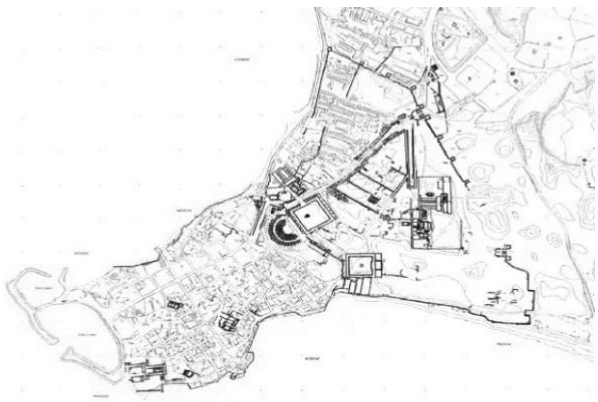

Figure 2 – City Plan (S. Aydal,2014)

The locations of structures and small archaeological findings belonging to the periods should be shown on the map. In Figure 2, we can see that the map of the region and some important structures are marked. [16] And important structures are listed. Within the scope of the study, especially city walls, nymphaeum, agora, ancient theatre, temple of Apollo and Athena, harbor bath, Southern Basilica, columnar street and Vespasian Monument were examined.

The third part, ancient writers that can be subjective sources on this field were examined. Although the sources of ancient times are limited, it is stated in the sources that they spoke a different language around the region. Apart from this, there is no other source to obtain data on the sounds.

The fourth part, it is evaluated whether the data provides on the sound source, context or acoustic environment. In addition, it is debatable whether the predicted sound sources can be background, signals or soundmarks. The conclusions about sound sources in this section should be supported by expert opinion. Explanations on fields and sound sources are given in Table 1.

Table 1 –Different areas and predictions of the sound environment

	Sound Sources
Nymphaeum(URL2) 	***-Sounds from human beings****-Speech, conversation etc.)* ***-Natural sounds****-Water sounds*
Columnar Street(URL3) 	***-Sounds from human beings****-Speech, conversation etc.)*
Ancient theatre(URL4) 	***-Voice and instrument sounds*** *-Speech, conversation, music, singing etc.*
Temple of Apollo (URL5) 	***-Social / Communal sounds*** ***-Sounds from human beings****-Speech, conversation etc.)* ***-Natural sounds****-Wave sounds*

Only examples of sound sources are given in the table. Areas such as Theatre, Nymphaeum, harbor bath, Southern Basilica and city walls also have properties that affect the acoustic environment. For this reason, the effects of these areas on the sound environment should be considered. Although almost all of the sound sources in ancient cities are classified as "Sounds from human being" according to ISO 12913-2[17], their contexts and characters are very different from each other.

The fifth and last part, the determination of the present acoustic environment and the effects of the past are tried to be determined. This part is missing in the study.

3.2 Future Studies

In the study, sound measurements were not carried out in the field, and visitor surveys were not applied. The current measurements of partially protected areas such as the city walls, as well as the analysis of the past effect through simulations and models, can be discussed in future studies. In addition, it was thought that an interactive map and a software in which all data could be viewed together would be useful in the study.

4. CONCLUSIONS

In order to determine the soundscape of historical areas, it should go through a comprehensive determination and evaluation. Understanding historical soundscapes is important to understanding these areas and past lives. In these regions where people from many disciplines work together, it will be useful for other studies to determine the acoustic effects of the existing data. In most of the archeological studies, a way is followed to protect the concrete elements of the region. The concept of conservation, which includes the preservation of buildings and objects belonging to the period, should change over time and the concept of "heritage" should be considered holistically. And that sounds should be included in this understanding of protection.

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The acoustics of singing voice

PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

Room acoustic effects on singers voice parameters

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ABSTRACT

A classical singing performance of the same repertoire in different acoustic environments can exhibit adaptations. Changes in the singer's delivery may occur due to multiple factors related to the singer's perception of the acoustics within the performing venue and the measured parameters of the spaces. Voice production behaviors were evaluated to explore the effects of room acoustics on vibrato rate and extent, and on pitch inaccuracy. The subjects were nine classically-trained professional or semi-professional singers. Subjects sang the same aria in five different performance venues. The following acoustics parameters were measured in the five spaces: C50, EDT, IACC_late, and STv. It was observed that the vibrato extent was positively correlated with acoustic clarity and support, while it was negatively correlated with perceived reverberation and sound envelopment. Vibrato rate was negatively correlated with acoustic clarity and support, while it was positively correlated with perceived reverberation and sound envelopment. Finally, the pitch was more accurate in rooms with higher values of C80 and lower values of EDT. This finding indicates the importance of auditory feedback in singers' performance and the need for an acoustical design that takes into account the performers' needs.

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PROCEEDINGS of the 2nd Symposium: The Acoustics of Ancient Theatres
6-8 July 2022 Verona, Italy

The effect of maxillary dental arch and singing style

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ABSTRACT
In classical singing techniques, it is common to manipulate the vocal tract to channel airflow to increase voice quality and volume. Although these practices are intentional, fixed physiological aspects of a singer's vocal instrument also play an extremely impactful role in determining voice quality. In the present study, the relationship between the dimensions of the maxillary dental arch and voice quality were examined in professional singers. The dimensions of the palate were measured from the maxillary dental casts of fourteen female singers. Audio recordings were made for the same participants while singing. The dimensions of the palate were measured from maxillary dental casts. From the recordings, two parameters were calculated: (1) the Singing Power Ratio and (2) A_2 A_1 ratio. Higher SPR values indicate a stronger ring in the voice, typical of operatic singing style, while higher A_2 A_1 ratio values are associated with the belting singing style. Singers with larger frontal palate depth, smaller posterior palate depth, larger frontal palate width, and smaller posterior palate width seem to be more suitable for an operatic singing style. Singers who had larger overall depth and width of the palate measurements produced an increased second harmonic, typical of the belting style.

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Vocal adaptation to simulated acoustic environments: the role of cognitive effort and auditory imagery skills

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ABSTRACT

Acoustic conditions vary across theaters, changing the way singers hear themselves. This study evaluated the effects of virtually simulated acoustic environments on singers' vocal behaviors, and how they relate to the singers' auditory imagery skill and cognitive effort. Five singers, who completed the minimum of undergraduate-level training, participated in the study. The participants sang the American national anthem. Their voice signal was digitally processed to add reverberation using a real-time effect processor. The average T30s were 1.13 s, 1.39s, and 1.90 s for low, medium, and high T30 conditions. The processed sound was played back to the participants through open headphones. For each condition, the participants rated the level of overall effort, mental effort, physical effort, frustration, and performance using a modified NASA-TLX scale. Their cognitive effort was also measured with pupillometry during the tasks. The participants' imagery skills were measured by their response to the Clarity of Auditory Imagery Scale. Their voice recordings were acoustically analyzed for intensity, singing-power ratio, alpha ratio, pitch accuracy, and rate and extent of vibrato. The presentation will discuss individual differences in the participants' vocal responses to varying acoustic conditions, and the relationship between vocal behaviors, cognitive effort, and auditory imagery skills.

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6-8 July 2022 Verona, Italy

Choir conductors: voice and acoustic environment.

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ABSTRACT
Choir conductors belong to the profession where voice is the primary working tool. Almost one-third of Latvian choir conductors participated in the study investigating a broad spectrum of voice ergonomics factors impacting conductors' vocal load. The paper will discuss one aspect extracted from the study - the relationships between conductors' voices and acoustic environments. The study consisted of three parts: an online survey, a vocal loading experiment, and interviews with conductors.

Keywords: choir conductors, vocal load, noise

1. INTRODUCTION

Choir conductors belong to professions where voice is the primary working tool; therefore, they have a high risk of acquiring voice disorders. The current studies show that a significant number of choral conductors reported laryngeal and vocal symptoms [1]. The choir conductors have specific work conditions that include rehearsals in rooms of different sizes and acoustics, singers of different numbers and ages, and work with musical material of various complexity intended for different types of voices. The conductor's voice is produced in response to a particular rehearsal condition. Vocal demand or a requirement of the vocal communication environment, vocal demand response, vocal effort, and vocal fatigue are related concepts [2]. Choir conductors' perception of the rehearsal rooms' conditions reflects the vocal effort and vocal demand response, which are directly related to vocal fatigue.

The research "An investigation of vocal load in choral conductors in the context of voice ergonomics" was carried out in 2021. Almost one-third of Latvian choir conductors participated in the study. The study investigated a broad spectrum of voice ergonomic factors impacting conductors' vocal load. The paper will discuss one particular aspect of voice ergonomics extracted from the study - the relationships between conductors' voices and acoustic environments.

2. MATERIAL AND METHODS

2.1 Study Design and Methods

The study consisted of three separate parts. The first part (Study I) included an online survey investigating choir conductors' knowledge about voice ergonomics and factors impacting voice. The one block of questions was related to noise and reverberation. Additionally, Vocal Symptom Scale (VSS), Voice Handicap Index-10 (VHI-10) and Singing Voice Handicap Index-10 (SVHI-10) were included in the questionnaire allowing to obtain information about the singers vocal health.

The second part (Study II) was organised in a group of selected choir conductors. It included a vocal loading experiment organised in rooms where each conductor usually had choir rehearsals. The study aimed to investigate vocal load expressed in time, cycle and distance doses during the vocal loading tasks. The room volume was estimated, and reverberation time (T30) was measured in unoccupied rooms using a dodecahedron loudspeaker GSR (Outline s.r.l.) as a sound source according to the ISO standard 3382-1:2009. The reverberation time was measured by a handheld acoustic analyser XL2 (NTi AUDIO) and microphone M4261 (Class 2/Type 2, sensitivity 15.2 mV/Pa). The vocal loading experiment included three tasks: vocal warm-up (with an average duration of 8.1 minutes), singing a well-known song (average duration of 26 minutes), and load reading of a neutral text (average duration of seven minutes). The average length of the experiment was 42.3 minutes (standard deviation (SD) of 1.9 minutes). The vocal loading tasks were performed under background noise conditions to simulate the natural rehearsal conditions. The piano accompaniment created the background noise during the vocal warm-up when the participant performed vocal scales. The STIPA test signal with 60 dBA@1 m was played during the singing and reading tasks. The TalkBox (NTi AUDIO) was placed where a choir would be located during rehearsal at a 1.5 m distance from the floor and a 2 m distance from the conductor. The vocal parameters (phonation time percentage ($D_{t\%}$), mean fundamental frequency (F_0), and mean sound pressure

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level (SPL)) and level of the background noise (LAF90, LA_{eq}) were obtained by calibrated voice dosimeter Vocal Holter Med (VHM) (PR. O. Voice s.r.l.). The cycle and distance doses were estimated using the algorithms developed by Švec, Popolo & Titze [3].

The third part (Study III) included a qualitative study design, and the primary data-gathering method was semi-structured interviews. This study aimed to investigate the choir conductor's unique individual experience working with the choir within the context of voice ergonomics. The interview included predetermined questions about rehearsals' room acoustic conditions. The interview was organised remotely by ZOOM. The method of thematic analysis was used for the analysis of interview content.

2.2 Participants

Study I. One hundred fifty-five choir conductors completed the online questionnaire, out of which 74.2% were female. The mean age of female respondents was 48 (SD =13.3) years and 45.5 (SD = 15.1) years for male respondents. The working experience in the choir conductor's profession was less than five years in 11% of respondents; all others were experienced conductors with a length of service from 6 to more than 40 years. Most of the conductors (72.3%) worked with mixed choirs. Fifty-seven per cent of conductors worked with two or more choirs.

Study II. Eighteen choir conductors (13 female, five male) participated in the vocal loading experiment. The mean age of female participants was 48.9 (SD = 15.8) years. Moreover, seven of the 13 participants had working experience of more than 30 years. The mean age of male participants was 46.6 (SD = 22.1) years; two of them had working experience of more than 30 years. All the participants had vocal training backgrounds and had professional education in choir conducting. In addition, they were non-smokers, and none had voice disorders in anamnesis.

Study III. Six well-known leading choir conductors were invited to take part in the interview. Besides choirs' conducting, two participants were composers and arrangers, and one of the conductors also worked with a symphonic orchestra. All of the respondents taught music in colleges and universities. The participants were males, 36-40 years old.

3. RESULTS

3.1 Study I

Fifty-two per cent of conductors identified indoor noise in rehearsal rooms. Ventilation systems, lamps and air conditioners were noise sources mentioned more often by respondents. The presence of outdoor noise (traffic, adjoining rooms, corridors) was mentioned by 62.6% of conductors.

The relationships between activity noise (AN) or choir discipline during rehearsal, vocal effort (VE), vocal fatigue (VF), and results of the self-assessment scales (VSS, VHI-10, SVHI-10) were evaluated by Spearman's Rank correlation coefficient (Table 1). Statistically significant correlation was found between indoor and outdoor noise and activity noise during rehearsals (r_S = .165, p = .04; r_S = .272, p = .001). Also, between outdoor noise and VHI-10 (r_S = .193, p = .016).

Table 1 – Relationships between activity noise, vocal effort, vocal fatigue during rehearsals and scores of Vocals Symptom Scale, Voice Handicap Index-10, and Singing Voice Handicap Index-10

Variables	AN	VE	VF	VSS	VHI
AN	1				
VE	.399**	1			
VF	.344**	.659**	1		
VSS	.254**	.458**	.506**	1	
VHI	.267**	.325**	.300**	.467**	1
SVHI	.318**	213**	.374**	.444**	.683**

** Correlation is significant at the 0.01 level (2-tailed)

3.2 Study II

The vocal loading experiment consisted of three separate tasks: vocal warm-up, singing, and loud reading. The time, cycle, and distance doses were estimated for each vocal task. Data were analysed separately in male and female participants by Paired Sample t-test and Wilcoxon Signed Rank Test.

The average $D_{t\%}$ during intensive singing was 76% in female conductors and 79% in males (Figure 1). $D_{t\%}$ was significantly higher during singing than producing warm-up scales in female and male conductors (p = .012, p = .038). Also, $D_{t\%}$ was higher during singing than reading in females and males (p < .001, p = .031).

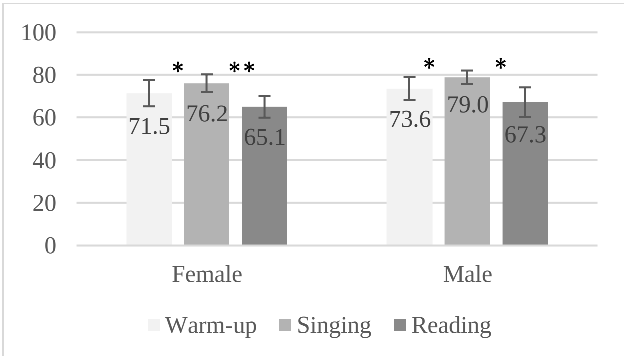

Figure 1 – $D_{t\%}$ and SD during warm-up, singing and reading in male and female participants (* significance at the 0.05 level; ** significance at the 0.01 level)

Cycle dose (D_c) quantifies the total number of oscillatory periods completed by vocal folds over time [3]. The highest average amount of kilocycles completed per minute was observed during singing tasks in female and male conductors. There were statistically significant differences between amount of D_c during singing and warm-up and reading (p = .003, p = .001) in females and in males (p = .042, p = .032) (Figure 2). There was statistically significant difference between male and female subjects in the mean D_c in warm-up scales, singing, and reading (Z = -3.205, p = .001; Z = -3.207, p = .001; Z = -2.918, p = .004, Mann-Whitney Test)

The third estimated vocal dose was a distance dose (D_d), the approximate distance tissue particles in the vocal folds travel in a cyclic trajectory over many cycles [3]. The analysis showed a statistically significant difference in D_d between singing and reading in female and male conductors (p = .001, p = .039). Vocal folds during intensive singing travelled 34 m per minute in female participants and 36.8 m per minute in male conductors (Figure 3).

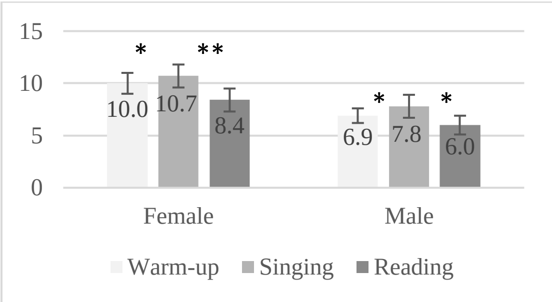

Figure 2 – Average D_c (k/cycle/min) and SD during warm-up, singing and reading in male and female participants (* significance at the 0.05 level; ** significance at the 0.01 level)

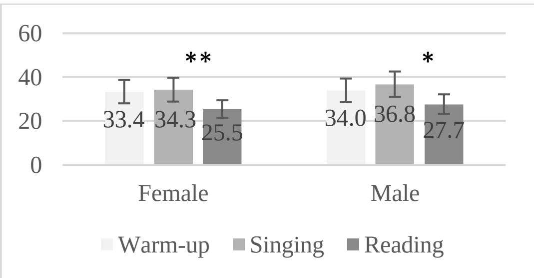

Figure 3 – Average D_d (m/min) and SD during warm-up, singing and reading in male and female participants (* significance at the 0.05 level; ** significance at the 0.01 level)

The correlation analysis did not find associations between the average amount of vocal doses during different vocal loading tasks and LA_{eq}, T30 and the volume of rehearsals rooms. However, positive strong correlation was found between background noise LAF90 and $D_{t\%}$ (r = .648, p = .017), and D_c (r = .643, p = .018) in female participants during singing task. While in males, during the singing task was observed a robust correlation between LAF90 and D_d (r = .900, p = .037). The average background noise level (LAF90) during singing task was 67.6 (SD = 2.8) dB in females and 67.8 (SD = 3.5) dB in males.

The reverberation time $RT_{0.5\text{-}1kHz}$ was measured in 21 rehearsal rooms (all experimental rooms and three rooms where worked conductors were not included in the study). There were seven small rehearsal rooms (Volume (V) = 45-200 m^3), four medium sizes (V = ≥ 200 m^3), and 10 large rehearsal rooms (V = ≥ 700 m^3). The $RT_{0.5\text{-}1\ kHz}$ only in seven of 21 measured rehearsal rooms (33.3 %) complied with the RT normative for quiet music in rehearsal rooms according to the Norwegian Standard NS 08178 [4]. Eighty per cent of large rooms, 50% of medium-sized rooms and 57% of small rooms did not meet reverberation time criteria defined in the NS 08178.

3.3 Study III

The conductors' answers during the interviews demonstrated that they were aware of interfering factors in the acoustic environment, such as indoor and outdoor noise and bad reverberation. They clearly understood the association between vocal comfort and rehearsal or performance rooms' acoustical environment. The conductors agreed that acoustics play a considerable role in choral singing. There are some quotes that conductors expressed about singing and reverberation: "the room can support singing, and the room can destroy it", and "different spaces with different reverberation times can change a choir sonority; therefore, it is a challenge for a conductor to maintain the same choral sound in acoustically different rooms", "any room is suitable for singing and can be filled with the sound", "it is technically hard work for conductor and singers to achieve good sonority in rooms with bad acoustics". Conductors shared their observations that the better is room acoustics, the less vocal effort during singing is perceived to be required. They mentioned that besides reverberation time, the vocal load could depend on the size of the room, number of singers, and choir discipline during the rehearsal. The choir discipline or increased activity noise during rehearsals is crucial when working with children, especially boys' choirs.

4. DISCUSSION

The questionnaire study results showed that a noisy environment promotes increased activity noise. The activity noise creates more vocal effort and vocal fatigue and affects the conductors' voice quality. Conductors who reported a higher level of activity noise in the rehearsals had more vocal symptoms and had higher VHI-10 and SVHI-10 scores. Unfortunately, in the current literature, few studies investigate choir conductors' voices and their relations with room acoustics; therefore, comparing our results with other studies is limited. Nevertheless, our results agreed with other studies [1, 5], concluding that vocal alterations usually are consequences of excessive use of speaking and singing voices and neglecting room acoustics.

The interview data revealed the conductors' personal experience working in rehearsal rooms with different acoustics. In general, their answers reflected the data obtained by the online survey that the acoustical environment can impact vocal effort and health. The interviews provided a deeper insight into how conductors perceive the room's acoustics and their impact on the choir sound. However, the essential conclusion was that artistic ambitions and goals were priorities for conductors leaving behind the acoustical and health factors.

The non-compliance of the choir rehearsal rooms with the recommended reverberation time was an important finding in the study. Choir rehearsals usually occur in large and small halls, in large schools classrooms or in other rooms where there is space for singers and piano. The selection of rehearsal rooms often is based on the choir's financial possibilities neglecting voice ergonomics.

The study results demonstrated that singing is more vocally demanding than load reading. Statistically significant differences between these activities were observed in female and male conductors in $D_{t\%}$, D_c, and D_d. The obtained D_d during warm-up and singing for female conductors (0.56 m/s and 0.57 m/s) were close to the D_d obtained in two female graduate voice performance students with experience in teaching and opera singing during teaching classes (0.53, 0.56) [6]. In addition, we found that female conductors produced more vibratory cycles (D_c) than males, which is explained by the difference in fundamental frequency between males and females. This finding was in line with Zuim, Stewart, and Titze's study investigating vocal doses in student singers participating in musicals [7] and concludes that female conductors are at higher risk of developing voice problems due to a higher number of vibratory collisions.

We did not find the impact of rehearsal rooms' volume and reverberation time on vocal doses. However, significant associations were observed between the LAF90 in the rehearsals rooms and $D_{t\%}$, D_c, and D_d during the singing task. Unfortunately, no studies investigated relationships between acoustic parameters of spacious choir rehearsal rooms and vocal doses obtained by voice dosimetry were found. Therefore, references to studies focused on investigating the interaction between acoustics and vocal doses in other environments were made. Results regarding the impact of reverberation time on vocal doses align with Bottalico and Astolfi's study results [8]. Their study investigated vocal load in primary school teachers working in two acoustically different environments. It was observed that vocal doses and parameters did not differ between classrooms with high and low reverberation times. Similarly to our findings, Rabelo et al. found that the $D_{t\%}$ and D_c significantly increased in the background noise conditions. They investigated women between 22 and 50 years of age in a university classroom [9].

A partial discrepancy between objective and subjective measurement results was observed in the study. The questionnaire and interview results indicated the effect of reverberation and background noise on vocal effort and vocal fatigue. Therefore we expected to observe more associations between parameters of the acoustic environment and vocal doses during loading tasks. The limitation of the current study is that author did not investigate the impact of rehearsal room acoustic on voice gain and voice support which would be helpful to better understanding the relationships between the use of voice and the acoustic environment by choir conductors.

5. CONCLUSIONS

The subjective measurements confirmed that specific vocal demand conditions (high background noise in rehearsal rooms and long reverberation time) increase vocal effort and cause fatigue in choir conductors. The reverberation time in many rehearsal rooms does not meet the norms specified in the standard NS 8178: 2014. It is possible that the impact of the reverberation time on a vocal load that we did not observe during the vocal loading experiment could be more prominent if vocal dosimetry were provided during the real choir rehearsal.

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Assessing acoustic parameters in Early Music and Western Operatic singing

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ABSTRACT

Classical singing is not a homogenous basket. After two centuries of silence, since 1950s has made a comeback on the stages all over the world Early Music, comprising repertoires from the VI to half of the XVIII century. The so-called historically informed performance, which aims at playing a given piece of music as faithfully as possible to the approach and manner of the musical era in which a work was originally conceived, has developed a style of singing Early Music which has gradually differentiated it from the way we now intend the more common Western Operatic singing style. Perceptual differences when comparing Early Music and Western Operatic singing regard contrasts in intelligibility, flexibility, sound power, timbre, approach to passages of register, and vibrato features. This study focuses on differences in vibrato acoustics and formant analysis in Renaissance (1500-1600) and Western Operatic (1800) singing styles, by comparing acoustic recordings acquired from professionally trained singers specialized in the two repertoires. Possible differences will regard a less precise characterization of vowel in Western Operatic singing, resulting in an overall decrease in intelligibility, and a less pronounced singer's formant and vibrato extent in Early Music singers.

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Horizontal directivity patterns for the singing voice

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ABSTRACT
Singers rely on auditory feedback from reflective surfaces to regulate voice production. However, the reflected spectrum received at the singer's ear will depend, in part, on the location of the reflective surface(s) around the singer. This is because acoustic directivity patterns for human vocalizations are non-uniform with respect to direction and frequency. Using multi-channel anechoic recordings, we analyzed these radiation patterns out to 20 kHz for both singing and speech produced by trained singers. Radiation for higher frequencies tends to be more directional toward the front of a singer, whereas lower frequencies tend to radiate more omnidirectionally around the singer. Consequently, unless the singer is directly facing a reflective surface or receiving electronically reinforced feedback (e.g., in-ear monitoring), the auditory feedback received will be dominated by the lower frequencies of the voice spectrum. Although extended high frequencies (>8 kHz) in singing are audible and affect perceived voice quality, their role in auditory feedback for vocal production regulation remains unknown.

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The voice in the ancient spaces

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ABSTRACT

Voice and singing in historical and archaeological places to travel through time through sound. Sound and vocal performances through research and experimentation within spaces that have extraordinary architectures and reverberations. To have a connection with the historical, geographical and cultural depth of the origins through our "Voices of Inside" to create "Other Spaces" and improve perceptual and vocal emission qualities. With Voice and musical instruments it's possible to improvise in total freedom, being inspired by the strong relationship with the places and using instruments that conform to environments such as percussion, wind instruments, string and string instruments, shells, stones and water. The places of the performances were: The ancient Baths of Baia, The Castel Sant 'Elmo (Naples), The Castel Maschio Angioino (Naples) In addition to the artistic, therapeutic, sound and experimental experience, the project proposes itself as a path to enhance and enjoy historical, archaeological, modern and postmodern sites and communication between old and new traditions, creating live performances and audiovisual productions. Marco Francini has been bringing the experimentation and research of "The Voice in the Ancient Spaces" to various Italian universities, conferences and academies for over 10 years.

Keywords: voice.

1. INTRODUCTION

"The Voice in the Ancient Spaces" is a research path within places that have acoustic details and unique geographical positions. The possibility of emitting sounds with the voice and with some musical instruments, within these spaces, allows us to establish a very strong relationship with the history of the environment and the surrounding landscape.

Entering an archaeological-historical place that has certain reverberations, emitting a sound, listening and perceiving its effect is one of the most extraordinary experiences I have ever had in life. From here began my research path "The Voice in the Ancient Spaces" within environments with which I create a special relationship that has lasted for over twenty years.

In such a condition the voice expands, transforms, envelops you and transports you to other dimensions as if your whole body and soul were hooked to a sound to travel through time in an "Other Space" where present, past and future coexist.

Together with other musicians we create free improvisations with the voice and with musical instruments (strings, winds, percussion, shells), sometimes we also use materials found on the spot such as stones, water, earth and branches.

"The Voice in the Ancient Spaces" has a powerful symbolic value and always requires a type of performance with very intense physical and psychic energy. Perception, breathing, emission, listening, everything is amplified and improves our vital qualities.

It is very important to understand the "relationship voice space body" with "voice space environment": from this connection comes my research that develops on several levels and with different phases of study:

2. INSPECTIONS

The first aspect of the Voice in the Ancient Spaces is the identification of the site through inspections, to understand its history, myth and geographical connotation.

The second element is the perception of the energy of the space we have identified, observing its architecture, the material of which it is composed, learning the olfactory sensation, the surrounding soundscape and above all starting the acoustic test with the voice and with some musical instruments to establish the type of reverberation and any resonance frequencies.

Through the first vocal improvisations I can decide what kind of sound and emission are suitable for the space, including the rhythmic aspect that is very important because some natural reverberations allow to create, with the percussive instruments, extraordinary atmospheres.

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To have a thorough knowledge of the places you must spend a lot of time on site and let yourself be carried away by the sensations that project us into the journey we are about to undertake. Capturing historical memory and making it live in the present becomes a fabulous and fascinating task.

During the inspections I am always accompanied by a sound engineer who knows my research well and by one or two musicians who have been collaborating with me for a long time.

At the end of this stage, we begin the training phase for the performance that we are going to do.

3. PREPARATION

In the preparation phase we establish the possible **"Musical Ensemble"** imagining the type of acoustics of the space and the sound character we want to build.

In addition to the creative part, we organize the phonic and technical aspect for audio-video shooting by carefully choosing the equipment and microphones suitable for the circumstances.

Regarding the voice: I deepen the poetics to be used by immersing myself in the texts of historical and mythological literature, I extrapolate phrases, quotes, images that I often combine with elaborations created by me, I also try to understand which phonemes and which languages are more suitable for the performance, although this aspect is conditioned by the moments of vocal improvisation that I am going to do in the place.

Finally, I create musical canvases on the basis of tones that seem more suitable to me, but I leave ample freedom to the musicians to **create** and **compose.**

4. PERFORMANCE

The days of the performance of the Voice in the Ancient Spaces are always exciting, and we are all very full of energy: we prepare a first set of audio recording exactly like a real cinematic ciak and after a few seconds of silence we start with **improvisations.**

The aspect that concerns this phase is to play freely immersed in natural reverberations letting go of the flow of the moment. The duration of the pieces varies according to the sensations, perceptions and looks of the musicians.

Another element is to move in space in order to create different **audio sets** that exploit the acoustics from various angles and perspectives and that act on the sound emission in a different way.

Another important component is the **interplay** between the musicians, based on listening to the melodies, harmonies and rhythms that are produced.

Another interesting element concerns the production of sound **harmonics**: vocal spatialization allows the voice to produce harmonics that, in this context, are heard with great naturalness, clearly facilitating the quality of the sound.

5. THE VOICE IN THE ANCIENT SPACE IN CAMPANIA – NAPOLI

In each place we spent many hours to get in touch with its acoustics, the type of reverb and its atmosphere. Each space always imposes its own intensity, its own breath and its own time; we must be very patient and careful to create an authentic, ancestral and deep relationship.

Churches, castles, temples, theaters, quarries, caves, each of these buildings preserves an extraordinary historical memory that communicates with us beyond time. With sound and voice we can tear through the space-time dimensions to connect with what **Pythagoras** called *the harmony of the spheres.*

The places that have characterized my research in recent years are in the Flegrea Campana area and in the city of Naples.

5.1 THE MIRABILIS POOL

Is an ancient water cistern, very large, built in the Augustan era and located in the area of Bacoli in the province of Naples. The Mirabilis Pool was entirely dug into the **tuff** of the hill near the port, slightly raised above sea level. With a rectangular plan, it is very high and is surmounted by a ceiling with barrel vaults, supported by many pillars.

The reverberation of this structure is quite homogenous in every part of the space and has a delay of about **3.5 s** but it is above all its architecture that acts on the sound in a strong and incisive way in addition to the dominant characteristic of the tuff as a supporting material. All this made it possible to create extraordinary compositions in whole days of audio shooting. The enormous internal spatiality has allowed us to move freely with the instruments, determining perspectives and sound geometries impossible to recreate in other types of physical and virtual contexts.

5.2 TEMPLE OF MERCURY

Inside the **Archaeological Park of Baia**, a fraction of the municipality of Bacoli, is located The sector "of Mercury" so called because it includes a building that was initially believed a temple dedicated to Mercury, but in reality it was a *frigidarium*, a cold water pool. The externally square-shaped building had a circular internal environment and a domed roof that is the oldest example of a large spherical roof. It dates back to the end of the first century a.C. and in *the Severian age* other rooms with sumptuous decorations were added. The vault, placed to cover the building, is equipped with a central skylight made using large flakes of **tuff** made wedge-shaped.

The reverberation of this place has a delay of about **6 s** and each performative action has an extraordinary fluidity, it seems to be immersed directly in the sound that is produced. The presence of water within space contributes to the perception of sounds as if they were *ancient sea creatures* talking to us from other worlds. Wanting to make a rough encoding I could say that the tonality that resonates better than the others is the F# along with some frequencies of the same musical scale. The harmonics of the voice that are highlighted with great intensity starting from **F#2** are **8°, 5°, 8°, 11#.**

5.3 MASCHIO ANGIOINO

Castel Nuovo, also called Maschio Angioino, is a historic medieval and renaissance castle, as well as one of the symbols of the city of Naples. The construction of its ancient nucleus, today partly re-emerged following restoration and archaeological exploration, is due to the initiative of Charles the First of Anjou. Located near the sea in the center of the city, the castle has several rooms with interesting acoustics including the **Palatine Chapel** and the **Hall of the Barons**. Both places face the sea, with large windows inside. **Tuff** and **piperno** are the cornerstones of the whole building. In this place the Voice in the Ancient Space tells us about the extraordinary events of the history of Naples

6. YELLOW TUFF

Many of the underground buildings that today the city of Naples jealously preserves were born thanks to the massive presence, on the territory, of tuff that constitutes a precious value for the Campania region.

The Neapolitan tuff is very suitable for the Voice in the Ancient Space and also known as yellow tuff, comes from the volcanic activity of the **Phlegraean Fields**. It is the production of ash that for the Neapolitans takes the name of "pozzolana" to give life to this material, the so-called "pozzolana" in fact has been settling in the sea, then re-emerging due to tectonic pressures that occurred, according to experts, about thirty-five thousand years ago.

The tuff was used by the ancient civilizations settled in Naples to recreate extraordinary, inhabited structures, which the city still preserves in perfect condition as an incredible historical legacy. The construction of architectural works, dug into the tuff, was made possible by the thermal insulation capacity of the material, which also proved to be skilled in containing moisture.

This precious characteristic is made possible in turn by the absorption property of zeolites, minerals that make up the tuff, enriching it with new and peculiar abilities. It is precisely the latter who assimilate water molecules or dissolve them again, making tuff a cold material during the warmer months and warmer during the colder months. These properties have the merit of making tuff the perfect material for the construction of works and constructions, some of which today are considered inestimable.

All that the geological substrate of Naples owes its value to the formation of the tuff. To it also owes much the historical and cultural heritage of the city, which has been enriched over time thanks to the presence of this material, exploited in a masterful and refined way by Greeks and Romans. In fact, the underground quarries have been obtained from the Neapolitan tuff. These quarries served in antiquity as catacombs, crypts, funerary hypogea, houses, shops and works of a military nature.

7. SOUNDSCAPE

Many of the places where we have been having natural settings, such as birds, wind, sea and many other sounds that contribute to making each performance even more authentic. The whole landscape gives us a symbolic image and strong vibrations that continually bring us back to deep memory and our roots. Our visual and sound journey reminds us of the close bond we have with the land and its history. The Voice in the Ancient Space tells the story of humanity and its evolution.

8. REPORTS, OOBSERVATIONS, DATA

The research "**The Voice in the Ancient Spaces**" has produced incredible results over the years, thanks to two printed discs as well as conferences, conventions, video material, audio and acquired knowledge.

8.1 CD

Echos 1 performance of voices, shells, guitar and percussion (2001).

Echos 2 performances of voice, cello, sax, guitar, trumpet, shells, harp and percussion (2017).

8.2 CONVENTION AND CONFERENCES

12th International Course Phoniatrics and Speech Therapy **"The artistic voice"** speaker with the research project ***The voice in the ancient spaces*** (2019).

13th International Course Phoniatrics and Speech Therapy **"La voce artistica"** live video performance for voice and cello of the ***E-Nea*** project (2021).

8.3 WORK IN PROGRESS

All the material collected, together with the experience in the field, allowed us to make important considerations and establish more precise parameters:

The first important fact is that the voice changes and transforms according to the places in which it is produced, so it makes us understand the close relationship that man has with the environment as if it were a ***"single body"***

Another consideration concerns the sound, which turns into something powerful and unique with a force that balances all our extreme and opposite qualities such as sweet and violent, light and dark, melancholic and cheerful, restless and happy.

Another aspect concerns the **perception of listening**: every little movement and every little action is amplified and supported by the spatiality of the place that concerns not only its reverberation and resonance but also the type of atmosphere that is created. I could define this type of energy as two types, the first composed of **light colors** and the second of **dark colors**, understanding every shade that is in the middle. In this regard, I like to quote the writer **Elémire Zolla** who spoke of **the aura** of places.

Another fact of the Voice in the Ancient Space listening to the recordings made that we made with great attention: we realized that some sounds of musical instruments, in particular percussion, were not recognized immediately but we had to listen to them repeatedly to understand the source.

All this highlights the incredible aspect of a true **"timbre metamorphosis"** conditioned by the place and its living energy.

9. CONCLUSIONS OF THE VOICE IN THE ANCIENT SPACE

Our research is developed on two parallel tracks, on the one hand the experimentation of new musical architectures thanks to the wonderful reverberations of these spaces and on the other the enhancement, increasingly targeted and attentive, of historical places.

To make live, through the ***sound journey,*** in a total way, all those who participate, communicating new and ancient traditions. In this way you can share musical experiences with a passionate and attentive audience.

Man, lives in close relationship with his environment, he must respect and care for it continuously. Culture, history, and art are the foundations of a healthy and evolved community because without history and without memory there is no future.

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THE PAST HAS EARS

PHE : The Past Has Ears project overview

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ABSTRACT

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 space's tangible construction and furnishings. We present an overview of the "Past Has Ears" project and current progress, exploring how the acoustics of heritage spaces can be documented, reconstructed, and experienced for spaces existing, altered, or destroyed.

Keywords: Archaeoacoustics; Digital heritage reconstructions; Audible virtual and augmented reality; Acoustic heritage; Methodology guidelines

1. INTRODUCTION

Hearing is one of our most pervasive senses. There is no equivalent to closing our eyes, or averting our gaze, for the ears. The acoustics of a site is ephemeral, while also a concrete result of the physical nature of the environment. Research regarding the acoustic heritage of a site, its cultural and sociological position, how it was used, plays a key role. This places the study of heritage acoustics at the intersection of many scientific disciplines. With the recent adoption of UNESCO resolution 39 C/49, "The importance of sound in today's world: promoting best practices", complementing the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage [1, 2], we are in a new era where acoustic soundscapes of places both existing and historical merit reflection, preservation, and scientific study.

Inspired by the project's namesake (Phé, for the constellation Phoenix), and the relatively recent fires at *Cathédrale Notre-Dame de Paris* (2019) and *Teatro La Fenice* opera hall [3] (1996, *Fenice* also meaning Phoenix), the PHE project focuses on the preservation, conservation, and reconstruction of heritage sites, bringing them back from the ashes for use by researchers, stake holders, cultural institutions, and the general public [4, 5].

2. PROJECT OVERVIEW

Three principal objectives have been identified concerning the project: *Documentation*, *Modelling*, and *Presentation*. These research concepts are directed towards three case studies, adjusting to the unique requirements of each site. The overlying goal being the formulation of techniques, tools, and a system prototype that is adaptable to various site conditions and test cases, providing a flexible yet realistic immersive audio rendering of historic states of cultural heritage buildings. It is intended that the results of such a project will facilitate increased acceptance and integration of acoustic aspects within heritage research and communication with the public.

Comprising research teams with experience in acoustic reconstructions and historical research, paired with national heritage monuments of acoustic importance, the project is developing a joint methodology for addressing relevant archaeological acoustics issues across Europe with historians of different disciplines. Three heritage sites from the participating countries (France, Italy, and the UK) join the consortium as active Associated Partners. These sites are the Tyndaris Theatre (IT), Cathédrale Notre-Dame de Paris (FR), and The Houses of Parliament (UK). Throughout the project, these institutions will participate as case studies for all 3 axes, representing public sites of importance in the form of an ancient Greek theatre (far from its original condition), a Gothic Cathedral (in the midst of recovering from a serious catastrophe, inaccessible to the public for some years), and the House of Commons Chamber (generally inaccessible to the public, of significant importance to UK politics and governance).

For historical research, PHE brings sound to the forefront of attention, focusing on analysis, recreation, and communication of the intangible heritage of sound and soundscapes. As an innovative research tool, historically authentic simulations and reconstructions provide a new perspective for understanding, interpreting, and experiencing the past. Such sensorial and perceptual experiences can confirm, or contradict, hypotheses and assumptions based on insufficient information or fragile extrapolations. The ability to take an immersive perspective provides the opportunity to re-contextualise interpretations of written documentation and witness accounts. Such understandings can be easily communicated to the public, through similar mediated experiences, rather than simply though traditional written elements, providing a new means of information transmission and community engagement.

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The project further includes prototyping next generation exploration tools for presenting digital acoustic reconstructions to scientists and museum visitors alike. Presentation methods provide first-person in-situ or off-site explorations, with the ability to experience various historical periods. For deteriorated sites, this approach provides access to situations impossible to experience on-site. On-site experiments with partner sites will take place in the later parts of the project. Additional uses include participative experiences, employing real-time reconstructions for on-site concerts and other events experienced within the acoustics of these heritage sites.

3. NOTRE-DAME (FRANCE)

The Cathédrale Notre-Dame de Paris is amongst the most well-known worship spaces in the world. Its large volume, in combination with a relatively bare stone construction and marble floor, leads to rather long reverberation times. The cathedral suffered from a significant fire in 2019, resulting in damage primarily to the roof and vaulted ceiling. Despite the notoriety of this space, there are few examples of published data on the acoustical parameters of this space, and these data do not agree. Archived measurement recordings from 1987 were recovered and found to include several balloon bursts. In 2015, a measurement session was carried out for a virtual reality project. Comparisons between results showed a slight but significant decrease in reverberation time (8%) in the pre-fire state. Measurements were recently carried out on the construction site, 1 year since the fire. Compared to 2015 data, reverberation time significantly decreased (20%). Preliminary results of these measurements provide documentation of the acoustics, both prior to and since the 2019 fire, and have been reported in [6].

The study of acoustics as intangible cultural heritage is an active field of research with implications beyond the scientific community. We are examining the potential influence of the acoustics of the "new" Gothic cathedral of Notre-Dame de Paris on the medieval singers who pioneered a style of plainchant known as the School of Notre-Dame using interactive virtual acoustic environments (VAEs) and real-time auralization. The experiment compared the approximated acoustics of the prior cathedral (torn down in 1163 CE to make room for Notre-Dame) with Notre-Dame which partially opened in 1182 CE. A speculative VAE of the pre-1163 cathedral was created by modifying a calibrated model of an extant and contemporaneous Roman basilica, while the early Notre-Dame VAE was generated by time-regressing a calibrated model of the modern cathedral to match its earlier state. A choir specializing in historically informed performance practices was studied as they sang *Organum Purum* and *Organum* Notre-Dame inside the VAEs of the pre-1163 cathedral and the early cathedral of Notre-Dame de Paris. Musical parameters were extracted from the recordings to examine what influence the different architectures may have had on musicians' performances [7, 8, 9]. This works builds upon previous studies concerned with methods for creation and calibration of historical acoustic simulations, as well as their objective and perceptual validations [10, 11].

Extending beyond the targeted site of Notre-Dame, similair techniques as mentioned above have been used to recreate the historical ambiences of a major heritage site for music in the Mediterranean region: the Pontifical Chapel of the Palace of the Popes in Avignon. This building, which was one of the major centres of polyphony in the 14th century, is still today one of the most suitable places in the region for the interpretation of medieval vocal music as instrumental music. The aim was to question the listening of 14th century heritage music through a corpus of polyphonic works, interpreted via an immersive virtual acoustic environment reproducing the papal chapel around 1362 [12]. This reconstruction enabled exploring new avenues of research into historically informed musical practices and the interaction between the musical gesture and sound space with which it resonates.

Bringing together acousticians, historians and religious anthropologists, we examined the lives of choirboys at Notre-Dame between the 14th and 18th centuries, estimating sound propagation by children's voices during liturgical celebrations based on their location inside the choir using acoustic simulations [13]. The enclosed liturgical choir of Notre-Dame created an acoustical subspace in the cathedral with suitable acoustics for the clergy within the choir, but not for the laypeople in the nave. Simulations demonstrated that this liturgy was probably destined just for the canons who sang it. In addition to testing source conditions within the chancel with and without the jubé, we also investigated the situation of singing from atop the jubé, as occurred on certain special occasions. While singing atop the jubé may have had visual appeal or ceremonial importance, simulations reveal that such change would have likely had a negative effect on loudness and clarity as perceived by the canons in the choir.

In public communications of research, and in honour of the International Year of Sound and for the 1 year memorial of the Notre-Dame cathedral fire, we created a virtual reconstruction of a concert in the cathedral, using close-mic recordings made on 24-April-2013 of a performance of *La Vierge* by Jules Massenet with 83 musicians, 6 singers and a 160 person choir spatially distributed throughout the cathedral, offering a natural spatial composition highlighting the complex acoustics and interactions between source and listener positions. This reconstruction[1] was carried out during the period of strict COVID-19 confinement. Distributed on-line, the website presenting this virtual reconstruction has been visited from users around the world, including a listener opinion survey (see [14] for details). *Looking for Notre Dame / À la recherche de Notre Dame*[2] is a bi-lingual 3D sound experience that takes us into the mind of a young Victor Hugo as he begins his research for his future "cathedral novel", Notre-Dame de Paris. This series of audio fictions currently in production uses Victor Hugo's imagination

[1] Notre-Dame virtual concert: lavierge2020.pasthasears.eu

[2] Notre-Dame audio fiction: lookingfornotredame.pasthasears.eu

to visit historic moments and acoustic reconstructions developed from the scientific research team [14, 15].

4. TYNDARIS (ITALY)

The ancient theatre of Tyndaris is situated on the northern coast of Sicily. It is surrounded by the remains of the city of Tyndaris, founded in 396 BCE by the Greeks as a colony for exiles of Messenia (modern Messina). Its shape has changed considerably over centuries: in the 4th century BCE a scenic building was added in front of the cavea, while during the late imperial age of the roman empire it underwent substantial modification for hosting gladiator spectacles and fights against ferocious animals. Destroyed by a landslide and two earthquakes, Tyndaris saw light again thanks to archaeological excavations begun in 1838 and later resumed between 1960 and 1998. The theatre again hosts concerts, but its current acoustic is compromised by many factors: lack of the original scenic building, providing useful reflections supporting the actor's voice; absence of a large part of the steps of the cavea and the general deterioration of the materials, impacting the reflectivity; and increased background noise levels due to traffic.

A combination of visual and acoustic experience in a virtual reality environment provides an immersive exploration of all the different phases of its evolution, reconstructed by modifying shapes and materials of a calibrated model of the existing conditions. The visual rendering consists of equirectangular panoramic images, reconstructed from several viewing points, each associated with a computed High Order Ambisonics (HOA) impulse response (IR). Anechoic samples are convolved with these IRs to create the virtual soundtrack for different points [16]. Resulting 360° video files are publicly available[3].

A subjective analysis of three types of Ambisonics recordings (i.e. chamber music, female speech and singing) has been conducted to be used for the calibration of a proposed acoustic shell to be installed in the orchestra. The recordings have been listened to by a range of users (not just experts) of different ages (18 to 50 years). The aim of this research is to design the acoustic shell based on the subjective feedback of the users. The recordings with the presence of a shell have been compared with the original conditions of the theatre and assessed based on subjective parameters like loudness, reverberance, apparent source width, definition, distance and coloration. The determination of its shape has been realised based on the results obtained by the evaluation of the subjective parameters.

Future developments will be focusing on the creation of a six-degree-of-freedom (6DoF) experience of the theatre across all the modifications that occurred throughout the centuries, both in Virtual Reality (VR) and on-site through Augmented Reality (AR), allowing visitors to experience the sonority of the theater using of cost-effective devices, such as smartphones or other Augmented Reality gear.

[3]Tyndaris 360° reconstruction: youtu.be/H-75GT68DUE

5. HOUSE OF COMMONS (UK)

As the elected house of the UK Parliament, the House of Commons has met in a number of spaces in and around the Palace of Westminster since the 14th century. A key development came in 1548, during the English Reformation, when the Commons took possession of the royal chapel formerly belonging to St. Stephen's College at Westminster: the first permanent home of the lower house of Parliament. Parliament remained here until the Palace fire of 1834, when the historic Commons chamber was gutted and demolished. Rebuilt in a consciously medieval Gothic style, the Commons was destroyed again during the Second World War, but was once again restored to a similar design. At each stage, the oppositional format of the chamber with benches on either side of a central aisle – recalling the layout of the lost St. Stephen's Chapel – was retained, thus shaping the architectural context and political culture of the UK House of Commons to this day.

This aspect of the PHE project explores the acoustic characteristics of the historic House of Commons chamber as it evolved within the former St. Stephen's Chapel between the 16th and 19th centuries, and in terms of its modern legacy. This lost building is compared with surviving spaces used for meetings of Parliament in Oxford during the 17th century, including the University of Oxford's Divinity School and Convocation House. Both survive with few interior changes, and are still accessible to visitors. The architectural similarities between the Holywell Music Room in Oxford, and the Commons chamber, as re-ordered by Christopher Wren c. 1707, are also remarkable. A study of this space as a potential comparator to the acoustics of the lost Commons chamber is ongoing. Results obtained from in-situ measurements of these parliamentary, and comparable related spaces, are presented in the companion paper [17], with a particular focus on speech intelligibility given their primary use as places for political speech-making and debate.

This work continues with the development of an acoustic model of the pre-1834 House of Commons, based on information gathered from written sources[4], drawings and engravings of the site, as well as objective acoustic results obtained from the in-situ measurements of the spaces discussed above. As part of this reconstruction, the ventilator space above the ceiling of the historic Commons chamber has been added to the acoustic model. Here, women gathered to listen to political debates from which they were formally excluded during the early 1830s. Speech intelligibility across different measured positions where Members of Parliament spoke and listened will be assessed, with the aim of investigating the impact of acoustics in parliamentary debates and decision-making.

6. FINAL REMARKS

With a little over 1 year remaining in the PHE project, a significant portion of those months will be spent on experimental studies employing virtual reconstructions both on and off-site, contributing to fundamental studies on

[4]The House of Commons, 1707-1834, www.virtualststephens.org.uk/explore/section5

performance and listening conditions, navigable virtual and augmented reality, collaborative studies regarding social science and the humanities, as well as prototype museum exhibits. We all look forward to sharing these results with both the scientific community and the public at large.

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Opening the Lateral Chapels and the Acoustics of Notre-Dame de Paris: 1225–1320

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ABSTRACT

Significant architectural modifications were made to Notre-Dame de Paris between the 1230s and the middle of the 14th century despite the completion of the central volume in the 1220s. These changes include the restructuring of the windows and attics along the clerestory and the gradual outward expansion of the building. Mainly, the transept arms were widened and side chapels were constructed between the buttresses along the perimeter of the cathedral. This study explores the acoustic effect the modifications to the transept and side chapels may have had on sound produced in the cathedral.

Keywords: room acoustics, cultural heritage acoustics, Notre-Dame de Paris

1. INTRODUCTION

Notre-Dame, the emblematic cathedral of the city of Paris, is an extraordinary monument of Gothic architecture with a storied history. Though the 2019 fire and plans around its restoration brought Notre-Dame de Paris back into the public eye, it is important to realize that large cathedrals such as Notre-Dame are "living" buildings, constructed and modified through centuries of development. Many multi-disciplinary projects are currently invested in detailing and preserving "intangible" cultural heritage [1, 2]. The present study focuses on the changes in the acoustics of Notre-Dame between the late 1220s and 1320s as the building was enlarged by expanding the transept and the construction of 35 chapels around the periphery of the cathedral.

Construction on the Cathédrale Notre-Dame de Paris began in the middle of the 12th century under the auspices of the bishop Maurice de Sully [3, 4]. By the year 1182, the apse-end of the cathedral was sufficiently completed such that the religious community began using the *chancel* (the holy eastern end of a church used by clergy) for religious ceremonies [5]. At this time, the vaulting above the chancel was not completed, and a temporary dividing wall would have separated the chancel from the yet-incomplete transept and nave. Around 1220, the body of the nave was completed, though nearly immediately, the cathedral underwent several significant changes. The clerestory windows and attics along the triforium level were restructured, the transept was enlarged and adorned with large, stained-glass rose windows, and 35 lateral chapels were added along the perimeter of the building between the buttresses [5, 6]. The acoustics of the earliest states of Notre-Dame (1160–1225) are discussed in [7], while the expansion of the transept and chapels (1225–1320) is the main subject of this study.

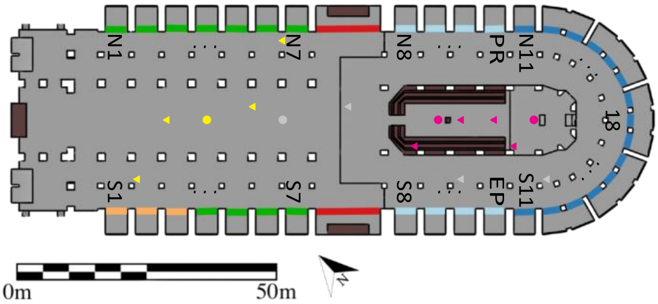

Figure 1 – Plan view of Notre-Dame between 1225–1320, showing the expansions in 1230 (red), 1240 (orange), 1250 (green), 1295 (cyan), and 1320 (blue). Source (•) and receiver (◂) locations used to calculate Figs. 2 and 3 are shown in magenta (apse), yellow (nave), and gray (not plotted).

2. CHANTRY CHAPELS

In the 13th century, many cathedrals built *chantry* chapels that were funded and used by private foundations [8, 9, 10]. These chapels served several purposes, including providing a locations for divine services, commemorating the dead, and displaying statues, stained-glass, and artwork for wealthy laypeople of the community. In Notre-Dame, the chapels were appended to the building in between the existing buttresses. While this structural limitation meant the chapels of Notre-Dame were relatively small and uniform in size (each about 5.2 × 3.3 × 10.3 m with an entrance approximately 30 m^2), many other French churches copied their style. Doquang [10] argues that the lateral chapels of Notre-Dame had a large effect on the use of the cathedral as there were many (sometimes simultaneous) daily masses held within them.

There is textual evidence that there were chantry altars in the aisles of Notre-Dame before the chapels were built [3, 9, 10]. In 1209, the clergy in Notre-Dame passed an ordinance regulating the schedule and timings of private masses inside the cathedral due to their disruptive noise [11]. Over the course of ≈ 95 years, 35 chapels were appended (see Fig. 1). Their construction were overseen by several distinct craftsmen across multiple construction campaigns. The first several chapels were built in the nave on the south

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side (S). Following this, the seven chapels were completed on the north side (N) and first 4 chapels on the south side were complete. All the nave chapels were likely finished by 1250. Following the construction of the nave chapels, the first three straight chapels along the apse were completed by the end of the 13th century. Finally, the remaining chapels, including the double and tripled bays curving around the end of the cathedral, were completed by 1320 [12].

3. MATERIALS AND METHODS

Reverberation time (T_{30}), early decay time (EDT_{15}), and sound pressure (L_p) were calculated from simulations using a geometric acoustic (GA) model of Notre-Dame at different points during its construction. T_{30} provides a general impression of the reverberant conditions while EDT relates more to the perceived reverberance while sound is being produced.

A calibrated model of modern Notre-Dame (ca. 2015) [13, 14] was used as a starting point. Modifications were then made to the model to reflect the state of its construction between 1225–1320, as was done in [7, 15]. Acoustic simulations were run using CATT-Acoustic (v9.1f, TUCT v2.0e) [16] using algorithm 1 (split order $N = 1$) with 350,000 first-order rays to compute 10 s impulse responses for the sources and receivers shown in Fig. 1. Acoustic parameter results were averaged across 5 runs to account for variation due to stochastic processes. Mapping simulations were also produced using 150,000 rays to compute 4 s of data on a 0.5 m grid across the main floor of the cathedral.

Six model states were selected spanning approximately 1225 to 1320. These states, summarized in Table 1, include the "finished" state of the building when the nave was completed in 1220, a version with the expanded transept, several intermediate states as the chapels were built, and the state in 1320 after all the side chapels were completed.

It is important to note that these dates, and the associated models, are speculative. By consulting primary sources and through forensic inspection, historians can still only hypothesize—and disagree—about the timeline of the construction of Notre-Dame [3, 4]. Construction is a slow, physical process, and only important dates, such as when an altar was dedicated, funds received/allocated, or construction commenced or ended, are typically recorded. Even with a wealth of documentation, there are many aspects to the history of Notre-Dame that historians and archaeologists simply do not know. Especially in the early phases of construction, it is also likely that multiple sections of the cathedral were built simultaneously, so choosing "stable" milestones is likely anachronistic.

In order to understand the influence of the expansion of the perimeter of the cathedral, decor and material properties in the cathedral were kept constant across versions of

Table 1 – Approximate model dates with volume (V) and sur-face area (S) for Notre-Dame simulated in this study.

Year	V (m^3)	S (m^2)	Notes
1225	79,345	28,800	Nave completed
1230	82,380	29,710	Transept widened
1240	83,815	30,125	S1–3
1250	86,605	31,635	All nave chapels
1295	87,540	32,690	N8–10 and S8–10
1320	90,795	34,425	All chapels

the model. The geometry of Notre-Dame in 1320 is substantially similar to that of the base 2015 model. The main differences are that the modern choir stalls and altar have been replaced with ones modeled after depictions such as Jean Marot's painting of the *Te Deum* and the work of historians such as [5]. Additionally, the modern pews and carpeting have been removed from the nave. Finally, the building was simulated in an unoccupied state.

4. RESULTS AND DISCUSSION

4.1 Chapels and Reverberation

Fig. 2 shows mean octave band T_{30} and EDT calculated from simulations of two omnidirectional sources and four receivers distributed throughout the choir. These sources (in the center of the choir and at the altar) and receivers (along the central line and in the choir stalls) were selected to give a general impression of the acoustic behavior in the space inhabited by the clergy of Notre-Dame. As the perimeter of the building was expanded, it seems likely that the reverberation time actually decreased. In all but the lowest 2 frequency bands, T_{30} and EDT drop by less than 5 % across the total time period considered.[1] In the 125–250 Hz bands, T_{30} decreases by less than 10 % and EDT decreases about 11 %. The choir stalls provide a substantial amount of early reflections, creating an acoustic subspace and leading EDT to be considerably lower than T_{30}. In the rest of the cathedral, EDT approaches T_{30} (see Fig. 3).

Between 1225 and 1320, the volume of the cathedral increased nearly 15 %, and the surface area by nearly 20 %. The fact that the surface area increased at a faster rate than the volume is one possible explanation for why the reverberation time decreased as the cathedral was expanded. That said, the expansion of the cathedral progressed at a gradual rate. Considering that 1 JND is the perceptual limit where a change is barely noticeable, it is reasonable to conclude that the opening of the chapels would have had a relatively minor effect on the perceived reverberation in the cathedral year by year due to the slow rate of construction.

In the current model, all side chapels have been modeled identically, however that does not truly conform to the

[1] 5 % is typically considered the JND for T_{30} and EDT [17], Though recent work [18] suggests that these limits for EDT may be too conservative.

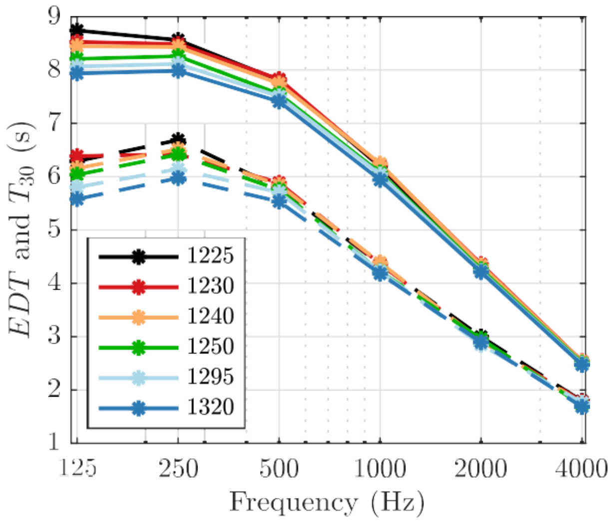

Figure 2 – Spatial average of Notre-Dame T_{30} (—) and *EDT* (- -) for source and receiver positions in the choir as a functionof building state.

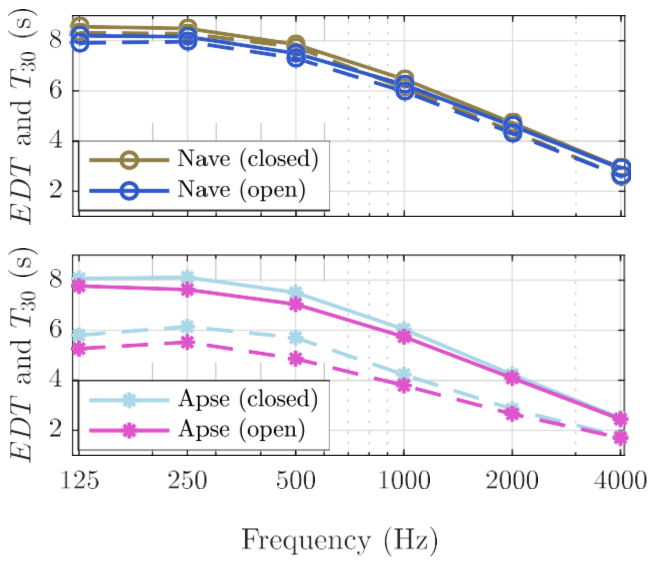

Figure 3 – Comparison of 1295 state T_{30} (—) and *EDT* (--)with open vs closed exterior walls in chapels S8–10 and N8–10. Source/receiver positions in the nave (top) and apse (bottom).

real cathedral. Since the chapels were sponsored by private foundations, each was ornately decorated by their benefactors. When the chapels were first constructed, they would likely have had plain windows that were gradually replaced with more ornate stained-glass over time [8]. Since so little is known about the early state of the chapels, it is interesting to consider the influence of the construction process on the reverberation time. Fig. 3 shows a comparison of mean T_{30} and *EDT* of the 1295 state with the outer wall of the chapels removed (i.e., 6 chapels open to the outside, modeled as fully absorbing). Here, it is possible to observe a 3–6 % reduction in T_{30} and a 10–15 % reduction in *EDT* from within the chancel. In the nave, further away from the holes in the building, the *EDT* and T_{30} change by 3–5 %, a much more modest amount. From within the chancel, this change in reverberation might be considered significant. Considering the rose windows in the transept took years to complete [5], the overall process of construction may have had a more significant effect on the reverberation in the cathedral than the end result of the expansion of the building.

4.2 Chapel activity and noise

It is also worthwhile to consider the effect of the use of the lateral chapels by chaplaincies. In the Middle Ages, there is evidence of a significant number of masses taking place at altars in the side aisles, and later at those of the lateral chapels [10, 11]. Fig. 4 shows a sound pressure level map across the cathedral in the 1225 and 1320 states for a single source at either an altar in the side of the cathedral in the apse or nave. Considering the sound of a chaplain saying a private mass, a vocal directivity pattern [19] and speech spectrum of a male voice speaking at a normal level [20] were used. For the 1225 model, the altar is assumed to be facing the external wall of the cathedral (north), while for the 1320 model, the altar is positioned on the wall facing liturgical east. As the differences can be challenging to see, Fig. 4 also shows the difference between the two conditions.

Beyond the longer reverberation time in the 1225 model, the mapping results demonstrate a slightly elevated background noise level (2–5 dB; L_p JND ≈ 1dB) in the ambulatory when a source is in the aisle in contrast to a side chapel. When considering a sound source in the nave, this effect is surprising given the large distance between the source in the nave and the receivers in the ambulatory. In light of the documented concern of the clergy with the noise level produced by the chaplaincies [10], it seems like the construction of side chapels may have helped mitigate noise issues, even if by a small amount.

5. CONCLUSION

This study explored the relatively minor change in reverberation time seen in Cathédrale Notre-Dame de Paris between the years of 1225 and 1320 as 35 lateral chapels were constructed around the perimeter of the building. T_{30} and *EDT* likely decreased throughout this time period, but by a relatively small amount (5–11 % in total). When the exterior walls of 6 chapels were removed entirely, as could have been the case during construction, the *EDT* for source/receivers in the chancel decreased by a more significant amount (10–15 %) while the T_{30} only decreased by 3–6 %. In the nave, further away from the open walls, both T_{30} and *EDT* for source/receivers there decreased by less than 5 %. Other factors likely had a more significant effect on the acoustics of the cathedral, such as tapestries and other adornments that would be displayed during holiday celebrations, and the occupation of the space during daily activities in the Middle Ages. These questions are the subject of future studies currently in preparation. Finally, a sound source within

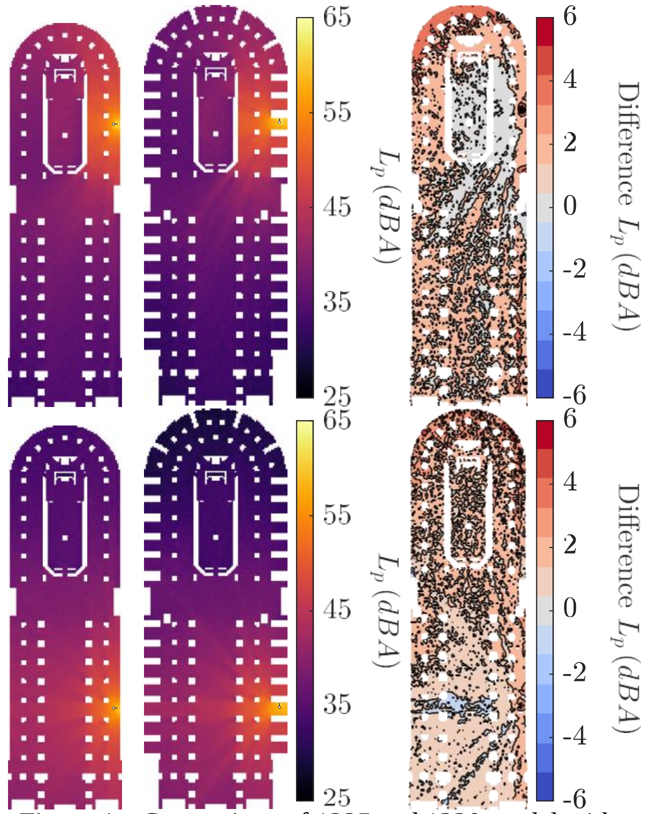

Figure 4 – Comparison of 1225 and 1320 model with source located in the aisle vs side chapel, and their difference (the level of the 1225 state minus the level of the 1320 state). Source in the apse (top) and nave (bottom).

a side chapel radiates differently throughout the cathedral compared to a source located in the aisle.

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Virtual reality inside the Greek-Roman theatre of Tyndaris: comparison between existing conditions and original architectural features.

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ABSTRACT

Archeoacoustics has become a field of great interest in the last decades, which has constantly bridged the knowledge of three main disciplines: acoustics, archaeology, and computer simulation. This synergy is considered very beneficial when the cultural heritage subject to be studied is a historic construction of the Roman or Greek Age. The case study relies on the reconstruction of the acoustic conditions of the theatre of Tyndaris, located in Sicily, South of Italy. This paper deals with the application of the Ambisonics methodology to recording audio in combination with the panoramic view taken in one of a few selected locations across the theatre. The sound signal during the post-processing has been auralized in two digital environments: the existing conditions and the original reconstruction. The absorption coefficients of the digital models have been calibrated with Ramsete based on the measured results. The difference between the two outcomes has been compared.

Keywords: Virtual reality, Ancient theatres, Auditory VR

1. INTRODUCTION

The virtual acoustic reconstruction of archaeological sites opens the possibility to experience new feelings of immersive visits by including a dynamic audio to the playback recordings [1]. This paper deals with the virtual exploration of a 3D soundfield applied to the Greek-Roman theatre of Tyndaris.

From a site survey, several impulse responses (IRs) of the existing conditions have been gathered [2]. In order to proceed with the auralization, different phases were considered necessary to achieve the objectives, as summarised below:

- Selection of a recording sample undertaken under anechoic conditions;
- Realization of a acoustic model to be calibrated with the measured IRs;
- Elaboration of 3rd Order Ambisonics (3OA) IRs gathered by the digital model;
- Convolution of the anechoic signal with the 3OA digital IRs;
- Creation of binaural soundtracks to be listened to by using a Head Mounted Display (HMD) device, or similar.

The immersive listening experience has been realised by combining the audio output with a visual rendering, consisting of panoramic images taken at the specific locations selected for the acoustic measurements [3].

Before gathering the 3OA IRs related to the original shape of the theatre, a calibration process of the absorption coefficients has been carried out with the 3D model representing the existing conditions.

2. ENVIRONMENTAL BACKGROUNDS OF THE SITE

2.1 Original Construction

The town of Tyndaris is located on the northern coast of Sicily, Italy. The theatre was built by Greeks during the 4th century BCE, having an original capacity of 3000 seats [4]. It represents one of the few Hellenistic monuments who survived as an important document of the architectural traditions. The original construction was composed of a cavea having a diameter of 76 m, and the orchestra of 23 m width [4]. The Hellenistic scene remained untouched during the Roman period but has been destroyed during the Middle Age.

2.2 Existing Conditions

During the 1st century BCE, the Romans modified the theatre into an arena by lowering the level of the orchestra of 0.9 m and by destroying the first four steps of the *cavea* to build a podium of 2.5 m height [4]. This represents the main change with respect to the Hellenistic construction.

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Nowadays, the damage of further architectural elements compromises the faithful integrity of the original acoustics as it should be perceived inside the Hellenistic theatre. The absence of a scenic building useful to support the sound reflections and the deterioration of the stone as finish material of the *cavea* determine a noticeable change.

3. DIGITAL MODELS

3.1 3D Model of the actual condition of the theatre

The numerical model has been realised in AutoCAD software by the creation of 2261 3D faces. The AutoCAD layers have been grouped based on the existing finish materials and architectural components and then exported in dxf format, ready to be used for the acoustic calibration. The software chosen for the calibration and simulations is Ramsete 3.02.

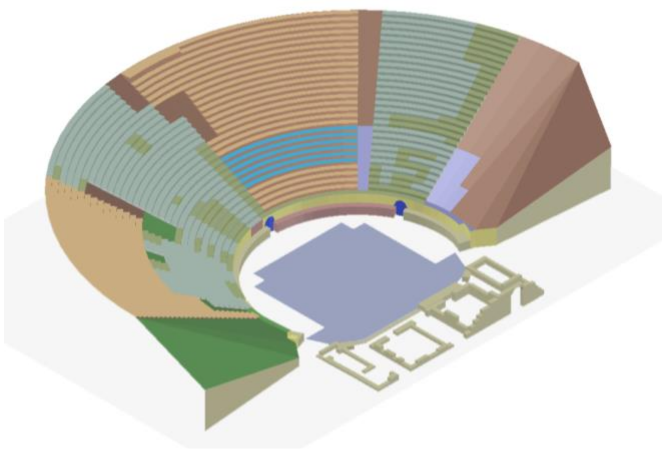

Figure 1 – View of the 3D model representing the existing conditions of the theatre of Tyndaris.

The calibration process of a digital model consists of a loop procedure of room acoustic modelling to increase the accuracy of the simulated results. As such, the absorption coefficients have been tuned based on the measurements undertaken in situ [5]. Figure 1 shows the digital model representing the existing conditions of the theatre.

3.2 3D Model of the Hellenistic shape of the theatre

Based on archaeological anastylosis and previous literature, a digital model of the theatre representing the Hellenistic architectural features has been realised similarly to the model representing the existing conditions.

The main differences with the current configuration are in the cavea, that has been taken back to the original perfectly circular shape, altered in the following centuries by the gradual sliding of the soil, and in the scenic building that stands behind the orchestra providing a wide reflective surface. The Roman podium has been removed and four steps has been added in its place.

Figure 2 shows the digital model representing the Hellenistic shape of the theatre.

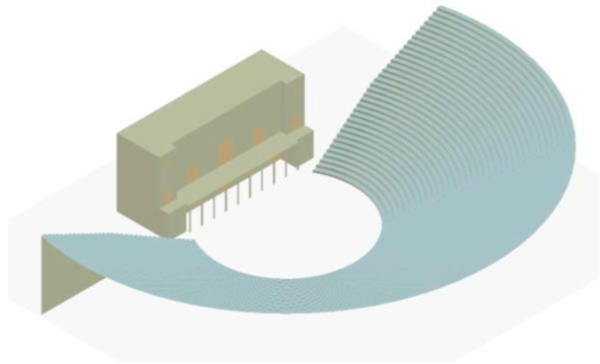

Figure 2 – View of the 3D model representing the Hellenistic shape of the theatre of Tyndaris.

4. IMMERSIVE AUDIO APPLICATION

Once the absorption coefficients of the 3D models have been calibrated, the 3OA IRs can be gathered with Ramsete and be exported in B-Format [6]. The 3OA IRs represent the environmental conditions of the two "room" types to be used for the convolution with anechoic recordings of speech and/or music. The convolution of the sound signal with the IR has been developed by using the plugin Aurora suitable for Audacity software [7].

The sound signal selected for the convolution is a faithful reconstruction of a musical performance reflecting the composition written by Euripides for the choir of Orestes in 408 BCA [7].

5. VISUAL COMPONENT AND VR REALIZATION

A 360° view taken at each receiver position has been considered as the visual rendering, although the use of photogrammetric scan would be improving the fully immersive experience.

The panoramic photos having equirectangular format have been associated with the corresponding 3OA IRs. The panoramic photos have been converted into a .mov file by using FFmpeg software. The combination of the 3OA audio with the image/video has been realised with the extended version of Spatial Media Metadata Injector modified by Prof. Farina to accept HOA audio files. The results are stored in video files with proper metadata which allow them to be watched with an HMD (such as an Oculus Quest 2) or on Youtube.

Figure 3 – Rendering of the 3D model representing the existing conditions of the theatre.

Figure 4 – Rendering of the 3D model representing the Hellenistic shape of the theatre.

Figures 3 and 4 show the rotation of the immersive experience taken at the same position in the cavea, related to the existing conditions of the theatre.

6. CONCLUSIONS

The archaeological sites have always been investigated under an architectural perspective throughout the centuries. It is practice of recent decades to make the ancient monuments usable to community by exploring the VR composed of audio-video rendering.

On this basis, this paper explains how a 3OA audio file can be merged with a panoramic view of the theatre of Tyndaris. Two 3D models have been explored and compared, in particular the existing conditions and the Hellenistic shape. The audio files have been gathered from the IRs elaborated with Ramsete after a calibration process of the absorption coefficients with the measured values. Thereafter, the 3OA IRs have been convoluted with a sound signal reproducing a musical/vocal performance.

While future research will be focusing on the photogrammetric scan of the archaeological sites, at this stage the available tools are 360° photos taken at each position of the acoustic measurements across the cavea. The panoramic views have been transformed into .mp4 files by using the software FFmpeg Thereafter the 3OA audio has been combined with the video using the same software. Then the metadata have been modified with Spatial Media Metadata Injector so that the video can be read in 360° format with spatial audio. The result is a 3 degree of freedom (3dof) VR that faithfully reproduces the directivity of the sound in combination with the visual exploration.

ACKNOWLEDGEMENTS

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Acoustic design optimization through the use of auralization: how does it sound?

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ABSTRACT
The reuse of ancient theatres has been widely debated among acousticians; many of them still do not have functional activities due to the lack of acoustic comfort. Scope of this paper is to optimize the project of an acoustic shell using audio renderings played inside the VR environment. The sound signal was auralized in 3rd OA and played in two numerical models: the digital reconstruction of the Hellenistic configuration and the proposed acoustic project. A comparison between the two products has been then assessed by 12 students.

Keywords: Adaptive reuse, Ancient theatres, Auditory VR

1. INTRODUCTION
Recent years have seen a growing interest in the use of virtual reality, together with specialized audio, to make our cultural heritage more accessible [1]. Another possible application of these tools is the evaluation of the effect of architectural interventions on the acoustic performance of historical buildings during the design process [2].
This paper proposes a procedure to integrate ambisonic auralization in this task and describes how it was applied in the project of adaptive reuse of the ancient theatre of Tyndaris. A description of the geometry and the materials employed for the proposed acoustic shell is also introduced.

2. FRAMEWORK OF THE CASE STUDY
The ancient theater of Tyndaris is situated on the northern coast of Sicily, on a promontory facing the spectacular view of the Tyrrhenian Sea from a height of 180m. It is surrounded by the remains of the city of Tyndaris, founded in 396 BCE by the Greeks as a colony for exiles of Messenia (modern Messina).
Its shape has changed considerably during the centuries: in the 4th century BC a scenic building was added in front of the cavea while during the late imperial age of the roman empire, it underwent substantial changes necessary to be able to perform gladiators' spectacles and fights against ferocious animals.
Destroyed by a landslide and two earthquakes, Tindari saw the light again thanks to some archaeological excavations that started in 1838 and resumed later on between 1960 and 1998.
Today the theater is hosting concerts once again, but its current acoustic performance is compromised by many factors: the lack of the original scenic building, responsible of useful reflections supporting the actor's voice, the absence of a large part of the steps of the cavea and the general deterioration of the materials, impacting the reflectivity, and the increasing noise levels of the surroundings due to traffic.

3. CREATION OF THE MODELS
The study makes use of the results of a previous research, which has validated an acoustic model of the current deteriorated state of the theatre by matching the acoustic parameters obtained in the virtual simulation with those obtained by real on-site measurements [3].

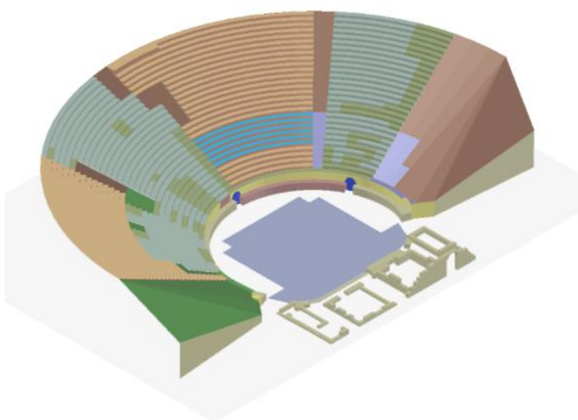

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Figure 1 – Axonometric view of the calibration model of the theatre of Tyndaris showing the mapping of the materials.

3.1 Hellenistic configuration

From the baseline of the calibrated model, shapes and materials were modified to create a virtual reconstruction of the Hellenistic configuration of the theatre [4].

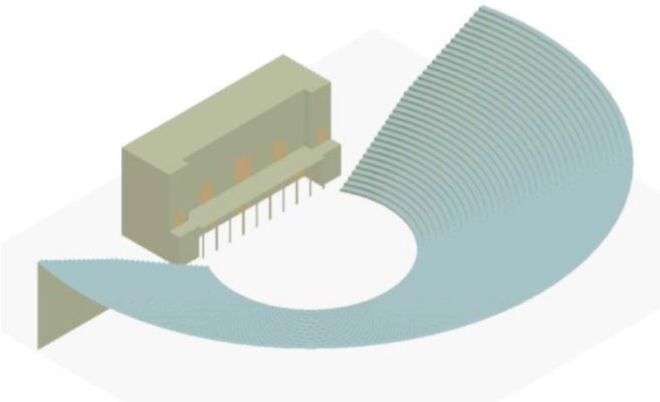

Figure 2 – Axonometric view of models used for the simulation of the Hellenistic configuration.

3.2 Proposed acoustic project

The solution chosen for the project of adaptive reuse was proposed in 2016 by Giovanni Bouvet. Its consists in a new scenic structure that take advantage of the Canac Laws to create early reflections that can contribute to the perceived loudness of the signal [5].
The curved shape of the reflector was generated by an evolutionary solver, Galapagos, a plugin for Grasshopper deploying computational morphogenesis, using a simple ISM (Image Source Method) algorithm, partially based on François Canac's studies.
The structure was designed taking into account recommendations of the Syracuse Charter [6], asserting that temporary structures can integrate the gaps in order to optimise the acoustic performance: the modular approach allows for a lightweight removable structure, that doesn't impose any permanent impact on the archeological site [5].

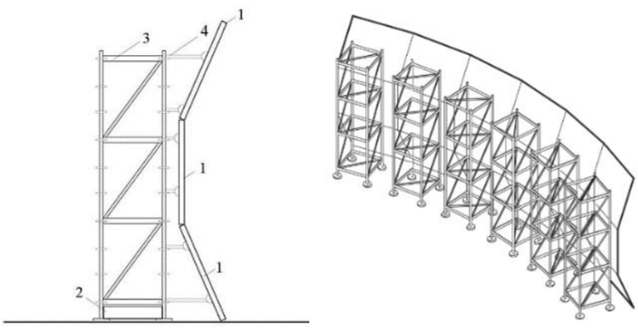

Figure 2 – Structure of the acoustic shell

4. OPTIMIZATION THROUGH AURALIZATION

The dimensions and materials of the acoustic shell were modified to find the configuration that was more effective in recreating the contribute of the original scenic building to the sound field of the theatre.
A summary of procedure for the optimization of the acoustic project is presented here with the names of the specific software utilized in this case, but the general workflow can be applied using many other applications:

1. Define the expected values for the quantitative parameters (T20, G, C50, C80).
2. Define a geometry for the project.
3. Cad modelling in Autocad and export in .dxf format.
4. Import into GA software Ramsete [7].
5. Add source and receivers.
6. Define absorption and scattering coefficients.
7. Trace and check the values of the quantitative parameters. If they are not comprised in the attended range, go back to steps (6.), or (3.) if major changes are needed.
8. Export IR and choose a sample for convolution.
9. Convolve IR and chosen sample with Aurora Convolver, a plugin for Adobe Audition and Audacity, or X-MCFX [8] for real time convolution in any DAW.
10. Mux audio with the 360° video (which in this case was made with the equirectangular rendering function in Blender) with FFmpeg.
11. Inject the proper metadata with Spatial media Metadata Injector.
12. Proceed to the evaluation of the project through listening tests. View the resulting 360° video with a HMD (such as an Oculus Quest 2).

Figure 3 – Rendering of the 3D model of the theatre in the current state with the addition of an acoustic shell.

Figure 4 – Rendering of the 3D model of the theatre in the Hellenistic configuration of the theatre.

5. LISTENING TESTS

The videos resulting from the optimization phase were evaluated by 12 students with different levels of musical education. The subjective parameters considered in the questionnaire where: loudness, reverberance, apparent source width, definition, distance, and coloration.

Three different anechoic samples were chosen for the auralizations: an instrumental music sample, a speech sample and a soprano singing.

6. CONCLUSIONS

The conjunction of VR and spatialized audio can provide new insides on the projects of adaptive reuse beyond what the analysis of objective parameters can tell us. It can also allow more people to appreciate the protentional results of architectural interventions on the sound quality in ancient theatres [9].

The comparison between the values of subjective and objective parameters for the reconstructed Hellenistic configuration and the project solutions chosen, shows that an optimised acoustic shell can recreate part of the contribution that the scenic building had on the theatre before its collapse, but it can’t counterbalance the effects of the high degree of deterioration of the cavea on the sound field of the theatre.

Currently the procedure allows an immersive experience with three degrees of freedom (3DoF), further development will be focused on reaching 6DoF, making it possible to move around the virtual reconstruction of the site.

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The funding for this study has been provided by the European Union’s Joint Programming Initiative on Cultural Heritage project PHE (The Past Has Ears, phe.pasthasears.eu).

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Preliminary analysis of vocal ensemble performances in real-time historical auralizations of the Palais des Papes

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ABSTRACT

In the middle of the 14th century, the recently constructed Great Clementine Chapel of the Palais des Papes had a flourishing reputation for the composition and interpretation of polyphonic singing in the emerging Ars Nova musical style. In modern times, the space is still employed for musical performances. However, the acoustic conditions between the two periods vary greatly, and as such, can be expected to have an impact on vocal performances. As part of the IMAPI and PHE projects, the impact of the acoustics of the Great Clementine Chapel on the performance of a conducted vocal ensemble specializing in medieval music was examined for these two periods. A numerical simulation of the medieval acoustics was developed, based on a calibrated geometrical acoustics model of the modern-day chapel which was then regressed in time to a historically informed medieval state. Experiments were carried out with singers performing repetitions of several pieces in a Virtual Acoustic Environment (VAE) using close-mics and headphone renderings. Recorded performances were analyzed using various metrics, with objective results paired with questionnaires acquired for each VAE condition. Preliminary analysis of these results is presented in this study.

Keywords: cultural heritage acoustics, virtual acoustic environment, vocal ensemble performance

1. INTRODUCTION

1.1 The Palais des Papes in the 14th century

In 1309, the Holy See relocated to Avignon, France, where Pope Clement V established his residence, remaining there until 1403 [1]. Construction of the Palais des Papes, which is the largest Gothic edifice ever built, started in 1335 under the pontificate of Benoît XII, was continued by Pope Clement VI from 1342, and was completed in 1352. Masses accompanied by music performance, especially polyphonic singing, were usually performed in the Great Clementine Chapel (a.k.a. Great Chapel). The Great Chapel attracted music composers, cantors, and musicians, particularly those belonging to the movement known today as the Ars Nova style. Ars Nova is a polyphonic musical style that developed in France in the 14th century as the successor of the Ars Antiqua exemplified by the School of Notre-Dame. It allowed for a higher degree of musical expressiveness and for more elaborate rhythmic modes due to a new standardized system of musical notation, even though some studies have shown that interpreting Ars Antiqua and Ars Nova as two radically different styles is probably excessive [2].

1.2 The impact of room acoustics on musical performance

Practitioners of choral music have long been aware that room acoustics play a significant role in musical performance [3]. However, despite this awareness, there has been no unified approach or theory to guide performance practice in response to different acoustic environments. In fact, while empirical studies have shown measurable effects on musical performance as a result of changes in acoustics, these effects tend to be rather small and/or individual [4, 5]. In short, it is still not well known precisely how room acoustics affect musical performance, and the evidence within the context of historical music is even less sufficient.

This study aims at assessing the impact of room acoustics on the musical performance of the conducted vocal ensemble *Diabolus in Musica*, consisting of three male vocalists (one baritone and two tenors) trained in medieval performance methods and with familiarity singing in the modern-day Great Chapel of the Palais des Papes.

2. VIRTUAL ACOUSTICS OF PALAIS DES PAPES

The acoustics of the Great Chapel of the Palais des Papes in two historical states, namely medieval (ca. 1362) and modern (ca. 2020) states, were generated through geometrical acoustic (GA) models designed in CATT-Acoustic v9.1e.

For that, the geometry of the room was first designed with reference to a 3D laser scan point cloud. Then, the definition of the construction materials of the modern-day room was carried out through an acoustic calibration procedure [6], in which the acoustic properties of the materials were adjusted until various acoustic metrics fell within the range of ± JND of the measured acoustic values, based on recorded room impulse responses.

Next, a GA model of the medieval state of the Great Chapel was obtained by carrying out a time regression of the

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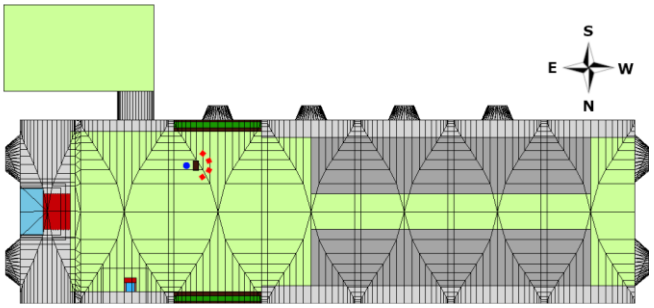

Figure 1 – Top-down view of the modeled Great Chapel in the medieval state. The various materials are represented by different colors. ■: singers; ●: conductor; ı: lectern.

modern-day GA model with the help of historical records of the interior furnishing and decoration from that time era [7]. The presence of absorbing materials such as wall tapestries, floor rush matting, stalls, pews, the pope's throne, cloth on top of the altar and the stalls, and canopies above the altar and the pope's throne (represented by different colors in Fig. 1) make the medieval Great Chapel significantly less reverberant than the modern-day Great Chapel which is, essentially, a large empty shoe box made of dense limestone. A comparison of the reverberation time between the two historical states of the Great Chapel is shown in Fig. 2, including the presence of a simulated audience which tends to reduce the reverberation time.

3. SINGING EXPERIMENTS

The experiments were aimed at assessing the impact of the acoustics of the Great Chapel under different conditions on the musical performance of the vocal ensemble *Diabolus in Musica*. It was therefore important to provide the singers with performance conditions that were as close as possible to a real concert situation, while allowing for an audio recording quality sufficient to be used for further objective analysis (see Section 4). The experimental setup used in this study was guided by findings in [8].

3.1 Hardware setup

The singing experiments were carried out in a hemi-anechoic room at the PRISM laboratory in order to reduce interference of the recording room as much as possible. Singers were each equipped with a close microphone (head-band cardioid microphone, DPA4088) in order to reduce the level of inter-singer crosstalk while having them distributed close together in a usual concert configuration. Virtual Acoustic Environments (VAEs) were reproduced for each individual singer over open-back headphones (Sennheiser HD650). Open-back headphones were chosen as they allow the direct sound from one's own voice and from other singers to pass through relatively unobstructed, while the reverberated voice sound is reproduced inside the headphones. The ratio between direct and reverberant sound levels was adjusted prior to the experiments through a calibration procedure to achieve realistic balance [9].

3.2 Auralization system

The VAEs were auralized via convolution with pre-rendered Binaural Room Impulse Responses (BRIRs) from the GA models with the direct sound removed. Each singer playing the role of a source and a receiver at the same time, the reproduction system included a total of $3 \times 3 = 9$ BRIRs for 3 singers, to which 3 extra BRIRs intended for the conductor were added, for a total of 12 BRIRs (i.e. 24 convolutions). The computational cost of such a reproduction system is of concern, especially considering that the BRIRs in the modern-day Great Chapel are 10s long in accordance with the reverberation time in the lowest octave band (see Fig. 2). The auralization architecture was created in MaxMSP to facilitate real-time processing. The convolution was done using the object `multiconvolve` from the HISS Impulse Response Toolbox[1] which employs a fixed partitioning scheme. The system was configured with an internal audio buffer size of 64 samples at 48 kHz, corresponding to an I/O delay of 1.3ms, without artifacts. This delay was compensated for by removing the 64 leading zeros in the BRIRs, providing correct time synchronization between the natural direct sound and the virtual reverberated sound.

3.3 The VAEs

The VAEs used in this study differ in their historical state, namely medieval (ca. 1362, when the Great Chapel was actively used for papal masses) and modern-day (the Great Chapel is still used as a performance space for concerts of vocal ensembles). The choir was positioned in the third bay starting from the east (the *parcus cantorum*, which included stalls in the medieval era), halfway between the chapel symmetry axis and the southern wall. The singers were distributed along an arc spanning 90° centered on the position of a virtual lectern and at a distance of 1.2 m. Sources were simulated with the singing voice directivity pattern `singer.SD1` from CATT-Acoustic, pointing at the

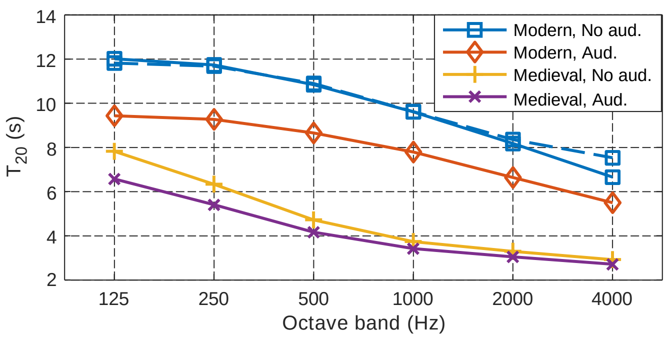

Figure 2 – Estimated T_{20} as a function of frequency band, averaged across sixteen positions evenly distributed along the Great Chapel. For the modern, unoccupied state, the measured (– –) and modeled (—) T_{20} s are shown.

[1] http://eprints.hud.ac.uk/id/eprint/14897/

virtual lectern with the conductor facing them. The positions of the singers and conductor are shown in Fig. 1.

3.4 Experiment protocol

The repertoire comprised two pieces of polyphonic music from the Ars Nova style: "Petre Clemens" by Philippe de Vitry, and "Kyrie Rex Angelorum" (anonymous). The recordings were organized in separate sessions, each rendering either the medieval or modern-day room. In each session, the music pieces were interleaved and repeated 3 times. To compensate for a slightly different positioning of each individual singer's microphone, each microphone gain was adjusted at the beginning of each session to ensure a good consistency between individual singers' voice levels in the overall rendered audio scene. After each session, the participants answered a questionnaire on their subjective experience regarding the simulated acoustics and their performance in that particular space.

4. MUSIC PERFORMANCE ANALYSIS

Features were extracted from recordings of the performances which can be broken down into four musical categories: timing, dynamics, timbre, and pitch.

To represent timing, the note-level tempo was calculated by taking the inverse of the time interval between the onsets of adjacent notes weighted by the written note duration. The note onsets were obtained by manual annotation of one performance followed by audio-to-audio alignment using the `Match` plug-in[2] in Sonic Visualizer[3] followed by manual verification and adjustment.

A-weighted RMS was chosen to serve as a measure of musical dynamics or loudness. As a simplified measure of timbre, the spectral centroid was calculated. The spectral centroid represents the center of gravity of the spectrum and has been shown to be strongly correlated with the perception of a signal's "brightness" [10]. Both the spectral centroid and A-weighted RMS were extracted as time-series vectors with a window size of 2048 samples and a hop size of 10 ms. These vectors were later shortened to a grid of 8th note durations utilizing the note onset information necessary for calculating tempo. The 8th note segments corresponding to rests in the score were removed prior to analysis.

The fundamental frequency of each singer's performance, which was necessary to calculate higher level pitch-related features, was extracted using the `pYin` algorithm [11] in Sonic Visualizer. Because vibrato is a common expressive tool for singers, both the vibrato rate (mean pitch variation rate, in Hz) and vibrato extent (mean absolute distance to the note pitch center, in cents) were calculated on all notes with a duration ≥ a dotted-quarter.

Other researchers have used pitch drift, or the amount the pitch center changes throughout the course of the piece, as an indicator of overall ensemble intonation [5]. However, some amount of pitch drift is normal and may simply be the result of an unaccompanied ensemble singing in a non-equal temperament [12]. So, rather than using pitch drift as a measure of intonation, normalized pitch error was used. Normalized pitch error describes individual note intonation compared to its nominal pitch adjusted for overall pitch drift; a slight modification of the methodology outlined in [5].

5. RESULTS

As a preliminary analysis of the data, box plots were produced for each feature to examine whether or not there was a significant difference between the two acoustic settings. No significant differences were found with the exception of the loudness feature which indicated that each singer sang louder overall in the modern acoustics (see Fig. 3), however, the average difference was only 1.2 dB± 0.2 dB in "Kyrie Rex Angelorum" and 0.8 dB $\pm$ 0.5 dB in "Petre Clemens". A Friedman test with singers as blocks and acoustics as group variable showed that these differences were statistically significant ($p < 0.001$ for both pieces). This greater vocal effort may be partly as compensation for the more reverberant nature of the modern acoustics, however, given that the difference is so small, too much emphasis should not be put on this finding at this time.

Rating questionnaires were given to the participants which asked about the following categories: reverberation, ease of ensemble singing, sound support, quality of the space, and size. No broad consensus was reached in any of these categories with the exception of reverberation, in which all the participants correctly ascertained that the modern state was more reverberant than the medieval state.

In addition to the questionnaire, participants were also encouraged to provide commentary freely which indicated some preferences. Two participants reported that the acous-

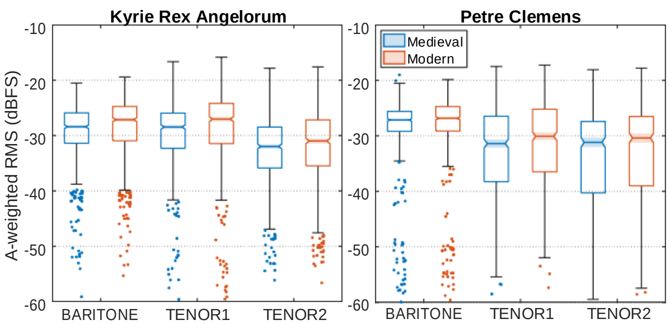

Figure 3 – Box plots of loudness measure in medieval (blue) and modern (red) acoustics by voice, for "Kyrie Rex Angelorum" (left) and "Petre Clemens" (right). Whiskers extend from upper & lower quartiles to non-outlier maxima and minima.

[2] www.eecs.qmul.ac.uk/~simond/match/index.html
[3] www.sonicvisualiser.org

tics of the medieval state were more satisfactory than that of the modern state to the interpretation of complex polyphonic music. One participant reported that singing in the modern state was less demanding than in the medieval state. In accordance with his previous singing experiences, this individual claimed to sing with less diligence in the modern state than in the medieval state, and that a longer reverberation time is more forgiving of small inaccuracies and defects in a performance, as heard from the audience. He also mentioned that as a listener, he would prefer the medieval state because it was "musically more satisfying". Despite their open design, two participants reported an unwanted "filtering" effect of the headphones , producing experimental conditions somewhat less comfortable than normal situations. Although open headphones let external sounds pass through, they still attenuate high frequencies, coloring the sound of one's voice, and the direct sound of the other singers.

6. CONCLUSION AND FURTHER WORK

In this study, all participants were able to correctly identify the more reverberant VAE indicating some perceptual validation of the auralization. However, there were some complaints about the usage of headphones which leaves room for improvement in future performance auralizations. There was no consensus as to which acoustic setting was optimal for the performance of music in the Ars Nova style.

Timbre, tempo, intonation, and vibrato did not seem to have been significantly affected by the acoustics. There is an indication, however, that the singers sang louder in the more reverberant modern configuration of the Great Chapel, but more data would be needed to strengthen this conclusion as it may be somewhat dependent on the style of the musical composition. Additionally, the impact of the acoustics on ensemble-specific features like inter-singer synchrony and intonation could be of interest in future analysis.

Finally, there are still recordings from this experiment which have not been analyzed, including those of a 4-voice ensemble interpreting a repertoire comprising one piece of monodic Gregorian chant and an additional choir configuration and position in the two acoustics. Analysis of these recordings could strengthen some of the preliminary findings of this paper as well as shed light on additional trends which may be a function of these additional variables.

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Directivity of a Small Pipe Organ Buffet

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ABSTRACT

While the radiation pattern of small instruments can be measured in anechoic chambers, it is challenging to study the directivity of large, unmovable instruments such as pipe organs associated with cultural historic sites. The soundfield outside an organ buffet is the result of the convolution of the sound of the pipe with the surrounding scattering system, the enclosing cavity of the instrument, and the apertures between the pipes in the façade of the instrument. The directivity of a small, proxy organ buffet consisting of a plywood enclosure with PVC pipe scatterers was studied in an anechoic chamber using omnidirectional and cylindrical loudspeaker sources. This proxy buffet grants access to modeling parameters such as the pipe spacing and density. These laboratory measurements were then compared to *in situ*, free-field directivity measurements of the same sources inside a real positive organ buffet of comparable size and shape located inside a church.
Keywords**:** musical acoustics, pipe organ acoustics, directivity

1. INTRODUCTION

Pipe organs are among the largest musical instruments in western tradition. In addition to often being located in historical, cultural heritage locations like churches, the instruments themselves are unique historic monuments. The sound of these instruments is intrinsically linked to their host buildings, and their design is tailored to the specific locations where they are installed. The cultural importance of organs has also been recognized by UNESCO, which has inscribed several organs and organ-builders in the Representative List of the Intangible Cultural Heritage of Humanity in 2017 [1]. Over the last several decades, studies have explored possible improvements to the instrument [2] and means of understanding how people may acoustically interface with these complex sources [3]. Nonetheless, while the radiating field of pipes [4] and sound intensity distributions [5] have been widely studied, pipe organ façade directivity patterns starting from the buffet are not widely presented in the literature, with the exception of the swell [6].

The current study investigates the radiation patterns corresponding to small organ buffets. Because organs have intricate internal geometry, several approaches were taken. First, a small proxy organ buffet was measured in anechoic conditions. This proxy was designed (as part of a larger study) to reduce the complexity to a 2D problem [7]. Measurements were conducted with a line-array source (from here onwards referred to as the 2D proxy) and an omnidirectional source (3D proxy). Subsequently, the positive section of an organ was measured *in situ*. Finally, some observations were verified with computer simulation.

Section 2 provides details on the measurement process. The radiation patterns are presented and analyzed in Section 3, followed by concluding thoughts Section 4.

2. EXPERIMENTAL SETUPS AND METHODS

The **proxy** organ was composed of a 134 × 98 × 58 cm box made of 1.5 cm thick plywood panels, and is capable of holding up to 170 foam-filled PVC tubes (Fig. 1a). The tubes all have the same diameter (4 cm) and are arrange in a staggered grid with 8 cm center-to-center separation (5.7 cm on the diagonal). This arrangement, along with the decision to make the tubes the same height as the box, was selected to reduce the modeling complexity to a 2D problem. The directivity of the proxy was measured with 34 tubes randomly removed to approximate the non-uniform pipe placement inside a real organ. Additional measurements were made with other pipe arrangements (e.g., empty, 50 %, full, pipes only in the façade, etc.) [7].

The **positive** of the Suret organ in Église Sainte-Élisabeth-de-Hongrie de Paris has a buffet similar in size and shape to the proxy described above [8, 9]. The positive protrudes off the tribune level (6 m off the floor) and radiates into free space in the nave (Fig. 1b). It is composed of a wooden box (255 × 230 × 100 cm), housing 58 tin-lead alloy pipes per rank. For aesthetics, the facade contains three evenly spaced towers that protrude in the center and the edges. The wind-chest provides pressurized air (at 804 Pa) to ≈ 500 pipes, organized in 10 stops.

The proxy was measured under anechoic conditions and the positive only *in situ*.[1] In both cases, the systems were excited with exponential sine sweeps. Two types of excitation sources were used: a line array of 18 Aurasound NSW2-326 (as a cylindrical source) for the 2D problem and a Dr. Three 3D-032 dodecahedron (as an omni source) for the 3D setup. In all the cases studied, the loudspeakers were po-

[1] The reverberation time (T_{30}) of St. Elisabeth, measured in octave bands 125–4000 Hz, is [2.7, 3.1, 3.5, 3.5, 3.0, 2.2].

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sitioned near the center of the rear wall and at mid-height in the cavity. The sources were clamped to fixed positions in the buffets non-invasively. Sound pressure was measured with omnidirectional measurement microphones (BAMT1). The proxy was measured in the horizontal plane radially at a distance of 150 cm in $\vartheta = 10°$ angles ($\pm 70°$ (see Fig. 1a); 14 measurements) and linearly at a distance of 2 m with a 5 cm spacing, yielding a maximum angular resolution of $\vartheta < 1.4°$ (29 measurements) for the frontal region between $\pm$ 19°. The positive was measured in the horizontal plane linearly across the width of the nave of St. Elisabeth at a distance of 180 cm with a spacing of 20 cm yielding a maximum angular resolution of $\vartheta < 5°$ (44 measurements) spanning $\pm 65°$ (see Fig. 1b).[2]

In post-processing, recorded sweep responses were deconvolved to obtain impulse responses (IRs) for each microphone location. These IRs were compensated in time and level according to the relative positions of the microphones to the source to achieve angular results with constant radii. Then, the IRs were time-windowed to avoid wall reflections. Two window lengths were used: one for the transient state without wall reflections (4.7 ms) and another one for the system's steady-state operation including reflections (208 ms)—the former was imposed by the microphone position closest to the walls. Proxy measurements were equally windowed accordingly to the same lengths. Octave band RMS levels were calculated (125–8000 Hz, Chebyshev filters (−40 dB stopband, 0.5 dB passband ripple)).

(a) Proxy buffet in anechoic chamber.

(b) Positive buffet in St. Elisabeth d'Hungary. Grand organ, showingpositive section in inset.

Figure 1 – Images of measurement setups.

3. RESULTS AND DISCUSSION

Octave band results are shown in Figs. 2 to 3.[3] The directivity patterns are plotted with polar coordinates and normalized in the 0° direction. The wideband pressure (WB) is included with a −10 dB offset for visual clarity.

The horizontal directivity of the 3D proxy organ is shown with a resolution of 10° over a total span of $\pm 65°$ for both short and long windows (Figs. 2a and 2b). Fig. 2c shows the horizontal directivity measured with the cylindrical source in the same proxy buffet, but with pipe densities of 50 % and 100 %. These results are shown with higher angular resolution but smaller angular span.

The horizontal directivity of the positive organ is plotted over $\pm$ 65° with both short and long time windows (Figs. 3a and 3b). In this way, it is possible to appreciate the influence of the first reflections from the lateral walls of the church, which were excluded by windowing the first 4.7 ms.

In addition to measurements, the proxy organ was simulated using a FDFVTD scheme [10, 7] with the same pipe configurations. These simulations helped interpret phenomena observed in the measurements, however simulation figures are not included here due to available space.

We focus our analysis on the frequency and spatial variation of the façade response by comparing data from the laboratory and *in situ* measurements in three spectral regions of the audible range.

3.1 Low Frequencies (125 Hz, 250 Hz, 500 Hz)

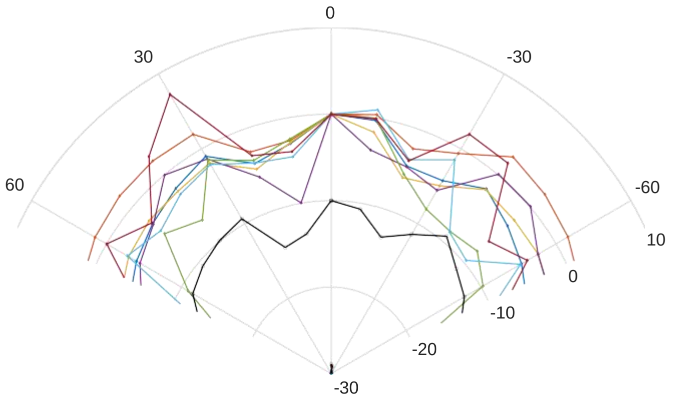
In both the proxy and positive, low frequency bands display similar directivity patterns. They show homogeneity across all data with a tendency to lateral energy predominance; especially in the 250 Hz band for 3D proxy organ (Figs. 2a and 2b). This phenomena is also observed in the 50% dense 2D proxy (Fig. 2c), while in St Elisabeth, the 125 Hz band at 200 ms is found to converge towards a cardioid-like directivity (Figs. 3a and 3b). At these frequencies, the pipes and PVC tubes inside the buffets have little acoustic effect, and frontal projection is primarily due to the cavity response. It is pertinent to note that with the 4.7 ms window, no frequency-related differences can be resolved between 125–250 Hz other than the overall level. With the 200 ms window, it is possible to see the energy contribution of the first wall reflections in the lateral measurements.

An analogy can be extended between the 3D proxy (Figs. 2a and 2b) and the positive (Figs. 3a and 3b) for

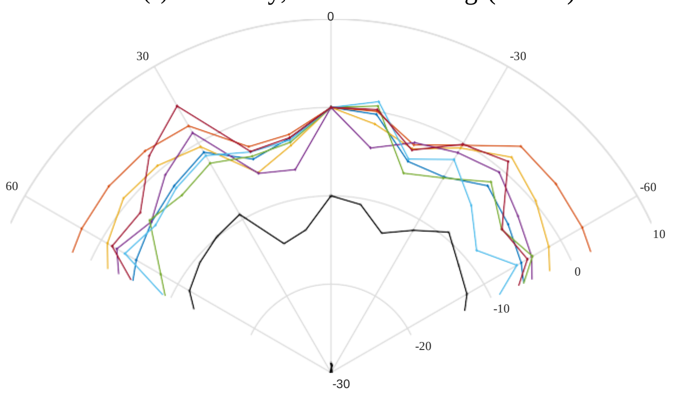
[2] All measurement distances are considered from the source inside the cavity to the receiver location.

[3] The legend is common to all figures, shown in Fig. 2c.

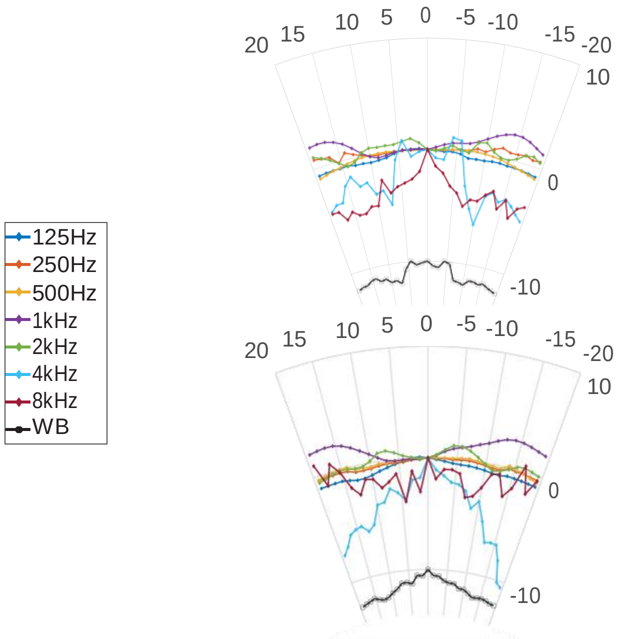
the 500 Hz band. One central lobe markedly rises in the 3D proxy for the 4.7 ms window, and the added energy at 200 ms pushes the levels towards lateral projection leading to three large lobes. The positive shows 3 main frontal lobes for 4.7 ms. The levels increase towards 0 dB using



(a) 3D Proxy, short windowing (4.7 ms).



(b) 3D Proxy, long windowing (200 ms).



(c) 2D Proxy, 50% pipe forest density (top) and 100% pipe forest den-sity (bottom).

Figure 2 – Horizontal directivity in 2D and 3D proxy.

the 200 ms window. These lobe half-width are similar in size and shape: 15° in the positive and 20° in 3D proxy.

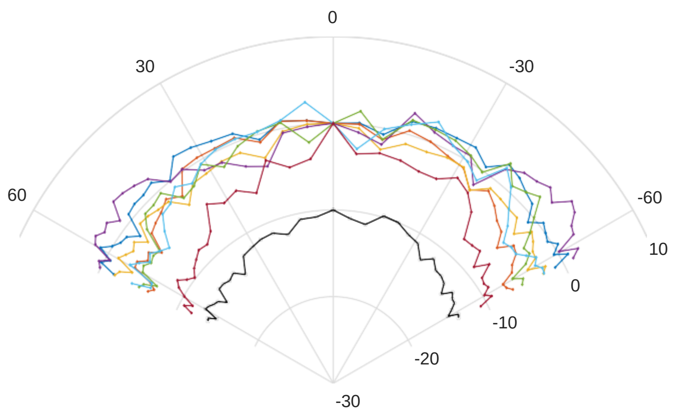
The bands of 125 Hz, 250 Hz, and 500 Hz exhibit the same tendency to the lateral projection between 3D proxy measurements and FDFVTD data. A level difference of 6–7 dB between 125 Hz and 250 Hz in the 3D proxy is correctly approximated in the simulation with both short and long time windows. The left-right asymmetry observed in the 500 Hz band is also found in both for ± 45°, although its magnitude is overestimated by 4 dB in the simulation.

3.2 Mid Frequencies (1 kHz, 2 kHz)

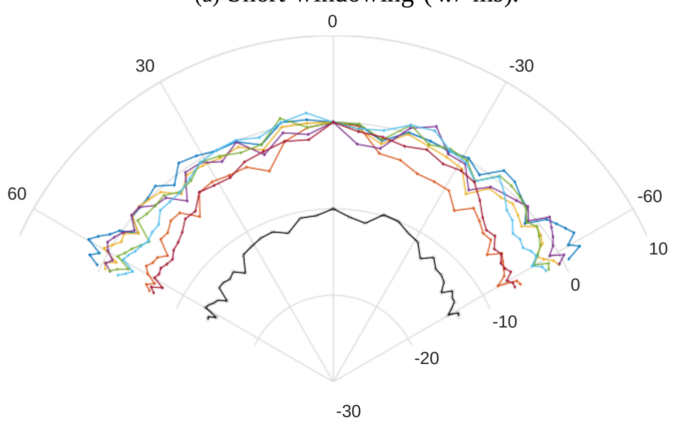
The presence of the pipes becomes apparent at 1 kHz for the positive organ (Figs. 3a and 3b). There are two prominent and noticeable effects. First, the pipes in the round towers of the façade augment the energy propagation towards the lateral sides (± 60° Fig. 3a). Second, the inner pipes work as propagation obstacles, attenuating and diffusing the buffet’s internal field before transmission through the façade (Figs. 2a and 2b).

Additionally, the 2D proxy (Fig. 2c) shows consistent angular periodicity at 1 kHz of 2.5 dB, irrespective of pipe-forest density. This leads us to believe that the effect is due to the presence of the pipes and their regular spacing.

Scattered pressure at 2 kHz caused by the regularly spaced pipes of the facade shows lobe behavior similar to the



(a) Short windowing (4.7 ms).



(b) Long windowing (200 ms).

Figure 3 – Horizontal directivity in St Elisabeth.

observations in the 1 kHz band, but now with an increasing number of peaks: 3 wide frontal ones in Fig. 3a followed by narrower ones as the angle become steeper. The 3D proxy shows similar tendencies in the broad lobe projections (6–8 dB) with differences in the sub-lobes due to the different forest geometries. Note the wideband pressure also suggests this periodicity.

The wavelengths between the high end of the 2 kHz band and the low end of the 4 kHz band are comparable in size with the diameter and center-to-center spacing of pipes in the façade. This means the presence and size of the side towers of the positive should not be considered acoustically invisible at these frequency bands (Fig. 3a).

3.3 High Frequencies (4 kHz, 8 kHz)

The 2D proxy showed strong directional frontal lobe behavior in transient time windows, swapping between 5–10 dB peaks on-axis for the 4–8 kHz bands, especially when considering differences between 50 % and 100 % pipe densities. This tendency is followed by the 3D proxy preserving an angular periodicity of $\approx$20° and dynamic ranges of again 5–10 dB. When window times were lengthened to 200 ms, the decay at the limits becomes apparent as also seen in the positive measurements, coherent with the idea that the buffet becomes much more directional at high frequencies. In the positive, the frontal projection is 10 dB higher than in the lateral measurements.

In the high frequencies (8 kHz band) the 3D proxy shows an asymmetric lobe at 30° with a dynamic range of 7–10 dB in short and long windows respectively. This is matched (and overestimated by 5 dB) in simulations. The level drop at angles corresponding with the limits of the façade are equivalent to those seen in St Elisabeth results.

4. CONCLUSIONS AND FUTURE WORK

The present study examined the horizontal directivity of a pipe organ. To better analyze the sound propagation from the organ buffet, preliminary measurements were made using a simplified proxy organ. Employing linear and omnidirectional sources made it possible to investigate 2D and 3D sound propagation. All data collected from the simplified case provided a useful basis for analysis and comparison to measurements of a real organ. *In situ* horizontal directivity measurements of the positive section of the St. Elisabeth organ were made. The simplified proxy was useful for studying the sound propagation through a regularly spaced façade, however the internal contents of the buffet (idealized cylinders) did not well resemble a real organ buffet. That said, the contribution of the room acoustics made *in situ* measurements challenging to analyze.

One possible next step is to measure a chamber organ that could be situated in the anechoic chamber. Further studies will also explore other excitation strategies, such as exciting the buffet with individual and clusters of organ pipes. With this approach, one reproduces the internal field of the buffet more legitimately in terms of source location, source radiation pattern, and intensity level. Finally, moving from horizontal directivity to vertical will make it possible to further explore the propagation of sound from the buffet, investigating whether there is a tendency for the sound to be directed towards audience, which is typically positioned at a lower level than the organ buffet.

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Workshop: New trends in sound system design for open-air venues

Design, installation and tuning issues for audio systems in large outdoor areas with artistic and archaeological constraints

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ABSTRACT

The design, the installation and the tuning of an audio system in a large outdoor space of great archaeological or artistic importance, are significantly constrained by the architecture of the site itself. Compared to a system installed in a conventional location, aspects such as the cables path, the dimensions and the positions of the speakers must be subject to limitations that require special attention from the contractor, in defining the layout of the system and above all in its tuning. The system installed in St. Peter's Square, even if it is not a very recent work, can be considered a bit like a showcase of all possible problems. Also, the temporal alignment of the speaker clusters will be discussed, with focus on the reduction of the effect of echoes ("macro delay" - time domain) and comb filters ("microdelay" - frequency domain).

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Implementation and use of Electronic Beam Steering techniques to optimize the performance of the audio system

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ABSTRACT

The ability to digitally adjust the dispersion of a line array system is a major advantage when it comes to guaranteeing the identical listening experience to all audience members in large venues. Advanced optimization algorithms are employed to shape the sound beam with extremely high resolution in frequency, thus providing a more uniform frequency response in the seating area and a stronger reduction of the noise pollution in the areas where the sound pressure must be kept at a minimum. This presentation discusses advantages, limitations and future developments of Electronic Beam Steering (EBS) techniques with examples of applications in large outdoor spaces.

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