AN ARCHAEOACOUSTIC STUDY ON CAPPADOCIA; ACOUSTICAL IDENTIFICATION OF RELIGIOUS AND SECULAR INDOOR SPACES

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By
Ali Haider Adeeb

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

AN ARCHAEOACOUSTIC STUDY ON CAPPADOCIA; ACOUSTICAL IDENTIFICATION OF RELIGIOUS AND SECULAR INDOOR SPACES

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M.S. in Architecture

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The goal of this study is to identify the indoor sound fields of Cappadocian special rock-cut structures and by this to provide the platform of discussion on the aural effects in the original use and context of spaces. Cappadocia's rock-cut structures have been enlisted as mixed -natural and cultural- World Heritage Sites by UNESCO. The spaces of Cappadocia from the Middle Byzantine Era have been studied from an archaeological perspective; however, this study is the first of its type as it investigates such spaces from an auditory perspective. Similar acoustical studies have been conducted on natural caves (Paleolithic caves) and man-made structures (Neolithic structures, Roman catacombs) from around the world.

The methodology of this study is composed of three steps; in-situ field tests of five rock-cut structures (one church and four residential halls) from Middle Byzantine sites of Hallaç, Açıksaray and Avanos, impedance tube tests on rock samples from Göreme and Ürgüp for estimating their sound absorption coefficients, and virtual reconstruction of Çanlı Kilise by ray-tracing simulations. According to tube measurements and room acoustics simulations, the Cappadocian tuff from different parts of the region is found to have different sound absorption properties and thus, various physical properties. Acoustic parameters (EDT, T20, T30, C80, D50, and STI) are obtained for the spaces under study by field tests and room acoustic simulations. Based on acoustic analysis from field measurements and simulations, both the church spaces are suitable for liturgical practices. On the other hand, the residential halls are found to favor speech-related activities more. The acoustics of rock-cut spaces are also compared with natural caves and man-made structures from other parts of the world; when the acoustic parameter results are compared, the Cappadocian tuff is found to be more sound absorptive than the karst in natural caves but less absorptive than the tuff in Roman catacombs.

Keywords: Archaeoacoustics, Sounds of Cappadocia, Historical Acoustics, Cave Acoustics, Rock-cut Architecture

ÖZET

KAPADOKYA ÜZERİNE ARKEOAKUSTİK BİR ÇALIŞMA; DİNİ VE SEKÜLER İÇ MEKANLARIN AKUSTİK ÖZELLİKLERİNİN BELİRLENMESİ

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Bu çalışmanın amacı Kapadokya'nın özellikli kayadan oyma yapılarının iç mekân akustik özelliklerini tespit etmek ve işitsel özellikleri özgün kullanımında bağlamı ile birlikte tartışmaya olanak sağlamaktır. Kapadokya'nın kayadan oyma yapıları UNESCO tarafından dünya karma -doğal ve kültürel- mirası arazilerine dahil edilmiştir. Kapadokya'nın Orta Bizans Dönemi yapıları/arazileri arkeolojik olarak pek çok çalışmaya konu olmuştur. Bu çalışma bölgedeki yapıların işitsel özelliklerini araştırması bakımından bir ilk olacaktır. Benzer akustik araştırmalar arkeoakustik kapsamında dünyada doğal mağaralar (Paleolitik mağaralar) ve kayadan oyma yapılar (Neolitik yapılar, Roma katakombları) üzerinde yürütülmüştür. Bu çalışmanın yöntemi üç başlıktan oluşur; Orta Bizans dönemine ait Hallaç, Açıksaray ve Avanos bölgesinde yer alan beş kayadan oyma yapının (bir kilise ve dört yerleşim yeri/konut salonu) sahada akustik ölçümleri; Göreme ve Ürgüp yöresinden toplanmış kayaların empedans tüpü ile ses yutma katsayılarının belirlenmesi; Çanlı kilisenin ışın izleme simülasyonları ile işitsel olarak yeniden oluşturulması/canlandırılması. Tüp ölçümleri ve simülasyonlar sonucunda Kapadokya'nın farklı bölgelerinde farklı ses yutuculukta ve dolayısıyla değişken fiziksel özellikte tüf kayaları olduğu belirlenmiştir. Saha ölçümleri ve akustik simülasyonlar ile çalışılan mekanların akustik parametre (EDT, T20, T30, C80, D50, ve STI) değerleri elde edilmiştir. Sonuç değerlere göre hem kayadan oyma Hallaç Kilisesi hem de kagir yapı Çanlı Kilise işitsel anlamda dini pratikler için kullanımına oldukça uygundur. Diğer yandan görece düşük çınlama süreleri ve yüksek anlaşılabilirlik dizinleri ile çalışılan konut salonları konuşma temelli kullanımlara daha uygun bulunmuştur. Kayadan oyma yapılar dünyada arkeoakustik çalışmalara konu olmuş benzer yapılarla karşılaştırılmış; akustik parametre değerleri karşılaştırıldığında Kapadokya tüfü doğal mağaralarda bulunan karst kayasına göre daha ses yutucu, Roma katakomblarındaki tüf kayasına göre ise daha yansıtıcı bulunmuştur.

Keywords: Arkeoakustik, Kapadokya'nın Sesleri, Tarihi Yapı Akustiği, Mağara Akustiği, Kayadan Oyma Mimari

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To Zakia and Ameer

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CHAPTER 1

INTRODUCTION

"In many ways, sound is rather more transient than the visible world. It is 'non-continuous, fragmentary in space, and episodic in time'. Sound is a sensation, and belongs to the realm of 'activity' rather than 'artefact'. Sound brings the world to life. It can appear to fill spaces, create atmospheres, and have an intense emotive power."

Watson, 2003, 180

"Just as we may trace Western attitudes toward politics to ancient Greek culture, so we can trace our attitudes toward aural architecture to earlier cultures as well."

Blesser & Salter, 2007, 67-8

1.1 Problem Statement

Cappadocia is registered as a mixed -natural and cultural- heritage site by UNESCO and remains a popular touristic destination. 'Cappadocia' is the name given to a particular region in central Anatolia, known for its idiosyncratic volcanic landscape, and is marked by the present-day cities of Aksaray, Nevşehşir, Kayseri, and Niğde. Most of the surviving rock-cut and masonry structures, in the region correspond to the Middle Byzantine period, especially to the ninth to eleventh centuries (Öztürk, 2017b). The majority of the structures date back to the 9th and 11th centuries, and there was once again a peak in construction activities especially between the end of the Arab invasion in the 10th century and the gradual takeover by the Seljuks by the end of the 11th century (Mathews et al, 1997) when Cappadocia remained a provincial settlement under the rule of the Byzantine Empire. The advent of Seljuks, however, does not mean an end of the "Byzantine moment" in Cappadocia as Byzantine architectural and artistic production revived in the region in the thirteenth century (Öztürk, 2017b). Hence, the Cappadocian spaces are not primarily from the Middle Byzantine period, there is evidence of structures that were built with Byzantine standards after the years that are known as the Middle Byzantine Period.

Even though Cappadocia was a strategic area for the Byzantine Empire (Öztürk, 2014), the academic work on the Middle Byzantine period of Cappadocia often suffered from a perspective that perceived the region essentially as a monastic center. The region indeed was a robust religious center starting from Early Christian period onwards and housed significant monastic establishments. And yet, while recent studies started to establish that a number of regular settlements were misidentified as monasteries, the general scholarly narration on the settlement characteristics of the Byzantine Cappadocia continues to be rectified accordingly.

However, there still exist a number of problems that hinder a comprehensive understanding of the settlement patterns of Byzantine Cappadocia and archaeological fieldwork conducted in the region remains limited (Ousterhout, 2017). Therefore, studies concentrating on the domestic setting from different perspectives would contribute to a better understanding of the spaces of the Byzantine Cappadocia. One such physical character is the indoor acoustical climate of these spaces.

Archaeoacoustics is an interdisciplinary field that revolves around acoustical analysis of archaeological sites. With the development in this relatively new field, instead of just discussing the history of music, researchers have moved to discussing soundscapes: acoustic environments based on functional context and perception by humans (Brown et al, 2016). Scholars who are interested in archaeoacoustics try to gather non-material pieces of evidence from the human past. A contextual acoustical study of a space can reveal a number of important features regarding the function of the space and the people that inhabited it. Acoustics can bring us invaluable information about intangible parts of a culture such as music, ritual and religion (Gibson, 1966). Consequently, it becomes vital to gather acoustical information regarding places of the past in order to have a better understanding of their context.

With the current scholarly debates on the functions of Cappadocian rock-cut structures due to a lack of textual sources, it is noteworthy to try to study these spaces acoustically as well. An archaeoacoustic analysis of these spaces can provide insight to the intangible parts of the Byzantine Cappadocian culture and help us contextualize the spaces, which had unfairly been associated with monasticism. With a study that focuses on a sensory aspect of a space, we can learn about the certain spatial nuances that could have made the Cappadocian spaces different from each other, and perhaps with other similar spaces from around the world.

1.2 Aim and Scope of the Thesis

The thesis primarily focuses on documenting the soundscapes of different spaces of Cappadocia, which as a region has been enlisted in the World Heritage Sites by UNESCO. There has always been a debate regarding the spaces of Cappadocia and numerous research projects have been conducted to study these spaces from archaeological and historical points of view. However, there has been no attempt at trying to comprehend the soundscapes of Cappadocia. This study is the first of its type that is based on studying the acoustics of Cappadocian spaces. Given the peculiarities and ambiguities that are associated with Cappadocia's rock-cut and masonry structures, as well as their functions, it is important to collect data related to the acoustic environments of such spaces can develop a better understanding..

The documentation and analysis of these acoustic environments is done through on-site field tests involving signal generation and collecting room impulse responses for analyzing sound energy decays within each space. The study also uses computer-aided simulation programs for creating a virtual 3D space for analyzing the performance of sound in the space. Apart from evaluating acoustic environments, the thesis also documents the acoustic properties of the volcanic tuff found in Cappadocia. The study of the volcanic rocks is important as it gives an insight about the material properties of the rocks. One of the main goals of the study is to provide a methodological approach, which can be used when analyzing the acoustics of Cappadocian structures for future studies. In a nutshell, the thesis aims to provide data regarding Cappadocia and its spaces from an acoustical perspective, which can be used to strengthen certain hypotheses about the region's spaces or to enrich the collective scholarship on the region, its history, and practices.

1.3 Structure of the Thesis

The main focus of the thesis is to document, study and analyze the aural architecture of Cappadocian rock-cut spaces. In order to actualize the aim of the research, the thesis follows a simple and straightforward framework. Chapter 1 begins with establishing the problem statement by highlighting the importance of studying the soundscapes of archaeological sites, such as Cappadocia, so as to get a better grasp of their historical and social context. Cappadocia and its rock-cut structures have always been a topic of discourse, especially in regards with their intended functions. Therefore, it is noteworthy to document and evaluate the articulation of sound in the rock-cut structures of Cappadocia as they can provide a different perspective in understanding the activities regarding these sites. Moreover, the virtual and aural reconstruction of Çanlı Kilise is also pertinent in providing evidence about the acoustical performance of Byzantine masonry churches in Cappadocian region.

Chapter 2 constitutes of two sections. The first part is an amalgamation of all the pertinent acoustical parameters which have been employed while assessing the rock-cut structures of Cappadocia and a masonry church, Çanlı Kilise. These parameters are presented with the aim of revisiting the definition and significance of the acoustical terms. The second part of the chapter is a summary of the scholarly works carried out in the field of archaeoacoustics. The section highlights some of the prominent studies and their findings related to both natural caves and rock-cut structures all around the world. These are mentioned to further compare and discuss the current knowledge on archaeoacoustics of natural caves and man-made structures.

Chapter 3 discusses the geography and history of Cappadocia. It provides an introduction to the region by discussing the monastic connotations that had been associated with Cappadocia. The section further mentions recent studies that have brought to light the secular features of Middle Byzantine Cappadocian life. The chapter also provides a brief architectural and historical description of the four sites under study; Hallaç Complex, Açıksaray, Avanos, and Çanlı Kilise.

Chapter 4 is a description of the methodological approaches that have been used as part of the study. First of all, in-situ field tests have been performed in Hallaç Complex, Açıksaray, and Avanos. These field tests are executed using the tools and principles that have also been used in other similar studies related to cave acoustics. Moreover, rock samples from two different towns of Cappadocia have also been studied using impedance tube tests. This part of the study is to document the relevant physical properties of the rocks. Lastly, one of the Byzantine churches, Çanlı Kilise, has been virtually and aurally constructed using 3D modeling tools. By dint of ray tracing, the church's acoustic environment has been documented and analyzed.

Chapter 5 encompasses the main findings of the thesis. The results of the field measurements are presented and discussed. The measurements are used to draw conclusions about the use of the spaces under study. Moreover, the results of the field tests are compared first among the three sites (Hallaç Complex, Açıksaray, and Avanos) and then with the results of other prominent studies across the world. The chapter also discusses the impedance tube results of the rocks from Ürgüp and Göreme. These results signify the absorption performances of the rocks. The last part of the chapter is composed of the discussion regarding the Çanlı Kilise simulations, after calibrating the model based on the field test results of the Hallaç Church.

Chapter 6 of the thesis summarizes the main results of the study. It is a brief summary of the whole thesis and its findings with concluding remarks at the end.

CHAPTER 2

ACOUSTICAL TERMINOLOGY AND ARCHAEOACOUSTICS

2.1 Room Acoustics

The following are the main acoustical parameters that have been used to analyze the acoustic characteristics of the spaces under study. These parameters have been chosen in regard to other studies that have been conducted in other natural and man-made structures around the world. These parameters are significant not only in documenting the acoustics of Cappadocian spaces, but also in evaluating their acoustical performance relative to other structures that have been acoustically studied worldwide.

2.1.1 Reverberation Time and Early Decay Time

Reverberation time is one of the most important parameters that are studied while evaluating the room acoustics of a space (Maekawa & Lord, 1994). W.C. Sabine was the first person to study the phenomenon, and brought it forward (Gade, 2014).

Reverberation Time is defined as the time in seconds for the initial sound level to drop by 60 dB after the sound source has been stopped (Egan, 1988). In other words, the time required for a sound to roughly decay into inaudibility after the source stops (Cavanaugh et al, 2009). The following figure shows a sample decay curve and the definition of reverberation time. In practice, the slope of the decay curve is measured after the decrease in sound level is between the range of -5dB to -35dB (Fig. 1).

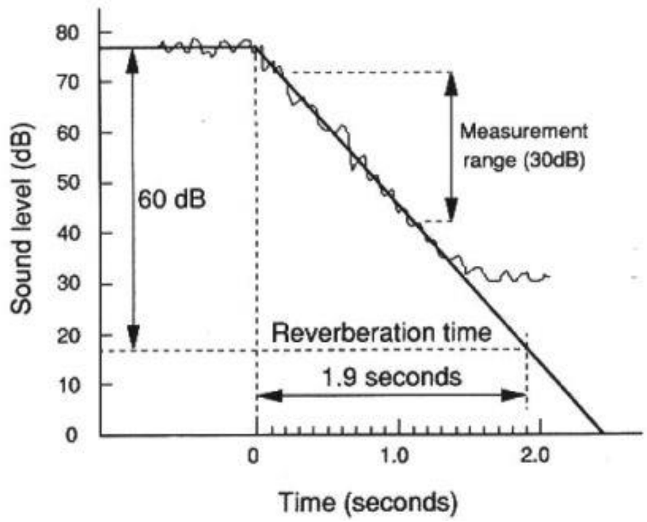

Fig.1. A sample decay curve with the definition of Reverberation Time (Barron, 2009, p. 28)

There are three formulas that can be used to calculate the reverberation time of a room, depending on the type of room. The liveliness of a room is directly related to its reverberation time which is high. On the contrary, depending on the space volume, space geometry, and the amount of sound absorptive material, a room can have a reverberation time of less than 1.5 s and is thus, considered dry or dead (Maekawa & Lord, 1994; Dorris, 1992).

The first formula is Sabine's formula which is applicable for live rooms. The formula is as follows:

$T = 0.163 / A$

where, A = the equivalent sound absorption area in m² ($= \sum S\alpha_{av}$)

$\sum S\alpha_{av} = S_1\alpha_1 + S_2\alpha_2 + \ldots + S_n\alpha_n$

V = the volume in m³

S = the surface area in m²

α = sound absorption coefficient (Cremer et al, 1984)

Eyring Formula and Millington & Sette Formula are appropriate for dead rooms. Their formulas are as follows:

Eyring Formula:

$\alpha_1 \approx \alpha_2 \approx \alpha_3 \approx \ldots \approx \alpha_n$,

$T = (0{,}163\ V) / [-S\log_e (1 - \alpha)]$ in seconds. Where, $\alpha = \sum S\alpha_{av} / S$

Millington & Sette Formula:

$\alpha_1 \neq \alpha_2 \neq \alpha_3 \neq \ldots \neq \alpha_n$,

$T = (0{,}163\ V) / [\sum -Sn\log_e (1 - \alpha_n)]$ in seconds (Maekawa & Lord, 1994)

It is difficult to reach a complete 60 dB drop in sound level due to the presence of background noise. Hence, a decay range of 20 and 30 dB are used where the corresponding time is multiplied by 3 and 2 respectively. According to ISO 3382-1, T20 and T30 are used to indicate the reverberation times from such limited decay ranges.

Another parameter, Early Decay Time or EDT, was introduced by Jordan (1969). It is the time for the energy to decay by 10 dB immediately after the arrival of the direct sound. This time is multiplied by 6 to correspond with reverberation time values. The parameter is known to be a good indicator of the subjective interpretation of reverberation time (Barron, 2009). EDT is based on the decay of the first 10 dB, therefore, it is more sensitive to early strong reflections. As a result, EDT is dependent on local measuring positions and room geometry (Templeton, 1998).

2.1.2 Clarity and Definition

Clarity (C80) is the ratio between energy received in the 80 ms and the energy received afterwards (Diaz & Pedrero, 1999). The ratio is expressed in dB. In subjective terms, clarity is a parameter associated with the perceptibility of differences in individual musical instruments and is thus, used by performers in order to hear the details of their musical instruments (Makrinenkno, 1994). The formula for calculating C80 is as follows:

$$\mathrm{C80} = 10\log\left\{\frac{\int_0^{80\mathrm{ms}} \mathrm{g}^2(\mathrm{t})\mathrm{dt}}{\int_{80\mathrm{ms}}^{\infty} \mathrm{g}^2\,(\mathrm{t})\mathrm{dt}}\right\}\mathrm{dB} \qquad \text{(Kuttruff, 2009)}$$

Our hearing system characterizes sound into early and late parts; the early parts are used for clarity and definition while the late reverberant parts provide context for hearing the early sound. The significant time interval for early sound in regards to music is 80 ms, while it is 50 ms for speech (Makrinenkno, 1994). For good clarity, sufficient early reflections should be provided otherwise, objective clarity would significantly decrease if one moves away from the stage (Barron, 2009).

Definition (D50), commonly presented as a percentage, is the ratio between the effective energy received in the first 50 ms and the total energy (Diaz & Pedrero, 1999). The effective energy includes both the direct sound energy and the energy of reflections within the first 50 ms. D50 is associated with speech-related functions. It is the parameter that provides the distinctness of sound and is measured based on the human ear's response to successive impulses. The following formula is used to calculate D50:

$$\mathrm{D50} = \left\{\frac{\int_0^{50ms} g^2(t)dt}{\int_{50ms}^{\infty} g^2(t)dt}\right\} \qquad \text{(Kuttruff, 2009)}$$

There is a strong relationship between D50 and speech intelligibility; D50 values should be greater than 0.15 in order to satisfy speech-related activities (Templeton, 1998).

2.1.3 Speech Intelligibility

The requirement for speech in any space is that it should be intelligible. The percentage of correctly received phrases is an estimate of speech intelligibility. There are a few conditions that can improve speech intelligibility; high speech level, low levels of noise, short reverberation times, the presence of strong early reflections and the absence of strong late reflections (Makrinenko, 1994). There are two concerns regarding speech intelligibility: the signal-to-noise ratio and the impulse response. Similar to how noise masks speech signals, long reverberation times reduce speech intelligibility. Speech level in a space is depends on factors such as source receiver distance, orientation of the speakers, room reflections, etc. As a result, speech intelligibility varies within the space (Egan, 1988). Regarding the impulse response measures, the early energy fraction must be high for good speech intelligibility. Therefore, strong early reflections should be provided to places further away from the source (Barron, 2009). Hence, it is important to be able to predict the quality of speech using a metric that can help assess speech intelligibility of a space.

In that case, speech intelligibility can be assessed by means of the Speech Transmission Index (STI), which is a metric that denotes the quality of speech while considering the loss of speech articulation caused by reverberation (Steeneken & Houtgast, 1980). It is an objective method that is used to evaluate the quality of speech. The STI ranges between “0” and “1”, where the low values indicate bad intelligibility while higher values denote better speech intelligibility (ISO, 2003). Table 1 shows the relationship between an STI value and the quality of speech intelligibility. The STI has been used for predicting speech intelligibility from an impulse response as it deals with both the signal-to-noise-ratio and the impulse response. The underlying logic is that the envelope of the sound signal must be preserved in order to have better speech intelligibility (Kuttruff, 2009).

Table11. Relation between speech transmission quality and STI (RASTI) (Beranek, 1988, p. 623)

Quality Score	STI (RASTI) Value
Bad	0 to 0.32
Poor	0.32 to 0.45
Fair	0.45 to 0.60
Good	0.60 to 0.75
Excellent	0.75 to 1.00

2.1.4 Signal to Noise Ratio

The signal-to-noise ratio (SNR) is defined as the ratio of the signal power and noise power and is expressed in decibels (Carlson, 1968). This simple definition of SNR assumes that both the signal and the noise are measured when they are limited to the same bandwidth. In simple words, the ratio is a measure of the signal strength in regards with the background noise level. If the value of the SNR ratio is high, it signifies that the signal is much stronger than the background noise and therefore, it is clear and less blurry.

The formula to calculate the SNR is as follows:

$$\mathrm{SNR} = 10 \log 10 \frac{\frac{1}{\mathrm{N}} \sum_{\mathrm{k}=1}^{\mathrm{N}} [\mathrm{s}(\mathrm{k})]^2}{\frac{1}{\mathrm{M}} \sum_{\mathrm{k}=1}^{\mathrm{M}} [\mathrm{n}(\mathrm{k})]^2}$$

where, s(k) is the noise free sample

n(k) is the noise sample (Huszty & Sakamoto, 2012)

Peak-to-noise ratio (PNR) is usually used when studying room acoustics. It slightly differs from SNR as here the numerator is the square of the signal's peak value and is divided by noise.

PNR is calculated according to the following formula:

$$\mathrm{PNR} = 10 \log 10 \frac{1}{\frac{1}{\mathrm{N}} \sum_{\mathrm{k}=1}^{N} [n_n(\mathrm{k})]^2}$$

where, $n_n(k)$ is the noise present in a 0 dB normalized room impulse response.

(Huszty & Sakamoto, 2012)

For this study, PNR values have been used to assess the spaces where in-situ field tests have been performed.

2.1.5 Sound Absorption Coefficient

Sound absorption coefficient (α) is usually expressed as a decimal value to indicate the sound absorption effectiveness of a material or layers of materials (Cavanaugh et al, 2009). Sound absorption is a phenomenon that is a consequence of sound energy being dissipated into heat energy. The quantity, sound absorption coefficient, is a dimensionless ratio of absorbed sound energy to incident sound energy. The phenomenon is described by the following formula:

$$\alpha = E_a / E_i$$

where, α is the absorption coefficient

E_a is the absorbed acoustical energy by the material

E_i is the incident acoustical energy on the material (Diaz & Pedrero, 1999)

Theoretically, the decimal value of the coefficient can range from "0" (absolutely no absorption of sound energy) to "1" (complete absorption of all sound energy) (Egan, 1988). The sound absorption coefficient of an acoustical absorbent is dependent on the frequency of the sound and its incident angle. The coefficient values also vary considerably based on the material's installation or mounting (Diaz & Pedrero, 1999).

2.2 Archaeoacoustics

Archaeoacoustics is the combination of archaeology and acoustics; it is an interdisciplinary field that focuses on the sound of the past (Díaz-Andreu & Mattioli, 2015). It is important to understand the human past from an acoustic and auditory aspect that can give clues and intangible evidence regarding the lifestyle of the people of the past. With the contemporary development in archaeoacoustics, there has been a shift from an initial interest in the history of music towards the current debates on soundscapes: acoustic environments based on functional context and perception by humans (Brown et al, 2016). Early studies on the subject of soundscapes have been done by a number of music composers including Barry Truax (1992) and R. Murray Schafer (1994). These composers started looking beyond the creative use of sound to find out the phenomena around sound creation and how human agency can create a place or time aurally unique. Anthropological hints were used in their pursuit of exploring soundscapes. This idea has further been explored in escomusicology by researchers who are interested in ecologies of sound and the study of music, culture and nature (Pedelty, 2013).

With the advancements in technology, it has become easier and convenient to use advanced tools on different archaeological sites that could previously only be used in labs. This has enabled researchers to study the aural characteristics of prehistoric sites more precisely (Till, 2014a). Portable audio equipment led to one of the very first archaeoacoustic studies by Watson and Keating in 1999 at Stonehenge. While the study could not declare if the people of the time deliberately designed the space for its acoustic performance, however, it did declare that the behavior of sound would have been prominent in the use of such spaces (Scarre & Lawson, 2006; Watson & Keating, 1999). Ever since the first pilot study, there have been a number of studies conducted on the Neolithic structure, Stonehenge, and the results of these studies support the presence of aural ritual performance. The studies conclude that the acoustics of the space must have been an iconic and unavoidable part of the site (Till, 2014a; Till, 2019).

There have been a variety of other archaeological spaces that have been acoustically documented and studied. The following sections highlight some of the main studies that have been conducted in natural caves and other man-made structures from around the world.

2.2.1 Cave Acoustics

Researchers have studied the acoustics of underground places and caves in understanding the prehistoric human interactions. Multiple ancient sites, including caves, have been studied (Plummer, 1969; Reznikoff, 2008). The articulation of sound in such spaces could provide additional evidence concerning the people that inhabited certain spaces as well as their context. The caves, dating from the prehistoric periods, feature a range of unusual visual characteristics such as paintings, engravings, patterns and, hand stencils which have been reinterpreted from a perspective that focuses on their acoustical performance (Plummer, 1969; Reznikoff, 2008; González et al, 2008). Paleolithic caves in Spain seem to have motifs at moderately reverberant locations (Fazenda et al, 2017) and the depictions tend to cover large areas at locations where distinct acoustic properties can be documented (Till, 2019; Waller, 1993; Till, 2014[2]; Díaz-Andreu et al, 2014).

Other studies have evaluated the acoustics of natural caves in comparison to modern-day spaces. Many natural caves have become tourist attractions and host musical performances. The monaural acoustic parameters of caves from Spain (González et al, 2008), Italy (Iannace & Trematerra, 2014a), and Portugal (Carvalho & Sousa, 2015) have been found to be comparable to modern-day performance spaces. The acoustics of the caves in Attica, Greece are found to be better than recent spaces of worship (church and mosque) of comparable volumes (Yioutsos et al, 2018). Hence, it is probable that the people were aware of the acoustic characteristics of these caves and were using them accordingly.

2.2.2 Acoustics of Man-made Structures

Apart from natural caves and cavities, studies have also been conducted on man-made spaces. In the acoustical analysis of six ancient man-made Neolithic and Iron Age structures in the UK and Ireland, Jahn observed strong resonances in the range of 95 Hz to 125 Hz (Jahn et al, 1996). The resonances in this frequency range could have helped in the augmentation of human chanting during sacred rituals in such spaces (Cook et al, 2008). In another study, acoustic measurements were carried out in underground galleries in Peru; the results indicated acoustical characteristics which, according to the authors, could have contributed to the ritual experience (Abel et al, 2008). The acoustics of hypogea in Italy and Malta have also been analyzed; the authors conclude that the resonance in these spaces would have supported ritual practices (Debertolis & Bisconti, 2014; Debertolis et al, 2015). Other man-made structures that have acoustically been studied are catacombs; underground cemeteries constructed during the Roman Empire.

These spaces are composed of negative spaces which are created by carving out live tuff, a porous material. Researchers have tried to understand the type of rituals that were performed in such underground spaces; the short reverberation times and high STIs in such spaces make them suitable for religious purposes such as prayer (Iannace et al, 2014; Ciaburro et al, 2020).

CHAPTER 3

BYZANTINE CAPPADOCIA AND CASE SITES

3.1 Overview of the Byzantine Cappadocia

Cappadocia is known for its unique landscape due to the repeated volcanic eruptions. During the Middle Ages, Cappadocia was a strategically important province of the Byzantine Empire, and therefore, became a popular site for habitation with people inhabiting the rock-cut structures. The rock-cut sites of Cappadocia are located in central Turkey scattered in an approximate area of 400 to 200 kilometers (Kostof, 1972). As opposed to natural caves, Cappadocia's structures are designed, which are constructed by cutting and carving the volcanic tuff (Kalas, 2004; Öztürk, 2017a).

Cappadocia is known to have connections with early Christianity; during the third century, the region became the center of Orthodox theology. It is often because of the advent of Orthodox theology that Cappadocia is known to have become a monastic center. Later, during the sixth and seventh centuries, Cappadocia was invaded by the Persians, and the region was further destabilized by Arab invasions up to the tenth century (Hild & Restle, 1981 as cited in Ousterhout, 2005). During this time, Cappadocia remained a Byzantine outpost; however, the remains are limited. After Iconophiles victory in 843, the Byzantine Empire grew stronger and Central Anatolia was reclaimed from the Arabs. During this time, Cappadocia developed strong ties with the Byzantine capital in Constantinople, as military campaigns were strengthened in the region and administrative bureaucracy became stronger. Most of the remains of Cappadocia's structures are from this period (Ousterhout, 2005). By the end of the eleventh century, the Seljuk Turks had taken control of most of Asia Minor; although the Seljuks were Muslims, they allowed Christian communities of Cappadocia to stay in the region. There is evidence of rock-cut churches with inscriptions from the thirteenth century. Christian communities, Greek-speaking populations, inhabited the region until 1922-23 when they were resettled to Greece (Ousterhout, 2005). Therefore, the Christian architecture of Cappadocia cannot be precisely dated and documented due to a lack of textual references.

The rock-cut structures of Byzantine Cappadocia remain debated as the peculiarities of the region cannot be explained by textual sources alone and detailed archaeological studies are still limited (Ousterhout, 2017). As a result, the archaeoacoustic qualities of multiple sites, accommodating both religious and residential uses in Cappadocia, have been the focus of this study in order to provide a missing perspective by documenting the sensorial aspects of these spaces.

3.1.1 Early Scholarship on Cappadocia

Cappadocia was essentially considered a region of Byzantine monastic communities, until the end of the 20th century (Tozer, 1881; Kostof, 1972; Epstein, 1979; Ousterhout, 1996). According to the early scholarship on the region, the rock-cut spaces of Cappadocia were associated with monks, their disciples and all kinds of monastic connotations. The region's monastic character was reinforced after European travelers associated monasticism with almost all the remains throughout Cappadocia due to the region's exotic landscape made of volcanic rock formations (Kalas, 2004). Similarly, nineteenth century travelers, including Henry Tozer, suggested that the apparent monastic establishments were associated with the bishop of Caesarea, St Basil the Great (Tozer, 1881). Later for most of the twentieth century, Cappadocia was mainly studied by art historians, who would be interested in the study of religious paintings (Kalas, 2004). As a result, the interpretation of these spaces as monastic settings remained a constant for the scholars as well as the visitors of the region, while many studies especially throughout the 20th century followed the same framework without much questioning, although there has been no literary evidence supporting the monastic character of Cappadocia.

3.1.2 Domestic Settlements in Cappadocia

The recent studies, however, convincingly challenged this perception (Kalas, 2004; Kalas et al, 2009; Öztürk, 2014; Ousterhout, 2017), while a number of domestic complexes have been studied in detail (Mathews et al, 1997; Ousterhout, 2005; Kalas, 2007; Öztürk, 2010). The rock-cut 'courtyard complexes' in Cappadocia that are mainly dated to the Medieval Byzantine period are an important group in this context, usually identified as elite residences (Öztürk, 2014; Ousterhout, 2017). Some of these residences are also associated with military aristocracy which gives the region much more strategic importance that it had been given by earlier scholars (Mathews et al, 1997; Ostrogorsky, 1971; Ousterhout, 2005). The secular characteristics of a few Cappadocian settlements have been highlighted in the following section.

3.2 Case Sites

The acoustics of various spaces from three selected sites in Cappadocia have been documented and analyzed in detail within the scope of this study, highlighting but not limited to domestic architecture. The two Middle Byzantine sites, Hallaç and Açıksaray are similar in the configuration of the settlement setting utilized for each domestic unit. Yet, while Hallaç Complex is an isolated single unit, Açıksaray comes forward as a compound of numerous similar residences. The contextual discussions on Açıksaray therefore vary; although it might still be perceived as a settlement of elite families with units similar to Hallaç, these units are multiplied at Açıksaray (Öztürk, 2010 & 2014), and alternative proposals such as an 'upscale stud farm' have also been put forward (Ousterhout, 2017). Whereas the state of conservation as well as their relatively complete on-site documentation prioritized Hallaç and Açıksaray among similar alternatives for this study, their characteristics offer comparative criteria that can provide additional data for the ongoing contextual debates. The third site is a dining hall which belongs to a traditional house transformed into a hotel at Avanos, a touristic town in Cappadocia. The site has mainly been chosen as it offered a stable power supply for the standard room acoustics equipment to be utilized and a relevant comparison to the main halls of the Hallaç and Açıksaray complexes in terms of volume and material. The fourth site is a Byzantine masonry church, Çanlı Kilise, found on the outskirts of present-day Aksaray. The church is one of the few masonry structures that have survived. The following pages provide a more detailed description of the four sites.

3.2.1 Hallaç Complex

Hallaç complex, near Ortahisar, is identified as an example of an elite secular residence (Mathews et al, 1997; Ousterhout, 2017), despite early claims that it was a monastery (Rodley, 1985). The spaces associated with the complex are distributed on the three sides of an open courtyard with a wide vestibule to the north connecting the two main spaces; the main hall, flanked by two unidentified small rooms, is positioned at the central entrance axis perpendicular to the vestibule and a smaller cross-in-square hall opens to the vestibule from the west. A cross-in-square hall is located on the west end of the portico and is perhaps a space used specifically by women, due to its proximity to the kitchen space and provision of privacy (Mathews et al, 1997). The area identified as the kitchen is located to the west of the courtyard and a small church with additional funerary spaces lies to the east (Fig. 2). The complex has been almost entirely carved out of living rock with the exception of the south masonry wall of the vestibule that no longer stands but once provided a monumental façade for the entrance. The widely accepted mid-eleventh century dating of the complex is essentially based on architectural evidence (Mathews et al, 1997).

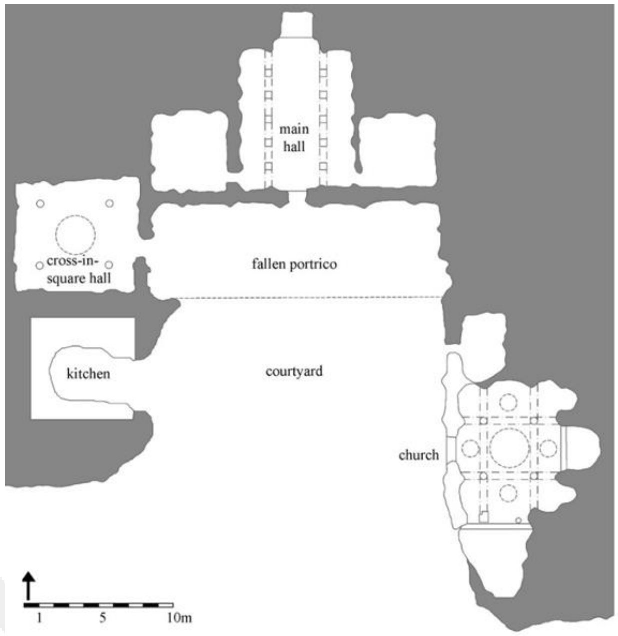

Fig. 2. Hallaç complex plan drawn by the author (based on Ousterhout, 2017, p. 281)

Fig. 3. Interior views of (left) the Hallaç Church, (right) the Hallaç Main Hall

For this study, acoustic data has been collected from the church and the main hall of the complex (Fig. 3). The cross-in-square church is decorated by carving and there are not any documented traces of plaster except for a fresco limited to a small panel behind the altar. The church is in a residential setting, and probably was used by a small congregation. As opposed to many rock-cut churches in Cappadocia, there is no evidence of a rock-cut templon between the apses and the nave of the Hallaç Church (Ousterhout, 2017).

The size, location and the configuration of the main hall confirms its identification as a ceremonial setting used for formal gatherings, and hence, is the most prominent space in the complex. It is a longitudinal three-aisled hall divided by a colonnade of five columns and flanked by walls which are articulated by blind arcades. Based on the spatial organization of the complex and the central location of the hall, it was perhaps used as an audience hall: for receiving guests and conducting daily business. The head of the household would be seated within or framed by the axial niche in the main hall at Hallaç (Ousterhout, 2017). The presence of such halls in a domestic setting emphasizes the ceremonialization of daily life, as the aristocracy would follow the traditions of the imperial family (Mango, 1987). The inverted T plan, the combination of a horizontal portico and a perpendicular hall, which is observed at Hallaç Complex, is a feature commonly seen in early Islamic palaces (Mathews et al, 1997), although its use at Cappadocia might be rather a reflection of the Constantinopolitan trends than a direct influence of the Islamic palaces. The complex at Hallaç seems to have adopted the architectural features of domestic setting from its neighbors in the Mediterranean region, and hence, the hall remains the principal space of communal activity in the complex.

3.2.2 Açıksaray

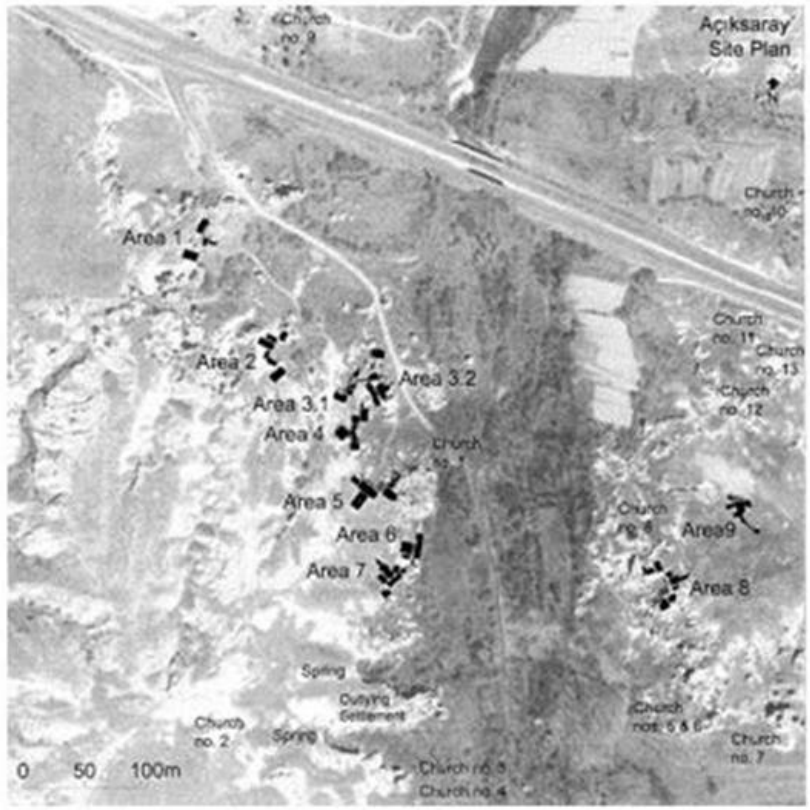

Fig. 4. An aerial view of Açıksaray (from Öztürk, 2014, p. 787)

The areas in the complex are defined in various detailed studies by Öztürk (2010 & 2014), whose plans, as well as the organizational system are followed in this study (Fig. 4). Açıksaray is a settlement that contains nine courtyard complexes and thirteen individual churches; the selection of the site for settlement must have been based on the landform which was suitable for carving several complexes next to each other. Some of the courtyard complexes have monumental facades, reception areas and other utilitarian spaces similar to Hallaç Complex (Öztürk, 2014). The courtyard complexes of Açıksaray have the features of tenth to eleventh-century Byzantine secular architecture (Öztürk, 2010). Due to the location of the site on the medieval border between Christian and Islamic worlds, Açıksaray has diverse architectural elements. It is also because of its strategic location that the site is known to have accommodated military aristocracy and veterans (Öztürk, 2017b).

Fig. 5. (left) interior views of the Açıksaray Cruciform Hall in Area 4, (top right) an exterior view of the Açıksaray Main Hall in Area 5, (top bottom)) an interior view of the Açıksaray Main Hall in Area 5

For this study, the main halls at Areas 4 and 5 of the settlement have been chosen to perform the field tests (Fig. 5). Area 4 comprises of an L-shaped organization around a narrow courtyard facing east. Although a major part of the vestibule has collapsed, the remains indicate a barrel-vaulted space with three arches (Öztürk, 2010). Built on the east-west axis, a cruciform hall, with a central dome resting on four columns, opens into the vestibule. The columns emphasize the axis of the space towards the apse. The square-based columns in the hall are connected with arches; small arches have been used to link walls and columns from all directions. The complex has six other spaces including a kitchen to the south, two barrel-vaulted rooms to the south and west, and a stable to the north-east of the courtyard (Öztürk, 2014).

Due to its size and prominent location, Area 5 seems to have been the main courtyard complex in Açıksaray (Öztürk, 2017b). The courtyard faces the north, while the vestibule and the main hall are towards the south. Such an organization with a barrel-vaulted horizontal vestibule and a perpendicular main hall create the inverted T-plan (Mathews et al, 1997). The complex has a vestibule and a main hall in the south, a church in the southeast, a kitchen in the southwest, and four barrel-vaulted rooms with unidentified functions. The façade, decorated with double recessed horseshoe-arched blind niches, is divided into three registers. The barrel-vaulted vestibule, which is behind the façade and is composed of five perpendicular arches, has the entrances to the main hall and another room. The main hall is carved along the axis that goes through the center of the courtyard. A transverse arch divides the main hall in two equal bays. At the end of the hall, opposite the entrance, a circular boss has been carved in the crest of the vault, which could symbolize the end of a sequential process (Öztürk, 2010). All the spaces in the complex are arranged around the three-sides of the courtyard; such a three-sided organization around a central courtyard is a common feature in both Açıksaray Area 5 and Hallaç Complex (Ousterhout, 2017).

3.2.3 Avanos

Fig. 6. A general view of the town of Avanos

Avanos is one of the most visited towns in Cappadocia. The town is known to have become an important center during Hellenistic and Roman periods (Strabon, 2000). Avanos has a vernacular morphology where large rock-cut spaces have been actively used in combination with masonry structures (Fig. 6). For this study, an underground dining hall, at Kirkit Hotel, has been chosen (Fig. 7). The hall is currently being used as a dining space for the hotel, along with a neighboring functioning kitchen on one side. Although the hall is probably not a medieval structure, the longitudinal vaulted rock-cut dining hall, with a number of niches in its walls and a chimney in the ceiling, serves as an adequate and fully preserved hall to be compared with the large halls, which are important components of the residential compounds at Hallaç and Açıksaray. Due to the availability of electricity, the dining hall's acoustics have been documented as part of the study in order to ensure that a standard omni-power sound source, which is preferred according to the guidelines in ISO 3382, 2009, could be utilized and its results could be compared with the results of a portable speaker. The details of the comparison are discussed in chapters 4 and 5.

Fig. 7. Interior views of the Avanos Dining Hall

3.2.4 Çanlı Kilise

The Çanlı Kilise settlement is located on the outskirts of present-day Aksaray. The church stands aloof from the rest of the settlement (Fig. 8). According to Ousterhout, as opposed to the perspective of previous scholarship, the Çanlı Kilise region was not a monastic center; instead, the region had significant residential and military character (2005). The church at the settlement is considered unique because it is one of the few churches in Cappadocian region that is a masonry construction as opposed to be carved out of the volcanic tuff. The church is located on a hill top, at the edge of the settlement;

and was the main church for the Çanlı Kilise settlement. Hence, it was different from the small churches in a residential context within the same settlement, which are closer to the Hallaç Church in terms of context and size

Fig. 8. (left) an exterior view of Çanlı Kilise, (top right) an interior view of the main church space (naos) with three apses, (bottom right) the entrance hallway (narthex) of the church

The church was built in three main phases (Ousterhout, 2005). Phase I of the church only included the main structure, the naos which is approximately 9.2 meters square, and was constructed in the early eleventh century (Ousterhout, 2017). The second phase of the church included a narthex to the south and the north, while during the third phase of the construction, a parekklesion (side chapel) was added to the church (Ousterhout, 2005).

The naos, with three apses on the east, has four central piers that supported the dome until the twentieth century. The dome holds immense importance as it is the only Middle Byzantine dome in Cappadocia that survived and could be documented in the 20th century. The dome is approximately 16 meters in height. While the drum of the dome is decorated with slit windows, it is smooth on the inside (Ramsay & Bell, 1952). The plan of the cross-in-square church remains compact; a characteristic that is in line with the local practice. Almost all Cappadocian churches are more compact versions of Constantinople examples (Ousterhout, 2017; Rodley, 1985).

The church with its underground structures, the finely detailed facades, the faceted apses, and thick mortar beds all affirm the notion that the design of the church comes from Constantinople, and a few builders must have received their training in the capital, while the rest of the work was carried out by local workforce (Krautheimer & Ćurčić, 1992; Ousterhout, 2005). There are some striking similarities in the design of the church with the churches of Constantinople; although there are a few aspects that make Çanlı Kilise different. Instead of using brick for the entire thickness of the walls, stone and brick has been utilized as revetments for a rubble core. The vaulting of the church is also made of stone, which reflects the local construction technique of the region (Ousterhout, 2017). Therefore, the limited use of bricks in the façade indicates the possibility of the bricks being imported in order to create a prominent landmark in Cappadocia, as a reminder of the center, Constantinople.

For the scope of this study, the earliest part of the church (the naos) is studied acoustically as the liturgical practices were carried out in the main church space (Marinis, 2014), and thus, it should be acoustically documented to trace the space's activity patterns. Instead of a permanent separation between the sanctuary and the naos, it is possible that a wooden screen was used during times of liturgy (Ousterhout, 2005). Therefore, the screen is included in the naos before carrying out acoustical simulation tests on the church. The study also documents the acoustics of the church with the additional features of the Phase II, which mainly included a double-storied southern narthex with a wooden roof (Ousterhout, 2005). According to Ousterhout, based on the iconography of the paintings in the naos, a painter from the center of Constantinople must have been hired by the patron of the church to do the job. It is possible that the painter would have reached the area well after the completion of Phase II (2017). Therefore, based on this theory, the study includes a virtual and aural study of the Phase I construction (naos) with and without the paintings found on the interior surfaces. These paintings were made with the application of a very thin layer of plaster on the interior walls, which could be the reason behind the present-day deterioration of the paintings (Ousterhout, 2005). The study also documents the acoustics of the church from both Phase I and Phase II, to evaluate the quality of aural performance of the space over time.

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CHAPTER 4

DATA COLLECTION METHODS

The data collection of the study has been conducted in three main parts. The following chapter is a description of the three methodological approaches that have been employed in the data collection and analysis process.

4.1 Field Measurements

On 27th and 28th of November, 2020, filed tests were performed in the selected sites of Hallaç, Açıksaray, and Avanos. The sites are acoustically isolated. Firstly, due to the travel restrictions during the pandemic, the sites were not occupied by tourists. Secondly, all the sites are located further away from main roads and streets. The purpose of the tests is to record impulse responses at numerous positions in the rock-cut spaces for further analysis, in accordance to the guidelines in ISO 3382, 2009 (ISO, 2009).

The full set of measurements are held by using a B&K (Type 4292-L) standard dodecahedron omni-power sound source, a B&K (Type 2734-A) power amplifier, a B&K (Type 4190ZC-0032) microphone combined with a B&K (Type 2250-A) hand held analyzer, and a portable PC. The sampling frequency of the recorded multi-spectrum impulse is 48 kHz, covering the interval of interest between 100 and 8000 Hz. The impulse response length is kept at 10 seconds. Noise signals are generated using DIRAC Room Acoustics Software Type 7841 v.4.1. The same software is also used for post-processing of the measured impulse responses for all receiver positions. Three types of signals are tested; E-sweep, MLS, and balloon pop. The balloon pops are treated as an external signal, while E-sweep and MLS are internal signals generated by the software. Rubber balloons have already been used in earlier studies under similar conditions, and they have presented satisfactory results (Iannace & Trematerra 2014a; Iannace et al, 2014; Ciaburro et al, 2020).

The omni-power sound source and the amplifier could only be utilized in Avanos. Due to the absence of an electrical supply in Hallaç and Açıksaray, the omnidirectional sound source is replaced by a Bang and Olufsen Beolit 17 speaker; the speaker has already been used in an earlier study (Fazenda et al, 2017) because of its battery autonomy and flat frequency response. The rest of the system comprises of units as described above.

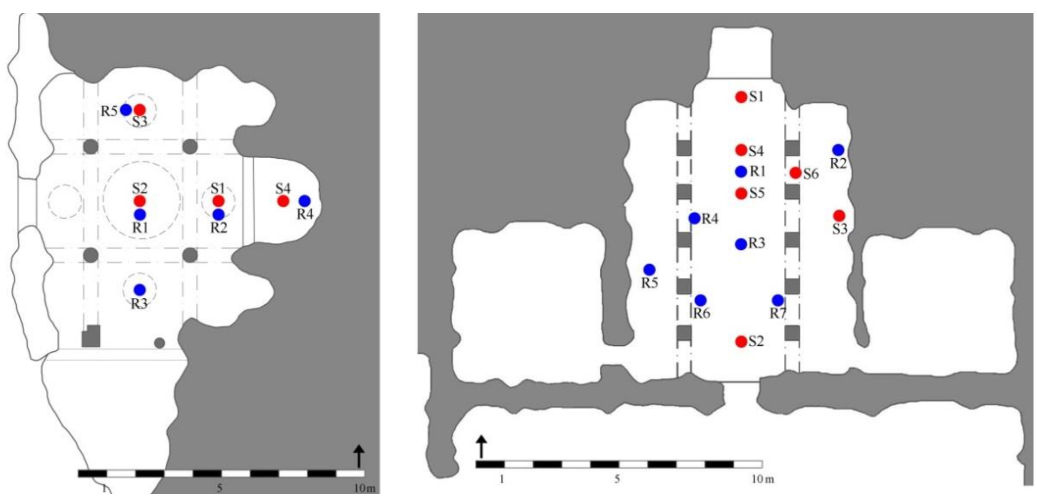


Fig. 9. (left) source (4) and receiver (5) positions at Hallaç Church, (right) source (6) and receiver (7) positions at Hallaç Main Hall (drawn by the author based on Ousterhout, 2017, p. 281)

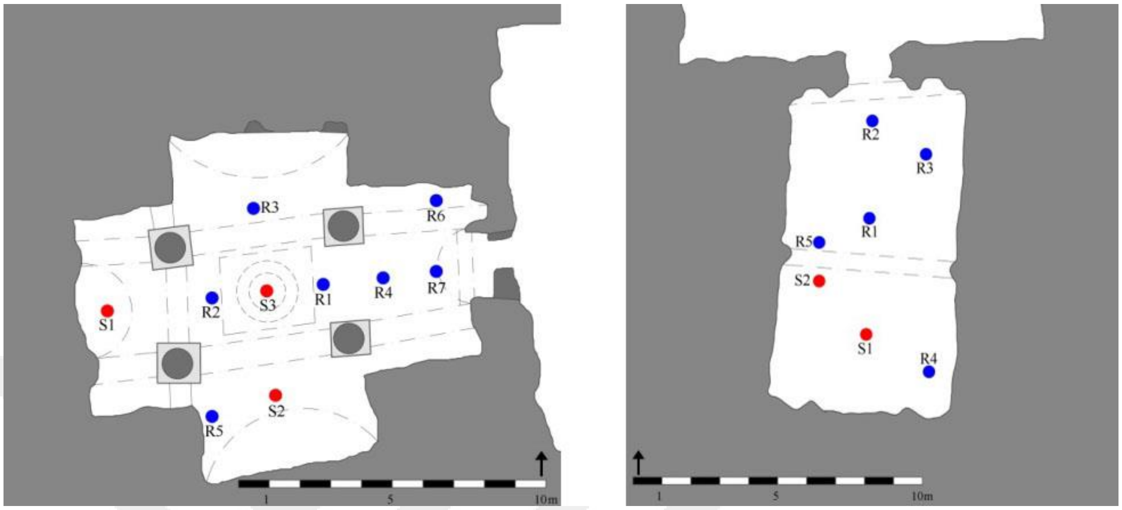


Fig. 10. (left) source (3) and receiver (7) positions at Açıksaray Cruciform Hall, (right) source (2) and receiver (5) positions at Açıksaray Main Hall (drawn by the author based on Öztürk, 2014, p. 795 and 789 respectively)

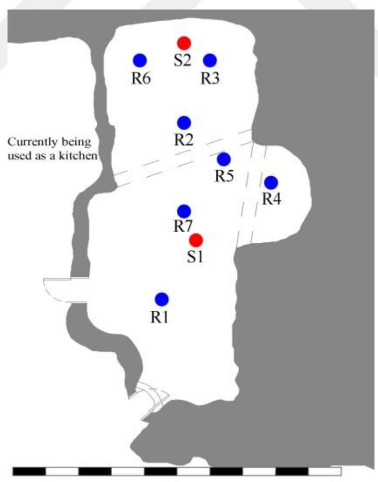


Fig. 11. Source (2) and receiver (7) positions at the Avanos Dining Hall, also showing the neighboring kitchen space (drawn by the author)

Overall, different source and receiver positions are used to get an average acoustic response to characterize interior sound field conditions. At least two different sound source positions must be used to record the impulse response (ISO, 2009). Therefore, 4 source and 5 receiver positions in Hallaç Church, 6 source and 7 receiver positions in Hallaç Main Hall, 3 source and 7 receiver positions in Açıksaray Cruciform Hall, 2 source and 5 receiver positions in Açıksaray Main Hall, and 2 source and 7 receiver positions in Avanos are used to record the impulse responses (Fig. 9, 10, 11). The sound and receiver positions are chosen in accordance to the function of the space. For instance, in the Hallaç Church, the speaker was placed at the altar where a person would have stood to address the people in the church. Similarly, the same reasoning of addressing people is used in the main reception hall of Hallaç, and the halls of Açıksaray. The speaker height is kept around 1.5m above the ground to imitate an average human body, while the microphone is held around 1.2m above the ground level. Background noise levels are also measured during the data collection in each space. The raw data collected in the spaces is presented in Appendix A.

4.2 Impedance Measurements

Impedance tube (S.C.S. Kundt Impedance Tubes) tests are performed on two rock samples from two different regions of Cappadocia, Göreme and Ürgüp. The tube tests are based on a transfer function method. The impedance tube measurement method is used to measure sound absorption coeffcients of different materials across a frequency range of 125 Hz to 4 kHz.

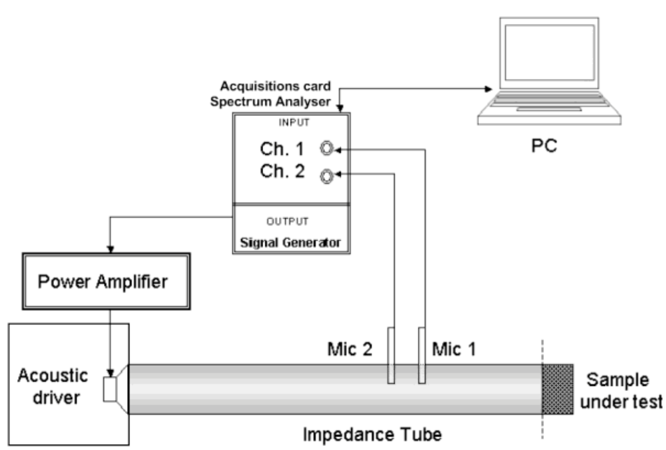


Fig. 12. A schematic diagram of the impedance tube setup (from McGrory et al, 2012, p. 3)

The results are obtained using an anlysis system with digital frequency and two microphones. For testing, the sample is placed at one end of the tube while a sound source is attached to the other end. The sound source produces plane waves in the tube. The microphones, which are mounted on the wall of the tube, record acoustic pressures to obtain interference area decomposition. The setup (Fig. 12) of the transfer function method is in line with the standard ISO 10534-2 (1998). The impedance tube method has been proven to be an efficient and faster method to calculate absorption coefficients of sound-absorbing materials than both Standing-Wave-Ratio (SWR) and reverberant room methods (Chung & Blaser, 1980; McGrory et al, 2012).

Fig. 13. Göreme rock samples (left) for low frequency and (right) high frequency setup

Fig. 14. Ürgüp rock samples (left) for low frequency and (right) high frequency setup

For this study, two types of samples are prepared for each rock. One sample is analyzed using the 100mm diameter tube for frequencies in between 50 Hz to 1 kHz. The other sample is smaller in diameter (28mm) and is used for mid to high frequencies in between 1 kHz to 4 kHz. For the low frequency samples, rings of cardboard have been stacked (14 cm deep for Göreme and 10 cm deep for Ürgüp) to create a mold. For the high frequency samples, a steel mold has been filled in with the rock tuff. Since the rock samples are porous, an acoustically transparent piece of cloth has been used on both ends of the mold to ensure that the material stays compact (Fig. 13, 14). Each sample for both low and high frequency setups has been tested in the tube for 10 times to ensure the repeatability and accuracy of the results. In order to use the apparatus, the steps mentioned in Amadasi's guide have been followed (2019).

A rock sample from Hallaç Complex has also been brought to study its acoustical properties (Fig. 15). The sample cannot be used for impedance tests as it is not a porous material and has been impossible to cut, using the same cutter that has been employed to cut the other two rock samples.

Fig. 15. Rock sample from Hallaç Complex

Unlike the samples of Göreme and Ürgüp, the rock from Hallaç could not be cut. This means that the rock samples from different areas of Cappadocia have different physical properties due to their different composition and exposure to environmental factors. Hence, it would be misleading to assume that all the rocks from Cappadocia have similar acoustical properties, and thus, it is important to document different rock samples and their absorption coefficients from different locations in Cappadocia.

4.3 Acoustical Simulations

With the current advancements in computer-aided tools to create virtual 3D spaces and document their acoustic environments, it has become very convenient to study the acoustics of spaces that are otherwise difficult or impossible to study. Çanlı Kilise is one such site; the remains of the Middle Byzantine masonry church only include the four walls that encapsulate the main hall of the church. Consequently, a virtual and aural model, with all the main volumetric arrangements, of the church is created.

The acoustics of the church are documented by means of ODEON Room Acoustics Software version 16.08. The program uses a hybrid calculation system that makes use of both image-source method and ray-tracing. The software is known to be accurate while assessing a room’s geometry and absorption values (Rindel, 2000).

Just noticeable difference (JND) is a measure of the smallest perceivable difference of a given parameter, and is used to correlate subjective sound perception to objective measurements (Martellotta, 2010). Therefore, JND is very useful in assessing the accuracy of a measurement and the reliability of a prediction software (Bork, 2000), such as ODEON. As a result, in order to study the acoustical performance of Çanlı

Kilise, the Hallaç Church and Avanos Dining Hall and their respective T30 values, from the field tests, have been used for the tuning process with a JND of 5%. It is a calibration process which is done to ensure that the virtual models are as close to the real spaces as possible. The two spaces are modeled to get information about the sound absorption qualities of their materials before creating an acoustic model of Çanlı Kilise.

ODEON is also used to get estimated volumes of the spaces. A simplified virtual model of the Hallaç Church (estimated volume: 595 m^3) has been created based on the plan drawing by Ousterhout (Fig. 2) and the geometrical measurements taken on the site. ODEON Room Acoustics Software version 16.08 has been used for acoustic analysis. The transition order is set at 2, the room impulse response length is kept at 5000 ms, with a resolution of 5.0 ms, and the number of late rays is set at 7736 as recommended by the software. Figures 16 and 17 show images of the church's virtual model.

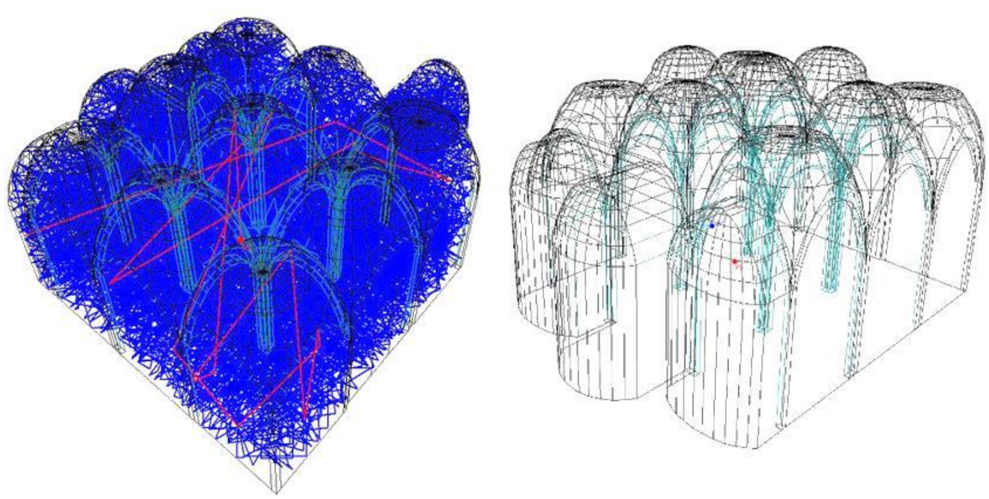


Fig. 16. Hallaç Church (left) ray tracing model, (right) acoustical model with source (red) and receiver (blue) positions

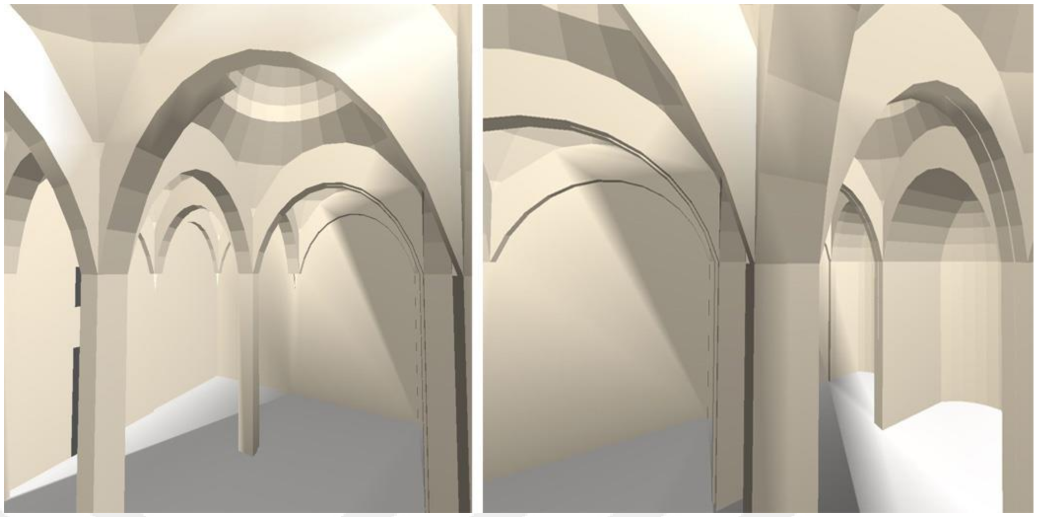


Fig. 17. 3D Open GL views of the Hallaç Church

The same process is repeated for the Avanos Dining Hall. A simplified version of the hall is virtually modeled based on the three-dimensional measurements taken on the site (estimated volume: 123 m^3). Once the virtual model of the space is imported in ODEON, the following parameters are used: the transition order is kept at 2, the room impulse response length is kept at 2000 ms, with a resolution of 2.0 ms, and the number of late rays is set at 1898 as recommended by the software. The images of the virtual model are shown in Figures 18 and 19. The results of the tuning process are further discussed in Chapter 4.

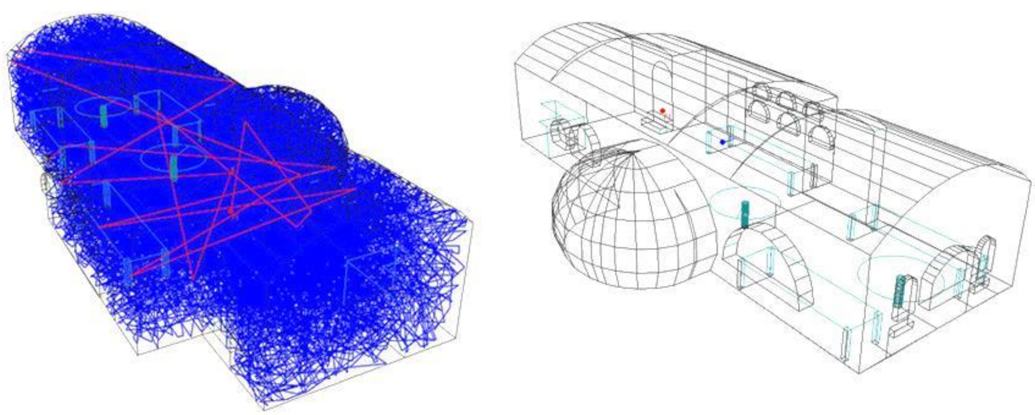


Fig. 18. Avanos Dining Hall (left) ray tracing model, (right) acoustical model with source (red) and receiver (blue) positions

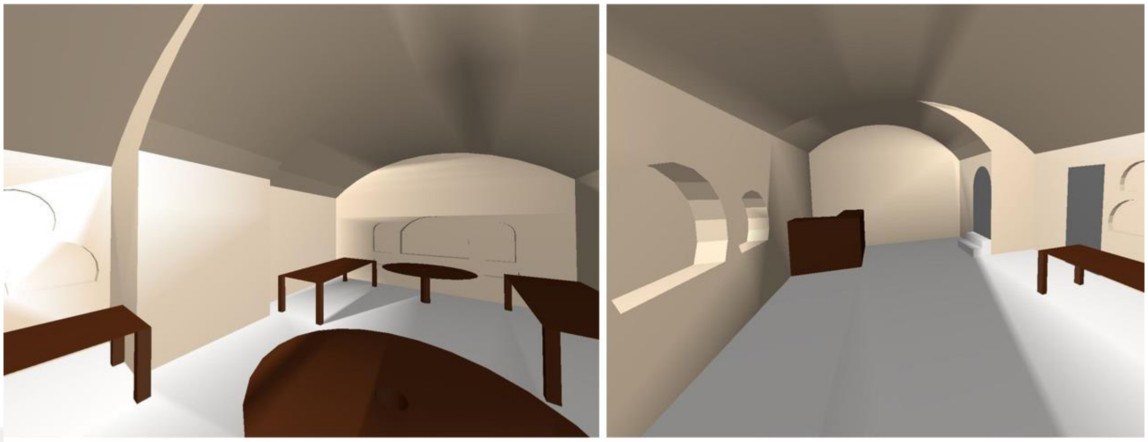


Fig. 19. 3D Open GL views of the Avanos Dining Hall

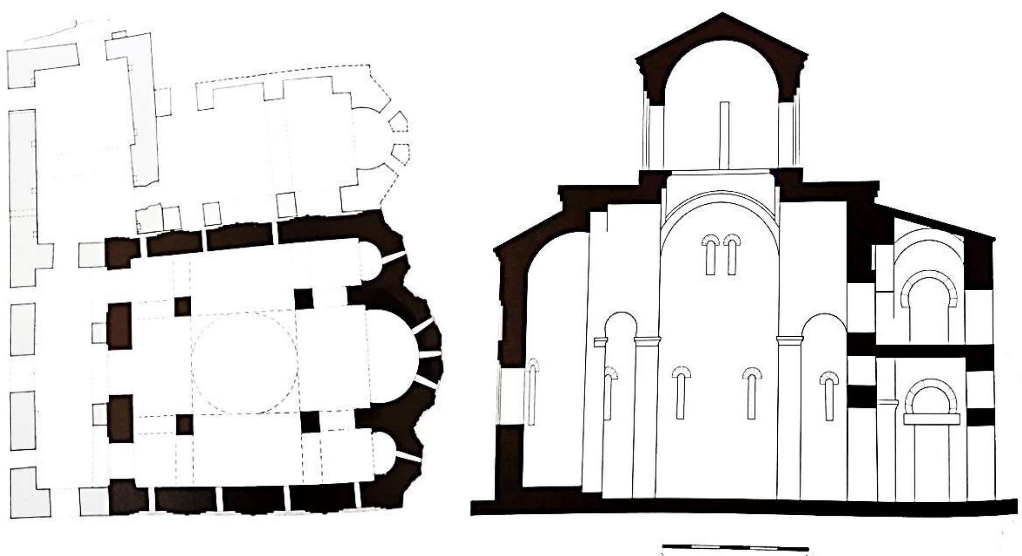


Fig. 20. Plan and section drawings of Çanlı Kilise (from Ousterhout, 2017, p. 92 and 94 respectively)

The architectural drawings (Fig. 20) and dimensions recorded at the site have been used to create simplified 3D models of Çanlı Kilise. The simulations are run on three different models of Çanlı Kilise; Phase I (without frescoes), Phase I (with frescoes), and Phase II (with frescoes and narthex). For both the models from Phase I (estimated volume: 975 m^3), the following parameters are used in order to collect acoustical data regarding the space in ODEON; the transition order is set at 2, the room impulse response length is kept at 4000 ms, with a resolution of 5.0 ms, and the number of late rays is set at 2000. The same materials are used for the floor and openings as in the model of the Hallaç Church. Furthermore, the Hallaç Church material (Table 6) is used for the walls and the dome of Çanlı Kilise. A wooden screen is added between the apses and the naos to represent an iconostasis (Ousterhout, 2005). Therefore, the sound source is placed behind the screen to recreate the acoustical environment during liturgical practices. Figures 21 and 22 show images of the church's acoustical model from Phase I.

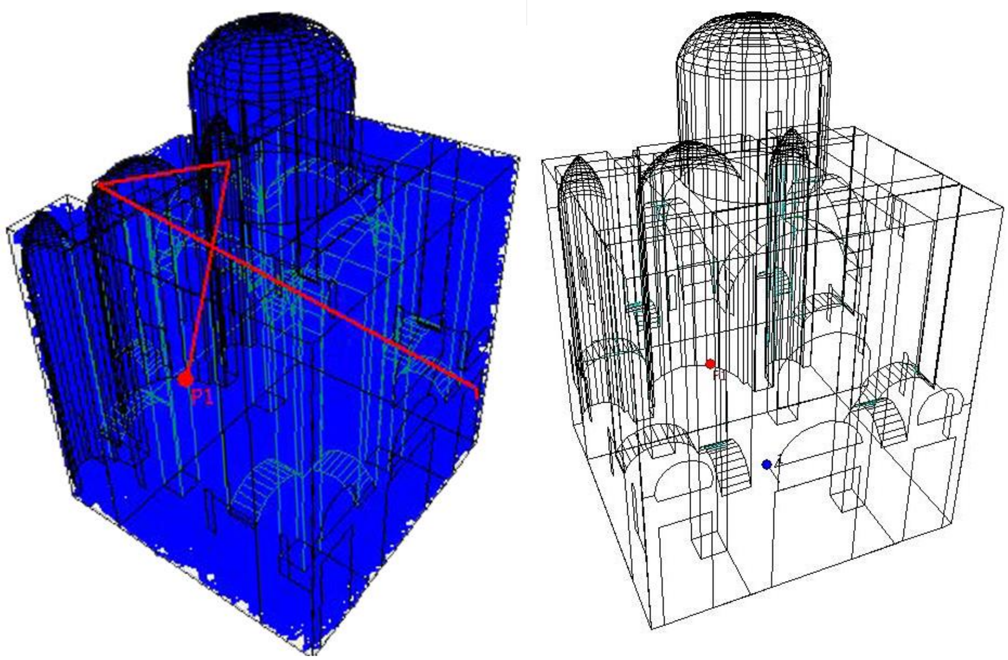


Fig. 21. Çanlı Kilise Phase I (left) ray tracing model, (right) acoustical model with source (red) and receiver (blue) positions

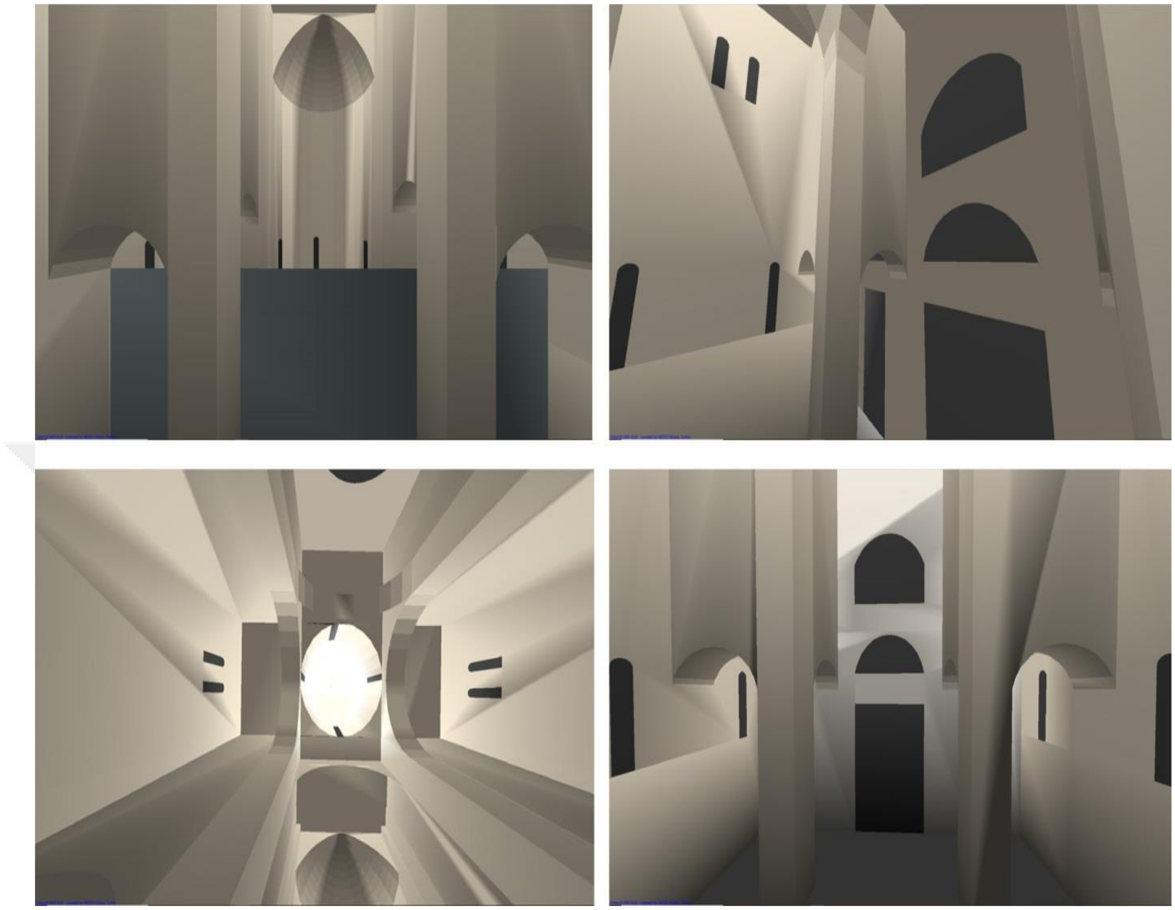


Fig. 22. 3D Open GL views of Çanlı Kilise Phase I

For Phase II of the model, a two-storied narthex, with a wooden roof, is added to the main church space. The estimated volume of the Çanlı Kilise Phase II model is 1200 m^3, In ODEON, the following parameters are used to collect acoustical data; the transition order is set at 2, the room impulse response length is kept at 4000 ms, with a resolution of 5.0 ms, and the number of late rays is set at 2000. Figures 23 and 24 present images of the Çanlı Kilise Phase II acoustical model.

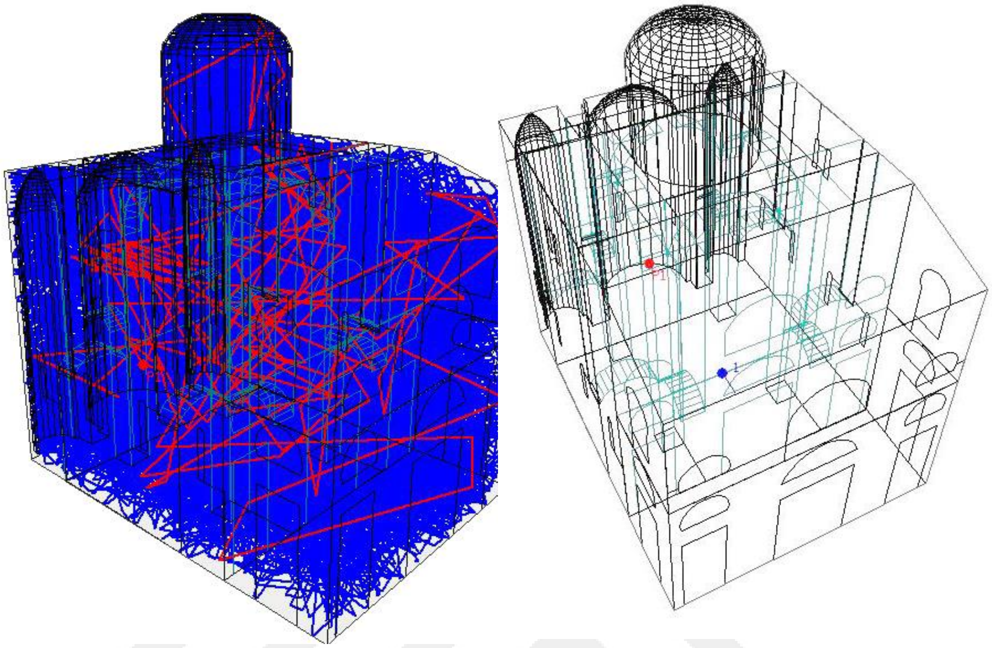


Fig. 23. Çanlı Kilise Phase II (left) ray tracing model, (right) acoustical model showing source (red) and receiver (blue) positions

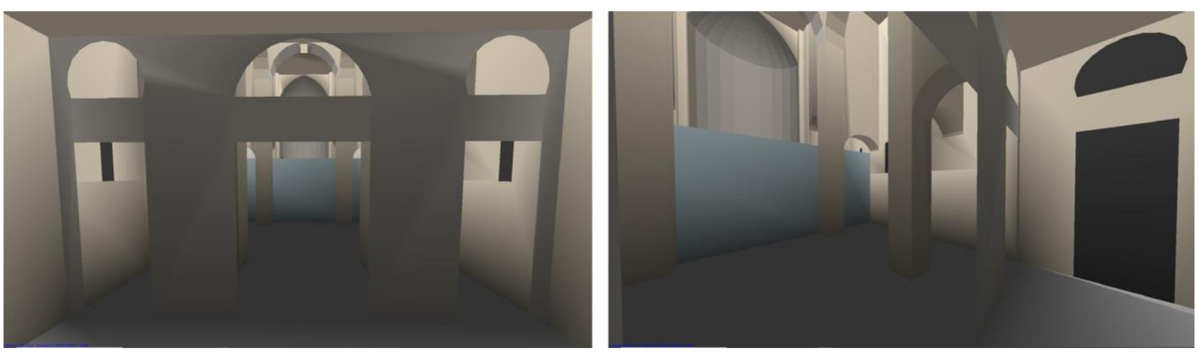


Fig. 24. 3D Open GL views of Çanlı Kilise Phase II

Once all the materials are assigned, the values for EDT, T20, T30, C80, D50, and STI are obtained from ODEON in order to evaluate the acoustics of the masonry church. The results of the simulation are discussed in detail in the following chapter.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Acoustical Field Tests of Hallaç, Açıksaray, and Avanos

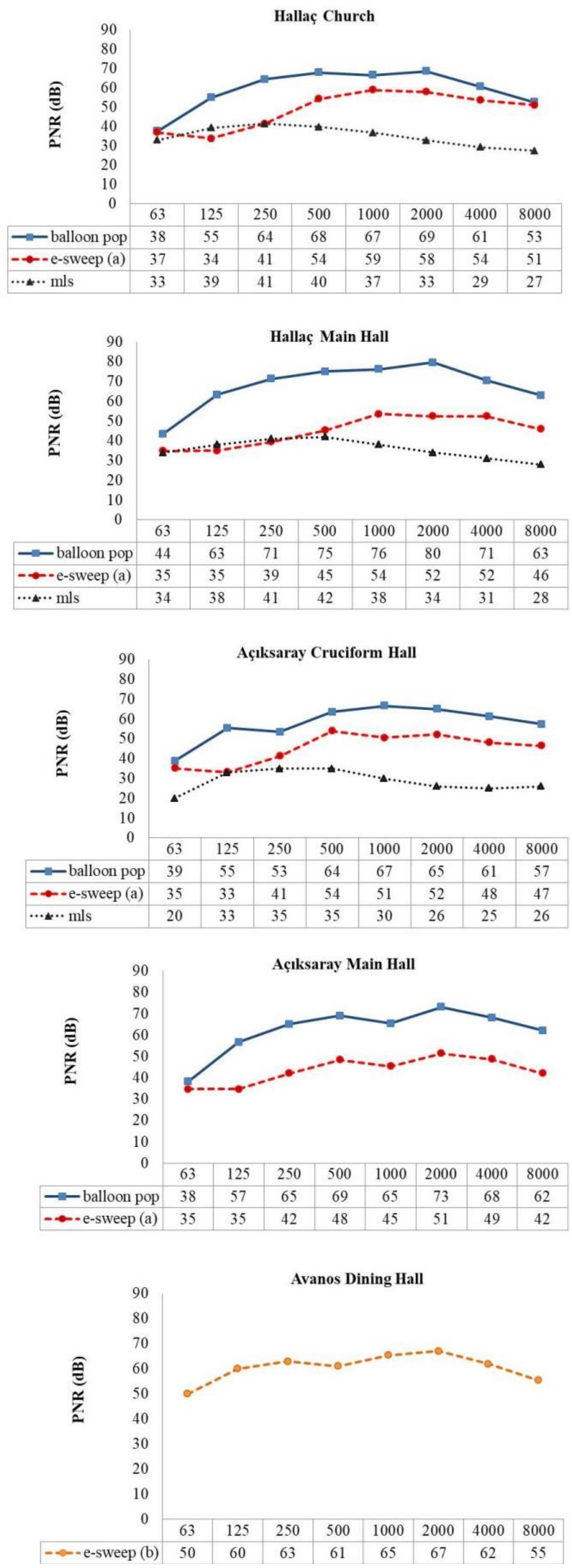
This section discusses the results of the in-situ tests performed at Hallaç, Açıksaray, and Avanos.

5.1.1 Assessment of Source Signals

Three different types of signals (e-sweep, MLS, and balloon pop) are employed during the field tests. It is advisable to obtain a signal which has at least a peak signal-to-noise ratio (PNR) of 45 dB higher than the background noise in all octaves (Sü Gül, 2019). Due to the lack of electricity in Hallaç and Açıksaray, electronic signals are produced with a limited sound level output. In order to obtain a high signal ratio, different source signals are also used to identify the signal that gives the highest PNR values over the whole frequency spectrum. The availability of electricity in Avanos made it possible to use a standard omni-directional sound source with an amplifier, thus only e-sweep is used as the test signal within that space.

As can be observed in Figure 25, e-sweep has always resulted in higher PNR values. For that reason MLS is not tested in Açıksaray Main Hall due to the lack of time; only e-sweep and balloon pop signals are utilized. The background noise level values are recorded to be around 32 dBA for both Hallaç and Açıksaray. Avanos has a slightly higher background noise level around 38 dBA. This is one other reason for the PNR values to be high within the isolated spaces of Hallaç and Açıksaray.

Different source signals have been compared with each other through PNR values over octave bands for each space (Fig. 25). Due to the small volumes of the spaces, a balloon pop excited the spaces sufficiently, and resulted in the highest PNR values for all bands from 63 Hz to 8000 Hz in both Hallaç and Açıksaray. Among the three signals tested (Hallaç Church, Hallaç Main Hall, and Açıksaray Cruciform Hall) there is a little deviation between the PNR values at lower octaves, especially between e-sweep and MLS. The MLS signal results in significantly lower PNR values than the other two signals for mid and high octaves. At mid and high octaves, the difference in the PNR of balloon pop and e-sweep is around 10-15 dB, except for the Hallaç Main Hall where the difference rises up to more than 20 dB. The balloon pop signal results are also comparable to the e-sweep results generated by an omni-directional speaker in Avanos; except for the low octaves, the balloon pop resulted in lower PNR values whereas it gives higher values at mid and high octaves. As a result, balloon pop signals are utilized in post-processing for extracting the monaural acoustic parameters for those spaces where the electricity is not available. In Hallaç and Açıksaray, e-sweep (output of Bang and Olufsen Beolit 17) has resulted in the second highest PNR values, while MLS remains the weakest signal among all three.



Hallaç Church

	63	125	250	500	1000	2000	4000	8000
balloon pop	38	55	64	68	67	69	61	53
e-sweep (a)	37	34	41	54	59	58	54	51
mls	33	39	41	40	37	33	29	27

Hallaç Main Hall

	63	125	250	500	1000	2000	4000	8000
balloon pop	44	63	71	75	76	80	71	63
e-sweep (a)	35	35	39	45	54	52	52	46
mls	34	38	41	42	38	34	31	28

Açıksaray Cruciform Hall

	63	125	250	500	1000	2000	4000	8000
balloon pop	39	55	53	64	67	65	61	57
e-sweep (a)	35	33	41	54	51	52	48	47
mls	20	33	35	35	30	26	25	26

Açıksaray Main Hall

	63	125	250	500	1000	2000	4000	8000
balloon pop	38	57	65	69	65	73	68	62
e-sweep (a)	35	35	42	48	45	51	49	42

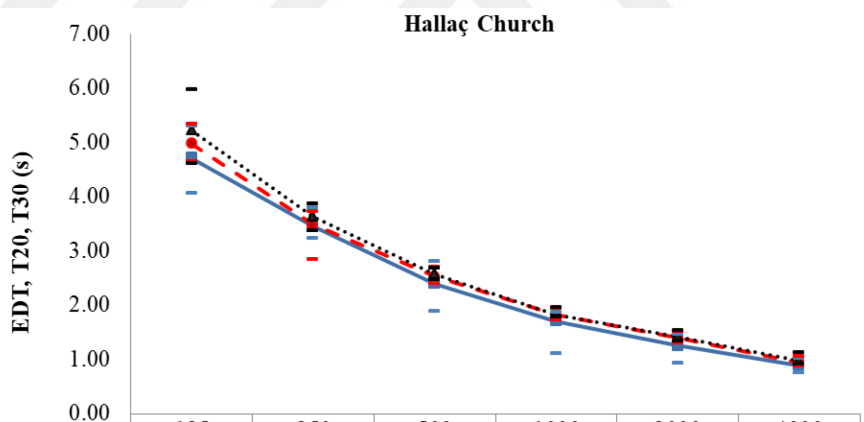
Avanos Dining Hall

	63	125	250	500	1000	2000	4000	8000
e-sweep (b)	50	60	63	61	65	67	62	55

Fig. 25. Comparison of PNR over 1/1 octave bands in Hz; comparison of balloon pop, e-sweep (a) using a Bang and Olufsen Beolit 17 speaker, e-sweep (b) using a B&K (Type 4292-L) omni-directional speaker, and MLS signals for Hallaç, Açıksaray, and Avanos

5.1.2 Decay Rate Results and Comparisons of the Rock-Cut Structures of Cappadocia

Over collected room impulse responses within the rock-cut structures, early decay time (EDT), and reverberation time (T20 and T30) decay rate parameters are analyzed. The primary room acoustics indicators T20 and T30 correspond to the time taken for the energy to drop from -5 dB to -25 dB and -5 dB to -35 dB respectively. On the other hand, EDT is the time for the energy to decay by 10 dB immediately after the arrival of the direct sound. EDT is more dependent on the early reflections and local positions. It also correlates more with the subjective perception of reverberation (Barron, 2009; ISO, 2009; Kuttruff, 2009).



	125	250	500	1000	2000	4000
EDT	4.72	3.45	2.40	1.71	1.25	0.89
EDT (max)	5.31	3.80	2.82	1.87	1.46	1.03
EDT (min)	4.06	3.23	1.89	1.10	0.92	0.76
T20	4.98	3.48	2.53	1.82	1.40	0.94
T20 (max)	5.33	3.73	2.70	1.95	1.52	1.06
T20 (min)	4.65	2.83	2.40	1.73	1.31	0.88
T30	5.23	3.63	2.57	1.83	1.42	0.97
T30 (max)	5.98	3.87	2.69	1.96	1.54	1.12
T30 (min)	4.61	3.37	2.47	1.78	1.34	0.91

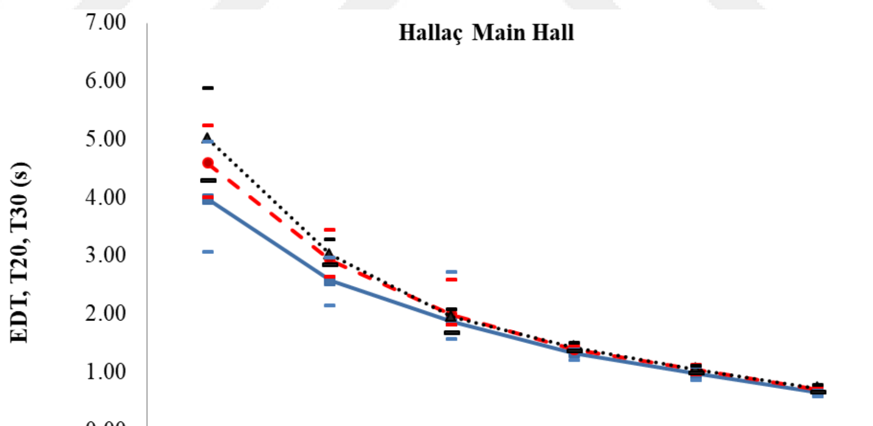
Fig. 26. Maximum, minimum and average values for EDT, T20, and T30, for Hallaç Church over 1/1 Octave Bands

Figure 26 shows the decay rate results for the Hallaç Church. The space seems to be relatively reverberant considering the volume of the space (571 m^3). The EDT for the church is around 2.0 s at the mid-range frequency, and it drops down to 1.0 s at high frequencies. As expected, T20 and T30 are very close to each other over the whole frequency spectrum. Since EDT values are numerically very close to the values of T20 and T30, there is no major difference observed in the decay rate between the specific source positions and the overall space. All the parameters show similar trends of showing larger deviations from the average value at lower frequencies than at mid and high frequency ranges.

The naos of a Middle Byzantine church was utilized during a liturgical practice. The practice would involve a congregation of people and clergy in the church (Teteriatnikov, 1996); some parts of the Divine Liturgy were composed of a dialogue between the two groups (Marinis, 2014). Singers used to be a distinguishing part of the congregation and they had fixed places in the church; the choir would either be on an ambo, an elevated platform in the naos, or divided into two groups on either side of the center of naos (Spyrakou, 2008 as cited in Marinis, 2014). Therefore, it becomes essential to evaluate the performance of liturgical music in the Hallaç Church.

An optimum range for liturgical music in the church has been estimated using the formula RT =0.55*log10(Vol.)-0.14 (Beranek, 1988). The optimum range has an RT of 1.4 s; the RT values of the Hallaç Church are higher than 1.4 s at mid frequencies. The optimum range has the highest RT of 1.7 s at 125 Hz and the lowest RT of 1.1 s at 4 kHz. The decay rates in the church are much higher than the optimum range for liturgical music, except for the values from 1 kHz to 4 kHz. The decay rates indicate that the tuff stone absorbs high frequencies greater than the low frequencies, creating a high bass ratio (BR) of around 2.0. BR is a ratio of the reverberation times of low frequencies over mid frequencies. The high BR is a means of augmented male voice (Sü Gül, 2021), which should have been an important part in the liturgical practices at a Medieval Byzantine church.

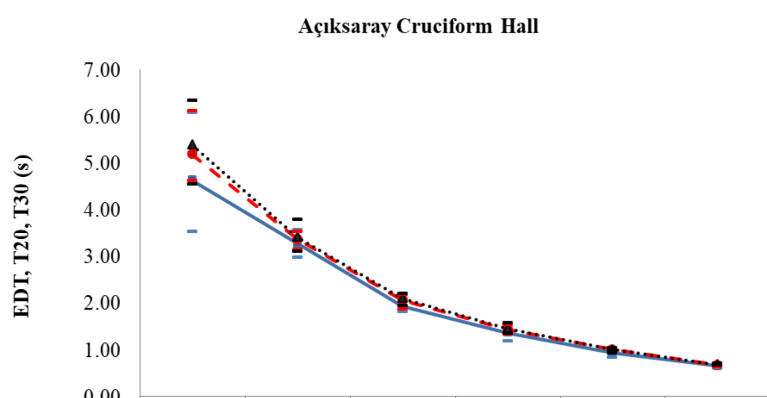
In the Main Hall at Hallaç (322 m^3), EDT is around 1.5 s at the mid-range frequencies, while T20 and T30 are around 1.7 s (Fig. 27). There is less than 10% difference between EDT values in comparison to T20 and T30 except for low frequencies, where the difference is slightly higher. The same differences are observed in Açıksaray Cruciform Hall (400 m^3) as shown in Figure 28. Since the volume of the space is slightly larger than the Main Hall at Hallaç, the reverberation time is also slightly higher.



	125	250	500	1000	2000	4000
EDT	3.97	2.57	1.87	1.33	0.98	0.65
EDT (max)	4.96	2.97	2.71	1.42	1.09	0.71
EDT (min)	3.07	2.14	1.56	1.20	0.85	0.57
T20	4.59	2.92	1.99	1.39	1.04	0.70
T20 (max)	5.23	3.44	2.59	1.44	1.12	0.74
T20 (min)	4.00	2.63	1.80	1.34	0.96	0.66
T30	5.01	3.02	1.94	1.43	1.05	0.72
T30 (max)	5.88	3.27	2.07	1.50	1.10	0.77
T30 (min)	4.29	2.85	1.68	1.36	0.99	0.66

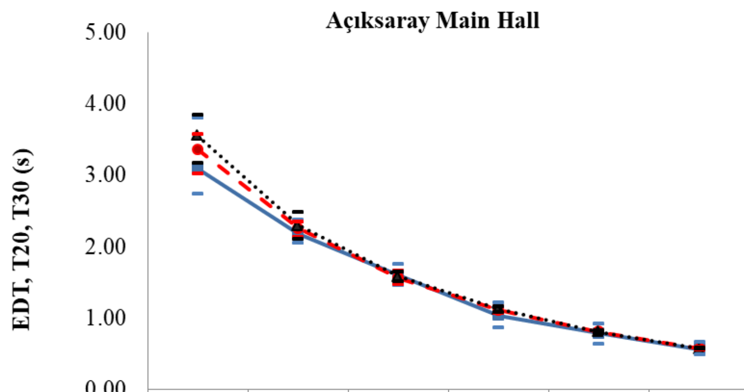
Fig. 27. Maximum, minimum and average values for EDT, T20, and T30, for Hallaç Main Hall over 1/1 Octave Bands

The third hall in the study, Açıksaray Main Hall (217 m^3), has an EDT of around 1.3 s at the mid frequency range (Fig. 29). The EDT and RT for Avanos (114 m^3) are around 0.7 s with less than 10% difference between their values (Fig. 30), which underlines a proper distribution of sound. Such halls are primarily known to be used for gatherings such as weddings, receiving guests, and funerals in the Byzantine Empire (Rautman, 2006). Furthermore, Özgenel has distinguished halls into three categories; the halls in this study seem to belong to the apsidal room (audience halls) category. These audience halls were mainly used by the men of a family to conduct business-related work; the apse in the halls was designed to reinforce the authority of the male head in front of his clients (Özgenel, 2007). Whether these gatherings employed only speech or both speech and music cannot be clearly distinguished based on the existing literature. In acoustical terms, it can be stated that the decay rates are much higher in comparison to speech-oriented spaces in the modern world.



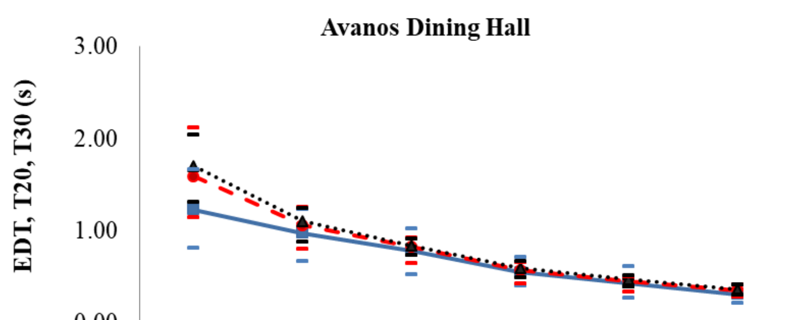
	125	250	500	1000	2000	4000
EDT	4.64	3.28	1.94	1.37	0.93	0.65
EDT (max)	6.08	3.56	2.18	1.54	1.01	0.71
EDT (min)	3.53	2.98	1.81	1.19	0.83	0.61
T20	5.20	3.37	2.07	1.44	1.01	0.67
T20 (max)	6.11	3.53	2.18	1.53	1.05	0.70
T20 (min)	4.63	3.15	1.88	1.33	0.97	0.64
T30	5.40	3.42	2.10	1.46	1.01	0.68
T30 (max)	6.34	3.80	2.21	1.57	1.05	0.71
T30 (min)	4.56	3.11	1.94	1.36	0.97	0.66

Fig. 28. Maximum, minimum and average values for EDT, T20, and T30, for Açıksaray Cruciform Hall over 1/1 Octave Bands



	125	250	500	1000	2000	4000
EDT	3.10	2.18	1.60	1.04	0.78	0.57
EDT (max)	3.80	2.38	1.75	1.21	0.92	0.66
EDT (min)	2.74	2.05	1.45	0.86	0.64	0.49
T20	3.36	2.26	1.56	1.11	0.81	0.57
T20 (max)	3.57	2.35	1.66	1.16	0.82	0.59
T20 (min)	3.02	2.13	1.47	1.07	0.79	0.55
T30	3.56	2.30	1.58	1.12	0.81	0.57
T30 (max)	3.85	2.48	1.65	1.16	0.83	0.59
T30 (min)	3.17	2.10	1.52	1.08	0.78	0.56

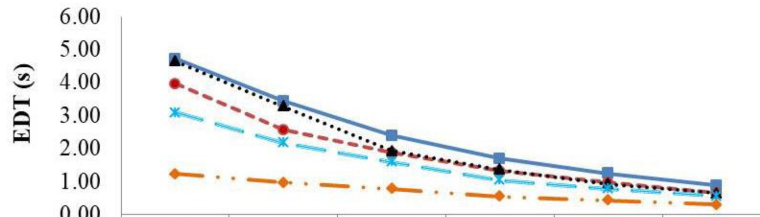
Fig. 29. Maximum, minimum and average values for EDT, T20, and T30, for Açıksaray Main Hall over 1/1 Octave Bands



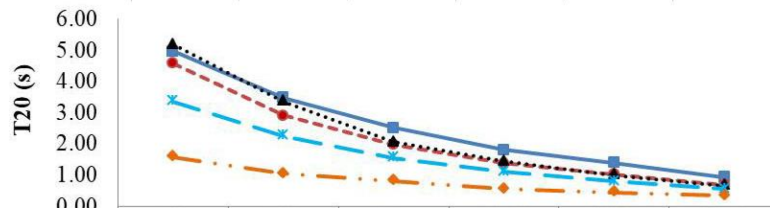
	125	250	500	1000	2000	4000
EDT	1.23	0.97	0.78	0.55	0.43	0.31
EDT (max)	1.67	1.23	1.02	0.72	0.61	0.41
EDT (min)	0.81	0.66	0.52	0.40	0.26	0.21
T20	1.59	1.06	0.82	0.57	0.45	0.35
T20 (max)	2.12	1.25	0.93	0.65	0.50	0.41
T20 (min)	1.15	0.80	0.64	0.42	0.34	0.28
T30	1.70	1.10	0.83	0.59	0.47	0.36
T30 (max)	2.04	1.24	0.91	0.67	0.51	0.41
T30 (min)	1.31	0.88	0.73	0.49	0.39	0.30

Fig. 30. Maximum, minimum and average values for EDT, T20, and T30, for the dining hall in Avanos over 1/1 Octave Bands

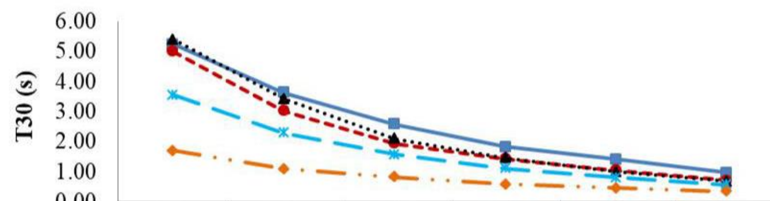
All the spaces show larger deviations from the mean value for the three decay rate parameters at low frequencies, whereas the differences between the highest values and the mean values become much smaller with increasing frequencies. As expected, the average decay rate values keep decreasing as the volume of the spaces get smaller (Fig. 31). In terms of T20 and T30, the acoustic response in the spaces follows a general trend of higher reverberation values at low frequencies and a decrease at higher frequencies. The reverberation times are generally between 1.5 s to 2.0 s, except for the Hallaç Church where RT is a higher than 2.0 s. A longer RT is good for creating a spiritual environment in a church. Although it might challenge speech intelligibility, a long RT augments the perception of rhythm and blurs the semantics of a chant while creating a spiritual aural effect (Pentcheva & Abel, 2017). The dining hall at Avanos, due to its small volume, is acoustically the driest space among all the five rock-cut structures.



	125	250	500	1000	2000	4000
Hallaç Church	4.72	3.45	2.40	1.71	1.25	0.89
Hallaç Main Hall	3.97	2.57	1.87	1.33	0.98	0.65
Açıksaray Cruciform Hall	4.64	3.28	1.94	1.37	0.93	0.65
Açıksaray Main Hall	3.10	2.18	1.60	1.04	0.78	0.57
Avanos Dining Hall	1.23	0.97	0.78	0.55	0.43	0.31



	125	250	500	1000	2000	4000
Hallaç Church	4.98	3.48	2.53	1.82	1.40	0.94
Hallaç Main Hall	4.59	2.92	1.99	1.39	1.04	0.70
Açıksaray Cruciform Hall	5.20	3.37	2.07	1.44	1.01	0.67
Açıksaray Main Hall	3.36	2.26	1.56	1.11	0.81	0.57
Avanos Dining Hall	1.59	1.06	0.82	0.57	0.45	0.35



	125	250	500	1000	2000	4000
Hallaç Church	5.23	3.63	2.57	1.83	1.42	0.97
Hallaç Main Hall	5.01	3.02	1.94	1.43	1.05	0.72
Açıksaray Cruciform Hall	5.40	3.42	2.10	1.46	1.01	0.68
Açıksaray Main Hall	3.56	2.30	1.58	1.12	0.81	0.57
Avanos Dining Hall	1.70	1.10	0.83	0.59	0.47	0.36

Fig. 31. EDT, T20, and T30 for all five spaces over 1/1 Octave Bands

5.1.3 Energy Ratios and Comparisons of the Rock-Cut Structures of Cappadocia

Clarity (C80) and Definition (D50) parameters are analyzed for all field tested spaces. C80 and D50 are ratios of early sound energy to late sound energy (80 and 50 ms respectively), where C80 is directly correlated to music while D50 is used to analyze speech (Barron, 2009). Both the parameters are dependent on receiver positions;

therefore, there are larger deviations from the average values (Fig. 32 to 36) in comparison to the decay rates.

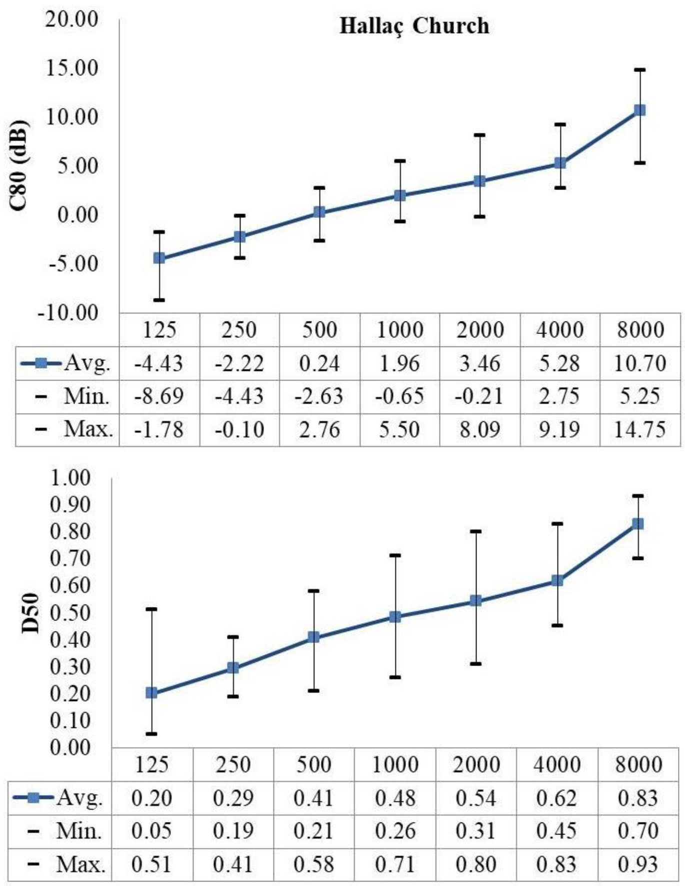
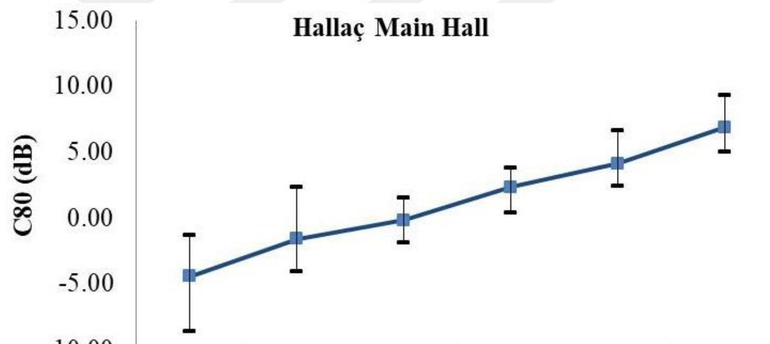
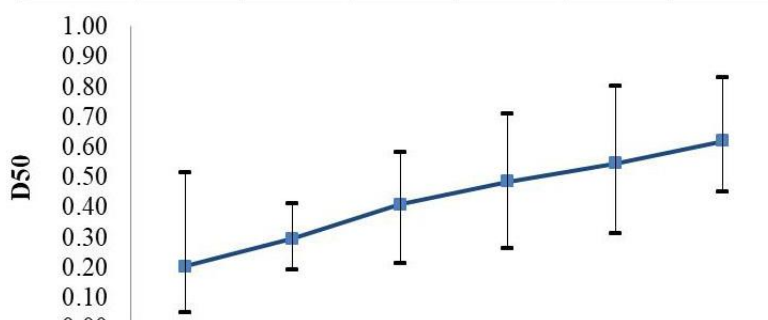


Fig. 32. Maximum, minimum and average values for C80 and D50 for Hallaç Church over 1/1 Octave Bands

In the Hallaç Church, the highest deviation from the C80 mean value is around 4.5 dB at 2 kHz, while the lowest deviation stays around 2 dB at 250 Hz. However, the deviations for D50 are the highest around the mid-range frequencies. The church has a C80 value of around +2 dB and a D50 of approximately 0.50 (Fig. 32). In general, considering the contemporary spaces, a satisfactory acoustical space should have clarity between -2 and +2 dB to satisfy both music and speech criteria, and between -1 and +3 dB for choral music (Kuttruff, 2009). C80 for liturgical music in the church can also be assessed by taking into account the location of the music source in relation to the receiver location. C80 values should be in between -2 dB and +3 dB for locations closer to the source where early energy dominates late energy. This early energy drops with increasing source and receiver distance and consequently, C80 can be in the optimum range of 0 to +5 dB for larger distances (Makrinenko, 1994). The Hallaç Church is a comparatively small space; therefore, the optimum values of C80 for positions close to the source can be utilized. Accordingly, C80 in the church is well within the optimum range for music except for the low frequencies.



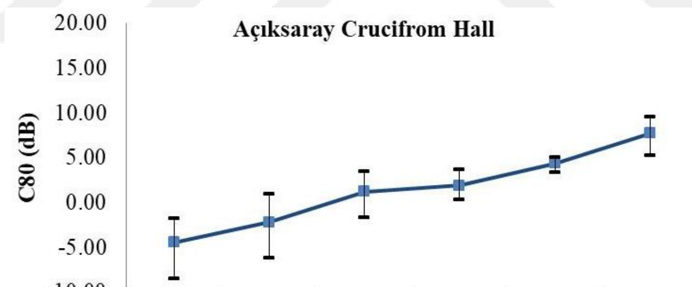
	125	250	500	1000	2000	4000
Avg.	-4.42	-1.55	-0.14	2.35	4.14	6.90
Min.	-8.63	-4.03	-1.88	0.39	2.46	5.03
Max.	-1.32	2.34	1.49	3.80	6.61	9.28



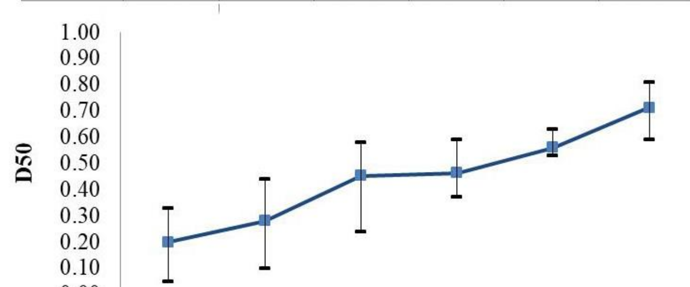
	125	250	500	1000	2000	4000
Avg.	0.20	0.29	0.41	0.48	0.54	0.62
Min.	0.05	0.19	0.21	0.26	0.31	0.45
Max.	0.51	0.41	0.58	0.71	0.80	0.83

Fig. 33. Maximum, minimum and average values for C80 and D50 for Hallaç Main Hall over 1/1 Octave Bands

The C80 at the Hallaç Main Hall also shows the highest deviations at low and high frequencies. The hall has a C80 value of slightly higher than 2 dB and a D50 value of 0.5 (Fig. 33). C80 values are in the optimum range except for 125 Hz where the value is much lower than -2 dB. For a speech-oriented hall, positive values of clarity are desirable as they result in crisp acoustics (Templeton, 1998). The Hallaç Main Hall has positive C80 values after 500 Hz, which is an important spectrum range for speech intelligibility. The values of D50 should be less than 0.25 for music purposes; however, they should be higher than 0.15 for speech activities (Templeton, 1998). According to the D50 values, the Hallaç Main Hall is proper for speech-related functions, but not for musical performances. This goes in accordance to the speech-related function of the hall as opposed to a liturgically significant space such as a church.

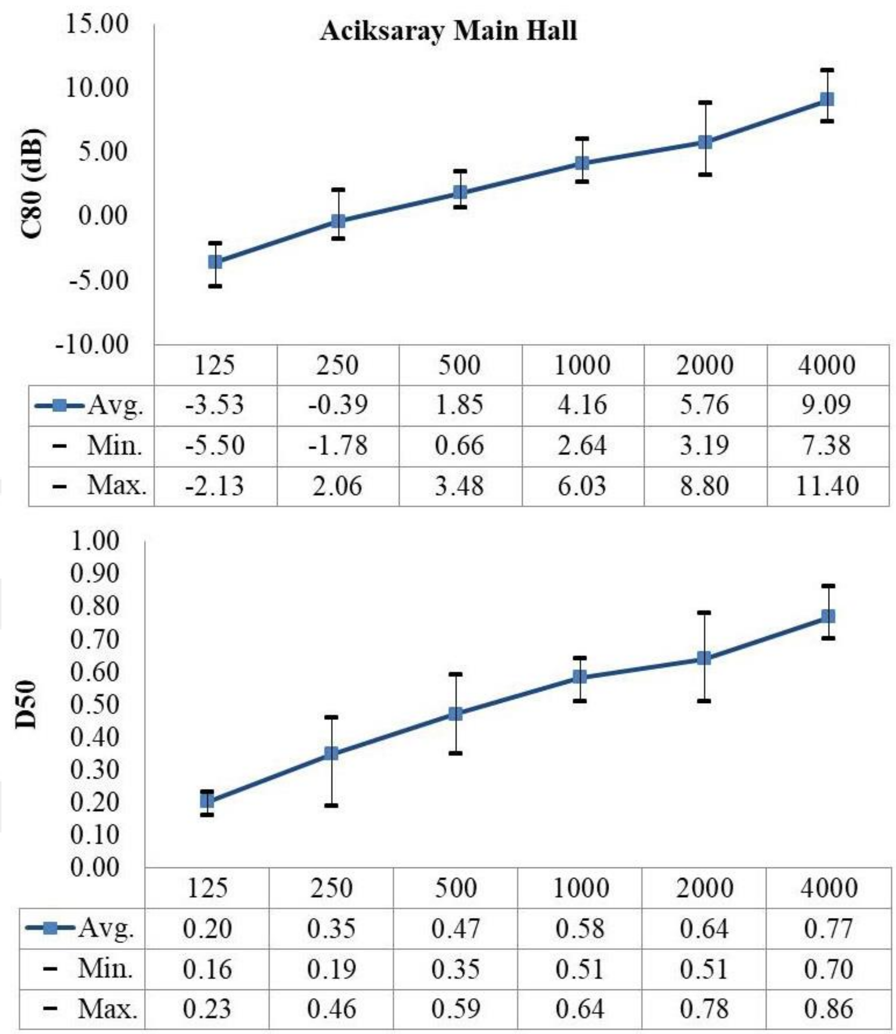


	125	250	500	1000	2000	4000
Avg.	-4.48	-2.26	1.16	1.86	4.31	7.68
Min.	-8.51	-6.21	-1.72	0.26	3.33	5.20
Max.	-1.79	0.86	3.41	3.64	4.96	9.45



	125	250	500	1000	2000	4000
Avg.	0.20	0.28	0.45	0.46	0.56	0.71
Min.	0.05	0.10	0.24	0.37	0.53	0.59
Max.	0.33	0.44	0.58	0.59	0.63	0.81

Fig. 34. Maximum, minimum and average values for C80 and D50 for Açıksaray Cruciform Hall over 1/1 Octave Bands



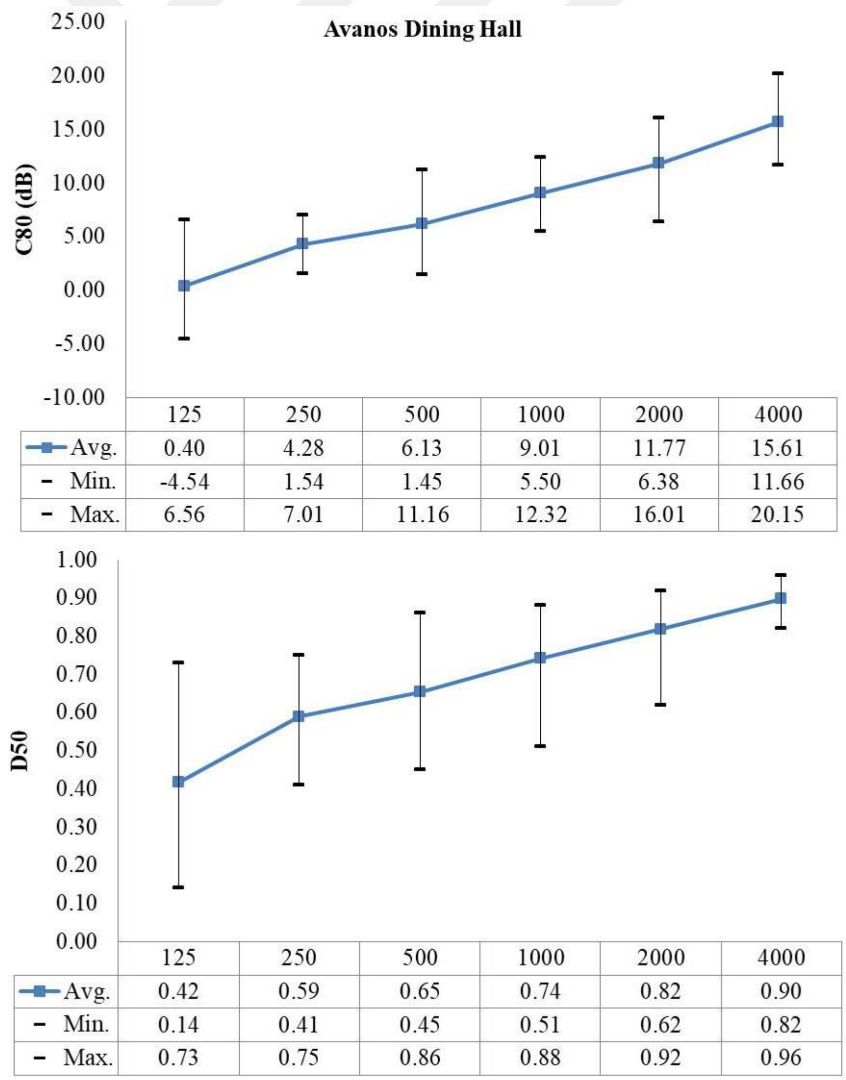
	125	250	500	1000	2000	4000
Avg.	-3.53	-0.39	1.85	4.16	5.76	9.09
Min.	-5.50	-1.78	0.66	2.64	3.19	7.38
Max.	-2.13	2.06	3.48	6.03	8.80	11.40

	125	250	500	1000	2000	4000
Avg.	0.20	0.35	0.47	0.58	0.64	0.77
Min.	0.16	0.19	0.35	0.51	0.51	0.70
Max.	0.23	0.46	0.59	0.64	0.78	0.86

Fig. 35. Maximum, minimum and average values for C80 and D50 for Açıksaray Main Hall over 1/1 Octave Bands

Figures 34 and 35 show C80 and D50 results for the two halls at Açıksaray. For C80, both the graphs indicate the least deviations from the mean value at the mid-range frequencies. The deviations for D50 are more irregular over the whole frequency spectrum. The results show a C80 of around +3.5 dB and a D50 of 0.50 for Açıksaray Cruciform Hall. A C80 of +4 dB and a D50 of more than 0.50 are observed for Açıksaray Main Hall. Therefore, the halls at Açıksaray do not have the -2 dB to +2 dB range for clarity but are suitable for speech-oriented activities as D50 values are higher than 0.15 for the whole frequency spectrum.

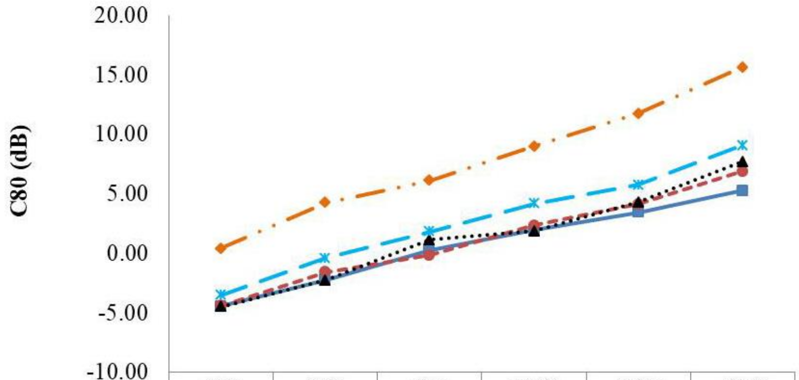
Avanos has comparatively much larger values for both C80 and D50 than the other spaces (Fig. 36). The results show that the dining hall in Avanos has a C80 of approximately +9 dB and a D50 of 0.70. Considering the small volume of the dining hall, the high value of C80 does not make it a suitable space for music. In addition, the D50 values indicate good speech intelligibility. The large difference in the C80 and D50 values of the dining hall, as compared to the other spaces, is due to its smaller volume, where surfaces are much closer to the receiver positions; therefore, the early reflected energy is greater.



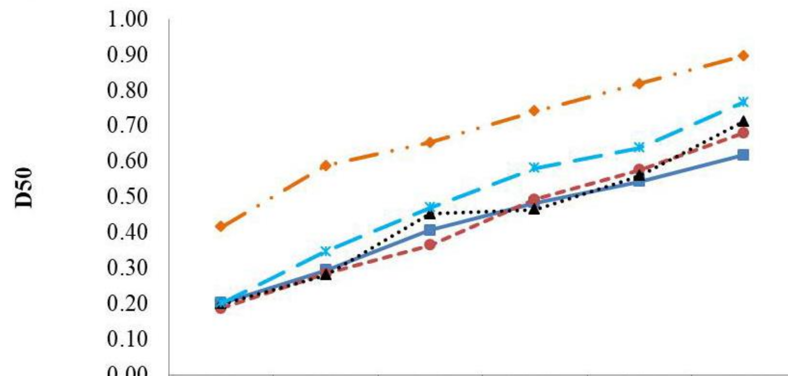
	125	250	500	1000	2000	4000
Avg.	0.40	4.28	6.13	9.01	11.77	15.61
Min.	-4.54	1.54	1.45	5.50	6.38	11.66
Max.	6.56	7.01	11.16	12.32	16.01	20.15

	125	250	500	1000	2000	4000
Avg.	0.42	0.59	0.65	0.74	0.82	0.90
Min.	0.14	0.41	0.45	0.51	0.62	0.82
Max.	0.73	0.75	0.86	0.88	0.92	0.96

Fig. 36. Maximum, minimum and average values for C80 and D50 for the dining hall in Avanos over 1/1 Octave Bands



	125	250	500	1000	2000	4000
Hallaç Church	-4.43	-2.22	0.24	1.96	3.46	5.28
Hallaç Main Hall	-4.42	-1.55	-0.14	2.35	4.14	6.90
Açıksaray Cruciform Hall	-4.48	-2.26	1.16	1.86	4.31	7.68
Açıksaray Main Hall	-3.53	-0.39	1.85	4.16	5.76	9.09
Avanos Dining Hall	0.40	4.28	6.13	9.01	11.77	15.61



	125	250	500	1000	2000	4000
Hallaç Church	0.20	0.29	0.41	0.48	0.54	0.62
Hallaç Main Hall	0.19	0.29	0.37	0.49	0.58	0.68
Açıksaray Crucifrom Hall	0.20	0.28	0.45	0.46	0.56	0.71
Açıksaray Main Hall	0.20	0.35	0.47	0.58	0.64	0.77
Avanos Dining Hall	0.42	0.59	0.65	0.74	0.82	0.90

Fig. 37. C80 and D50 for all five spaces over 1/1 Octave Bands

Figure 37 shows the decay ratio plots of all the spaces over the frequency spectrum from 125 to 4 kHz. The comparison graph indicates that with decreasing volumes, the values of C80 and D50 keep getting higher for these rock-cut structures. There is a strong relationship between D50 and speech intelligibility; D50 values should be greater than 0.15 in order to satisfy speech-related activities (Templeton, 1998). Considering this threshold, all the five spaces under study show values greater than 0.15. This signifies that the spaces are suitable for intelligibility of speech signals. The following section further discusses speech intelligibility.

5.1.4 Speech Intelligibility Results and Comparisons of the Rock-Cut Structures of Cappadocia

Speech intelligibility can also be assessed by means of the Speech Transmission Index (STI), which is a metric that denotes the quality of speech while considering the loss of speech articulation caused by reverberation (Steeneken & Houtgast, 1980). Figure 38 shows both male and female STIs for all the spaces studied. The differences between the average male and female STI values are considerably small in every rock-cut structure. The lowest STI value is 0.57 (STI female, Hallaç Church), whereas the highest value is 0.77 (STI male, Avanos). STI values between 0.60 and 0.75 indicate good speech intelligibility, while any value higher than 0.75 is considered excellent (Beranek, 1988). Therefore, all the spaces under study are proper for speech intelligibility.

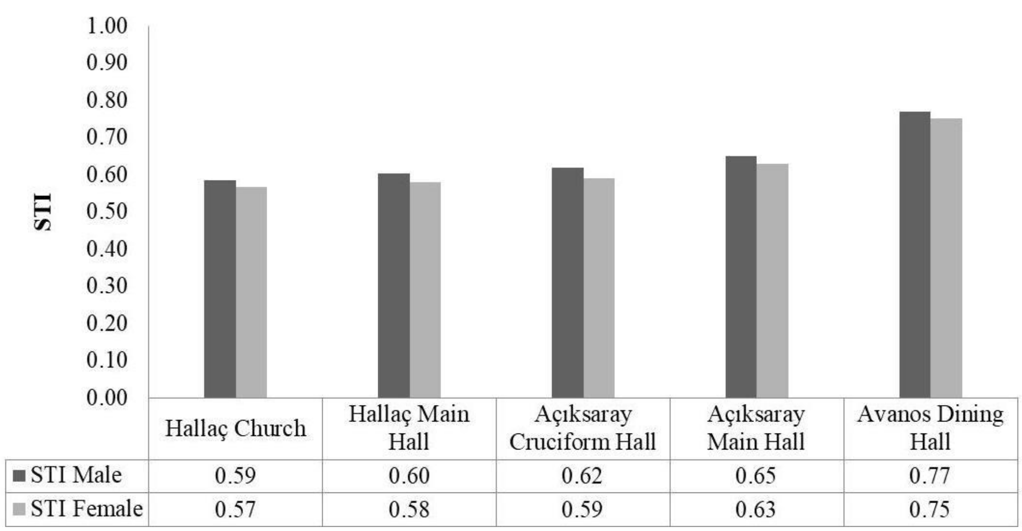


Fig. 38. Male and female STIs for Hallaç, Açıksaray, and Avanos.

Good speech intelligibility is also supported by the values of D50 in the Hallaç Main Hall, Açıksaray Cruciform Hall, Açıksaray Main Hall, and the Avanos Dining Hall. Although the reverberation times of the Hallaç Church are higher in comparison to the other spaces, the very low background noise level in the vicinity contributes for high STI levels. It also helps the church to acoustically benefit for a multi-function activity pattern; where both the sermons of the orator are intelligible and the high decay rates in low frequencies augment male voice supporting the spiritual soundscape of this religious space (Pentcheva & Abel, 2017; Sü Gül, 2021).

5.1.5 Acoustical Review and the Comparison of Natural Caves and Man-made Structures

This section is an overview of a few prominent studies that have been conducted in both natural caves and man-made structures in the literature together with the findings of this research. The purpose of the data accumulation is to comparatively exhibit the acoustic characteristics of all previously collected data. Previously studied caves or man-made rock-cut spaces originally belong to different eras and different regions, with differing interior volumes and various functions. As one acoustical parameter that is commonly discussed, in Table 2 EDT values for a number of natural caves from Italy and Spain are listed (Iannace & Trematerra, 2014a; Till, 2019). The volumes of these spaces (if provided) have also been included in the table to get a better grasp of the spaciousness of the caves, in comparison to the obtained decay rates and other metrics. When Table 2 is observed it can be stated that Grave Cave has the highest EDT of around 6.0 s; this could be because it is also the largest space with a volume of 30,000 m^3. Most of these caves are much larger than the Cappadocian rock-cut structures of this study. Although Castle Hall (220 m^3) has the closest volume to those spaces in Cappadocia (especially Açıksaray Main Hall that has a volume of 217 m^3), its EDT of around 1.6 s is slightly higher than the EDT of Açıksaray Main Hall which is around 1.3 s. The interior surfaces of the natural Caves of Pertosa are more reflective than the rock-cut Cappadocian structures. Thus, this may mean that higher sound absorption performance of the volcanic tuff of Cappadocia has resulted in lower decay rates. Accordingly, it may be much more porous than the natural stone (karst) of the Caves of Pertosa. On the other hand, the Paleolithic caves of Northern Spain have EDT values in the range of 0.6 s to 1.5 s at mid-range frequencies. These values are generally closer to the EDT values of Cappadocian rock-cut structures.

Table 2. EDT (s) values over 1/1 Octave Bands of different Paleolithic natural caves in Italy and Spain (based on Iannace & Trematerra, 2014a & Till, 2019)

Region	**Individual Space**	**125**	**250**	**500**	**1000**	**2000**
Caves of Castelcivita (Till, 2019)	Guano Hall (1,800 m^3)	3.46	1.99	1.85	1.73	1.29
	Castle Hall (2,750 m^3)	2.49	1.96	1.29	0.93	0.87
	Carbonic Acid Hall (2,000 m^3)	3.39	3.15	2.74	1.80	1.52
	Ballerina Hall (2,500 m^3)	3.39	3.15	2.74	1.80	1.52
	Cavern of Bertarelli (5,600 m^3)	3.26	2.89	2.30	2.27	1.74
Caves of Pertosa (Till, 2019)	Large Hall (1,300 m^3)	3.85	5.46	4.57	3.83	3.29
	Castle Hall (220 m^3)	2.77	2.40	1.66	1.61	1.22
	Throne Hall (1,000 m^3)	5.71	3.89	3.69	3.18	2.58
Caves of Castellana (Till, 2019)	Grave Cave (30,000 m^3)	8.60	6.20	6.60	5.62	4.56
	Cave of the Civetta, (1000 m^3)	2.98	2.02	2.13	1.59	1.70
	La Fonte (3,300 m^3)	2.19	2.17	2.25	2.00	1.79
Caves in Northern Spain (Iannace & Trematerra, 2014a)	Las Chimeneas	1.13	0.96	0.85	0.70	0.51
	El Castillo	1.33	1.20	1.28	1.15	1.12
	La Garma	1.20	0.68	0.65	0.56	0.42
	La Pasiega End	1.05	1.19	0.75	0.49	0.24
	La Pasiega Turret	1.92	1.62	1.58	1.40	1.16
	Tito Bustillo	2.24	1.11	1.36	1.35	1.46

Table 3 is a collection of acoustic measurements conducted in man-made structures including the rock-cut Cappadocian spaces and catacombs. These underground spaces are similar to the rock-cut spaces of Cappadocia as the two types of spaces are man-made (carved) (Iannace et al, 2014; Ciaburro et al, 2020). In terms of volume, Crypt of the Popes ($81m^3$) and Crypt of S. Cecilia (171 m^3) from the catacombs of San Callisto are similar to the rock-cut structures under study, specifically Açıksaray Main Hall (217 m^3) and the Avanos Dining Hall (114 m^3). The EDT values for these spaces range from 0.5 s to 0.9 s at mid frequency range.

Due to the similarity in their volumes, other monaural parameters of Crypt of the Popes and Crypt of S. Cecilia can also be compared with some of the rock-cut structures of Cappadocia (Table 4). The T30 values for these catacombs are in the range of 0.65 s to 0.85 s. These values are lower than the T30 values of the Cappadocian structures which are usually higher than 1 s, except for the dining hall in Avanos. This means that the porous tuff that the catacombs are excavated in has a higher sound absorption performance than that of the Cappadocian tuff.

Energy ratios (C80 and D50) of Crypt of the Popes and Crypt of S. Cecilia are generally higher than the ratios observed in the rock-cut structures of Cappadocia. All C80 values are positive in these catacombs and within the range of acceptable values as discussed above. D50 values range from 0.5 to 0.7, which means that these spaces are good for speech intelligibility. This is further supported by a high STI value of 0.70 in both of the spaces. With lower reverberation times and high speech intelligibility parameters, these spaces are appropriate for religious activities involving a verbal performance by a single speaker (Iannace et al, 2014; Ciaburro et al, 2020).

Table 3. EDT (s) values over 1/1 Octave Bands of Roman catacombs and rock-cut structures of Cappadocia (based on Ciaburro et al., 2020 and the data collected by the author)

Region	Individual Space	125	250	500	1000	2000
Catacombs of San Callisto in Rome (Ciaburro et al., 2020)	Crypt of the Popes ($81m^3$)	0.95	0.75	0.72	0.64	0.56
	Crypt of S. Cecilia (171 m^3)	0.88	0.96	0.96	0.91	0.79
Catacombs of San Gennaro in Naples (Ciaburro et al., 2020)	Lower Level (3,790 m^3)	1.80	1.58	1.20	0.90	0.72
	Upper Level (2,184 m^3)	2.12	1.72	1.23	0.91	0.65
Catacombs of Vigna Cassia in Syracuse (Ciaburro et al., 2020)	Cemetery of Marcia (4,394 m^3)	0.69	0.54	0.45	0.38	0.31
	Cubicle of the Well (2,494 m^3)	0.63	0.65	0.69	0.60	0.54
	Cubicle of Gennara & Ciriaco (1,985 m^3)	0.68	0.87	0.61	0.37	0.27
	Santa Maria del Gesù Cemetery (3,600 m^3)	1.30	1.05	0.72	0.49	0.35
Rock-cut Structures of Cappadocia	Hallaç Church (571 m^3)	4.72	3.45	2.40	1.71	1.25
	Hallaç Main Hall (322 m^3)	3.97	2.57	1.87	1.33	0.98
	Açıksaray Cruciform Hall (400 m^3)	4.64	3.28	1.94	1.37	0.93
	Açıksaray Main Hall (217 m^3)	3.10	2.18	1.60	1.04	0.78
	Avanos Dining Hall (114 m^3)	1.23	0.97	0.78	0.55	0.43

Such acoustical data, except for all positive values of C80, are also observed in Cappadocian rock-cut structures, especially in the Hallaç Church which is suitable for both speech and music as would be required for the liturgical practices at the church. The other halls at Cappadocia have D50 values of around 0.50, except for the Avanos Dining Hall which has a higher average D50 of around 0.70. These halls also have STI values of around 0.60, which indicate good speech intelligibility. Consequently, the residential halls in Cappadocia are similar to the two crypts of the Catacombs of San Callisto in terms of favoring speech-related activities (Table 4).

Table 4. Monaural acoustic parameters for Crypt of the Popes and Crypt of S. Cecilia (based on Ciaburro et al., 2020) and for Cappadocian rock-cut structures over 1/1 Octave Bands

Rock-Cut Spaces	STI	Freq. (Hz)	125	250	500	1000	2000
Crypt of the Popes (Ciaburro et al., 2020)	0.70	T30 (s)	0.90	0.80	0.73	0.68	0.60
		C80 (dB)	3.40	4.93	5.85	7.23	8.02
		D50	0.51	0.57	0.67	0.70	0.72
Crypt of S. Cecilia (Ciaburro et al., 2020)	0.70	T30 (s)	0.95	0.93	0.89	0.83	0.77
		C80 (dB)	4.42	4.19	3.56	3.51	4.83
		D50	0.55	0.55	0.49	0.51	0.58
Hallaç Church	0.58	T30 (s)	5.23	3.63	2.57	1.83	1.42
		C80 (dB)	-4.43	-2.22	0.24	1.96	3.46
		D50	0.20	0.29	0.41	0.48	0.54
Hallaç Main Hall	0.59	T30 (s)	5.01	3.02	1.94	1.43	1.05
		C80 (dB)	-4.42	-1.55	-0.24	2.35	4.14
		D50	0.19	0.29	0.37	0.49	0.58
Açıksaray Cruciform Hall	0.61	T30 (s)	5.40	3.42	2.10	1.46	1.01
		C80 (dB)	-4.48	-2.26	1.16	1.86	4.31
		D50	0.20	0.28	0.45	0.46	0.56
Açıksaray Main Hall	0.64	T30 (s)	3.56	2.30	1.58	1.12	0.81
		C80 (dB)	-3.53	-0.39	1.85	4.16	5.76
		D50	0.20	0.35	0.47	0.58	0.64
Avanos Dining Hall	0.76	T30 (s)	1.70	1.10	0.83	0.59	0.47
		C80 (dB)	0.40	4.28	6.13	9.01	11.77
		D50	0.42	0.59	0.65	0.74	0.82

5.2 Impedance Measurement Results of Rock Samples

Rock samples from Göreme and Ürgüp have been collected and studied. These samples can be different from other samples collected from the same region based on their different composition. However, as part of this study, it is an attempt to document the material properties of a couple of rock samples from Cappadocia. The samples can be considered porous sound absorbing materials. Porous materials are solid materials with irregular pores, usually smaller than 1 mm (Diaz & Pedrero, 1999).

The following section discusses the results of the impedance tube tests performed on the rock samples.

5.2.1 Absorption Coefficients of Rocks from Göreme and Ürgüp

The purpose of performing the impedance tube test on the two rock samples is to collect the acoustic properties of the volcanic tuff material. In this regard, the absorption coefficients (ɑ) of both the samples have been documented.

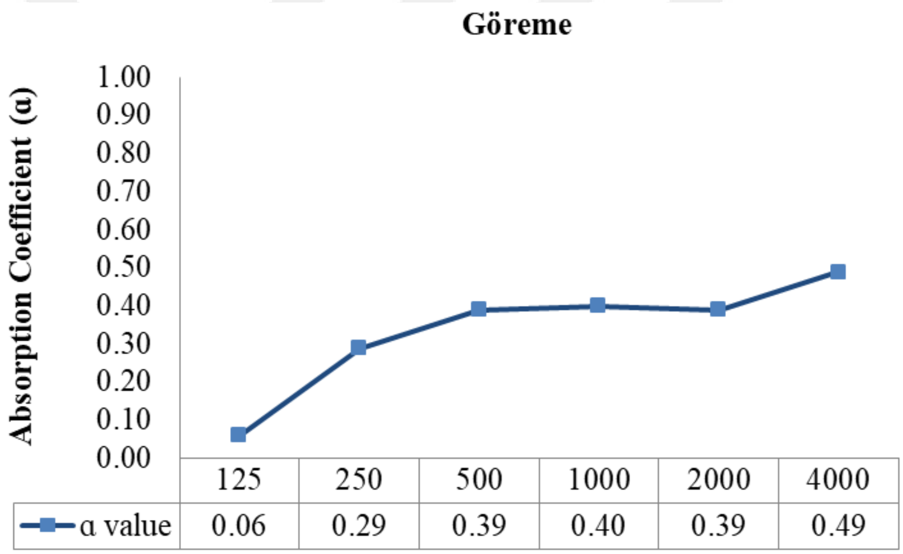


Fig. 39. Absorption Coefficient (ɑ) values of the rock from Göreme over 1/1 Octave Bands

Figure 39 shows the ɑ values over 1/1 octave bands from 125Hz to 4 kHz of the sample collected from Göreme. Absorption results at both 63 Hz (lowest band) and 8 kHz (highest band) have been omitted due to the high risk of getting faulty results. The material has the highest sound absorption at 4 kHz, where absorption coefficient's value is slightly less than 0.5. On the other hand, the lowest value (0.06) is recorded at 125 Hz. For the octave bands 500 Hz, 1 kHz, and 2 kHz the absorption coefficient has the same value of around 0.4. Similar to most absorptive materials, the Göreme sample shows a general trend of increasing absorption ability with an increase in the frequency.

As opposed to the sample from Göreme, the rock sample from Ürgüp does not show a linear trend (Fig. 40). The highest value of absorption coefficient (0.48) is obtained at 500 Hz. There is a dip in the graph after 500 Hz as the ɑ value drops to 0.31 at 1 kHz. The ɑ value rises to 0.47 at 4 kHz, which is almost the same as the value at 500 Hz.

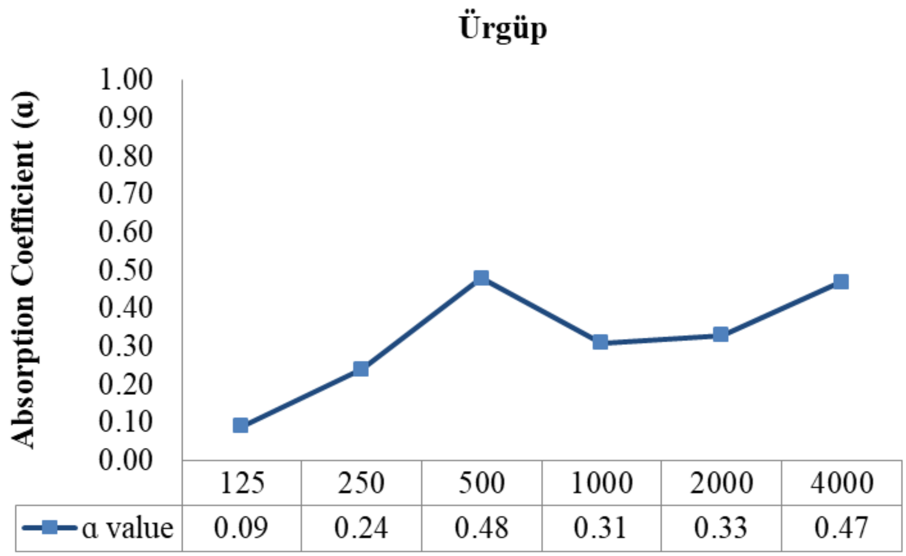
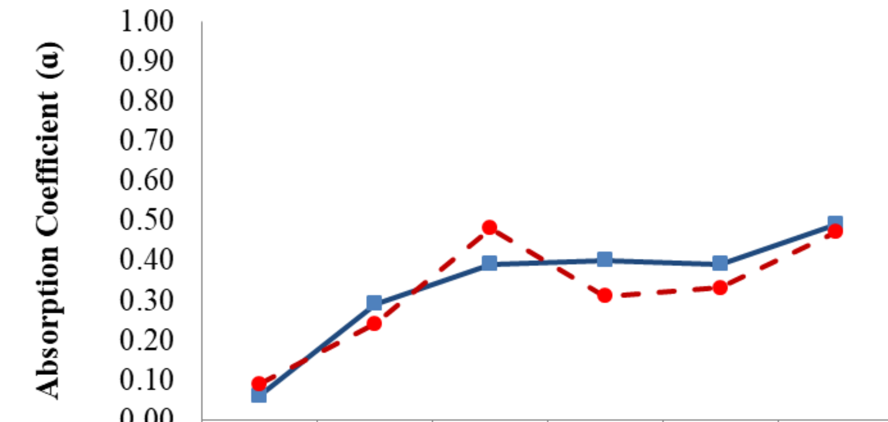


Fig. 40. Absorption Coefficient (ɑ) values of the rock from Ürgüp over 1/1 Octave Bands

5.2.2 Comparison of the Absorption Coefficients of Rocks from Göreme and Ürgüp

It is noteworthy to compare the absorption qualities of the two rock samples. The samples have been collected from two different regions of Cappadocia; therefore, it is likely that they have slightly different material properties.



	125	250	500	1000	2000	4000
Göreme	0.06	0.29	0.39	0.40	0.39	0.49
Ürgüp	0.09	0.24	0.48	0.31	0.33	0.47

Fig. 41. Absorption Coefficient (α) values of the rocks from Göreme and Ürgüp over 1/1 Octave Bands

Figure 41 shows the sound absorption coefficients of the two rock samples over the octave bands from 125 Hz to 4 kHz. According to the figure, the materials have very similar sound absorption properties. The absorption values of the samples are very close to each other except for 500 Hz where the absorption coefficient of Ürgüp's rock sample (0.48) is relatively much higher than the absorption coefficient of the sample from Göreme (0.39). Maximum sound absorption (0.49) is achieved by the sample from Göreme at 4 kHz. These results indicate that the collected and measured rock samples (not the hard sample that cannot be measured) are highly absorptive and can be categorized under today's diverse sound absorptive material umbrella, which include both natural and man-made materials.

5.2.3 Comparison of the Absorption Coefficients of Cappadocian Rocks with Commonly Used Materials

In order to evaluate the sound absorption qualities of the samples from Cappadocia, it is important to compare their sound absorption coefficients with other known materials.

Such a comparison can give a better understanding of the sound absorption qualities of the collected rock samples. Table 5 is a collection of the sound absorption coefficients of some of the most commonly used materials in construction and furnishings. The table also presents the sound absorption coefficients of the rock samples from Göreme and Ürgüp.

Table 5. Sound absorption coefficients of common materials over 1/1 Octave Bands (from Carpet Specifier's Handbook, 1987; Diaz & Pedrero, 1999; Harris, 1994; Hedeen, 1980; Mankovsky, 1971) and rock samples from Göreme and Ürgüp (collected by the author)

Material	**Frequency Band (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Rough Soil	0.15	0.25	0.40	0.55	0.60	0.60
Brick, unglazed	0.02	0.02	0.03	0.04	0.05	0.07
Brick, unglazed and painted	0.01	0.01	0.01	0.02	0.02	0.03
Concrete	0.01	0.01	0.02	0.02	0.02	0.02
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08
Steel	0.05	0.10	0.10	0.10	0.07	0.02
Carpet heavy, on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Carpet heavy, on foam rubber	0.08	0.24	0.57	0.69	0.71	0.73
Curtains, lightweight	0.03	0.04	0.11	0.17	0.24	0.35
Curtains, heavyweight	0.14	0.35	0.55	0.72	0.70	0.65
Cork floor tile, 1.9 cm thick	0.08	0.02	0.08	0.19	0.21	0.22
Asphalt or cork tile on concrete	0.02	0.03	0.03	0.03	0.03	0.02
Marble tile	0.01	0.01	0.01	0.01	0.02	0.02
Gypsum board	0.29	0.10	0.05	0.04	0.07	0.09
Plaster, gypsum or lime	0.01	0.02	0.02	0.03	0.04	0.05
Terrazzo	0.01	0.01	0.02	0.02	0.02	0.02
Plywood panel, 1 cm thick	0.28	0.22	0.17	0.09	0.10	0.11
Wood flooring	0.15	0.11	0.10	0.07	0.06	0.07
Wood panel, 1 cm thick, 5-10 cm air space	0.30	0.25	0.20	0.17	0.15	0.10
Glass, ordinary window	0.35	0.25	0.18	0.12	0.07	0.04
Glass, large panes	0.18	0.06	0.04	0.03	0.03	0.02
Göreme	0.06	0.29	0.39	0.40	0.39	0.49
Ürgüp	0.09	0.24	0.48	0.31	0.33	0.47

From the table above, it is seen that for the higher frequencies, heavy carpets on concrete and foam rubber show maximum sound absorption of around 0.70. From the list of the materials, unglazed and painted brick, concrete, marble tile, and terrazzo are the most reflective materials with the lowest sound absorption coefficients along the frequency spectrum.

Comparing the data presented in the table above, the rock samples from Cappadocia are relatively much more sound absorptive along the frequency spectrum. The absorption coefficients of both the samples are much higher than reflective materials such as concrete, marble tile, steel, etc. The sound absorption performance of the Cappadocian samples is mainly based on the porosity of the materials. Based on the data in Table 5, the rock samples from Göreme and Ürgüp are similar to rough soil in terms of their sound absorption qualities as they have comparable values along the frequency spectrum.

5.3 Results from Acoustical Simulations

Virtual models have been created for the Hallaç Church, Avanos Dining Hall, and Çanlı Kilise in order to run acoustical simulations. The following sections discuss the results obtained from the simulated models.

5.3.1 Acoustical Modeling of Hallaç Church and Avanos Dining Hall

The main reason for generating acoustical models of the Hallaç Church and Avanos Dining Hall is to gather information regarding the rocks' acoustical performance. It is important because even though all the spaces are composed of volcanic tuff, the make-up of Cappadocian rocks from different regions is generally different based on varying rock ingredients and physical conditions.

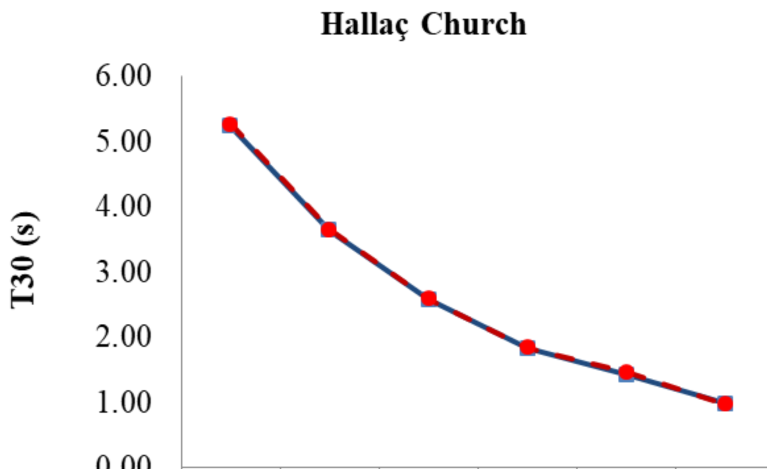
After the creation of the virtual models for the Hallaç Church and Avanos Dining Hall, the models have been tuned with the results of the field measurements in order to ensure that the models are as acoustically similar to the real spaces as possible. The process involves adjusting the T30 values of the virtual models within a 5% JND of the field test results by tuning the sound absorption coefficients of the wall and roof surfaces (ISO, 2009; Iannace, & Trematerra, 2014b).

In terms of materials, the floor of the church is assigned a stone material, chosen from the software's library. The two openings in the church (a door and a window) have been assigned as openings and thus, are assigned a 100% absorptive material. The absorption coefficients of these assigned materials are shown in Table 6. The walls and ceiling of the church are assigned one material and its absorption coefficient is obtained by tuning the T30 results of the model with site measurements.

Table 6. Sound absorption coefficients of the materials used in the Hallaç Church model over 1/1 Octave Bands

Materials	**Frequency Band (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Stone	0.01	0.01	0.01	0.02	0.02	0.02
100% Absorptive	1.00	1.00	1.00	1.00	1.00	1.00
Hallaç Church Walls & Ceiling	0.03	0.05	0.07	0.09	0.11	0.15

After adjusting the absorption coefficients of the walls and the ceiling of the church, T30 values close to (with less than 5% difference) the in-situ measurements are obtained. The results are shown in Figure 42.



	125	250	500	1000	2000	4000
Field Test	5.23	3.63	2.57	1.83	1.42	0.97
Simulated Model	5.26	3.65	2.58	1.84	1.46	0.97

Fig. 42. T30 values of the field test and simulated model of the Hallaç Church over 1/1 Octave Bands

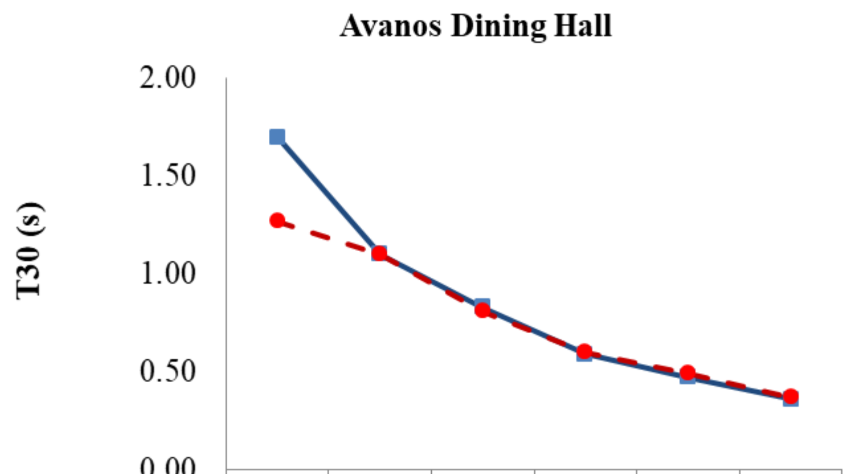
After achieving similar T30 values for the virtual model, estimated absorption coefficient values of the tuff material on the walls and the ceiling of the church are obtained. These values are also shown in Table 6.

The floor of the Avanos Dining Hall model is assigned as the same floor material as used in the model of the Hallaç Church. Similarly, the two openings are assigned a 50% absorptive material, due to the presence of kitchen space in the vicinity. Additionally, the furniture in the hall is assigned as a wooden pew from the software's library. Table 7 shows the absorption coefficients of the materials used for the model of the Avanos Dining Hall. The material for the walls and the ceiling is tuned according to the T30 results of the site measurements.

Table 7. Sound absorption coefficients of the materials used in the Avanos Dining Hall model over 1/1 Octave Bands

Materials	Frequency Band (Hz)					
	125	**250**	**500**	**1000**	**2000**	**4000**
Stone	0.01	0.01	0.01	0.02	0.02	0.02
50% Absorbent	0.50	0.50	0.50	0.50	0.50	0.50
Wooden Pew	0.57	0.44	0.67	0.70	0.80	0.72
Avanos Dining Hall Walls & Ceiling	0.01	0.05	0.07	0.13	0.17	0.24

After the absorption coefficients are adjusted to get T30 values for the model close to 5 JND (with less than 5% difference) to the field measurements, the tuning process is completed. The results are shown in Figure 43. The figure shows that the T30 values of both the field test and the simulated model are close to each other along the frequency spectrum, except for values at 125 Hz. Even when the absorption coefficient is kept at a minimum (0.01), the T30 value of the simulated model remains much shorter than the field test result. The additional energy obtained at 125 Hz in the field test could be due to the presence of neighboring galleries around the dining hall. The estimated absorption coefficients of the tuff material around the walls and the ceiling of the Avanos Dining Hall are shown in Table 7.



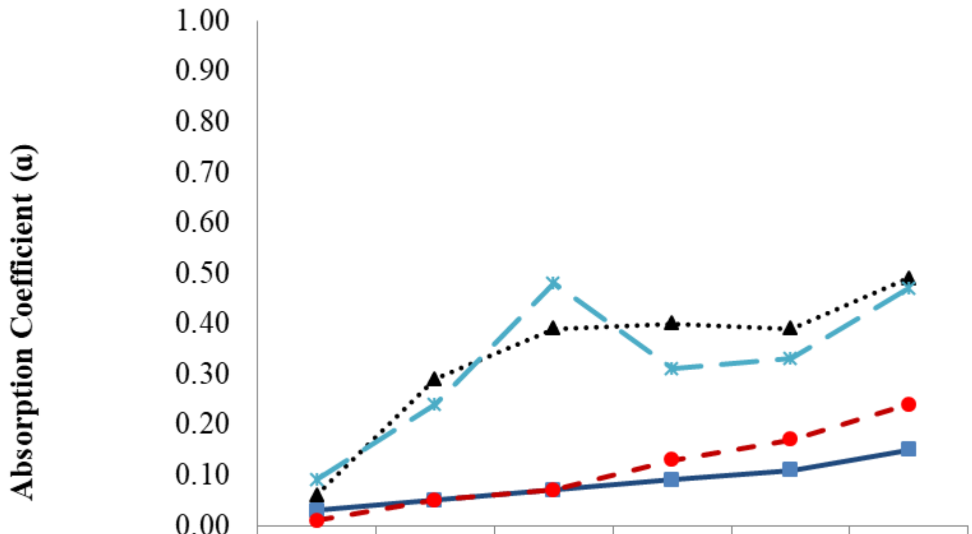
	125	250	500	1000	2000	4000
Field Test	1.70	1.10	0.83	0.59	0.47	0.36
Simulated Model	1.27	1.10	0.81	0.60	0.49	0.37

Fig. 43. T30 values of the field test and simulated model of the Avanos Dining Hall over 1/1 Octave Bands

5.3.2 Comparison of Simulations and Impedance Test Results

By means of impedance measurements and acoustical simulations, four materials from different parts of Cappadocia and their absorption coefficients have been documented. It is essential to compare the data regarding these materials in order to see the similarities and differences between their sound absorption performances, as shown in Figure 44.

According to the figure below, among all the materials under study, Göreme has the highest sound absorption, while the Hallaç Church seems to be the most reflective. The sound absorption values of the samples studied with the impedance tests (Göreme and Ürgüp) have an overall higher sound absorption than the materials obtained from the tuning of virtual models (Hallaç Church and Avanos Dining Hall).



	125	250	500	1000	2000	4000
Hallaç Church	0.03	0.05	0.07	0.09	0.11	0.15
Avanos Dining Hall	0.01	0.05	0.07	0.13	0.17	0.24
Göreme	0.06	0.29	0.39	0.40	0.39	0.49
Ürgüp	0.09	0.24	0.48	0.31	0.33	0.47

Fig. 44. Sound absorption coefficients of the materials from the Hallaç Church, the Avanos Dining Hall, Göreme, and Ürgüp over 1/1 Octave Bands

The higher sound absorption of the rock samples from Göreme and Ürgüp could be due to the fact that they are untouched rocks with higher porosity, as opposed to the materials of the Hallaç Church and Avanos Dining Hall which are in their current state after the tuff around them had been carved off and the final surface smoothened. Moreover, over time, the rock material in these spaces have been in contact with air, which could have led to the thickening of the surfaces, and hence their increased reflectivity.

Originally, the masonry church is constructed of hard gray tuff, set above an ash layer, which is different than the harder limestone found on the Çanlı Kilise plateau and the softer purple tuff which was carved to make rock-cut spaces (Ousterhout, 1997). Therefore, due to a lack of the data regarding the hard gray tuff, the material of the

Hallaç Church is used for the surrounding walls and the dome of the masonry church. The Hallaç Church's material is chosen for its similar smooth appearance (less porous) to the masonry blocks of Çanlı Kilise.

5.3.3 Acoustical Reconstruction of Çanlı Kilise

A number of historical structures have been acoustically reconstructed by means of simulation programs with different techniques in order to evaluate the spaces' acoustical characteristics for those locations that cannot be field tested due to restorations, limited time permissions or for in-depth sound field analysis (Sü Gül et al., 2016; Sü Gül et al., 2017; Sü Gül et al., 2018; Sü Gül et al., 2019; Sü Gül, 2019; Sü Gül, 2021). For instance, the acoustic properties of Benevento Roman theatre from 2 A. D. have been predicted using ray-tracing simulations by evaluating some of the major acoustical parameters such as EDT, T30, C80, etc. (Iannace & Trematerra, 2014b). Similarly, the acoustic make-up of churches has also been virtually recreated; these studies include the domus and basilica (Suarez et al, 2013), the Romanesque cathedral of Santiago de Compostela (Suarez et al, 2015), and the French Abbey of Cluny (Suarez et al, 2016).

All these studies analyze the acoustic adequacy of these spaces in regards to liturgical celebrations and other religious music. The effect of occupancy and festive decorations on the acoustics of a church from the Baroque Period have also been evaluated in one such study, where the results indicated reduced reverberation times during festive seasons of the era (Martellotta et al, 2008). In another study on the acoustics of a church, the simulation results showed that the presence of people would decrease the T30 values by 25% compared to the values obtained in the empty church. The authors used EDT, T30, and STI to investigate the effect of space occupancy, presence of the central dome and iconostasis (Đorđević et al, 2019). Similarly, Çanlı Kilise, which is at its current condition even cannot be assessed by field tests, can best be understood aurally through the utilization of virtual reconstruction and acoustical simulations. The common acoustical parameters, as previously utilized in other research on historical churches, are also used in this study to assess the acoustical characteristics and archive/document those in the scientific literature of historical acoustics.

As mentioned above, Çanlı Kilise was constructed in phases; this study documents the acoustical results of Phase I and Phase II of the construction. The main church space was constructed in the early eleventh century. The frescoes in the naos are thought to be painted by a painter that was brought from Constantinople; therefore, the frescoes were added to the interior walls well after the completion of the Phase I of construction. According to a theory, the frescoes could have been added after the church went through the Phase II of its construction, which included a narthex to the eastern wall of the naos (Ousterhout, 2017). Therefore, this study documents the acoustics of three plausible states of the church; Phase I (without frescoes), Phase I (with frescoes), and Phase II (with frescoes and narthex).

For Phase I (without frescoes), the materials used for the floor and the walls for the Hallaç Church have been used (Table 6). In order to obtain acoustical results for Phase I (with frescoes) from ODEON, the Hallaç Church wall material has been used for the walls without any traces of frescoes. In order to incorporate the effects of plastered frescoes, 80% of the wall surfaces are kept as masonry walls (Hallaç Church wall material) and 20% assumed to have frescoes. The new material, to account for the church's frescoes, is used on parts of the naos where remains of frescoes have been documented in order to incorporate the effect of plaster on the indoor acoustical environment of the church. The main frescoes are found on the dome of the church, the three apses, and the eastern wall. For the iconostasis of the church, a wooden material has been used. The same material is also used for the roof of the narthex, which is added in Phase II of the church. The details of the materials applied in acoustical models of Çanlı Kilise are summarized in Table 8.

Distribution maps are visual representations of the quantitative probability of an acoustical parameter in a gridal form. In order to obtain distribution maps for Çanlı Kilise simulations, the floor of the naos and narthex (if present) were divided into a grid of 80 cm to 80 cm, with a height of 1.5 m to correspond to the average height of human ears. Acoustical parameter distribution maps of the Çanlı Kilise simulations, including EDT, T20, T30, etc. are included in Appendix B.

Table 8. Sound absorption coefficients of the materials used in Çanlı Kilise models over 1/1 Octave Bands

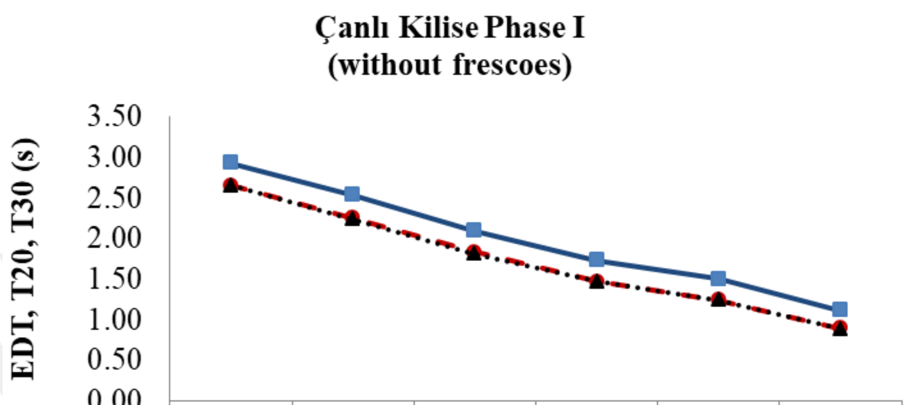
Materials	**Frequency Band (Hz)**					
	125	**250**	**500**	**1000**	**2000**	**4000**
Stone	0.01	0.01	0.01	0.02	0.02	0.02
50% Absorptive	0.50	0.50	0.50	0.50	0.50	0.50
Hallaç Church Walls & Ceiling	0.03	0.05	0.07	0.09	0.11	0.15
Çanlı Kilise Frescoes	0.02	0.03	0.03	0.05	0.06	0.07
Wooden Screen & Roof	0.15	0.20	0.10	0.10	0.10	0.10

5.3.3.1 Decay Rate Results and Comparisons of the Different Phases of Çanlı Kilise

Early decay time (EDT), and reverberation time (T20 and T30) values are estimated from the room impulse responses collected from the simulations run on the three models of Çanlı Kilise.

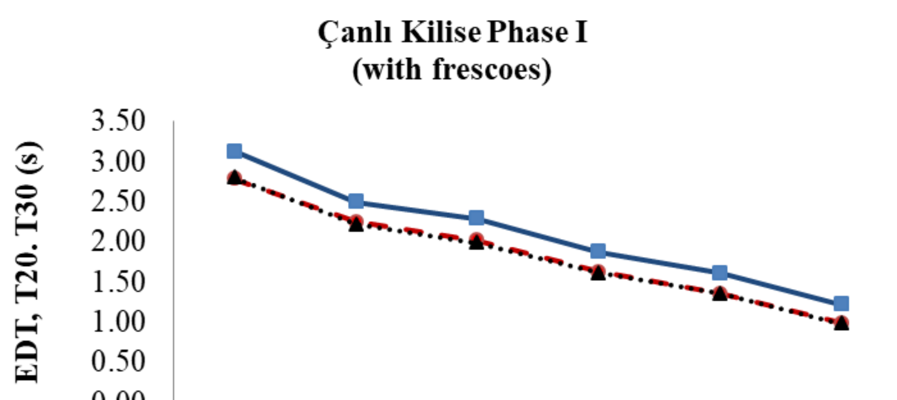
Liturgical practice is one of the main activities carried out in Middle Byzantine churches. Such practices are known to be carried out in the naos of a church, with a templon in between the clergy and the congregation (Teteriatnikov, 1996; Marinis, 2014), which would block any visible connection while maintaining an aural connection between the two groups. As a result, a wooden screen has been added in the simulation models for Çanlı Kilise and the sound source is placed behind the screen. Since the church is being documented in all its possible three states up to the Phase II of its construction, the performance of liturgical music is estimated in all three states with their different volumes and/or wall treatment.

The Phase I of the model (with and without frescoes) has an estimated volume of 975 m^3. An optimum range for liturgical music in the church has been estimated using the formula RT =0.55*log10(Vol.)-0.14 (Beranek, 1988), and the results indicate an RT of 1.5 s. Figures 43 and 44 display decay rate results for both conditions (with and without frescoes) of the Phase I Çanlı Kilise. An EDT of around 1.91 s is obtained for Çanlı Kilise Phase I (without frescoes). The RT value for the same condition of the church is found to be around 1.65 s (Fig. 45). Based on the results gathered from the simulations of Çanlı Kilise Phase I (without frescoes), the church satisfies the average value for liturgical music (1.50 s); hence, the church is appropriate for liturgical activities that would include both speech and music. The BR for the church is found to be 1.5, which as mentioned earlier, would be good for augmenting male voice in a space.



	125	250	500	1000	2000	4000
EDT	2.93	2.53	2.09	1.73	1.50	1.11
T20	2.65	2.25	1.83	1.47	1.24	0.89
T30	2.65	2.23	1.81	1.47	1.24	0.88

Fig. 45. EDT, T20, and T30 for Çanlı Kilise Phase I (without frescoes) over 1/1 Octave Bands

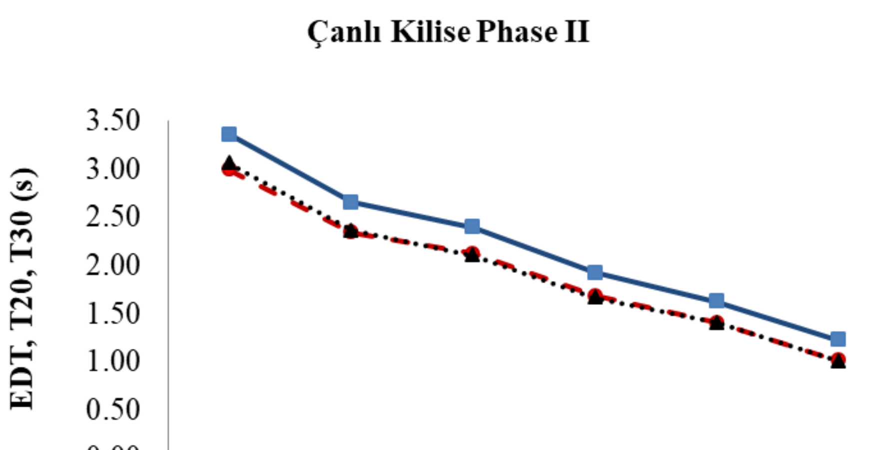


	125	250	500	1000	2000	4000
EDT	3.12	2.49	2.28	1.87	1.60	1.21
T20	2.78	2.24	2.01	1.62	1.35	0.98
T30	2.79	2.21	1.98	1.60	1.35	0.97

Fig. 46. EDT, T20, and T30 for Çanlı Kilise Phase I (with frescoes) over 1/1 Octave Bands

The second condition of the Phase I Çanlı Kilise (with frescoes) is found to have an EDT of approximately 2.10 s, and an RT of 1.80 s (Fig. 46). The optimum value of RT for liturgical music remains 1.50 s. The church remains suitable for practices related to liturgy with the addition of plastered frescoes in the naos. The BR of the space decreases slightly and drops to 1.4, which is still a high BR indicating the bass frequency augmentation.

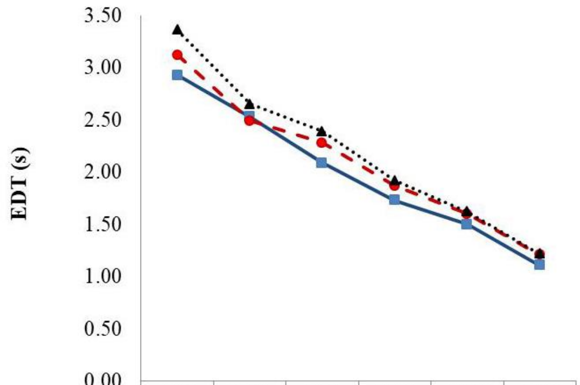
The Phase II of Çanlı Kilise includes the addition of a narthex and the frescoes in both the naos and the narthex. The estimated volume of the Phase II church is approximately 1200 m^3. Using the same formula used earlier to estimate the optimum RT for liturgical music for Phase II of Çanlı Kilise, a value of 1.55 s is obtained. Figure 47 shows that the church has an EDT of 2.2 s and an RT of 1.90 s at the mid-range frequencies. Hence, the church in its Phase II also favors liturgical practices. The BR of the church stays at 1.4.



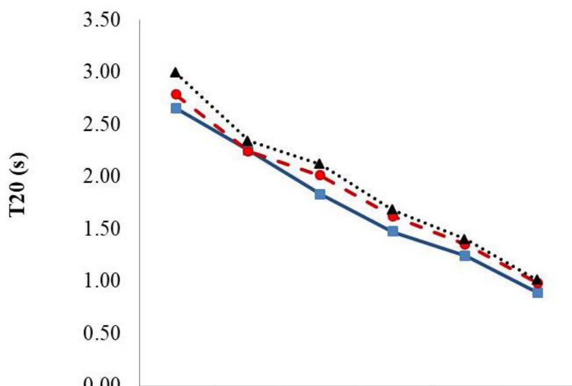
	125	250	500	1000	2000	4000
EDT	3.36	2.65	2.39	1.92	1.62	1.22
T20	2.99	2.34	2.12	1.68	1.40	1.01
T30	3.06	2.36	2.10	1.66	1.40	1.00

Fig. 47. EDT, T20, and T30 for Çanlı Kilise Phase II over 1/1 Octave Bands

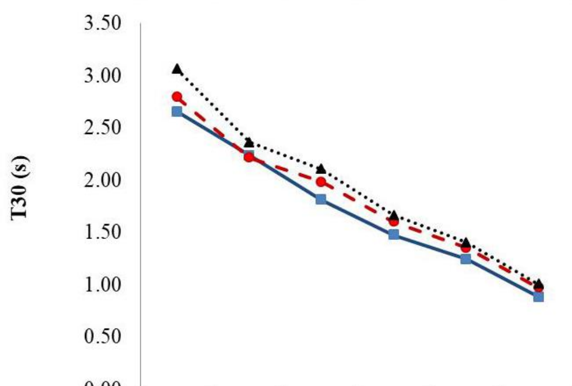
Overall, the EDT, T20, and T30 values are close to each other over the whole frequency range. In most cases, the difference between EDT and RT values is less than 10%. This signifies that there is an even distribution of sound within the church space in all its stages of construction and fresco decoration. Figure 48 compares and contrasts the decay rate results of all three phases of Çanlı Kilise. The RT of the Phase I Çanlı Kilise (without frescoes) is around 1.65 s. It can be seen that the decay rates of the church increase at every step of the analysis. With the addition of frescoes in the naos, the RT value increases to 1.80 s for mid-range frequencies. This is because the plastered surfaces in the church are more reflective as compared to the rock material of the wall surfaces of the church. Furthermore, the RT values increases to 1.90 s in the Phase II Çanlı Kilise model. This increase is due to the additional volume of the narthex. With the new additions to the Çanlı Kilise the interior space has become more reverberant, but in all cases the decay rates are high enough and consistent with the optimums defined in the literature of church acoustics.



	125	250	500	1000	2000	4000
Çanlı Kilise Phase I (without frescoes)	2.93	2.53	2.09	1.73	1.50	1.11
Çanlı Kilise Phase I (with frescoes)	3.12	2.49	2.28	1.87	1.60	1.21
Çanlı Kilise Phase II	3.36	2.65	2.39	1.92	1.62	1.22



	125	250	500	1000	2000	4000
Çanlı Kilise Phase I (without frescoes)	2.65	2.25	1.83	1.47	1.24	0.89
Çanlı Kilise Phase I (with frescoes)	2.78	2.24	2.01	1.62	1.35	0.98
Çanlı Kilise Phase II	2.99	2.34	2.12	1.68	1.40	1.01



	125	250	500	1000	2000	4000
Çanlı Kilise Phase I (without frescoes)	2.65	2.23	1.81	1.47	1.24	0.88
Çanlı Kilise Phase I (with frescoes)	2.79	2.21	1.98	1.60	1.35	0.97
Çanlı Kilise Phase II	3.06	2.36	2.10	1.66	1.40	1.00

Fig. 48. EDT, T20, and T30 for Çanlı Kilise models over 1/1 Octave Bands

5.3.3.2 Energy Ratios and Comparisons of the Different Phases of Çanlı Kilise

Energy ratios of Clarity (C80) and Definition (D50) are obtained from the room impulse responses gathered from the simulations of all the phases of Çanlı Kilise. C80 and D50 are ratios of early sound energy to late sound energy (80 and 50 ms respectively), where C80 is directly correlated to music while D50 is used to analyze speech (Barron, 2009). Both the parameters are dependent on the location of sourceand receiver. For the current simulations, the source is located behind a wooden screen, which acts as a templon.

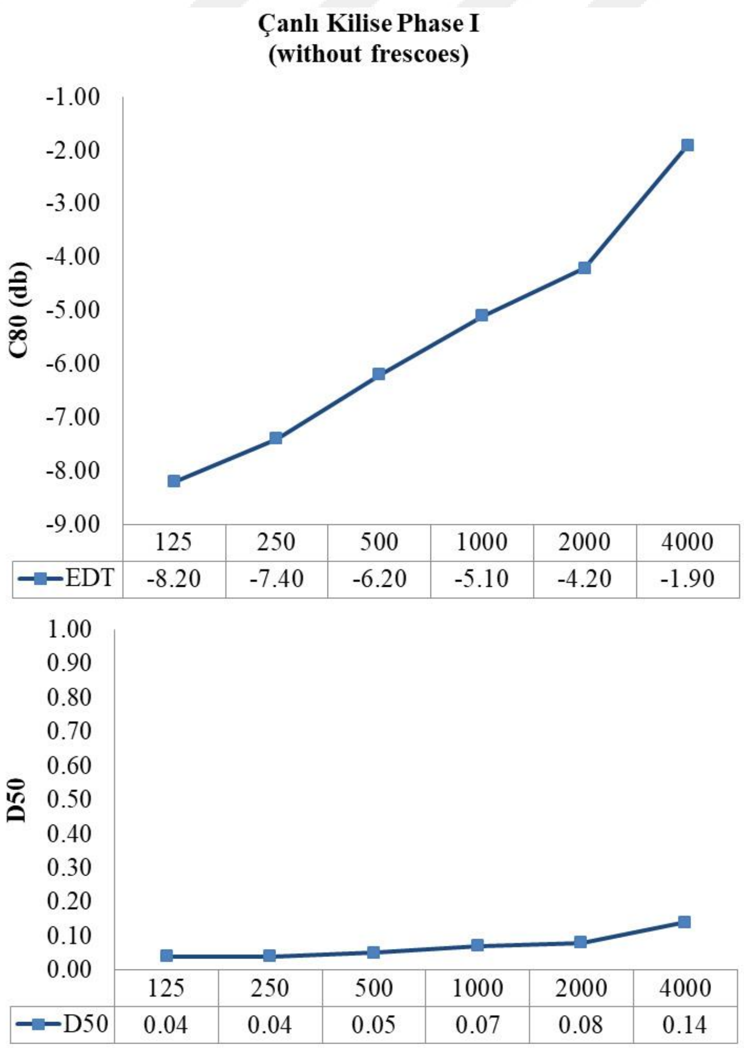


Fig. 49. C80 and D50 for Çanlı Kilise Phase I (without frescoes) over 1/1 Octave Bands

For Çanlı Kilise Phase I (without frescoes), the simulation results present negative values of C80 over the whole frequency range. The church is found to have an approximate C80 of -5.5 (Fig. 49). The values of C80 increase with increasing frequencies. The results indicate low values of D50, with a mean value of 0.06 at mid-range frequencies.

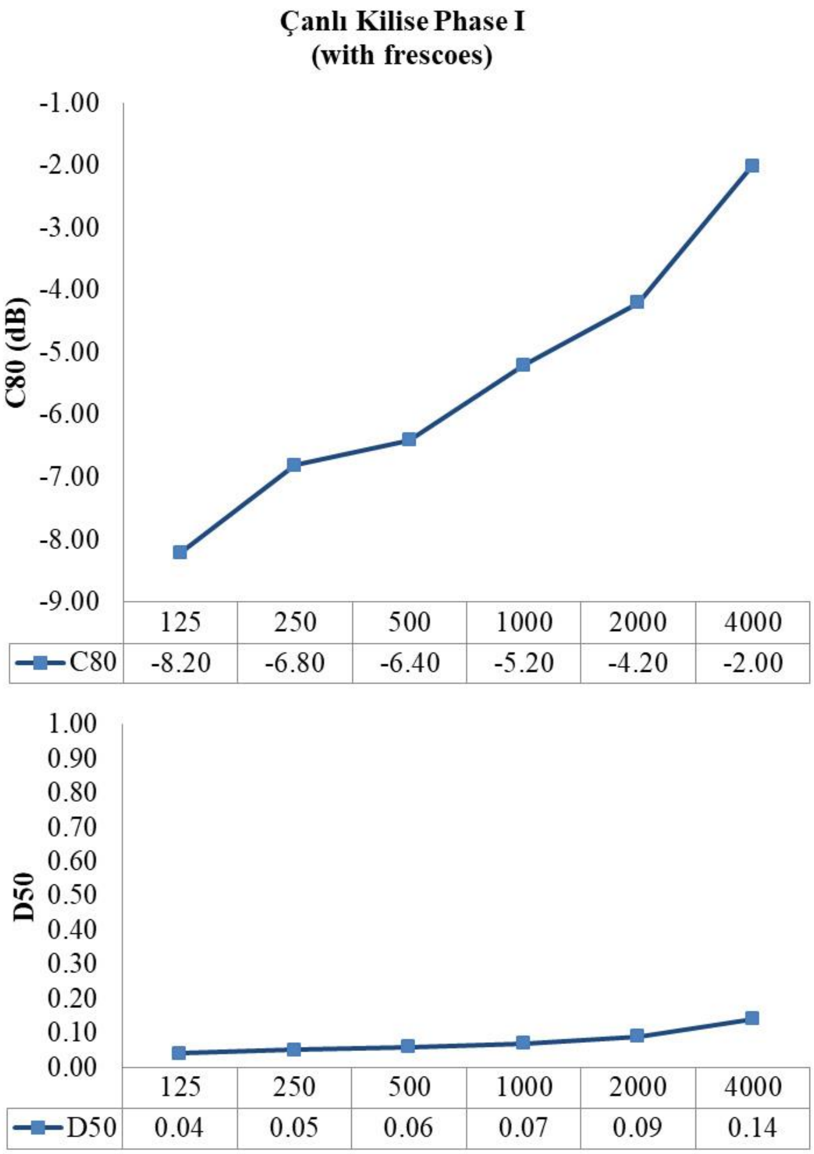


Fig. 50. C80 and D50 for Çanlı Kilise Phase I (with frescoes) over 1/1 Octave Bands

For Çanlı Kilise Phase I (with frescoes), negative values of C80 over the whole frequency range are observed. With the addition of frescoes, the church is found to have an approximate C80 of -5.8 (Fig. 50). The same effect of increasing C80 values with increasing frequencies is also observed. The figure shows low values of D50, with a mean value of 0.05 at mid-range frequencies. The highest value is 0.13 at 4 kHz, which is slightly lower than the required D50 value (0.15) that favors speech-related activities (Templeton, 1998).

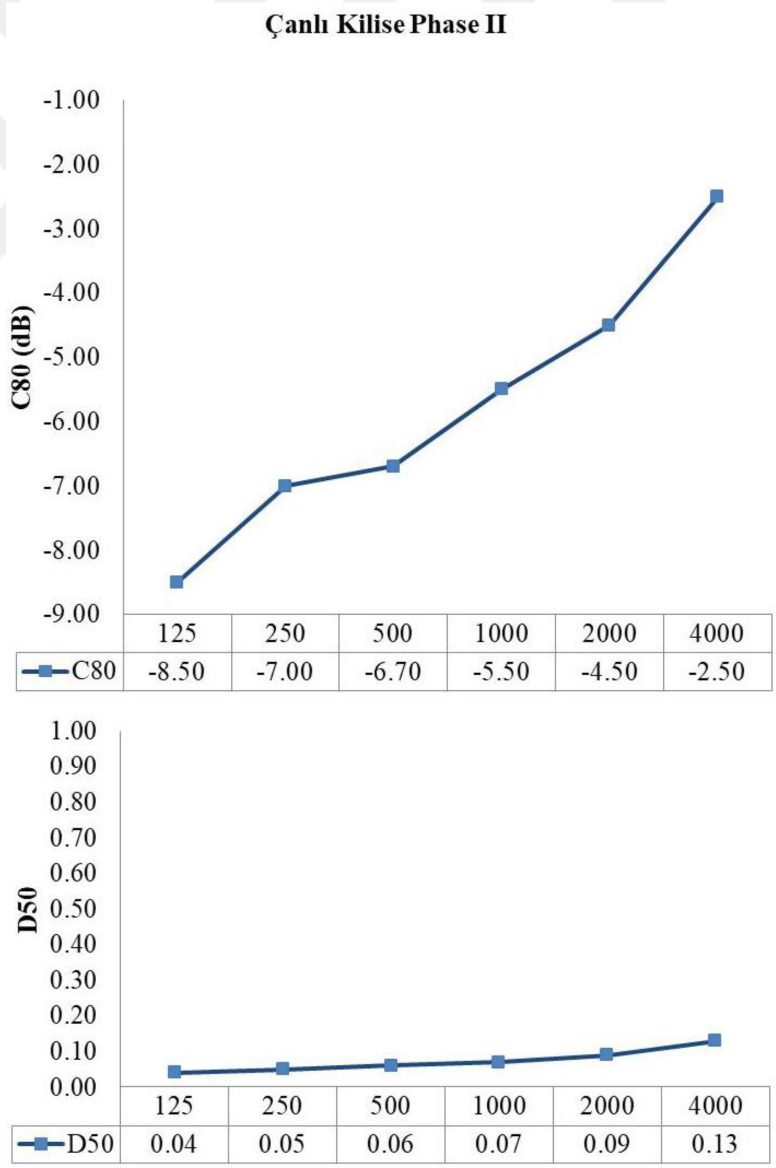
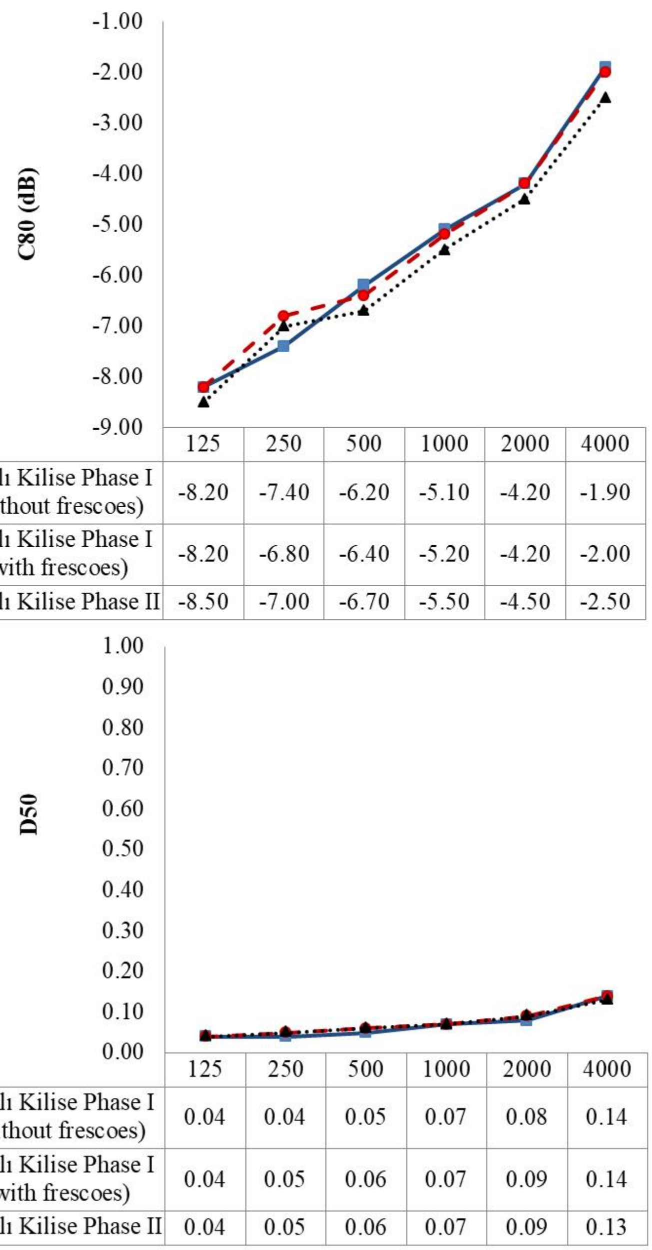


Fig. 51. C80 and D50 for Çanlı Kilise Phase II over 1/1 Octave Bands

Figure 51 shows energy ratios of the Çanlı Kilise Phase II simulation model. The negative values of C80 indicate the absence of crisp acoustics in the space. The mean C80 value is found to be around -6.1. Similar to Phase I results, the D50 values also remain lower than 0.15 for the entire frequency range (Fig. 51).



	125	250	500	1000	2000	4000
Çanlı Kilise Phase I (without frescoes)	-8.20	-7.40	-6.20	-5.10	-4.20	-1.90
Çanlı Kilise Phase I (with frescoes)	-8.20	-6.80	-6.40	-5.20	-4.20	-2.00
Çanlı Kilise Phase II	-8.50	-7.00	-6.70	-5.50	-4.50	-2.50

	125	250	500	1000	2000	4000
Çanlı Kilise Phase I (without frescoes)	0.04	0.04	0.05	0.07	0.08	0.14
Çanlı Kilise Phase I (with frescoes)	0.04	0.05	0.06	0.07	0.09	0.14
Çanlı Kilise Phase II	0.04	0.05	0.06	0.07	0.09	0.13

Fig. 52. C80 and D50 for Çanlı Kilise models over 1/1 Octave Bands

The energy ratio results show low values of C80 and D50 in all phases of Çanlı Kilise (Fig. 52) due to the blockage (barrier effect) provided by a wooden screen between the sound source and the receiver, as would be the practice during a liturgical ceremony in the church during the Middle Byzantine Era. Optimum values of C80 indicate that different musical instruments would be easily distinguishable by the listener. However, in the case of Çanlı Kilise, it appears that the distinctness of sound is less audible. In fact, with the blurriness of sound, it may have created a more spiritual environment for the people visiting the church. It is certain that the invisible sound source and its audible effect is much different than that of in the Hallaç Kilise or any other church, in the case that there is no templon separating priest form the group of prayers. All the phases of the church have very similar D50 values (Fig. 52). The low values of D50 indicate that the church is not the most suitable space for speech-related activities, which is reasonable as the church would mainly be used for congregational prayers and ceremonies where both speech and music must have been employed. The next section analyses the quality of speech in the church in more detail.

5.3.3.3 Speech Intelligibility Results and Comparisons of the Different Phases of Çanlı Kilise

Speech intelligibility can be evaluated by assessing Speech Transmission Index (STI), which is a metric that denotes the quality of speech while considering the loss of speech articulation caused by reverberation (Steeneken & Houtgast, 1980).

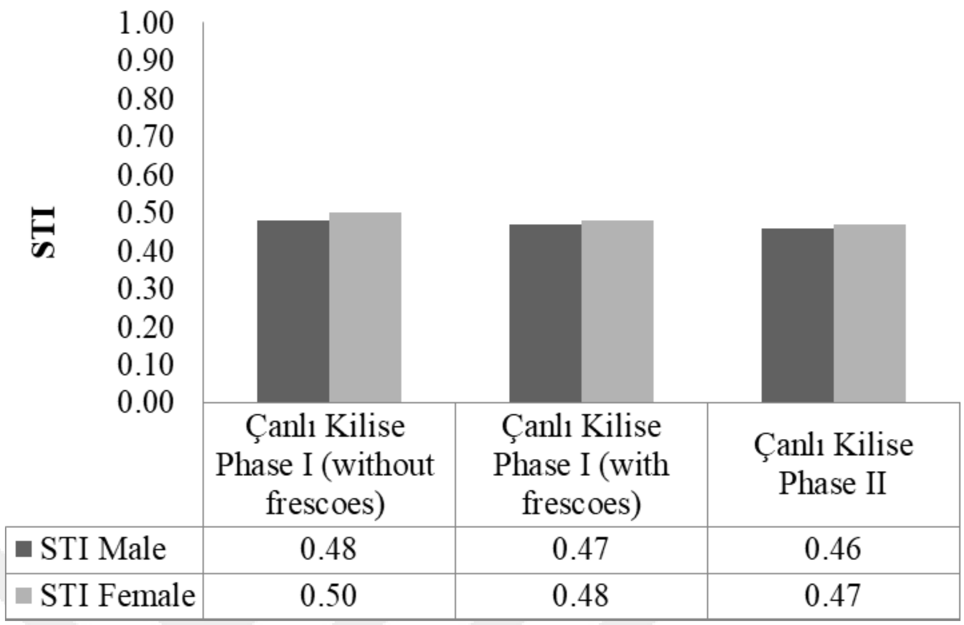


Fig. 53. Male and female STIs for all phases of Çanlı Kilise

Figure 53 displays male and female STI results of the three states of Çanlı Kilise under study. The differences between the average male and female STI values are considerably small in all three states of the church. The STI values seem to drop with the addition of plaster in the church space, as the reverberation in the space increases. The lowest STI value is 0.46 (STI male, Çanlı Kilise Phase II), whereas the highest value is 0.50 (STI female, Çanlı Kilise Phase I, without frescoes). STI values between 0.45 and 0.60 are fair for speech intelligibility (Beranek, 1988). Hence, Çanlı Kilise Phase I and Phase II results indicate that the space is fairly good for speech intelligibility.

CHAPTER 6

CONCLUSION

This thesis is a detailed study of the acoustics of five rock-cut structures and a masonry church from Cappadocia. Furthermore, the material properties of two rock samples from the region have also been evaluated in order to get a grasp of their sound absorption qualities. The motivation behind the study lies in the fact that the sound fields of Byzantine Cappadocia have not yet been documented. While the recent scholarship focuses on the settlement features and compounds of Cappadocia, it is important to document the indoor soundscape of Cappadocian structures in order to proceed further for a better understanding of their context.

In accordance with ISO 3382, in-situ field tests are performed in five Middle Byzantine rock-cut structures of Hallaç, Açıksaray and Avanos; necessary modifications have been made to the set-up mainly due to the lack of a power supply. Three main types of signals are used: balloon pops, e-sweep, and MLS. Comparing the peak noise to signal ratio (PNR) values from the three signals, balloon pops prove to be the most efficient type of signal to excite the rock-cut spaces. Balloon pops are even better than the e-sweep signal used by an omni-directional sound source in Avanos. For this reason, as a methodological outcome, for rock-cut structures or caves of similar volumes, there is no need to set-up a full-scale measurement system including the speaker amplifier, and associated parts and cables. The use of balloon pops may make it more feasible and time saving to do research in numerous such spaces.

From the field tests, decay rates (EDT, T20, T30), energy ratios (C80, D50), and intelligibility metric (STI) are obtained for each space. Overall, due to their similar volumes and materiality, the spaces have similar reverberation times, except for the Hallaç Church which is the most reverberant space with T30 values of around 2 s. The high BR (2.0) of the church signifies augmented male voice which is consistent with the liturgical practices of the space. With decreasing volumes, the reverberation times of the other halls keep getting shorter. Apart from the Hallaç Church, all other spaces are assumed to be halls which were used either for gatherings and celebrations such as weddings, funerals, and receiving guests.

The Hallaç Church has a C80 of around +2dB which, as discussed before, is within the optimum range of liturgical music. With favorable D50 and STI values, the church is also appropriate for a verbal performance by a single speaker. The other four halls do not show equally optimum C80 values, which become higher than +5 dB, especially in the case of the Avanos Dining Hall. On the other hand, these halls have better D50 and STI values, which mean that they are more favorable spaces for speech-related activities. Hence, these spaces are acoustically performing in accordance with the functions that they are known for.

The thesis also brings acoustical data of previous sources regarding both natural caves and man-made structures in a summarized form in order to draw parallel comparisons. Most of the natural caves that have been studied are much larger in volume than the Cappadocian rock-cut structures. For those with comparable volumes, the decay rates of natural caves are higher, indicating that they have a more reflective interior surface made of karst stone, than that of Cappadocia which is made of tuff. The Italian catacombs, on the other hand, are made of tuff as well but these spaces have comparatively lower reverberation times. Therefore, it can be deduced that the tuff from Rome is much more sound absorptive than the tuff of Cappadocia.

The results of the impedance tube tests on the rock samples from Göreme and Ürgüp reveal that the Cappadocian rock tuff is absorptive along the whole frequency spectrum. The absorptive quality of the rocks is based on the porosity of the material. Although the sample from Göreme shows a linear trend in terms of its sound absorption coefficient along all frequencies, as opposed to the sample from Ürgüp which has a major dip between 500 Hz and 1 kHz, both the samples have similar absorption coefficient values (around 0.40 at the mid-frequency range). Based on literature, these rocks are also compared with other most commonly used materials and furnishings to have a better sense of their absorption performances. The rocks lie somewhere in between the most reflective materials (marble tile, terrazzo, unglazed and painted brick) and the most absorbent materials (heavy carpet). In general, the samples have comparable sound absorption coefficients to rough soil. This means that these rock samples can be included under the current umbrella of sound absorptive materials, especially with values reaching up to 0.50.

The study also encompasses the virtual and aural reconstruction of a masonry church, Çanlı Kilise, because in-situ field tests are impossible to be conducted in the church as the roof of the structure is completely missing. First of all, the data from field measurements is used to recreate 3D models of the Hallaç Church and the Avanos Dining Hall as close as possible to the real spaces. This is achieved by tuning the T30 values of the acoustic model with a 5% difference (JND) of the field measurements by adjusting the sound absorption coefficients of the major interior surfaces. After the process is completed, sound absorption coefficients for the rock tuff in the Hallaç Church and the Avanos Dining Hall are obtained. The absorption coefficients of the material from these spaces are found to be much more reflective than those of the rock samples collected from Göreme and Ürgüp. It is concluded that the difference between the sound absorption performances of the rock samples with the tuff in the spaces may be due to the increased porosity of the untouched rocks and the thickening of the outermost layer of the tuff in rock-structures after it comes in contact with air. Hence, using the ray-tracing simulations, the Hallaç Church's tuff and its absorption coefficients are applied in the virtual models of Çanlı Kilise.

Once the acoustical simulations are performed, the results of three states of Çanlı Kilise, Phase I (without frescoes), Phase I (with frescoes), and Phase II, are obtained and compared with each other to see the effect of the architectural changes on the acoustics of the church. First of all, the decay rate results from all three sates of the church show that the space is suitable for liturgical practices. As expected, RT values show an increase with the addition of plastered frescoes and volume (narthex). Due to a screen between the source and the receiver, negative C80 values are obtained over the whole frequency range indicating that the distinctness of musical tones in a liturgical ceremony might not be clear to the listeners. In fact, it might have helped in creating a spiritual environment due to the blurriness of sound in the space. The same reason can be used to explain the low values of D50. STI results denote that the church space, in all its phases, is fair for speech intelligibility. In general, the results obtained from the simulation run on the masonry church present a different set of results (low C80 and D50 values), but these results present the characteristic indoor acoustical environment of Çanlı Kilise, which in combination with the unconventional architecture (e.g. wooden templon) of the church, would have made it a unique space offering a distinct aural experience.

The acoustical outcomes of the study highlight that in general Cappadocian spaces perform in accordance with the functions, as stated within this study, they are associated with. Future works related to this study can include the acoustical documentation of other Cappadocian rock-cut and masonry structures; especially those that have been archaeologically studied and documented before. This work attempts to serve as an example to carry out further research projects in Cappadocia. Research can be conducted on the natural rocks of Cappadocia from different places in the region to have an in-depth material analysis. Such a thorough material collection can inform us about the variety of the natural materials found in the region and their respective acoustical performances.

The study is an attempt to start an academic discussion on Cappadocia by focusing on the region's indoor acoustical environments. Future studies can also be aimed at understanding the differences of functions of different secular halls with different architectural features in the same area. For instance, as suggested by Öztürk, the cruciform halls, the inverted T plan halls, and flat ceiling halls from different areas of Açıksaray can be acoustically documented and studied in detail to reveal the reasoning behind the use of different architectural differences. The acoustics of halls or spaces which are known to be occupied mainly by one gender must also be studied in greater detail to assess the performance of these halls and their privacy. An example could be the secondary halls of Hallaç Complex. Such halls can be studied in relation to the main halls of the same complex to highlight any differences between the acoustical performances of these halls. Comparative studies on the acoustics of rock-cut structures and Cappadocia's limited masonry structures can also reveal the differences between the soundscapes of such spaces and may open a gateway to an academic discourse.

Due to the scope and the time limitation of this study, only a few prominent spaces from Cappadocia have been acoustically analyzed; however, with the aim of starting an academic discourse on the acoustical environments of Cappadocia, this study can serve as a methodological stepping stone. As this study compares different spaces from different parts of the region, perhaps a future study can focus on evaluating the differences in the acoustic environments of inter-connected spaces of Cappadocian settlements. The region has never been acoustically documented before and as this study demonstrates, like many other archaeoacoustic studies around the world, the acoustics of a space can provide major clues about the use of spaces and the culture of people that inhabited them. With the current debate on the functions and contexts of Cappadocian structures, similar acoustic studies can potentially provide us with authentic information.

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Appendices

Appendix A

Field Test Results

Table A 1. EDT at the Hallaç Church over 1/1 Octave Bands

EDT	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.59	3.29	2.55	1.72	1.23	0.83
s1r4	4.06	3.69	1.89	1.10	0.92	0.76
s1r5	5.01	3.37	2.61	1.69	1.38	0.95
s2r1	5.13	3.39	2.37	1.75	1.34	0.99
s2r2	4.69	3.23	2.19	1.81	1.12	0.85
s2r5	4.57	3.80	2.44	1.76	1.30	0.88
s3r2	4.71	3.45	2.56	1.73	1.09	0.83
s4r1	5.06	3.31	2.82	1.87	1.44	1.00
s4r2	4.25	3.43	2.28	1.67	1.25	0.81
s4r3	5.31	3.33	2.22	1.78	1.26	0.85
s4r5	4.50	3.61	2.46	1.87	1.46	1.03
avg	4.72	3.45	2.40	1.71	1.25	0.89

Table A 2. T20 at the Hallaç Church over 1/1 Octave Bands

T20	125	250	500	1000	2000	4000
s1r1	5.32	3.38	2.40	1.77	1.33	0.90
s1r4	5.33	2.83	2.45	1.78	1.31	0.88
s1r5	5.01	3.60	2.70	1.84	1.42	1.00
s2r1	5.13	3.53	2.58	1.89	1.39	0.92
s2r2	4.69	3.40	2.46	1.77	1.34	0.88
s2r5	4.77	3.73	2.57	1.95	1.52	0.99
s3r2	5.03	3.66	2.46	1.73	1.39	0.91
s4r1	4.65	3.36	2.59	1.90	1.47	1.06
s4r2	5.13	3.51	2.48	1.85	1.37	0.89
s4r3	4.81	3.65	2.53	1.78	1.39	0.94
s4r5	4.92	3.67	2.62	1.78	1.46	0.99
avg	4.98	3.48	2.53	1.82	1.40	0.94

Table A 3. T30 at the Hallaç Church over 1/1 Octave Bands

T30 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	5.51	3.60	2.47	1.79	1.34	0.93
s1r4	5.67	3.49	2.50	1.78	1.38	0.92
s1r5	5.29	3.77	2.69	1.89	1.46	1.00
s2r2	5.33	3.37	2.55	1.78	1.37	0.93
s2r5	5.14	3.71	2.66	1.91	1.54	1.02
s3r2	4.61	3.87	2.49	1.78	1.42	0.95
s4r1	4.98	3.44	2.69	1.96	1.50	1.12
s4r2	4.86	3.55	2.53	1.81	1.38	0.91
s4r3	5.98	3.80	2.51	1.79	1.36	0.92
s4r5	4.97	3.72	2.65	1.83	1.45	1.01
Avg.	5.23	3.63	2.57	1.83	1.42	0.97

Table A 4. C80 at the Hallaç Church over 1/1 Octave Bands

C80(dB)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	-2.07	-2.00	0.76	3.15	5.15	7.17
s1r4	-2.54	-0.20	2.08	4.57	5.84	6.14
s1r5	-4.97	-3.92	-1.75	-0.37	0.45	2.75
s2r1	-1.78	-1.56	2.76	5.50	8.09	9.19
s2r2	-4.86	-3.64	0.97	3.60	5.75	7.58
s2r5	-3.24	-0.10	1.22	-0.16	3.09	4.68
s3r2	-3.01	-0.81	0.94	2.85	2.81	4.66
s4r1	-6.43	-3.22	-0.47	-0.58	1.53	3.82
s4r2	-3.63	-0.23	0.76	4.02	4.73	5.40
s4r3	-7.54	-4.43	-1.97	-0.41	0.83	3.81
s4r5	-8.69	-4.31	-2.63	-0.65	-0.21	2.86
Avg.	-4.43	-2.22	0.24	1.96	3.46	5.28

Table A 5. D50 at the Hallaç Church over 1/1 Octave Bands

D50	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	0.23	0.35	0.47	0.55	0.67	0.74
s1r4	0.25	0.34	0.51	0.63	0.68	0.66
s1r5	0.17	0.23	0.32	0.37	0.35	0.45
s2r1	0.51	0.37	0.58	0.71	0.80	0.83
s2r2	0.17	0.25	0.49	0.62	0.70	0.75
s2r5	0.31	0.41	0.48	0.39	0.53	0.60
s3r2	0.14	0.32	0.46	0.52	0.49	0.58
s4r1	0.14	0.20	0.25	0.33	0.46	0.56
s4r2	0.14	0.36	0.46	0.62	0.64	0.65
s4r3	0.11	0.19	0.25	0.26	0.35	0.50
s4r5	0.05	0.21	0.21	0.32	0.31	0.48
Avg.	0.20	0.29	0.41	0.48	0.54	0.62

Table A 6. EDT at the Hallaç Main Hall over 1/1 Octave Bands

EDT(s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.96	2.72	1.85	1.28	1.07	0.64
s1r2	3.97	2.75	1.81	1.33	0.99	0.71
s1r3	3.91	2.97	1.91	1.36	1.09	0.66
s1r4	3.70	2.60	1.73	1.35	1.00	0.62
s2r1	3.52	2.14	1.81	1.28	1.01	0.71
s3r1	3.78	2.55	1.74	1.35	1.02	0.68
s4r3	4.69	2.34	2.03	1.36	1.01	0.70
s5r3	3.60	2.59	1.75	1.32	0.88	0.65
s5r5	3.86	2.91	1.76	1.33	0.93	0.57
s5r6	3.07	2.24	2.71	1.33	1.01	0.62
s5r7	4.11	2.29	1.56	1.42	0.85	0.60
s6r7	4.47	2.74	1.75	1.20	0.89	0.68
Avg.	3.97	2.57	1.87	1.33	0.98	0.65

Table A 7. T20 at the Hallaç Main Hall over 1/1 Octave Bands

T20(s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.55	2.86	1.97	1.38	1.12	0.70
s1r2	4.12	2.90	2.11	1.44	1.03	0.72
s1r3	4.44	2.70	1.99	1.42	1.12	0.74
s1r4	5.23	2.91	1.85	1.39	1.04	0.66
s2r1	4.33	2.93	2.07	1.38	1.08	0.74
s3r1	4.66	2.63	1.88	1.42	1.01	0.70
s4r3	4.74	2.82	1.96	1.42	1.04	0.71
s5r3	5.16	2.85	1.87	1.38	1.00	0.67
s5r5	4.80	2.95	1.80	1.37	1.01	0.71
s5r6	4.00	3.44	2.59	1.34	0.96	0.67
s5r7	4.53	3.02	1.94	1.36	1.05	0.69
s6r7	4.50	3.04	1.85	1.36	1.00	0.66
Avg.	4.59	2.92	1.99	1.39	1.04	0.70

Table A 8. T30 at the Hallaç Main Hall over 1/1 Octave Bands

T30(s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.74	2.95	2.01	1.40	1.09	0.72
s1r2	4.29	3.00	2.07	1.50	1.06	0.76
s1r3	4.73	2.90	1.99	1.43	1.09	0.75
s1r4	5.56	3.09	1.95	1.40	1.02	0.69
s2r1	4.50	2.98	2.06	1.45	1.10	0.77
s3r1	4.85	3.00	1.92	1.45	1.03	0.74
s4r3	5.40	2.91	1.99	1.44	1.05	0.75
s5r3	5.88	3.04	1.96	1.42	1.04	0.67
s5r5	5.32	3.27	1.68	1.41	1.02	0.72
s5r7	5.40	3.20	1.93	1.45	1.06	0.69
s6r7	4.40	2.85	1.83	1.36	0.99	0.66
Avg.	5.01	3.02	1.94	1.43	1.05	0.72

Table A 9. C80 at the Hallaç Main Hall over 1/1 Octave Bands

C80(dB)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	-2.92	-2.04	0.17	3.03	3.82	7.75
s1r2	-1.37	-2.85	-0.80	0.39	2.46	5.03
s1r3	-3.45	-2.80	-1.88	2.04	2.58	5.83
s1r4	-6.05	-2.87	0.11	1.39	4.04	7.68
s2r1	-1.32	2.34	0.65	1.60	3.66	5.60
s3r1	-3.03	0.02	-1.12	1.35	3.27	5.96
s4r3	-5.21	-1.70	-1.85	1.58	2.97	5.57
s5r3	-3.95	-0.05	-0.15	3.79	6.61	8.35
s5r5	-6.43	-4.03	0.60	2.65	4.52	8.01
s5r6	-5.27	-0.85	0.03	2.79	5.12	8.24
s5r7	-8.63	-3.35	1.49	3.74	6.37	9.28
s6r7	-5.40	-0.42	1.09	3.80	4.26	5.50
Avg.	-4.42	-1.55	-0.14	2.35	4.14	6.90

Table A 10. D50 at the Hallaç Main Hall over 1/1 Octave Bands

D50	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	0.24	0.30	0.33	0.53	0.56	0.72
s1r2	0.36	0.25	0.32	0.37	0.43	0.60
s1r3	0.25	0.20	0.25	0.50	0.52	0.58
s1r4	0.13	0.25	0.36	0.40	0.61	0.73
s2r1	0.35	0.32	0.39	0.46	0.56	0.64
s3r1	0.22	0.38	0.33	0.40	0.50	0.62
s4r3	0.13	0.22	0.29	0.44	0.49	0.60
s5r3	0.16	0.37	0.40	0.58	0.71	0.76
s5r5	0.12	0.22	0.43	0.56	0.59	0.73
s5r6	0.08	0.32	0.39	0.53	0.68	0.78
s5r7	0.05	0.18	0.47	0.59	0.70	0.79
s6r7	0.15	0.41	0.42	0.56	0.56	0.61
Avg.	0.19	0.29	0.37	0.49	0.58	0.68

Table A 11. EDT at Açıksaray Cruciform Hall over 1/1 Octave Bands

EDT(s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.60	3.38	1.92	1.54	0.94	0.69
s1r2	3.85	3.56	1.99	1.36	1.01	0.66
s1r3	3.53	3.28	1.96	1.40	0.98	0.66
s1r5	5.74	3.55	1.99	1.45	0.89	0.63
s2r1	4.78	2.99	2.18	1.38	0.85	0.64
s3r4	4.29	2.98	1.89	1.42	0.98	0.71
s3r5	4.42	3.20	1.81	1.21	0.83	0.63
s3r6	6.08	3.16	1.84	1.19	0.95	0.64
s3r7	4.48	3.44	1.86	1.40	0.95	0.61
Avg.	4.64	3.28	1.94	1.37	0.93	0.65

Table A 12. T20 at Açıksaray Cruciform Hall over 1/1 Octave Bands

T20 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.87	3.15	2.12	1.49	1.01	0.68
s1r2	4.93	3.21	2.05	1.48	0.97	0.69
s1r3	6.06	3.27	2.18	1.49	1.03	0.70
s1r5	6.11	3.45	1.89	1.33	0.99	0.67
s2r1	5.00	3.45	2.17	1.53	1.02	0.66
s3r4	4.80	3.53	2.14	1.52	1.05	0.69
s3r5	5.72	3.53	1.88	1.39	1.00	0.66
s3r6	4.63	3.45	2.14	1.41	0.99	0.64
s3r7	4.64	3.31	2.08	1.36	1.02	0.66
Avg.	5.20	3.37	2.07	1.44	1.01	0.67

Table A 13. T30 at Açıksaray Cruciform Hall over 1/1 Octave Bands

T30 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.94	3.38	2.13	1.50	1.02	0.69
s1r2	5.04	3.31	2.21	1.51	1.00	0.70
s1r3	5.53	3.34	2.18	1.47	1.02	0.71
s1r5	6.34	3.49	1.97	1.36	1.01	0.68
s2r1	4.96	3.58	2.14	1.54	1.05	0.68
s3r4	4.79	3.32	2.19	1.57	1.03	0.70
s3r5	6.10	3.80	1.94	1.40	0.97	0.67
s3r6	6.32	3.45	2.07	1.42	0.98	0.66
s3r7	4.56	3.11	2.09	1.39	1.00	0.67
Avg.	5.40	3.42	2.10	1.46	1.01	0.68

Table A 14. C80 at Açıksaray Cruciform Hall over 1/1 Octave Bands

C80(dB)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	-2.63	-2.03	-0.18	0.26	3.33	5.20
s1r2	-5.08	-1.37	1.06	1.17	3.42	6.46
s1r3	-8.51	-6.21	-1.72	0.97	4.72	6.72
s1r5	-4.85	-2.60	3.06	1.17	4.96	9.27
s2r1	-2.75	0.86	0.77	3.21	4.87	8.52
s3r4	-1.79	0.39	1.48	3.64	4.68	7.75
s3r5	-5.22	-3.98	3.41	1.94	4.29	8.40
s3r6	-5.87	-3.13	0.96	2.51	3.61	7.35
s3r7	-3.66	-2.24	1.59	1.88	4.91	9.45
Avg.	-4.48	-2.26	1.16	1.86	4.31	7.68

Table A 15. D50 at Açıksaray Cruciform Hall over 1/1 Octave Bands

D50	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	0.29	0.26	0.32	0.37	0.53	0.59
s1r2	0.18	0.36	0.47	0.44	0.53	0.66
s1r3	0.05	0.10	0.24	0.39	0.63	0.67
s1r5	0.23	0.28	0.58	0.41	0.54	0.78
s2r1	0.25	0.44	0.46	0.54	0.57	0.75
s3r4	0.33	0.42	0.47	0.59	0.58	0.74
s3r5	0.19	0.24	0.53	0.46	0.53	0.72
s3r6	0.12	0.19	0.50	0.50	0.54	0.69
s3r7	0.16	0.24	0.51	0.48	0.59	0.81
Avg.	0.20	0.28	0.45	0.46	0.56	0.71

Table A 16. EDT at Açıksaray Main Hall over 1/1 Octave Bands

EDT (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	3.80	2.20	1.75	1.21	0.92	0.66
s1r2	2.84	2.20	1.50	0.99	0.77	0.51
s1r3	2.82	2.18	1.64	1.09	0.80	0.61
s1r4	3.25	2.05	1.45	0.86	0.67	0.49
s1r5	2.74	2.38	1.56	1.03	0.64	0.55
s2r1	3.15	2.05	1.72	1.05	0.91	0.59
Avg.	3.10	2.18	1.60	1.04	0.78	0.57

Table A 17. T20 at Açıksaray Main Hall over 1/1 Octave Bands

T20 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	3.35	2.35	1.55	1.16	0.81	0.59
s1r2	3.45	2.30	1.62	1.10	0.82	0.56
s1r3	3.02	2.21	1.55	1.09	0.82	0.57
s1r4	3.35	2.27	1.51	1.10	0.79	0.56
s1r5	3.57	2.13	1.47	1.14	0.79	0.55
s2r1	3.43	2.29	1.66	1.07	0.81	0.59
Avg.	3.36	2.26	1.56	1.11	0.81	0.57

Table A 18. T30 at Açıksaray Main Hall over 1/1 Octave Bands

T30 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	3.17	2.43	1.60	1.16	0.81	0.58
s1r2	3.85	2.10	1.59	1.08	0.83	0.56
s1r4	3.64	2.23	1.52	1.09	0.78	0.56
s1r5	3.64	2.24	1.54	1.15	0.79	0.58
s2r1	3.48	2.48	1.65	1.14	0.83	0.59
Avg.	3.56	2.30	1.58	1.12	0.81	0.57

Table A 19. C80 at Açıksaray Main Hall over 1/1 Octave Bands

C80 (dB)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	-3.49	-0.87	1.86	2.64	3.19	7.38
s1r2	-2.13	-0.62	0.66	4.38	5.91	9.00
s1r3	-5.50	-1.45	0.88	4.72	5.76	9.13
s1r4	-3.02	2.06	3.48	6.03	7.51	11.40
s1r5	-3.65	0.35	3.18	4.18	8.80	10.11
s2r1	-3.40	-1.78	1.04	3.00	3.38	7.54
Avg.	-3.53	-0.39	1.85	4.16	5.76	9.09

Table A 20. D50 at Açıksaray Main Hall over 1/1 Octave Bands

D50	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	0.22	0.34	0.49	0.53	0.54	0.71
s1r2	0.17	0.33	0.41	0.60	0.66	0.78
s1r3	0.16	0.32	0.41	0.61	0.66	0.73
s1r4	0.22	0.46	0.59	0.64	0.68	0.86
s1r5	0.23	0.44	0.57	0.60	0.78	0.82
s2r1	0.21	0.19	0.35	0.51	0.51	0.70
Avg.	0.20	0.35	0.47	0.58	0.64	0.77

Table A 21. EDT at Avanos Dining Hall over 1/1 Octave Bands

EDT (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	1.11	0.66	0.58	0.46	0.26	0.23
s1r2	1.33	0.83	0.66	0.43	0.38	0.28
s1r3	1.67	1.19	0.99	0.55	0.44	0.34
s1r4	1.09	0.72	0.52	0.40	0.31	0.21
s2r3	1.20	1.08	0.89	0.60	0.48	0.34
s2r5	0.81	1.07	0.72	0.59	0.43	0.28
s2r6	1.40	1.23	1.02	0.65	0.61	0.37
s2r7	1.24	1.01	0.87	0.72	0.55	0.41
Avg.	1.23	0.97	0.78	0.55	0.43	0.31

Table A 22. T20 at Avanos Dining Hall over 1/1 Octave Bands

T20 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	1.15	0.94	0.64	0.46	0.40	0.30
s1r2	1.48	1.07	0.74	0.58	0.46	0.34
s1r3	1.63	1.15	0.90	0.65	0.47	0.36
s1r4	1.32	0.80	0.67	0.42	0.34	0.28
s2r3	1.53	1.15	0.91	0.58	0.49	0.37
s2r5	1.75	1.15	0.87	0.59	0.47	0.36
s2r6	1.73	0.97	0.92	0.63	0.50	0.41
s2r7	2.12	1.25	0.93	0.63	0.50	0.39
avg.	1.59	1.06	0.82	0.57	0.45	0.35

Table A 23. T30 at Avanos Dining Hall over 1/1 Octave Bands

T30 (s)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	1.31	0.96	0.78	0.52	0.41	0.31
s1r2	1.67	1.05	0.80	0.60	0.48	0.34
s1r3	1.70	1.20	0.91	0.63	0.50	0.37
s1r4	1.50	0.88	0.73	0.49	0.39	0.30
s2r3	1.53	1.23	0.86	0.59	0.49	0.38
s2r5	1.88	1.24	0.84	0.60	0.48	0.37
s2r6	1.97	1.04	0.85	0.67	0.50	0.41
s2r7	2.04	1.22	0.89	0.63	0.51	0.40
Avg.	1.70	1.10	0.83	0.59	0.47	0.36

Table A 24. C80 at Avanos Dining Hall over 1/1 Octave Bands

C80 (dB)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	4.35	5.07	8.40	10.92	14.91	18.75
s1r2	2.99	6.76	9.42	11.50	13.09	17.55
s1r3	-4.35	2.87	5.76	10.03	13.48	15.06
s1r4	2.66	7.01	11.16	12.32	16.01	20.15
s2r3	-4.54	3.06	3.78	7.24	9.38	13.18
s2r5	6.56	3.68	4.98	8.74	12.23	16.44
s2r6	-3.00	1.54	1.45	5.81	6.38	11.66
s2r7	-1.47	4.23	4.08	5.50	8.64	12.09
Avg.	0.40	4.28	6.13	9.01	11.77	15.61

Table A 25. D50 at Avanos Dining Hall over 1/1 Octave Bands

D50	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
s1r1	0.62	0.58	0.82	0.82	0.92	0.95
s1r2	0.60	0.75	0.79	0.88	0.89	0.94
s1r3	0.21	0.49	0.69	0.83	0.87	0.90
s1r4	0.53	0.75	0.86	0.86	0.91	0.96
s2r3	0.20	0.50	0.51	0.69	0.79	0.86
s2r5	0.73	0.58	0.56	0.75	0.84	0.93
s2r6	0.30	0.41	0.45	0.59	0.62	0.82
s2r7	0.14	0.65	0.55	0.51	0.71	0.82
Avg.	0.42	0.59	0.65	0.74	0.82	0.90

Appendix B

Acoustical Parameter Distribution Maps for Çanlı Kilise

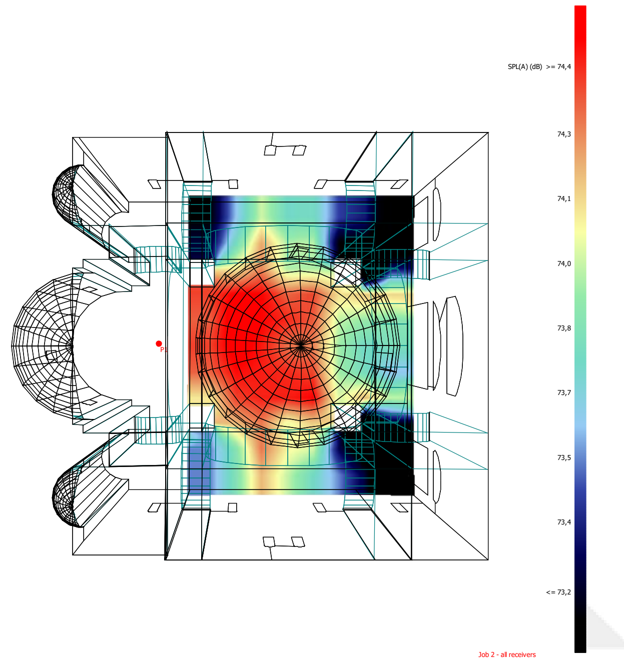


Figure B1. SPL (A) distribution map for Çanlı Kilise Phase I (without frescoes)

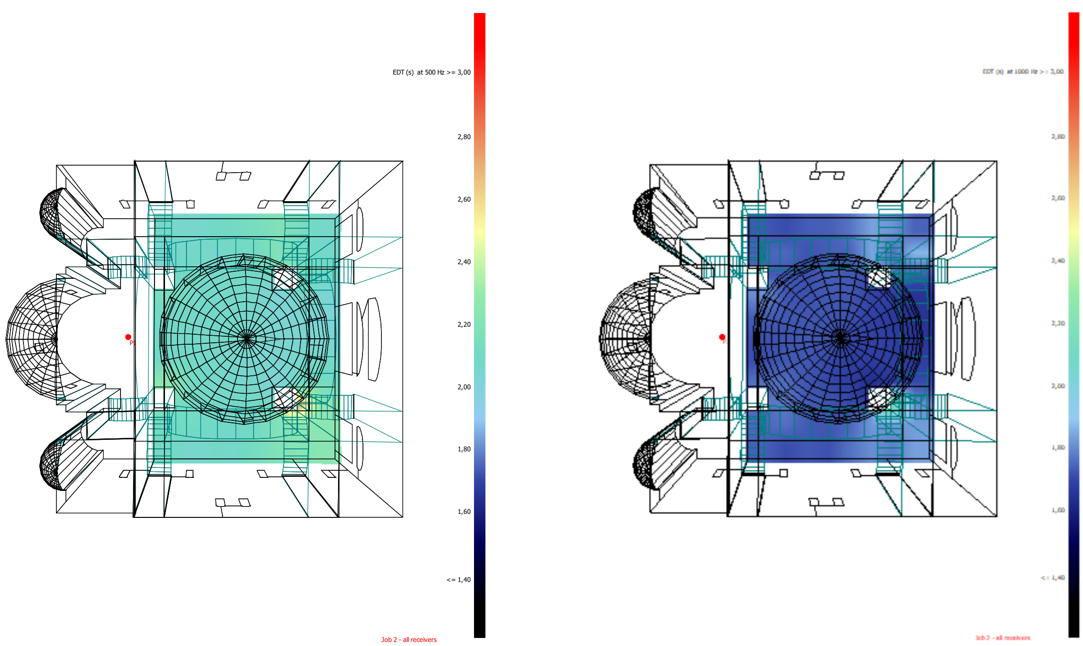


Figure B2. Çanlı Kilise Phase I (without frescoes) EDT at (left) 500 Hz, (right) 1 kHz

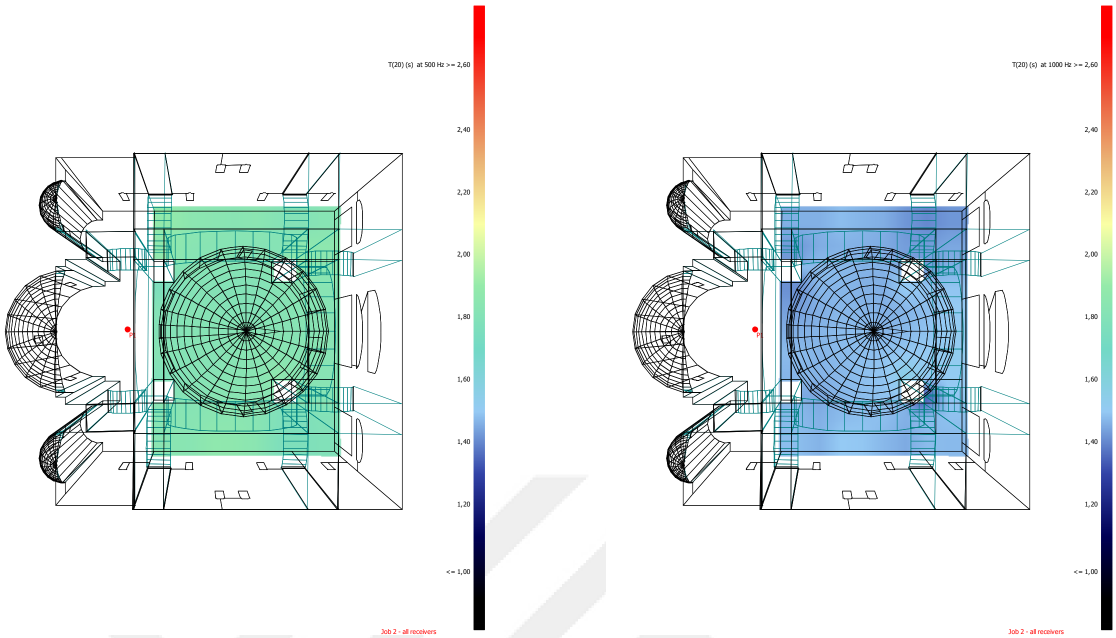


Figure B3. Çanlı Kilise Phase I (without frescoes) T20 at (left) 500 Hz, (right) 1 kHz

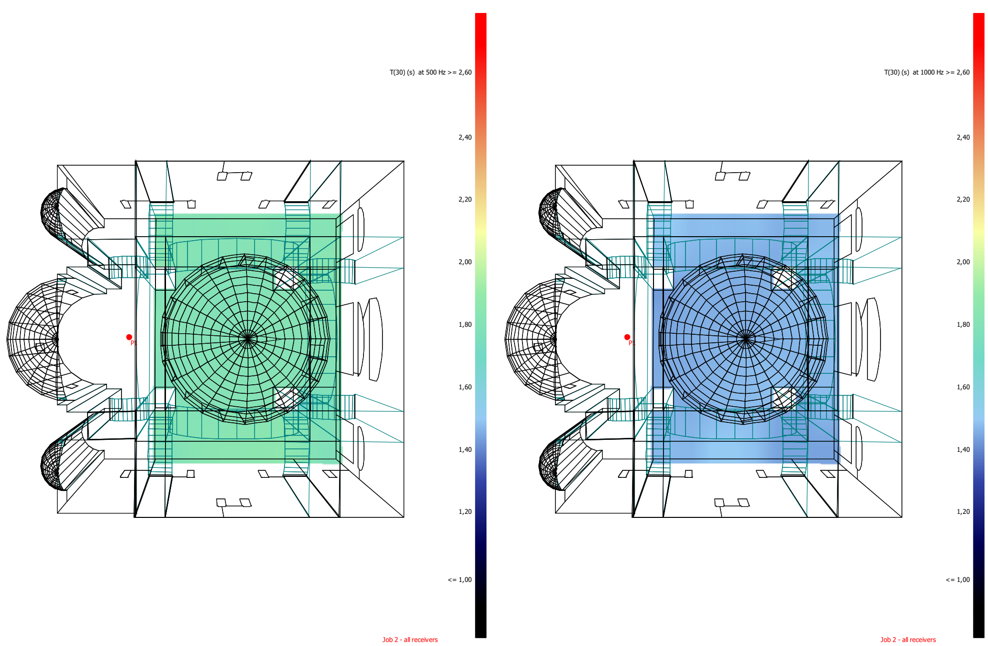


Figure B4. Çanlı Kilise Phase I (without frescoes) T30 at (left) 500 Hz, (right) 1 kHz

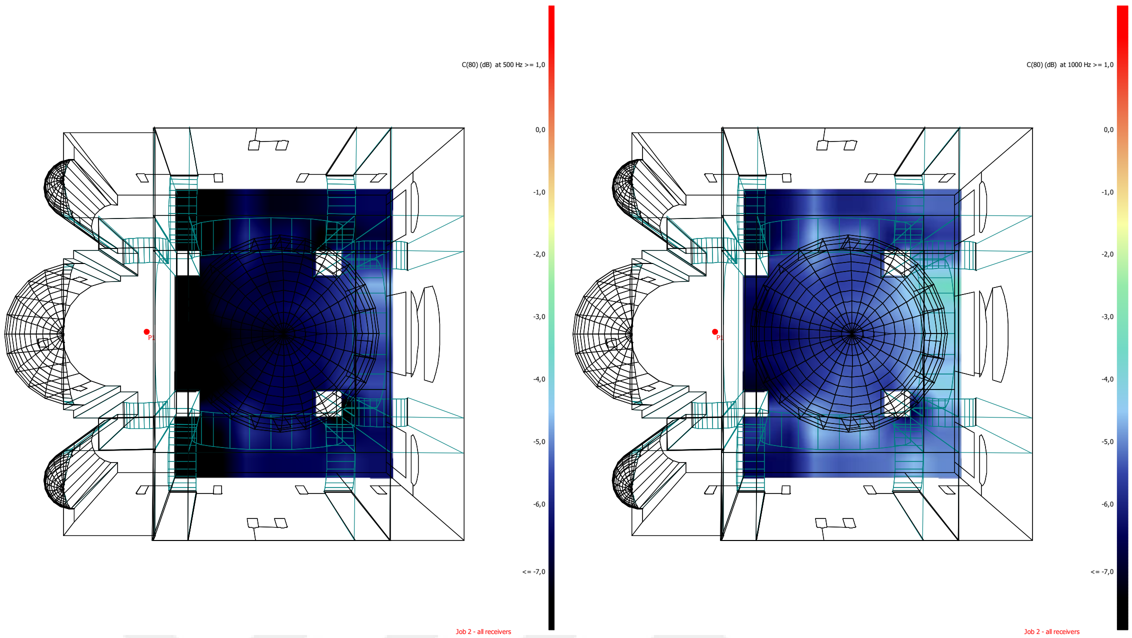


Figure B5. Çanlı Kilise Phase I (without frescoes) C80 at (left) 500 Hz, (right) 1 kHz

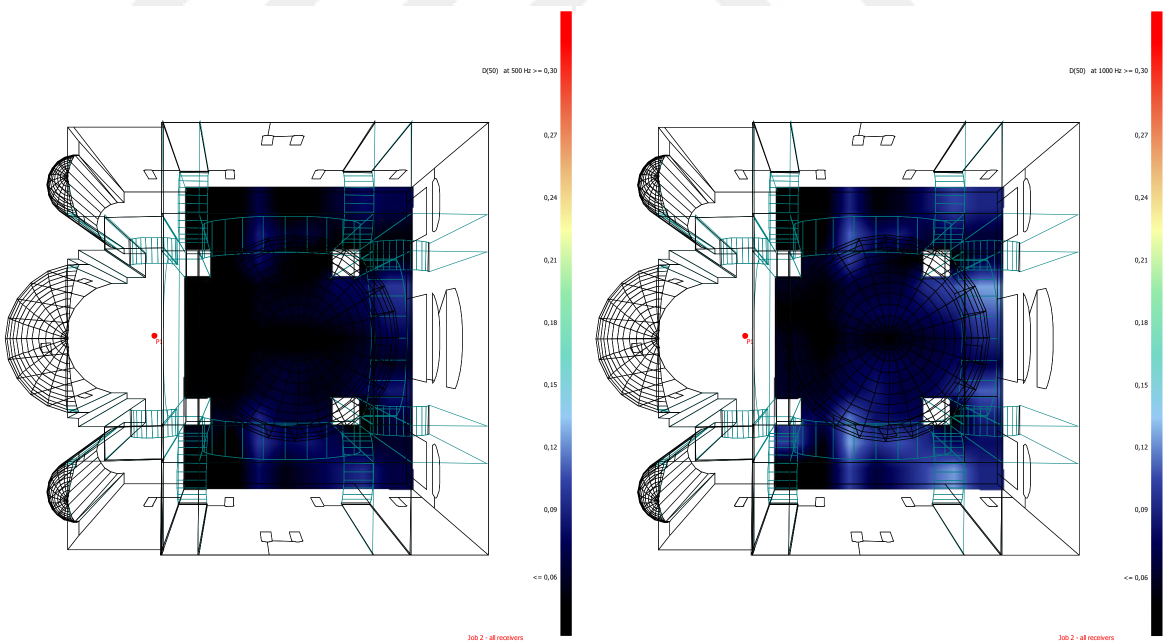


Figure B6. Çanlı Kilise Phase I (without frescoes) D50 at (left) 500 Hz, (right) 1 kHz

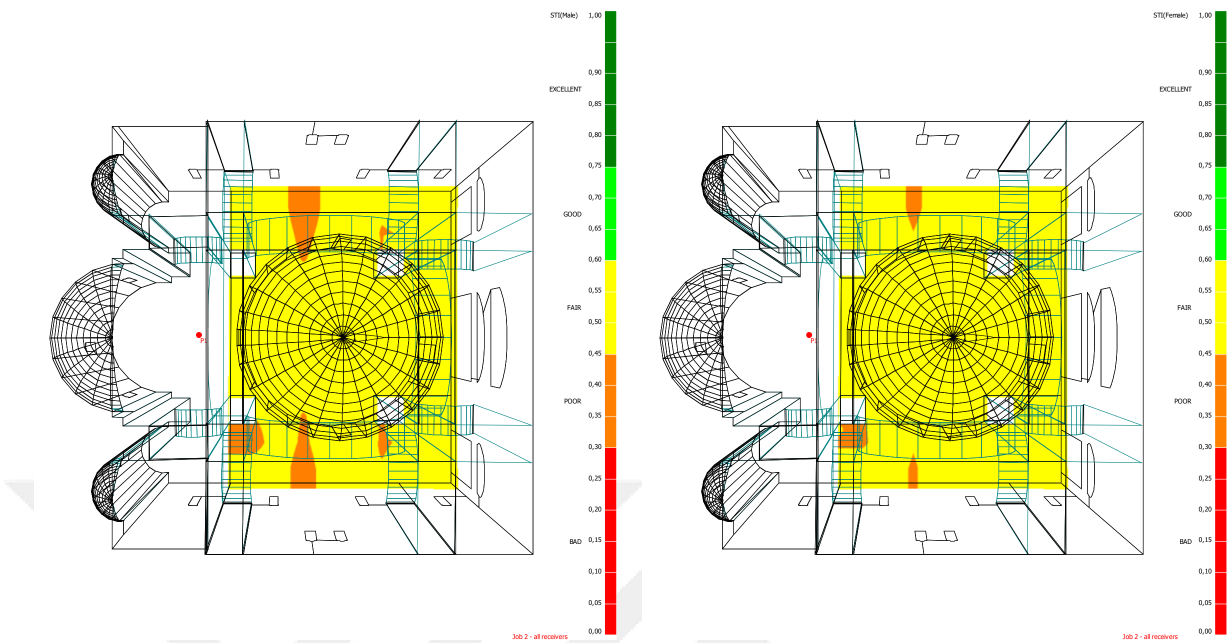


Figure B7. Çanlı Kilise Phase I (without frescoes) STI (left) male, (right) female

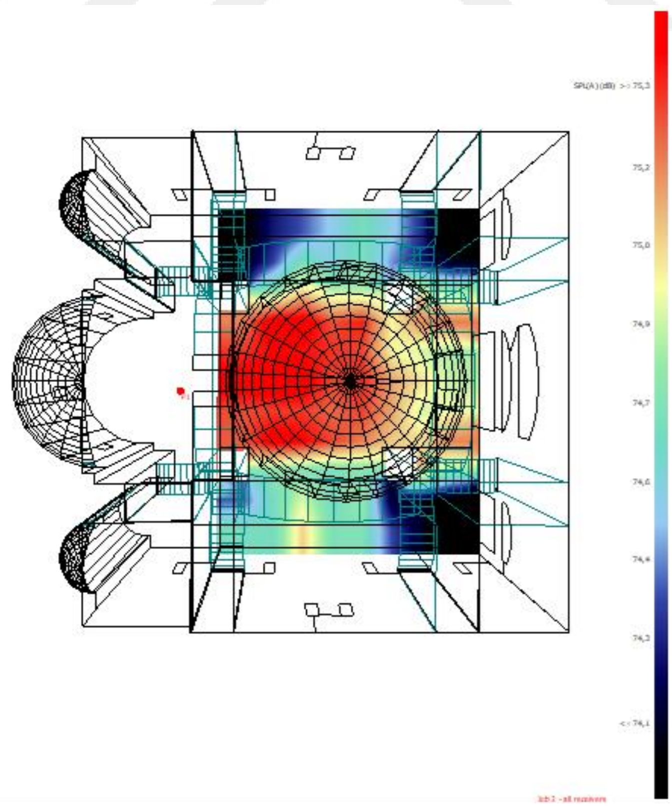


Figure B8. SPL (A) distribution map for Çanlı Kilise Phase I (with frescoes)

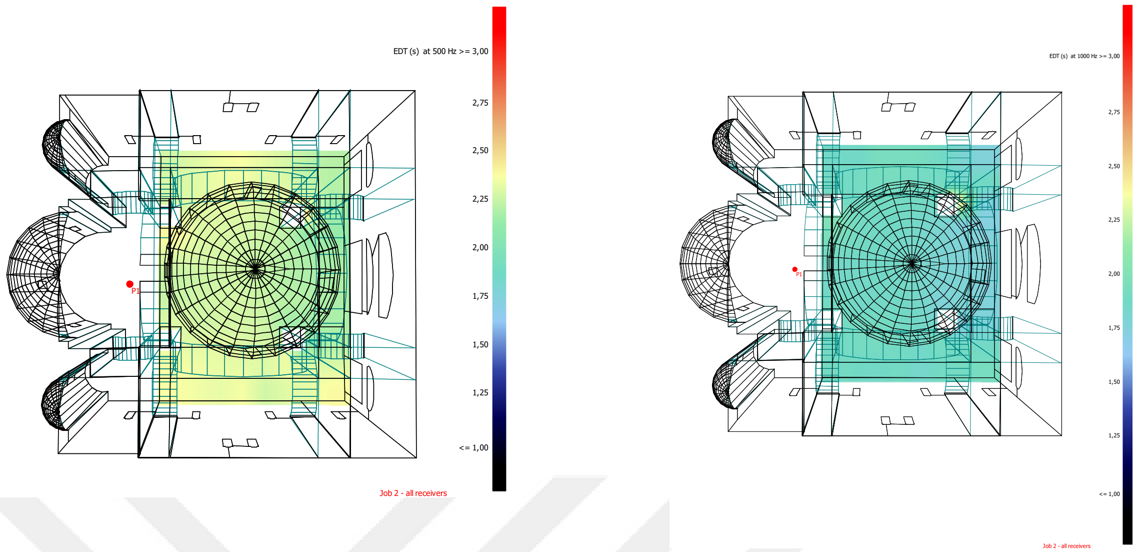


Figure B9. Çanlı Kilise Phase I (with frescoes) EDT at (left) 500 Hz, (right) 1 kHz

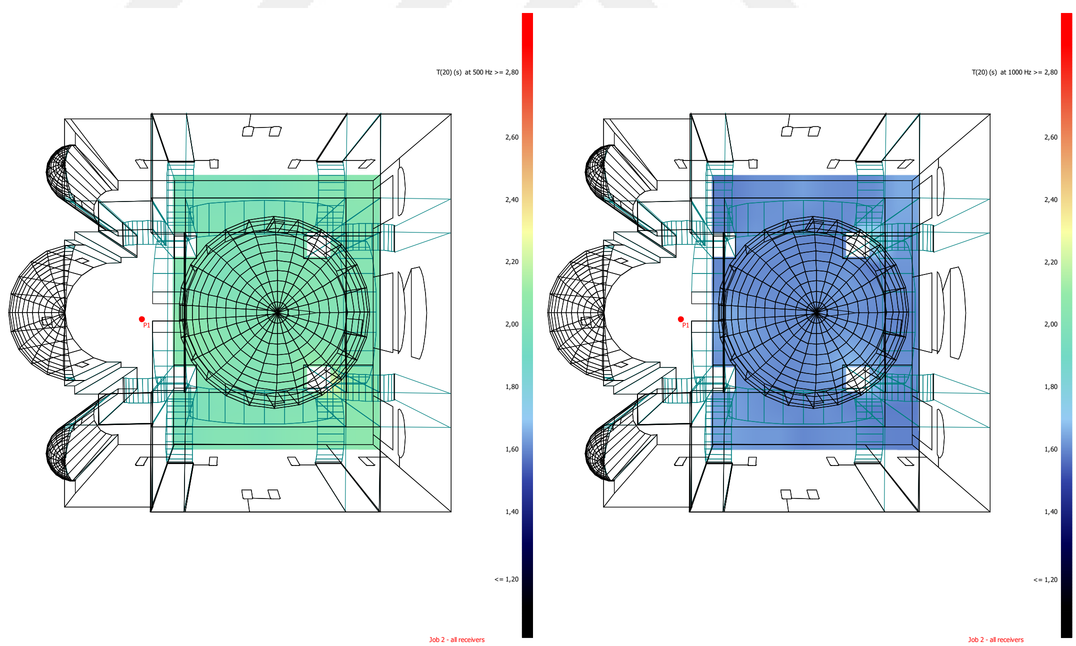


Figure B10. Çanlı Kilise Phase I (with frescoes) T20 at (left) 500 Hz, (right) 1 kHz

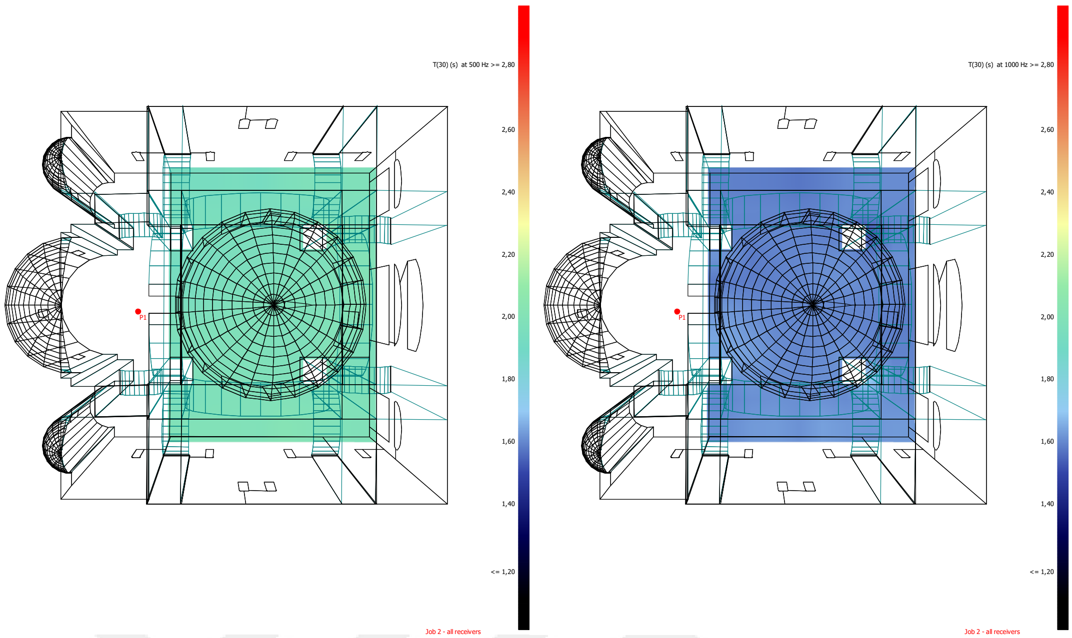


Figure B11. Çanlı Kilise Phase I (with frescoes) T30 at (left) 500 Hz, (right) 1 kHz

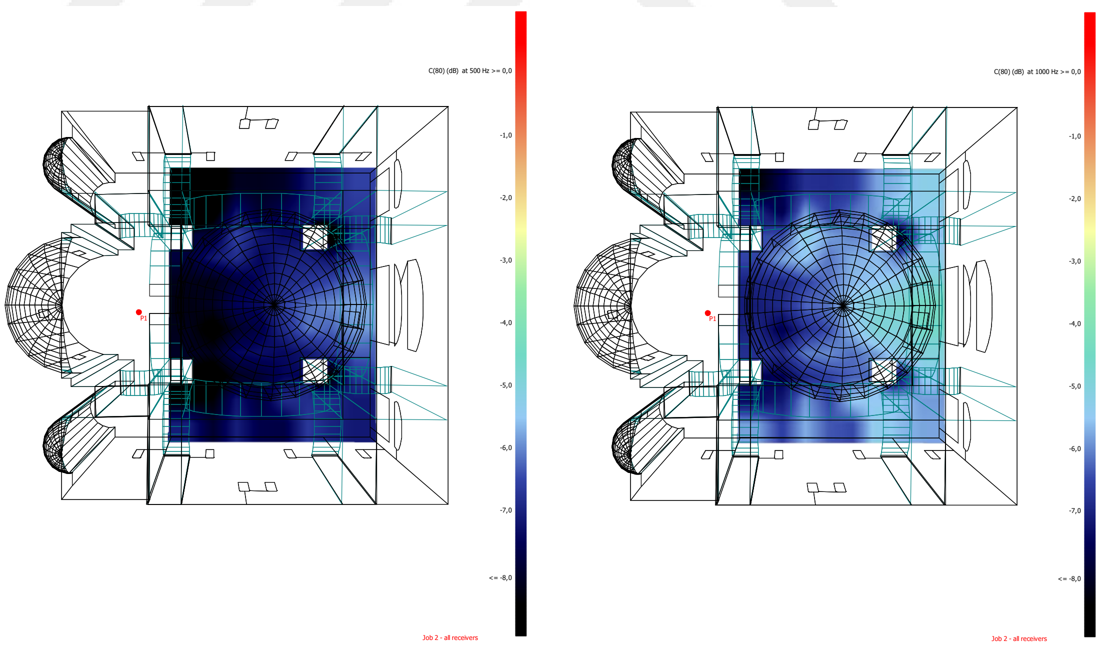
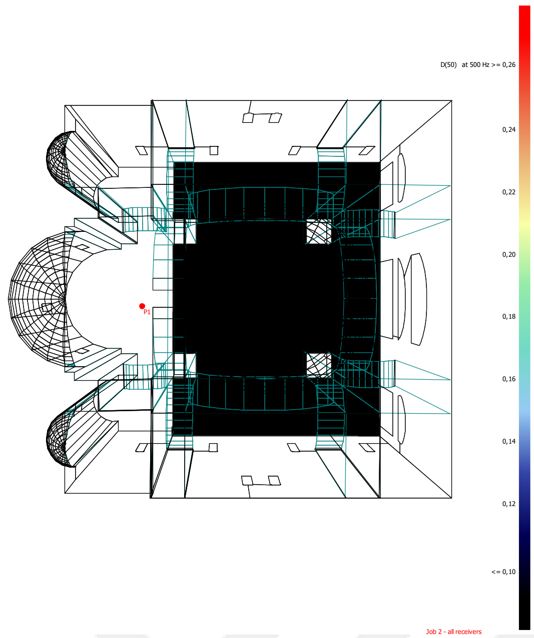


Figure B12. Çanlı Kilise Phase I (with frescoes) C80 at (left) 500 Hz, (right) 1 kHz



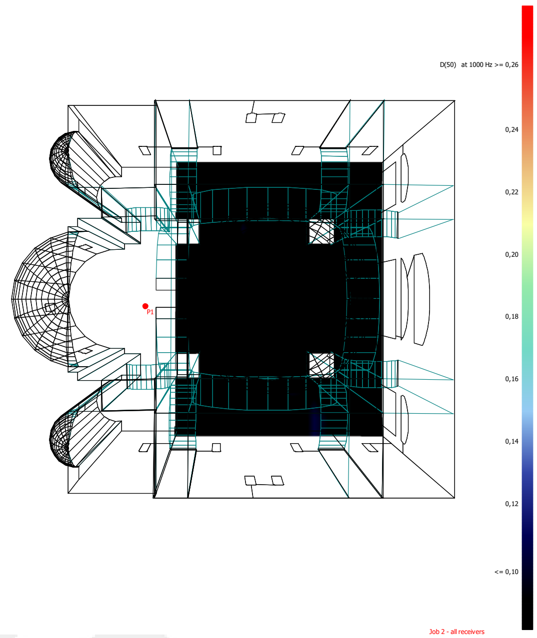
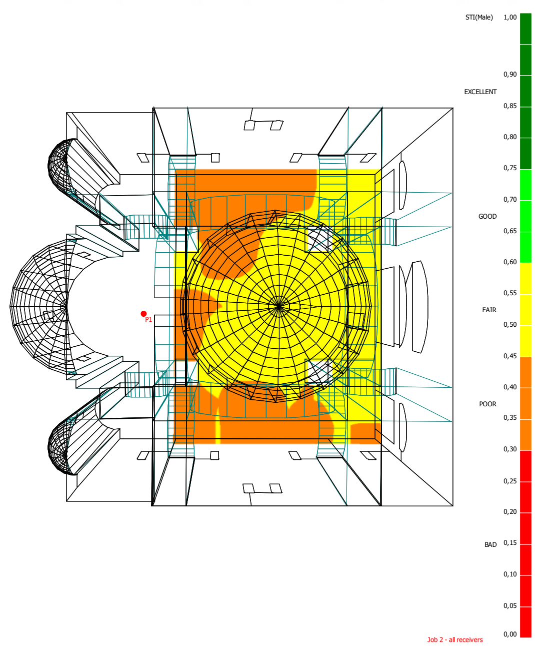


Figure B13. Çanlı Kilise Phase I (with frescoes) D50 at (left) 500 Hz, (right) 1 kHz



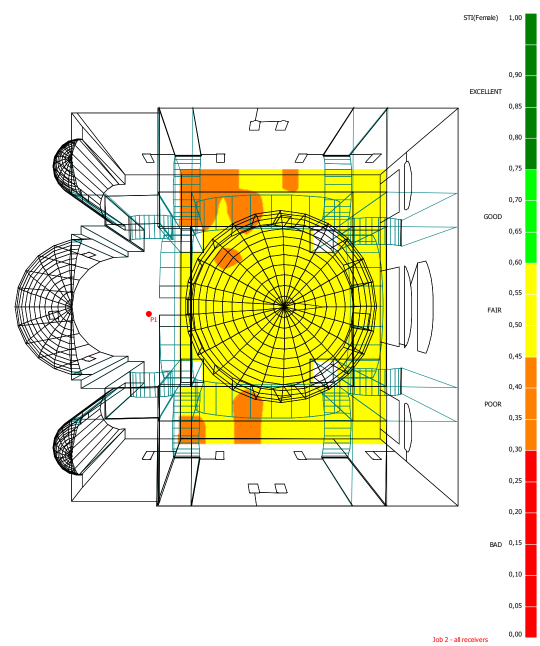


Figure B14. Çanlı Kilise Phase I (with frescoes) STI (left) male, (right) female

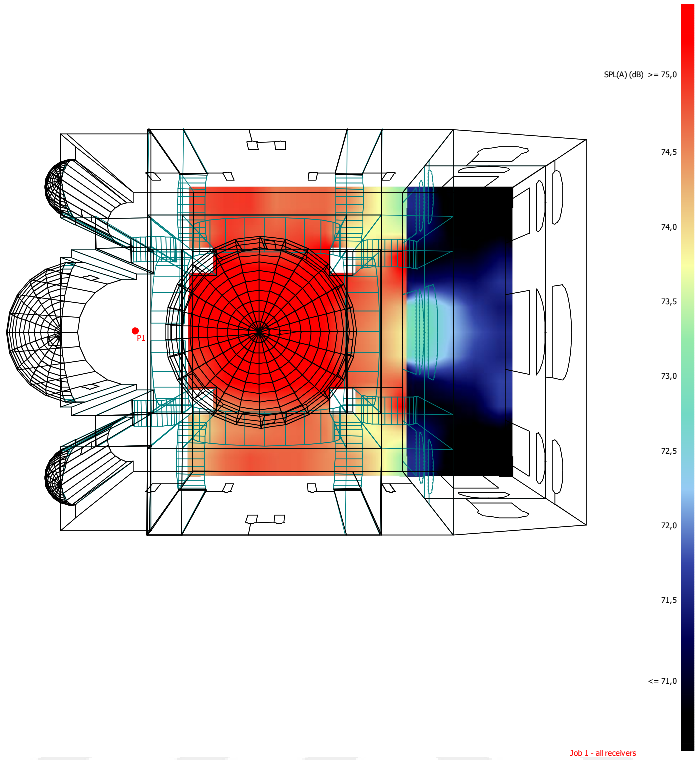


Figure B15. SPL (A) distribution map for Çanlı Kilise Phase II

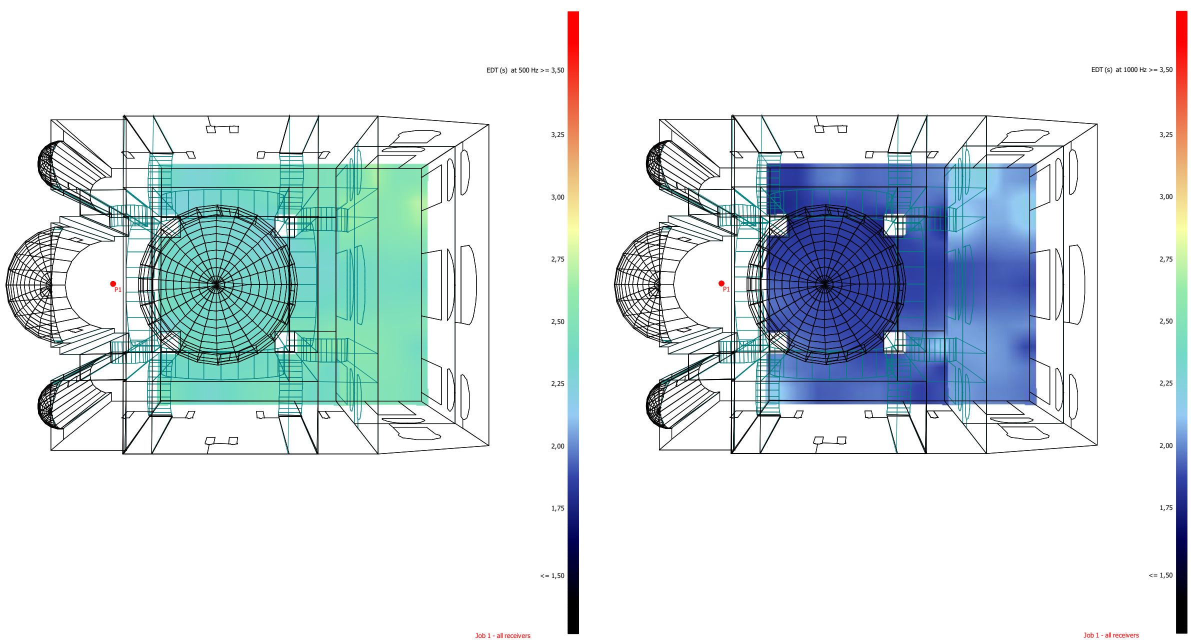


Figure B16. Çanlı Kilise Phase II EDT at (left) 500 Hz, (right) 1 kHz

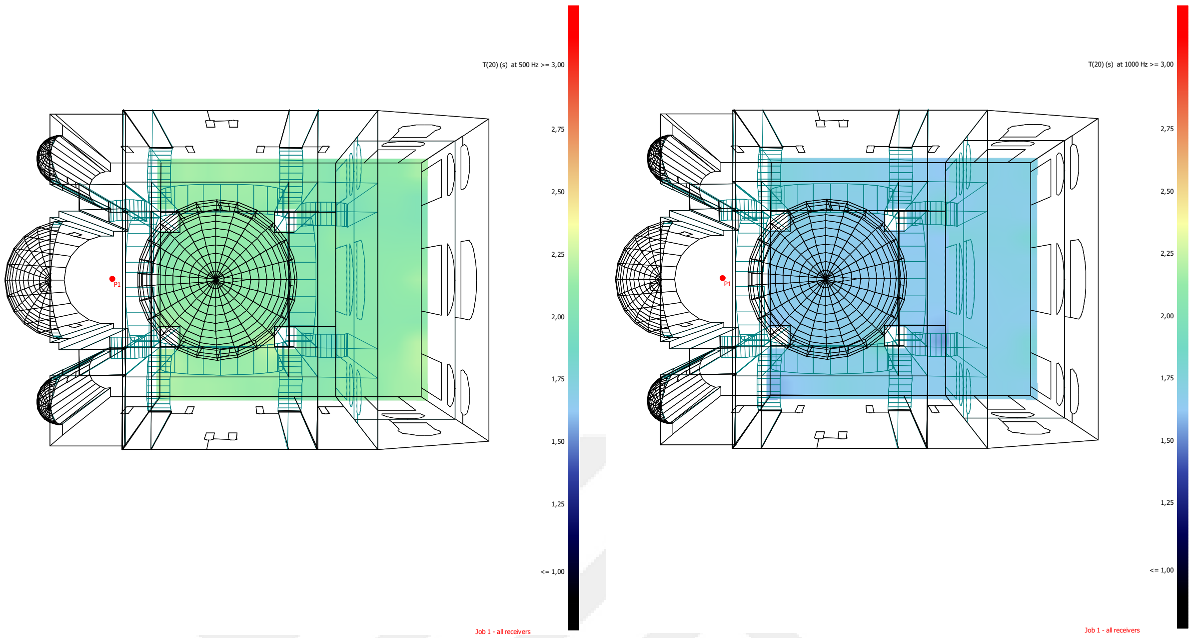


Figure B17. Çanlı Kilise Phase II T30 at (left) 500 Hz, (right) 1 kHz

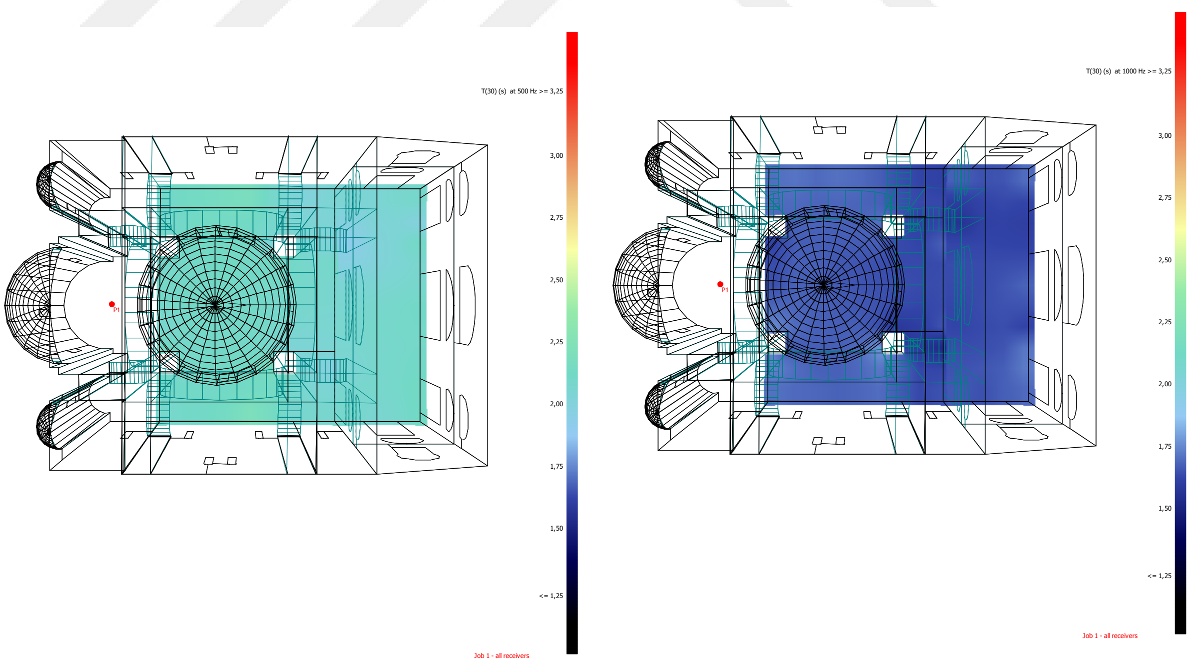


Figure B18. Çanlı Kilise Phase II T20 at (left) 500 Hz, (right) 1 kHz

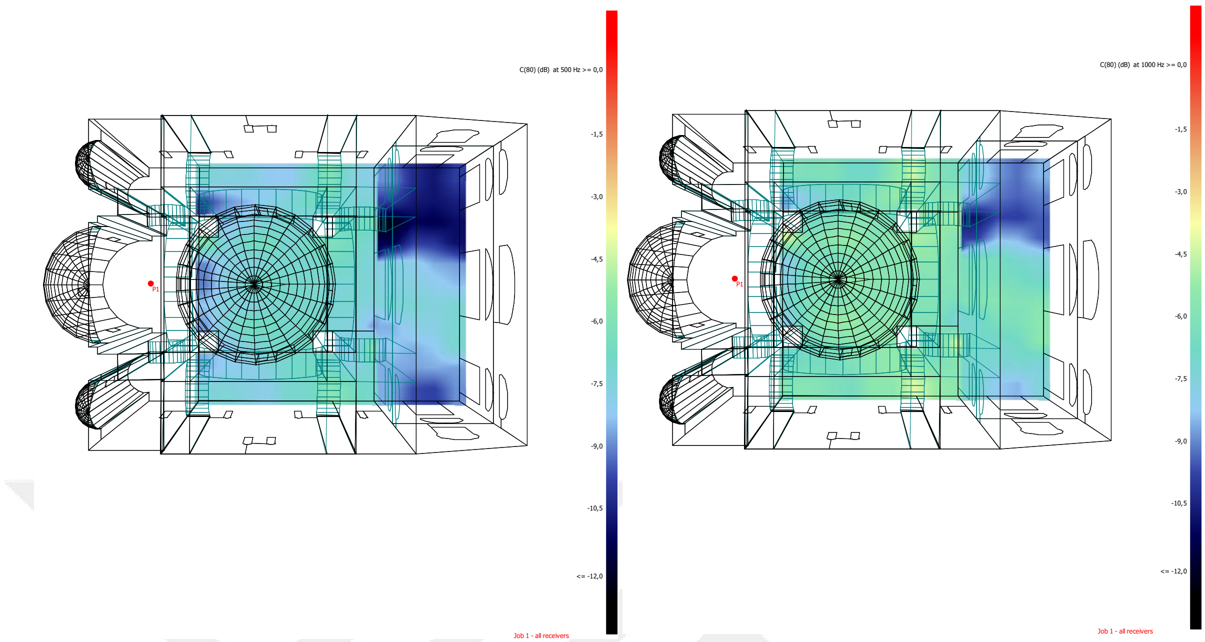


Figure B19. Çanlı Kilise Phase II C80 at (left) 500 Hz, (right) 1 kHz

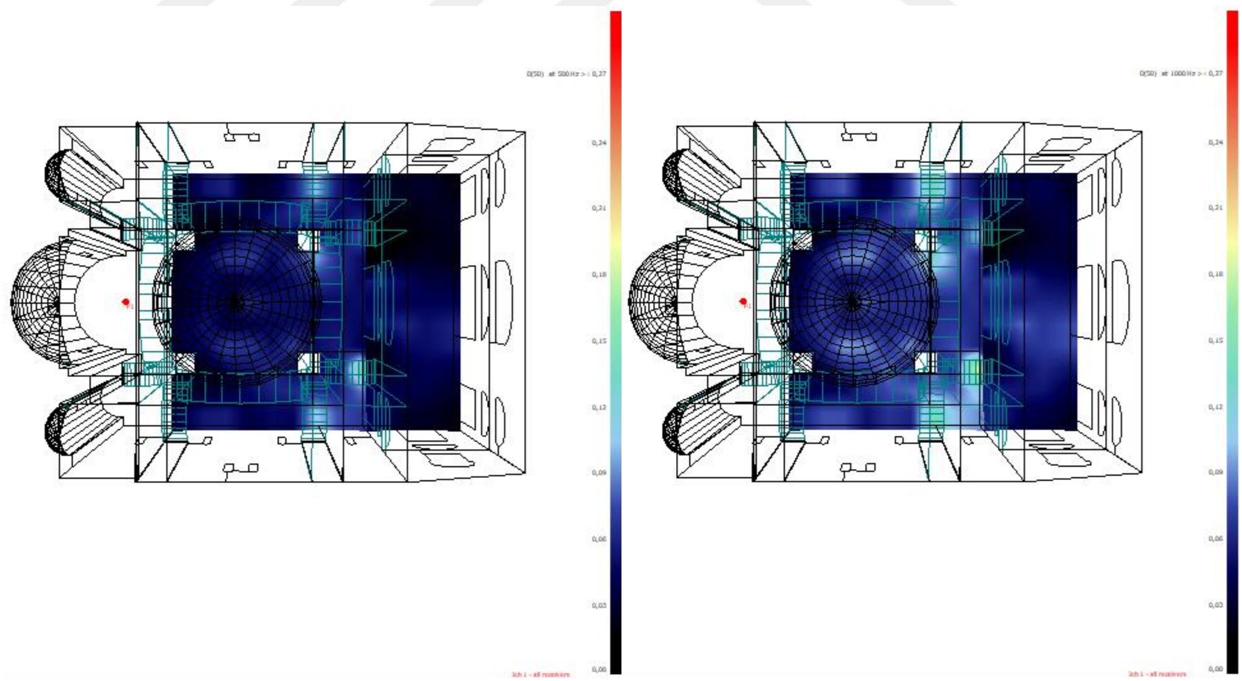


Figure B20. Çanlı Kilise Phase II D50 at (left) 500 Hz, (right) 1 kHz

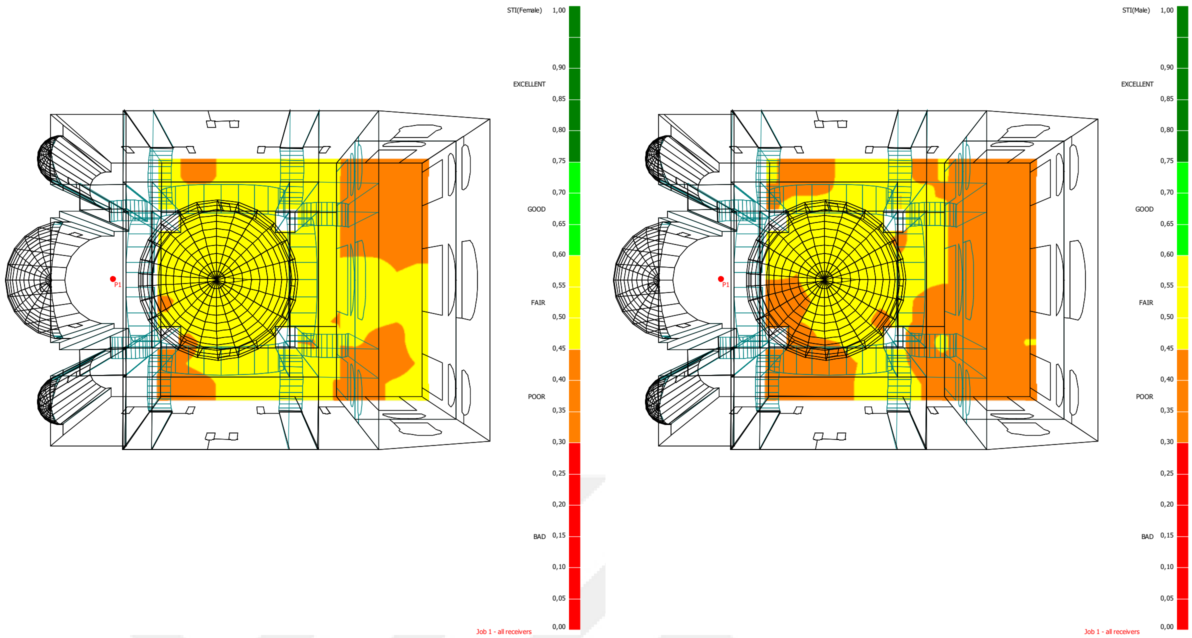


Figure B21. Çanlı Kilise Phase II STI (left) male, (right) female