ANCIENT AND CONTEMPORARY USE OF OPEN-AIR THEATRES: EVOLUTION AND ACOUSTIC EFFECT OF SCENERY DESIGN

Dissertation submitted for the Degree of PhD
School of Architecture

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DECLARATION

I would like to declare that this thesis is the result of my personal work and includes nothing which is the outcome of work done in collaboration, except where otherwise stated and referenced. This research has not been submitted for any other degree, diploma or similar qualification.

JUNE 2007

CONTAINS

PULLOUTS

ABSTRACT

The subject of this research is the acoustic properties of ancient theatres, focusing on their contemporary use and the effect of scenery design. Performance style, material use and influence of architectural characteristics and evolution on acoustics are of interest. Generic scenery designs are investigated and guidelines for architects and scenery designers are provided.

This dissertation is organised in twelve chapters. Chapter 1 is the introduction. The literature review is presented in Part 1. Chapter 2 examines the theory of sound in antiquity and today, currently used acoustic indices and commonly used acoustic software. Chapter 3 describes ancient performance spaces, in terms of layout, and forms of drama. Chapter 4 focuses on: stage building in antiquity, revival of ancient drama and scenery design categorisation.

Part 2, the methodology, contains Chapters 5 and 6. The former examines appropriate parameters for acoustic software use, on-site measurements, absorption coefficient measurements and subjective evaluation. Chapter 6 investigates the phenomena of diffraction in ancient theatres, which can be accurately calculated by applying appropriate scattering coefficients.

Part 3 presents the main analysis in four chapters. Chapter 7 examines theatre evolution in antiquity, revealing that the acoustic environment improved. Chapter 8 compares measurements, simulation and subjective evaluation for Epidaurus, Knossos and Philippi, and presents absorption coefficient measurements for porous stone. Chapters 9 and 10 acoustically investigate Mieza, Philippi and Dion in terms of ancient/present condition and restoration proposals with purposely-built stage enclosures, and effects of generic scenery categories respectively. Chapter 11 offers guidelines for ancient theatre and scenery design use, with applications to contemporary open-air theatres. Finally, Chapter 12 presents this study's conclusions, contribution to knowledge and further work. This study introduced and acoustically examined early theatre forms, emphasised on the acoustic improvements in theatre evolution, and demonstrated the usefulness of stage buildings/enclosures and scenery.

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CHAPTER 1

INTRODUCTION

1.1 PROLOGUE

This PhD study is a combination of several disciplines related to culture and science, particularly related to drama, architecture, archaeology and acoustics. It involves both past and present civilisations and cultures, and is related to a major kind of entertainment, theatre.

Although the etymology of the term theatre (*θέατρον*) is the place where one sees something, it is usually used for the place where drama is performed. In this study, spaces used for drama, as well as for other types of entertainment will be examined. Therefore, the term 'performance space' is sometimes preferred instead of theatre, as will be later seen.

Various meanings of space have been applied to the theatre. Space allows for what is seen and heard during a theatrical performance, providing a visual and acoustic context for relating objects, bodies, characters, and their manifestation in dramatic action. Space is the extension of objects and bodies in the theatre, something like their 'aura' viewed in material and not imaginary terms. Space is an umbrella that covers places, locations, regions, geographical features, and so on, whether present, represented, or referred to during a performance. What is not literally present can 'come to presence' in the space of the theatre, when (for example) a dramatic character powerfully evokes the place from which he or she arrives.

The theatre becomes a *theatric* (or *theatrical) space* when it houses a dramatic performance, that is, when the other spaces come into play. The term refers specifically to the spatial constraints and opportunities offered by the 5th century B.C. theatre. Therefore performance spaces existed long before the introduction of the 5th century B.C. drama. The physical nature of those theatrical givens has spurred significant controversy about the orchestra's shape, the facade of the stage (the *skēnē façade*), the presence and function of an orchestra altar, and the existence of a raised stage.

Previous studies have indicated that there is a category of space within the theatrical space [Rehm, 2002]. This category, the *scenic space*, involves the setting of a tragedy, specified by the stage building facade, by scenic elements (an altar or tomb, painted backdrops, significant props), and by references in the text (of the play).

Although the visual (as physiological and as metaphor) constitutes an important part of dramatic experience, theatrical space encompasses more than what one sees. Sound, no less than sight, requires a source, a space within the body, to produce it with and a spatial medium to spread it. Ancient sources indicated that the voice of the actor proved to be his most suitable tool. Aristotle calls it 'the most imitative [or '*performative*', *mimetikotaton*] of our parts, which provides the basis for the art of acting and epic recitation. The impact of visual, vocal and musical elements of drama depends on the space in which they were performed, even as they transformed that space into fictional worlds of great imaginative scope and compass. A major hypothesis of this study is that the scenery design in antiquity and today affected the acoustic environment of the theatre in antiquity.

This is a PhD study exploring the acoustics of ancient outdoor performance spaces, focusing on their evolution and the effect of the ancient stage building and temporary scenery design on the acoustic environment, the *soundscape* (the word soundscape is used because the spaces concerned are outdoor spaces of sometimes great size), both for their use in antiquity and today. Historical notes, old and recent studies have been examined to identify possible parameters that affect the acoustics. This is a study of interdisciplinary nature, since the subject is related to drama and theory of theatre, to physics and theory of sound, to archaeology and the findings during excavations, to architecture and theatre construction, to simulation and computer aided design, to art and its applications to theatre through scenery design.

1.2 Subject of PhD Research

Ancient historical notes suggest that sound was studied in antiquity with applications to private and public buildings [Guthrie, 1962; Hunt, 1978]. Contemporary acoustic indices can be used for the description of the acoustic environment of an outdoor performance space, while recent studies suggest that reverberation is measurable in open-air theatres [Gade *et al*, 2004; Chourmouziadou and Kang, 2006a]. Drama was born in antiquity and ancient Greek theatres were the foundations for its performance. The development of drama was related with the construction and transformation of ancient performance spaces and theatres [Baldry, 1971]. Climatic conditions and vegetation have affected the acoustics of each space [Goularas, 1995].

Contemporary theatre theorists suggest that the Greek theatre was not an empty space and that Greek performances were created within and in response to a network of pre-existent spatial relationships [Wiles, 1997]. Theatre was part of town planning and organisation [Rolland, 1967]. In this study, based on the author's background in architecture, particular attention is paid to the relationship between drama style and performance and the architectural development of performance spaces. Ancient theatres in Greece underwent a process that defined their architectural components and classified them into the Minoan, the Pre-Aeschylean, the Classic, the Hellenistic and the Roman types [Allen, 1963; Athanasopoulos, 1983; Bell, 1926; Robertson, 1979; Simpson, 1956]. The identifiable characteristics that enabled the typology of every theatre were either the results of new needs that emerged from the evolution of drama, new construction methods in terms of materials and position of the theatre in the city or the country, and individual transformation of theatres.

In particular, the same theatre could have evolved architecturally when the stage building gained a new shape, new components, or changes in heights and relative positions between the actors, the chorus and the audience, as historical notes and archaeological evidence suggest [Pöhlmann, 1995; Scullion, 1994]. This transformation was always a determining factor for the acoustic environment of the theatrical space. A question is the effectiveness of the architectural evolution on the acoustics. Therefore, in this study it would be useful to investigate the acoustic evolution of the ancient theatres during their architectural transformation in antiquity. However, the condition of the theatres today does not allow the researchers to apply the exact coefficients for absorption and diffusion to represent the ancient condition, due to different material finishes. Hence, appropriate material characteristics are examined for the accuracy of the acoustic simulation.

The study of a play is subject to understanding the original conditions of the performance. In the same way, the study of the acoustics of the performance space is subject to understanding the space in relation to the play. The audience's experience during and after a performance is determined by several parameters. Although the plot is an important part of it and the basic component in provoking feelings like excitement, relief, sadness etc, the stimulation of the senses can be particularly related to the 'sound' of the performance, constituted by words, songs and music. Therefore the acoustic environment of each performance space is significant for the play itself and the audience that attends it. The play, the space, the sonic environment and their interconnection are of main interest. Sound source and amplitude, reflection patterns, temperature and relative humidity affect the acoustics, while material characteristics, temporary structures that can function as boundaries, positioning of actors and percentage of occupation are forming the space.

The overall investigation of the acoustics of ancient theatres spans the historical scale from the Minoan Crete to the Roman times. By focusing on the Classic, Hellenistic and Roman types, it is suggested that the development of the stage building was of major importance [Chourmouziadou and Kang, 2007a]. The Hellenistic and Roman types are nevertheless still used for ancient drama performances. It has been indicated that the differences in the acoustic environment of Greek and Roman theatres are particularly based on the overall layout, as well as on the shape and volume of the stage building [Chourmouziadou and Kang, 2002; 2007a].

Moreover, focused on the scenic space, as described earlier, this study systematically examines the effect of scenery design on the acoustic environment of ancient open-air theatres. Previous research on ancient theatres has focused on their original forms in terms of layout, especially for the Hellenistic and the Roman types, including the stage building, as well as contemporary conditions with the destroyed stage buildings [Gade *et al*, 2004; Lisa et al, 2005; Mparkas, 1992; Mparkas, 2006; Rindel *et al*, 2006; Vasilantonopoulos and Mourjopoulos, 2003; 2004; Vasilantonopoulos *et al*, 2004; 2006]. However, the first excavations in the 19th century of representative theatre forms from these periods were the driving force for the revival of ancient Greek drama. Drama festivals were established and have since evolved into social summer events. Temporary scenery is a part of the theatre architecture and has become an ephemeral structure with short but profound presence, adaptable to many open-air theatres, both ancient and contemporary.

The present condition of the ancient theatres, with missing stage buildings, could lead to a decrease of reflections, stressing the importance of the orchestra floor. Therefore, the use of appropriate scenery designs is vital, to compensate for this inefficiency. Based on the architectural characteristics of previously defined forms of past and recent temporary scenery designs, this study identifies four categories, to investigate the effect of scenery design on the soundscape of ancient theatres, further divided into two to four subcategories, considering variables like height, material, density, volume, shape etc.

Regarding the acoustic analysis and methodology used for the examination of open-air theatres, three acoustic software can be used, namely CATT, ODEON and Raynoise The methodology used in this PhD study has been previously tested [Chourmouziadou, 2002], involving software comparison, appropriate model representation, selection of simulation parameters and applications like source directivity and background noise and is also validated through on-site measurements and subjective evaluation [Chourmouziadou and Kang, 2006a; 2006b]. It is noted that although the concept of reverberation is different outdoors than indoors, and that in order for reverberation to exist there must be a diffuse field, decay signals and decay times measured in this and previous studies are presented.

Additionally, the concept of diffraction, which has been mostly identified with noise reduction and the use of noise barriers, has been hardly examined before regarding its application to ancient theatres. It particularly corresponds to (a) diffraction to the shadow zone behind a panel, (b) diffusion/diffraction due to limited surface size, (c) diffraction from a panel edge, and (d) diffusion effects due to the acoustic roughness of panel surface.

Based on the literature review and the methodology of this study, the evolution of ancient performance spaces, with particular attention to the effect of material characteristics, is examined. Original and present conditions of ancient theatres that have not been previously discussed are presented and the application of temporary scenery design is examined in terms of acoustics. The need to investigate the effect of scenery design formed the initiative for the categorisation of generic scenery, as seen above, which is later simulated. The use of the term 'generic' in the architectural and construction literature of recent years seems to take place in different contexts; from theories on technology transfer from manufacturing to construction, to theories on the generic world and the generic city [Sakantamis and Chourmouziadou, 2006]. Although the term carries several connotations and meanings, in this study 'generic' is identified as 'the opposite to identity', according to Koolhaas and Mau [1995], extended to the 'simple, general but recognisable'.

The general aim of the proposed research is to systematically examine the effects of the architectural forms of ancient Greek and Roman theatres and of the application of scenery design on their acoustic environment. In particular the aims are to (a) review theatre evolution from the viewpoint of architectural layout, stage design, materials and usages during the centuries, in relation to acoustics and (b) investigate the scenery's effect on the acoustic environment of the theatre, through generic categorisation, and indicate appropriate forms of scenery design for optimum theatre soundscape, especially regarding Classic and Hellenistic theatres, which are still used. The analysis of the main body of this study is based on the hypothesis that changes in layout and materials during the theatre evolution have improved acoustics and that temporary scenery can significantly alter the acoustics of an open-air theatre, since it is the only changeable component that can transform the acoustics and affect the audience's perception of the performance.

The objectives of this study are to:

- review and relate the different disciplines of this study, in particular drama, archaeology, architecture and acoustics, in order to create the basis of the methodology and the analysis
- discuss the theory of sound, particularly in terms of outdoor propagation, examine the knowledge of acoustics in antiquity and compare it with today's acoustic indices, based on ancient theatres
- conduct a thorough review of theatre forms and details during the evolution process, particularly in the acoustic context. The first theatre forms were typically created in the 6^{th} century B.C. in Greece and developed later in the Hellenistic and Roman periods. However, other forms of performance spaces used for primitive types of drama existed since the 15^{th} century B.C. All these forms will be reviewed
- conduct on-site acoustic measurements considering reverberation in a selection of ancient theatres. Whilst measurements in well-known theatres have been limited, some recently discovered theatres have not been studied yet
- investigate the computer acoustic modelling methodology for ancient theatres, especially appropriate simulation parameters and material properties, by comparing measurement with simulation. Although much work has been carried out in room acoustics, simulation methods for open-air theatres of Greek/Roman type have not been carefully studied, especially in terms of boundary diffusion, absorption and diffraction
- examine the hypothesis that changes in theatre form, construction methods, materials, and space usages during the evolution had improved the acoustic quality
- systematically examine the effects of ancient stages as well as contemporary sceneries created for the revival of ancient drama to the acoustics, using the acoustic simulation techniques, with particular attention to sound source positions, materials and layout. Most theatres in antiquity included a stage building, used by the leading actors, while

the chorus was performing in the orchestra. Stages/sceneries could have determining effects on the acoustics of open-air theatres but this important issue has been largely ignored

- propose examples that would improve the acoustic conditions and provide guidelines for further theatre development. After the revival of ancient Greek drama in the 20^{th} century stage designers have used many shapes, materials, construction methods and visual effects in order to excite and aesthetically please the audience. However, little attention was given to the acoustic effects
- disseminate the research in a way that the research community and the design professions can make best use of. The theatre evolution is relevant to historians, archaeologists and architects; the design guidelines are useful for designers and practitioners in various sectors including architecture and performance; and the methodology for acoustic simulation will be important for researchers and designers.

It is expected that this study will make a significant contribution to knowledge and will benefit designers and practitioners by developing guidance for contemporary design of outdoor performance spaces and for contemporary use of ancient theatres, researchers by identifying appropriate simulation parameters and historians by providing indications of acoustic evolution of theatres in antiquity.

1.3 Organisation of PhD Research

The overall study is divided into twelve chapters. Ten of these compose the three parts of the research study, namely the literature review, the methodology and the analysis. The final chapter, Chapter 12, presents the overall results, the contribution to knowledge and further work.

Chapter 2 explores the theory of sound and the conditions that are particularly important for outdoor sound propagation. The effects of relative humidity, wind and temperature are also discussed. The birth of the knowledge of acoustics in antiquity is presented and the characteristics of the acoustic environment of ancient theatre, in their original and the present condition are referred to and compared. Then, acoustic indices that are used for examining the soundscape of a space are presented. Particular attention has been paid to previous research of ancient theatres, in terms of commonly used acoustic indices that are appropriate for open-air performance spaces. Also, it introduces the prerequisites for subjective evaluation of performance spaces according to Beranek, and especially the terms that are used for this purpose. Finally, it presents and compares common acoustic software that can be used for simulating open air theatres, namely CATT, ODEON and Raynoise. The comparison is based on simple theatre forms and resulting acoustic indices. Consequently, the software employed in the overall research will be selected and discussed.

Chapter 3 presents the literature review on drama and ancient performance spaces. The first part is a description of the Minoan period, its architecture and the characteristics of the performance spaces, called 'Minoan type' in this study. Town planning in the Classic period in Greece is then briefly discussed and the first forms of theatre are analysed. Theatre development is also shown during the Classic and Hellenistic times and conservatories, or *odeia*, as they are called in Greek, are also presented shortly. Greco-Roman and Roman theatres are introduced. To relate theatre architecture and development with drama itself, a presentation of the types of Greek Drama is carried out, in relation to the festivals and the audience's experience. Costumes and masks are also described. Finally, the types of drama and theatre architecture after the Roman period and until the 19^{th} century are depicted.

Chapter 4 involves an introduction to the stage building and scenery, their basic characteristics and the relation to the acoustics of ancient theatres. It discusses the creation of the stage building in antiquity, its original form and its development. Properties, like mobile objects are also discussed, especially regarding the overall performance perception and the different positions of the actors during the performance. An investigation of the forms of past and contemporary scenery designs is then presented, both from the aesthetic viewpoint but also in terms of identifying parameters and variables that formulate generic scenery designs, with different attributes to the acoustics. The categories are composed by sceneries that are: (1) visually creating a background wall, (2) represented by one large size object, (3) composed by many small objects and (4) concentrated on the orchestra's floor.

Chapter 5 initially presents the methodology of the acoustic simulation, based on previous analysis in Chapter 2. The optimum representation of the model is also described. Based on the pilot study, appropriate simulation parameters are suggested, including number of rays, reflection order, echogram and histogram options and time window. The way the software handles diffusion is described and repeated calculations show possible variations in results. Background noise and source directivity are examined and the effects of an area source representing the chorus, a vital part of the performance of ancient drama, are briefly shown. Also, simplified representation of the theatre model is discussed to maintain the accuracy of the soundscape. Additionally, in order to secure the accuracy of the simulation results, especially regarding reverberation, the research methods regarding on-site measurements, subjective evaluation and absorption coefficient measurements are described.

Chapter 6 initially refers to previous studies of diffraction in both theory and experiment, followed by the phenomenon of edge diffraction and its treatments. Computer simulation methods that consider diffraction are briefly discussed. Because the scattering effect of diffraction has not generally been considered, two methods are tested and evaluated. Method 1 applies an increased diffusion coefficient to the audience area of the ancient theatre. Method 2 uses formulas previously developed for specific receiver positions and reflection paths but modifies them to consider the layout and sound distribution of ancient theatres. The effect of edge diffraction is also examined by comparing different reflection patterns. In the mean time, diffusion due to surface roughness has been taken into account. The calculations are compared with measurements in the theatre of Epidaurus and some surface diffusion values are suggested. Moreover, a scattering method based on Lambert distribution law is discussed, regarding edge diffraction. Finally the conclusions about simulation methodology regarding the effect of diffraction are presented. In this chapter the term diffusion is related to the spreading of incident specular energy into non-specular directions.

Chapter 7 briefly reviews the theatre evolution in antiquity, as indicated in previous chapters. It then presents the methodology and the results of a series of acoustic simulations in six typical theatre forms, using a beam-tracing program, including some early forms for which no previous acoustic analysis has been made. It then presents the more focused analysis on the development of the Classic theatre type and the genesis of the Hellenistic, since these types are used today and will be of major concern in later chapters. Particular attention is paid to the comparison between Greek and Roman theatre types, with representative examples the theatres of Epidaurus and Aspendus respectively. The second part of this chapter is similar, although organised from the viewpoint of material characteristics. It divides the theatres into categories, according to the material they were built with. Consequently, stone, wood, earth as well as audience absorption have been examined in each subsection, by applying several values found in the literature, including maximum and minimum. The overall results are then presented in the form of two tables, for the unoccupied and the occupied conditions respectively. Particular attention is paid to the diffusion from the audience. Finally, a discussion on the nature of performance spaces that involves the cooperation of many disciplines and their interconnection with acoustics is presented.

The structure of Chapter 8 is mainly focused on the theatre of Epidaurus, especially from the viewpoint of research methods presented in Chapter 5, namely, absorption coefficient testing, on-site measurements and subjective evaluation and the interrelationship between these and acoustic simulation. It first describes the theatre of Epidaurus. Then, it presents the absorption coefficient testing and the final absorption coefficients of porous stone from 125 to 4kHz. Measurements that have been carried out in the ancient theatre of Epidaurus are compared with simulation results, while supported by the results of a purposely designed subjective evaluation test. Moreover, the theatre of Philippi and the performance space of Knossos are presented in terms of reverberation time measurements.

In Chapter 9 the case studies are presented as follows: First, regarding the theatre of Mieza, a brief review of the historic information about the theatre is presented, as recorded by the archaeologists and architects that carried out the excavations. It then illustrates the new proposals of restoration of the theatre. Moreover, the results from a series of acoustic simulations are discussed, with particular attention to the initial form of the theatre, its present condition and the restoration proposed. Then, several types of sceneries are applied to the theatre's layout, in order to investigate the appropriate acoustic environment for performances of ancient drama. Purposely designed scenery in the form of an enclosure has also been created especially for the theatre of Mieza. For the theatre of Philippi, which is the second case study, the section initiates with a description of the historical information and the process of evolution/development it underwent. Then, the acoustic simulation of the theatre in antiquity and in the present condition is carried out, as well as the application of carefully designed stage enclosure that reinforces initial reflections. The simulation for the contemporary condition is carried out both for an actor performing on the orchestra and traffic noise. The third case study concerns the theatre of Dion. First the information provided by the archaeologists/excavators is presented. Acoustic simulation is carried out both for the ancient and the present condition of the theatre. Purposely-built scenery design is also simulated. According to suggestions provided by the simulation of the theatre of Mieza, complex scenery is created and improved gradually, to improve reflection patterns and acoustic indices.

Chapter 10 is the main analysis of the influence of generic scenery design on theatre acoustics. The same theatres as in the previous chapter have been used, namely Mieza, Philippi and Dion. Initially the characteristics of the theatres that have been decided on for this part of the study are presented. The second part of the chapter is the categorization of the sceneries, followed by a brief discussion of the simulation procedure and methods used. The simulation results of each category are then presented, to identify the preferred layouts for each theatre. Additionally, ways of simplifying the representation of complicated sceneries, maintaining the acoustic characteristics of each performance are displayed, according to the methodology in Chapters 5 and 6. Moreover, because the actors rarely stay at the same position during the play, although in ancient drama most of the positions were predefined, simulations for several positions of the actors are compared. Furthermore, the acoustic effects of the combination of 2 or 3 categories are briefly discussed.

Chapter 11 indicates the relationship between architecture and acoustics in ancient theatres, and the effectiveness of scenery design in the acoustic environment of ancient theatres. Additionally, it provides guidelines for appropriately designed scenery to compensate for acoustic deficiencies of ancient theatres in the form of tables, easily read by the non-experts. Then, contemporary theatre structures are examined, with similar applications of scenery and reflector design in a variety of forms.

Finally, Chapter 12 presents the overall findings of the PhD research and analysis, its contribution to knowledge and proposals for further work.

PART 1

LITERATURE REVIEW

CHAPTER 2

REVIEW ON SOUND AND ACOUSTICS IN ANTIQUITY AND TODAY

"When there is no long race for...voice to run from start to finish, each of the words...must necessarily be plainly heard...but if the intervening space is longer that it should be, the words...must be confused...perceived yet not distinguishable in meaning,...so confused must be the voice when it arrives, so hampered...One voice...disperses suddenly into many voices...some scattered abroad without effect into the air: some dashed upon solid places and then thrown back,...deluding with the image of a word...In solitary places the very rocks give back the words...so does hill to hill buffet the words and repeat the reverberation...no one can see beyond a wall although he can hear voices through it. And yet even the voice itself in passing the wall of a house is blunted and confused when it penetrates the ear, and we seem to hear sounds rather than words".

[Hunt, 1978[1]]

[1] Translated from Lucretius, 1st century B.C.

2.1 INTRODUCTION

The objectives of this chapter are to discuss the theory of sound, particularly in terms of outdoor propagation and, relatively to ancient theatres, to examine the knowledge of acoustics in antiquity and compare it with today's acoustic indices. Also, in order to creatively use the contemporary condition of the theatre and the effect of scenery design in later chapters, an investigation of the influence of room acoustics knowledge, of temperature and of wind to the design of performance spaces is presented, with a review of the subjective evaluation developed by Beranek. For the acoustic simulation of this study, commonly used software are investigated and compared and Raynoise, selected for the simulation of ancient theatres, is described.

This chapter initially explores the theory of sound and examines conditions that are particularly important for outdoor sound propagation. Then, acoustic indices that are used for examining the soundscape of a space are presented. The knowledge of acoustics in antiquity is also presented. Although there have been some references on this subject, systematic research has been limited [Chourmouziadou, 2002]. Moreover, the characteristics of the acoustic environment of ancient theatre, especially in terms of acoustic indices, reverberation and background noise, in their original and the present condition are referred to and compared, with particular attention to previous research. Furthermore, this chapter introduces the prerequisites for subjective evaluation of performance spaces according to Beranek, and especially the terms that are used for this purpose. Finally, a presentation and comparison between common acoustic software that can be used for simulating open-air theatres, namely CATT, ODEON and Raynoise, is carried out, based on simple theatre forms and resulting acoustic indices. Consequently, the software employed in the overall research is selected and described.

2.2 BASIC ACOUSTIC INDICES

This section discusses the theory of sound and the acoustic attributes of performance spaces. Direct, early and reverberant sound are described and basic terms, including sound pressure level, reverberation time, definition, clarity, and strength are presented. There has been extensive research and presentation of sound propagation, reflection, diffusion, diffraction and transmission, as well as basic acoustic indices [Beranek, 1996; Egan, 1988; Knudsen, 1950; Kuttruff, 1973], thus this chapter will only briefly present the formulas and their interpretation.

2.2.1 BASIC SOUND MEASURES

The sound that is transmitted from a source is radiated in all directions and travels through the air at a speed of about 344m/s. A receiver that seats close to the source in an outdoor space or in a highly absorbent room can hear the tone as the source produces it. The sound that has reached the receiver is the direct sound. However in a room, sound is reflected many times, from different surfaces of the space. The early sound is defined as the direct sound and the reflections that take place within 80ms after the arrival of the direct sound. The reverberant sound is created by many reflections that occur subsequently [Beranek, 1996].

The frequency range in which human's hearing is most sensitive is from 1 to 3kHz. The subjective sensation of loudness corresponds to a logarithmic intensity scale rather than to a linear scale [Kuttruff, 1973]. The sound power level is given by the following equation [Egan, 1988]:

$$L_W = 10\log\frac{W}{W_O} \tag{2.1}$$

where L_W is the sound power level (dB), W is the sound power (W) and W_O is the reference sound power (10^{-12} W). The sound intensity level is given by [Egan, 1988]:

$$L_I = 10\log\frac{I}{I_o} \tag{2.2}$$

where L_I is the sound intensity level (dB), I is the sound intensity (W/m^2) and I_o is the reference sound intensity (10^{-12} W/m^2). The sound pressure level at a specific point is given by [Egan, 1988]:

$$L_p = 20\log\frac{p}{p_o} \tag{2.3}$$

where L_p[2] is the sound pressure level (dB), p is the sound pressure (N/m^2) and p_o is the reference sound pressure (2^{-5} N/m^2).

2.2.2 Basic Room Acoustic Indices

Each time sound is reflected from a surface, it is weakened in strength by the absorption of the surface, thus the sound is said to decay. The reverberation time is defined as the time it takes for the sound level to decay by 60dB after a sound source has been switched off. Rooms with small amounts of absorbing materials will have longer reverberation times than rooms with more absorbers. For normal rooms, with reasonable amounts of absorbers, the reverberation time is given by [Knudsen, 1950]:

[2] In the simulation the abbreviation for the sound pressure level is SPL.

$$RT = 0.16\frac{V}{A} \tag{2.4}$$

where *RT* is the reverberation time (s), *V* is the room volume (m^2), *A* is the absorption of the room, give by $A = S_1a_1 + S_2a_2 + S_3a_3 + ...S_va_v$ and 0.16 is an empirical constant determined by Wallace C. Sabine and published in 1898.

RT is usually determined separately at a number of frequencies. The frequencies used for the simulation are usually from 125 Hz to 4kHz in octave or third octave. Although reverberation time is defined as the time it takes for the sound to decay by 60dB, this is sometimes impossible to measure. Instead of measuring the complete decay, a 10, 20, 30dB decay is measured and from these values the reverberation can be derived.

The first 10dB of the sound decay after a source is cut off is called the early decay time (EDT), which is a very important measure for the acoustic quality of a space. RT20 is the reverberation time of the room evaluated over a 20dB decay range (from -5 to -25dB), while RT30 is based on a 30dB decay range (from -5 to -35dB). This study uses RT30, both for the simulation and the analysis of measurement results, unless stated otherwise.

The parameter of definition (D50) is the ratio of the energy of the early sound to the reverberant sound. It is expressed in percentage and defined as [Thiele, 1953]:

$$D50 = \frac{\int_0^{0.050s} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \tag{2.5}$$

where, *t* is the time (s). Additionally, Clarity (C50) is the ratio of the energy of the early sound to the late arriving sound. It is defined as [Reichardt, 1975]:

$$C50 = 10\log\left(\frac{D50}{1-D50}\right) \tag{2.6}$$

where C50 is clarity (dB) and D50 is definition (%). It is also common practice to calculate this parameter using 80ms, which is called C80. In this study C80 is used, except where indicated.

The central decay time (TCG or T_s) is another criterion, based on the ratio between early and late arriving energy, using a 'smooth' function [LMS Numerical Technologies, 2001]. It is the first moment of the area under the decay curve, defined as [Kürer, 1969]:

$$TCG = \frac{\int_0^{\infty} tp^2(t)dt}{\int_0^{\infty} p^2(t)dt} \tag{2.7}$$

and measured in ms. Strength (G) is the sound pressure level relative the free field sound pressure at a distance of 10m from the source [Vasilantonopoulos and Mourjopoulos, 2003], defined as [Paini *et al*, 2006]:

$$G = 10\log\left\{\frac{\int_0^{\infty}[E(t)]^2}{\int_0^{\infty}[E_A(t)]^2}\right\} \tag{2.8}$$

where E_A is the impulse response measured with the same sound source in an anechoic room at 10m. Moreover, Lateral Energy Fraction (LEF) is given by:

$$LEF = 100\frac{\int_{5ms}^{80ms} h^2(t)\left|\cos\psi\right|dt}{\int_{5ms}^{80ms} h^2(t)dt} \tag{2.9}$$

where ψ (°) is the reflection angle related to the ear to ear axis of the listener looking towards the main source as defined by the head direction [ISO 3382, 1997].

The simulation also presents values of speech transmission index (STI) and echo criterion (EC). The STI is an objective criterion used to characterise speech intelligibility. The loss of intelligibility of a speech signal is mainly related to reverberation, interference and background noise. Speech is an auditive flux of which the spectrum varies continuously in time. The individual sinusoidal components of the envelope of the speech signal have to be preserved as clearly as possible. The Modulation Transfer Function (MTF) is a response curve, expressing the attenuation of this envelope by the room (or environment in general). The reverberant transmission from the source and from other coherent sources (such as linked loudspeakers) and the degradation due to background noise are taken into account [LMS Numerical Technologies, 2001]. It is noted that although a single representative value is commonly used to evaluate the STI of a theatre, in this study values for different frequencies are presented, to identify the effects of absorption and/or background noise.

Finally, according to Dietsch and Kraak [1986], the EC is based on the ratio [LMS Numerical Technologies, 2001]:

$$t_s(\tau) = \frac{\int_0^{\tau} t p^n(t) dt}{\int_0^{\tau} p^n(t) dt} \quad (2.10)$$

measured in ms. The quantity used for rating the strength of an echo is based upon the running difference quotient of $t_s(\tau)$ [Dietsch and Kraak, 1986]:

$$EC = \max \frac{\Delta t_s}{\Delta \tau} \quad (2.11)$$

A critical value EC_{crit} must not be exceeded, to ensure that no more than 10% or 50% of the listeners will hear an echo, namely EC_{crit10} *and* EC_{crit50} [Dietsch and Kraak, 1986]. Suitable values for the exponent *n*, $\Delta\tau$, and EC_{crit} depend on the application, speech or music, at 2/3 and 1, 9 and 14, 1 and 1.8 respectively.

2.3 ACOUSTICS IN ANTIQUITY

The relationship between the science of sound and other sciences, including physics and mathematics, has played a prominent role in determining the scope of the subject matter of acoustics, and substantial changes in both have accompanied the gains achieved during two millennia of progress towards understanding the physical nature of sound. The interdependence of acoustics and the former sciences has had as much long-range significance as the growth in technical understanding itself. In ancient and medieval times, sound could be studied in splendid musical isolation, setting the subject apart from the rest of physical science, thus, restricting its study [Hunt, 1978].

2.3.1 DEVELOPMENT OF THE SCIENCE OF SOUND AND THE STRUCTURE OF THE THEORY OF MUSIC BEFORE THE 1ST CENTURY A.D.

The science of sound had its origin in the study of music and vibrating strings by Pythagoras (ca. 570-497 B.C.) during the 6th century B.C. [Chadwick, 1981]. Thales of Miletus (ca.640-546 B.C.) and Pythagoras introduced and established mathematics in the culture of ancient Greece [Merlan, 1968]. The contribution of the Pythagorean School to the science of sound was primarily concerned with the science of musical intervals [Burkert, 1972]. Pythagoras identified the musical consonances (octave, fifth and fourth) with the ratios of simple whole numbers, which was an advance in the theory of music [Guthrie, 1972[3]], initially using the auditory judgment, but later interpreted all phenomena as manifestations of mathematics [O'Meara,

[3] pp. 38

1989[4]. Pythagoras' major contribution to the acoustic theory was to establish the inverse proportionality between pitch and the length of the vibrating string [Chadwick, 1981[5]; Burkert, 1972[6]].

Later, one of Aristotle's pupils, Aristoxenus (ca. 320 B.C.) suggested that both auditory judgement and numerical ratios should be considered in musical theory. During the 1st century A.D. an astronomer, Ptolemy of Alexandria, united auditory sensation and numerical relations for the interest of musical scales [Chadwick, 1992]. This subject was investigated two millennia later by Bartholomeo Ramos de Pareia (ca.1440-1521), a Spanish musician who dealt with the problems of modality and musical scale, and by Zarlino who completed Bartholomeo's analysis and was assigned with the credit [Hunt, 1978].

In the 4th century B.C. Archytas (428-347 B.C.) described mathematics as composed of the 'related studies', astronomy (magnitudes in motion), geometry (magnitudes in rest), arithmetic (numbers absolute) and music (numbers applied), which eventually came to be designated as the classic *quadrivium* [Hunt, 1978]. He suggested that sound is produced when two objects strike against each other [Guthrie, 1962[7]], but also supported that high-pitched sounds reach the receiver quicker than low-pitched sounds, perplexing the effects of sound propagation and frequency. According to Burkert [1972] *"a less developed theory is found in Plato and Aristotle... speed of propagation is confused with frequency, so that higher tones are said to come to the hearer sooner than lower ones"*. Plato has correlated fast movement with high tone and slow movement with low tone, although in an attempt to explain concords, he suggested that slow tones finally catches up (*καταλαμβάνει*) with the fast. Hunt [1978] has indicated that Theophrastus of Eresus (372-288 B.C.), drawn by observation and logic, supported that since there are concords, the high and low tones must have the same speed.

Ancient mathematicians dealt with the musical scale. In addition to the mathematicians and generally the scientists of the antiquity, some philosophers had dealt with sound and hearing. Socrates' (469-399 B.C.) pupils and their followers founded four different schools, each responding to and developing different facets of his teaching. The best known of these schools was the *Academia* (*Ακαδημία*), founded by Plato (429-347 B.C.), whose philosophy merged both Pythagorean and Socratic principles. On hearing Plato suggested that the blow passes through the ears, transmitted by means of the air, the brains and the blood to the soul [Jowett, 1892[8]]. Chadwick [1992] indicates that Aristotle also supported this. It was believed that hearing is the vibration of this blow, which begins in the head and ends in the region of the liver [Guthrie, 1962[9]]. It was also believed that sense perception varies with the size, therefore large animals

[4] pp. 16
[5] pp. 79
[6] pp. 371
[7] pp. 371
[8] pp. 67B, based on the Greek and Latin edition printed by Henri Estienne (Stephanus) at Geneva in 1578
[9] pp. 227

hear loud and distance sounds, while small animals hear sounds that are minute and close [Stratton, 1917[10]]. It is therefore clear that in spite of an impressive growth of empirical knowledge of the skeleton and the circulatory systems of the body, the hearing mechanism was not clear for the ancients.

Aristotle, the philosophic heir of Plato, was concerned with the whole range of natural philosophy with the use of mathematics as a tool for examining nature. The optical principle of equal angles of incidence and reflection was probably pre-Aristotelian, but Plato first considered it a law that apart from light operates for sound too [Hunt, 1978]. He also compared the speed of sound created by a thunder as to that of lighting, but he wrestled with the question of how light could exist, invisible in space, during a finite time-interval between its emission and its perception. Regarding this subject Pliny the Elder (23-79 A.D.) indicated that light travels faster than sound [Hunt, 1978].

The analogy between the expanding pattern of ripples on a pool of water and the propagation of sound waves also received much attention in ancient times and is attributed to the Stoic philosopher Chrysippus (ca.280-207 B.C.). Marcus Vitruvius Pollio (ca. 80 B.C.-25 B.C.), the Roman architect known as Vitruvius, suggested that although the circles in water are propagated horizontally, the voice is propagated in infinite number of circular zones, both horizontally and vertically. Boethius collected and summarised many of these concepts and ideas [Chadwick, 1981], defining sound as a blow upon air, which persists until it is heard. His greatest remark was that sound is less clear to someone who stands away from the source [Hunt, 1978].

2.3.2 Architectural and Applied Acoustics

Although there is little evidence of the awareness of 'architectural acoustics' in antiquity, some observations can be interpreted in the light of contemporary acoustics.

The *Problemata*, a natural science catechism possibly written by Aristotle [Hunt, 1978], consists of some references on the acoustic effects of surface absorption. The author referred to the decrease of the chorus' voices in an ancient theatre when the *orchestra*, the main performance area, was spread with straw, but his explanation to this problem was limited to surface smoothness and there was no evidence on the significance of material absorption. He also referred to the reflection (the term used was 'refraction'), provided by the plaster on the walls [Hunt, 1978]. The most important point in Problemata was the observational basis of the logarithmic nature of sensory response: *"Why is it that when one person makes a sound and a number of persons make the same sound simultaneously, the sound produced is not equal nor does it reach correspondingly farther?"* It is obvious that although these questions showed their

[10] Theophrastus, *On the senses*

worries about acoustics, their explanations were rather restricted due to the acoustic judgement of the period.

Despite that, the observational accuracy of Lucretius is revealed in his concept of reverberation and of sound transmission. The first practical application of acoustics in ancient times was the military exploitation of acoustic location techniques at the end of the 6th century B.C., especially for finding the tunnels the Persians dug in order to enter the Libyan town of Barce by the use of a bronze shield [Herodotus, 1953[11]]. A similar method was described by Vitruvius' [1st century B.C.], whose most significant contribution was to architectural acoustics. With *The ten books of architecture* he provided a foundation for the theory and practice of Renaissance architecture, analysing theatre design, its site, structure and acoustics. He also provided an explanation about the harmonics, with reference to Aristoxenus' notes, and of the function of sounding vessels in a theatre, as will be described in Chapter 3. Characteristics of Greek and Roman theatres were also discussed. The following passage comes from the 8th chapter entitled: 'Acoustics of the site of a theatre' [Vitruvius, 1st century B.C.].

"1. All this having been settled with the greatest pains and skill, we must see to it, with still greater care, that a site has been selected where the voice has a gentle fall, and is not driven back with a recoil so as to convey an indistinct meaning to the ear. There are some places, which from their very nature interfere with the course of the voice, as for instance the dissonant, which are termed in Greek κατηχούντες; the circumsonant, which are named περιηχούντες; again the resonant, which are termed αντηχούντες; and the consonant, which they call συνηχούντες. The dissonant are those places in which the first sound uttered that is carried up high, strikes against solid bodies above, and, being driven back, checks as it sinks to the bottom the rise of the succeeding sound.

2. The circumsonant are those in which the voice spreads all round, and then is forced into the middle, where it dissolves, the case-endings are not heard, and it dies away there is sounds of indistinct meaning. The resonant are those in which it comes into contact with some solid substance and recoils, thus producing an echo, and making the termination of cases sound double. The consonant are those in which it is supported from below, increases as it goes up, and reaches the ears in words, which are distinct and clear in tone. Hence, if there has been careful attention in the selection of the site, the effect of the voice will, through this precaution, be perfectly suited to the purposes of a theatre".

Hunt [1978] suggested that Vitruvius' reference regarding the interference between the direct and the first reflected sound does not indicate the modern concept of wave interference. At the same time, the voice, which dissolves and dies away with 'indistinct meaning', is not an accurate description of reverberant sound decay. George [1997], on the other hand, has attempted to relate Vitruvius' attributes to modern acoustics using Beranek's [1962] terms of

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11 pp. 1-9

'liveness', 'echo', 'warmth', and 'intimacy', which are analysed in Section 2.5. Nevertheless, Vitruvius identified those difficulties that are to be avoided nowadays in the acoustic design, having little attributes from the state of science.

2.3.3 THEORY OF SOUND FROM THE 1ST TO THE 19TH CENTURY

This section deals with acoustics after the flourish of the Greek and Roman civilisations. The Greek scientific tradition was translated into Arabic during the 8th and the 9th centuries A.D. and then retranslated into Latin during the 12th and 13th centuries. The dissemination of the Greek scientific ideas throughout Islam was never uniform or complete and a substantial number of Muslim scientists had made independent discoveries, comparable to those made by Greeks. It needs to be mentioned the physics of sound production did not advance significantly beyond the stage achieved by the Greeks until very near the end of the medieval period. The Greeks had already accomplished a perceptive of the physical nature of sound that represented as much sophistication as could be sustained without explicit formulation of the laws of the dynamics and of the physical nature of sound [Hunt, 1978].

The Arabian musical tradition was carried on during the first half of the 9th century A.D. by Al-Kindī [Lindberg, 1976], one of the greatest philosophers of medieval times, and Al-Fārābī [Al-Fārābī, 1981], a Muslim philosopher and musician. On the other hand, the first scientific revival in the West appeared during the 11th century. During the 13th century many scientists helped to the evolution of natural science in the west and, although none could advance the frontiers of the science of sound, they affected the central core of science from which acoustics would ultimately draw. As a consequence, the received state of acoustic knowledge in Western Europe advanced very little beyond Aristotle [Hunt, 1978]. Little coherence can be found in the work of the following centuries. However, after the middle of the 19th century British and German scientists took the lead and three valuable books appeared: *On sensations of tone*, by Hermann von Helmholtz, in 1862; *On sound*, by John Tyndall in 1867; and *The theory of sound*, by John William Strutt in 1877 [Beyer, 1999].

There was little progress in understanding architectural acoustics in the first half of the 19th century. Reverberation was identified in 1853 by Upham, who published two papers that summed up the state of knowledge in the field [Beyer, 1999]. Although many problems at that time began to be illustrated, there was little progress in the field of acoustics in that century, at least until the birth of Wallace Clement Sabine in 1868.

2.4 ACOUSTIC CONDITIONS IN OPEN-AIR THEATRES

In a semi-free field, where there are no reflective boundaries except for the ground, the sound from a source is louder when the receiver is closer to the source. The formula that describes this is [Egan, 1988]:

$$I = \frac{W}{4\pi d^2} \tag{2.12}$$

where d is the distance from the sound source (m). This can also be described by [Egan, 1988]:

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2 \tag{2.13}$$

Clearly the listening conditions are not ideal in a semi-free field due to the large difference between different source-receiver distances. However, this can be improved by using an enclosure. In this way the boundaries around the source can reflect the sound to the receivers and increase the evenness of the sound field. Moreover, the receiver would be protected from possible background noises from outside. The enclosure can also help performers hear themselves, since sound can be reflected to their ears.

The audience's presence also influences the distribution of sound since people absorb sound. The conditions become poorer when the audience is seated on a horizontal plane and the sound source is at the same height, because the absorption is more effective when the sound incidence angle is parallel to the seating plane. Steeply raked seating increases the angle of incidence [Tsinikas, 1990], and prevents noises from *"sources at the back of outdoor performance spaces"* [Beranek, 1962]. The ancients must have considered this because they built the outdoor performance spaces (theatres and stadiums) with the seats sloping upwards or raked.

2.4.1 ACOUSTIC CHARACTERISTICS IN ANCIENT THEATRES

In ancient theatres, acoustics cannot be determined solely on the grounds of a semi-free field. In the latter, direct sound is of importance, whereas in ancient theatres, as mentioned before and will be further calculated in Chapter 7, the acoustic conditions seem comparatively improved, due to the hard reflective surfaces. The surfaces of the audience area, usually built from local stone, provide high amplitude reflections, enhancing the early sound. Usually sound is diffused from the destroyed edges of the seats, resulting in a relatively even field. Under the occupied condition, sound is diffused from the audience's heads.

As will be discussed later, reverberation outdoors is perceived in a different manner than indoors, mainly because the sound distribution patterns are different when the ceiling is replaced by air, due to air absorption; hence some reflections are lost. Section 2.2.2 defined the basic acoustic indices used for the evaluation of a room. In outdoor theatres, and other kinds of spaces, like squares, commonly used formulas are not considered as appropriate as for indoors. RT is very useful in ancient theatres although there is no evenly diffusive field. Recent studies have examined whether reverberation and other parameters are sufficient to test the acoustic quality of open performance spaces [Paini *et al*, 2006]. In this study it is indicated that recent research in ancient theatre reveals rather long RT values [Gade *et al*, 2004; Gade *et al*, 2005, Chourmouziadou and Kang, 2006a and b], which can still be used for comparative studies between different spaces. Although optimum values for RT have been studied for many types of space or usage, it appears that for outdoor performance spaces, the specifications on the optimum values have been rather limited. In this study RT30 and EDT are used in general as a tool for comparison, although the subjective feeling of reverberation could be different in indoor and outdoor spaces and in particular for cases when their presence has been proved through on-site measurements.

Moreover, the background noise observed in ancient theatres today is significantly higher than in antiquity. In antiquity there was limited noise from external sources. Birds and animals were the most common, as well as the crowd that watched the performance. Today ancient theatres are most of the times situated in Greek cities or nearby busy roads [Chourmouziadou and Kang, 2005]. Also, air traffic is disturbing. Hence, the ancient performance conditions were significantly better than today's.

The layout of ancient theatre varies according to the type, as will be further discussed in Chapter 3. When compared to more recent examples of enclosed spaces, like the shoebox shape, the ancient theatres succeeded in bringing a vast crowd as close to the performers as possible [Pöhlmann, 1995]. Their layouts allowed for different acoustic conditions, with focus areas for example for concave shapes and multiple reflections between parallel sides for the rectangular, determining the sonic environment [Chourmouziadou and Kang, 2002]. Also, their construction with the use of hard materials seems to be useful for the acoustics, even in the occupied conditions, since they reflect sound.

Compared to the condition in antiquity, theatres with missing stage buildings lack one major component of the whole structure. Temporary sceneries replace the stage building for the sake of the performances, although there is limited research about their effect on acoustics [Chourmouziadou and Kang, 2006a]. Moreover, restrictions applied by the Boards of Antiquities in Greece do not give the opportunity for the missing parts of the theatre to be restored, at least in such a large scale, unless all the materials have been found [Karadedos, 1994], with the exception of organised restoration projects, like in the palace of Knossos [Bell, 1926].

Nevertheless, restoration projects in general take time to be completed, while other excavation projects are carried out in the theatre.

The hard reflective surfaces usually characterise outdoor performances spaces, as mentioned earlier. The basic difference between them and enclosed auditoriums is that the latter have padded seating absorbing chairs to balance the difference between the occupied and unoccupied condition [Beranek and Hidaka, 1998]. In outdoor performance spaces the percentage of absorbing and diffusive surfaces depends on the occupancy and people's clothing [Chourmouziadou and Kang, 2007a], since the audience is very densely seated. Also, enclosed spaces have surfaces treated to control early and late reflections for accepted values of reverberation, clarity, lateral fraction and to avoid echoes and flutter echoes.

In terms of acoustical parameters, the linear decay of enclosed spaces is opposed to the initial time delay gap (ITDG), with identifiable flutter echoes of the outdoors [Paini *et al*, 2006]. Also, for outdoor spaces, due to the number of first and second order reflections that are lost in the sky, the amount of energy is rather reduced. Reverberation can be as high as indoors, although with characteristic late reflections and background noise from traffic noise, people and city noise.

Paini *et al* [2006] have examined the above factors and presented the insufficiency of RT, C80 and STI as indices that describe an outdoor space, mainly due to the problems of unidentifiable ITDG, echoes and high values of echoes and background noise respectively. Auralization, TCG and G can be used to describe the acoustics of an outdoor space, as well as LEF, C80, D50 and SPL [Chourmouziadou and Kang, 2002; Vasilantonopoulos and Mourjopoulos, 2003], Especially G, defined in Section 2.2.2, can be used for open spaces to know the level and the distribution of sound energy in the audience area and is recommended in case of non-amplified music, when problems of echoes are not so important, to identify the proper levels of music for all listeners [Paini *et al*, 2006]. In Vasilantonopoulos' and Mourjopoulos' study [2003] it corresponded to a distance of 18m for the unoccupied and 16m for the occupied conditions.

To summarise the above review, research should be carried out for ancient performance spaces, with particularly attention paid to the combination of acoustic indices calculated, mainly for the evaluation of a space, to the effect of materials, stage enclosure shapes, background noise and audience absorption. The calculation of RT, although in unique outdoor spaces, is still useful in relation to reflection patterns for the comparison between several layouts in occupied and unoccupied conditions. Also, inclinations of audience areas, preferred seating areas, consideration of background noise and effect of temporary stage enclosures or scenery applications should be considered.

2.4.2 EFFECTS OF TEMPERATURE, RELATIVE HUMIDITY AND WIND

This section focuses on the effects of environmental conditions on outdoor sound propagation. These are usually relevant to large distances, for example 1km, although previous studies on ancient theatres have indicated their influence on theatre acoustics and their consideration during theatre design, as will be seen below.

Sound waves travel outdoors through the atmosphere in constant motion. Turbulence, temperature and wind gradients, as well as absorption and reflections from the earth's surface affect the amplitude and create fluctuations in the sound received. As the transmission path increases the average amplitude changes and the received sound fluctuates. Previous studies have discussed two types of sound propagation, which are relevant to ancient theatres, ground-to-ground and air-to-ground [Kurze and Beranek, 1971]. The SPL is related to the sound power level (L_w) of the source, its directivity, the source-receiver distance and the excess attenuation caused by environmental conditions. For example, when there is fog or light precipitation sound propagation is improved, due to secondary effects. For example, during light precipitation, the gradients of temperature and wind tend to be small so that "*sound carries farther outdoors than on a sunny day with the attendant meteorological inhomogeneities resulting from the sun's heating*" [Kurze and Beranek, 1971]. Also, with fog and snow background noise diminishes.

The effect of the wind is also of particular interest. Vertical temperature and wind gradients almost always exist and cannot yet be calculated by the acoustic software commonly used. Heat exchange between the ground and the atmosphere and friction between the moving air and the ground cause these gradients, forcing the speed of sound to be altered with height, hence sound waves to be bent upwards of downwards. According to Kurze and Beranek [1971] it is possible for 'shadow zones' to be created by these conditions. With wind gradients near the ground the speed increases with height, bending the sound waves upward, creating a 'shadow zone' upwind from the source. On the other hand, the sound rays are bent downward with downwind. Also, with crosswind there seems to be a zone of transition. This has also been indicated by Goularas [1995], who suggested designing an open-air theatre so that the wind will be blown towards the audience.

Since the temperature is usually decreasing with height, the higher sound waves are transmitted with a certain delay, compared to the lower waves and the high temperature of the ground. This enforces the sound waves to be bent upwards. In exceptional cases, like in the sunset, the temperature increases with height, creating downward bent waves. For these reasons it has been suggested that the minimum audience inclination in an open-air theatre should be 8° [Goularas, 1995]. From the temperature's viewpoint, a strong negative temperature gradient can create a shadow zone, like on a clear afternoon with no wind, while a strong positive temperature gradient can create no shadow, on a clear calm night. Excess attenuation can be observed at low frequencies (300-600Hz), greater than the value predicted from geometrical acoustics, caused by interference between the direct and the reflected sound [Ingard, 1969]. Moreover, temperature and humidity varies with position, particularly the height above the ground, causing low attenuation with respect to the predicted. The latter is also related to air absorption. Previous measurements for large distances have shown that the anomalous excess attenuation is greater in daytime than at night and in the summer period [Kurze and Beranek, 1971], while the increase in temperature affects the attenuation (the attenuation is increasing by 8%, for every increase in temperature by 5°F [Goularas, 1995]. To find the total energy loss between the first and the last row in an ancient theatre, one has to calculate the air attenuation, the wind's effect, the material absorption and the inverse square law. Due to these and other variables and the final attenuation, the size of a theatre is limited.

Studies have also systematically investigated outdoor sound propagation and the effects of wind and temperature gradient theoretically, mainly regarding noise control and algorithm development [Horoshenkov, 1996; Taherzadeh *et al*, 1998].

2.4.3 Effects of Ground, Trees and Planting

Due to the nature of ancient theatres, especially Classic and Hellenistic, being part of the landscape of the city or the country, the effect of ground and surrounding trees, in most existing theatres, sometimes determines the acoustic environment. Ground attenuation is a function of the structure and the covering of the ground, varying from hard soil to grass or shrubbery, and of the heights of the source and the receiver above the ground [Kurze and Beranek, 1971]. Research that has been previously carried out has shown that the reflected from a non-rigid boundary wave will mostly interfere at around 300-600Hz [Ingard, 1953]. Usually the magnitude of the impedance decreases with increasing frequency [Attenborough, 2000]. In the case of the ancient theatres, where the orchestra is mainly soil, these frequencies are particularly important, since speech is the predominant ancient drama performance means. However, it has also been suggested that excess attenuation due to ground absorption can be neglected within a distance of 30-70m from the source [Kurze and Beranek, 1971], which applies to many source-receiver distances in open-air theatres. The former may imply a less important role of the orchestra ground for the receivers at the upper part of the auditorium, although in most of the cases the orchestra provides the most important early reflections. Moreover, as expected it is suggested that grass and shrubbery result in higher excess attenuation.

Equally important in the contemporary use of the ancient theatres are the trees that surround the audience area. These can absorb, diffuse and reflect sound, according to the density of the trees, the density of the foliage, the tree type and the height and width of the belt. Modest attenuation is caused by mature vegetation, with dense foliage and long and high belts of trees [Egan, 1988], while extra attenuation is a result of wide belts of tall and dense trees [Kotzen and English, 1999]. For example, the values for excess attenuation vary due to the vast varieties of trees and forests, from dense evergreens to bare trunks [Kurze and Beranek, 1971]. Also, the so-called 'edge effects' of a forest provide high excess attenuation at low frequencies (up to 400Hz), low at middle frequencies (500-1500Hz), while above 1500Hz they do not affect the final attenuation [Embleton, 1963]. With appropriate arrangements, trees and forest can be useful as noise barriers, for sound disturbance between a theatre and the surrounding areas.

Additionally, although the dense homogeneous forest of coniferous trees could, in combination with shrubbery, provided attenuation of 7dB per 30m of forest from 200 to 3kHz, it also helps the amplification of the source's signal within the first 30m, at around 1kHz, probably due to the resonance of the trunks and branches, of around 4dB [Empleton, 1963]. This can be applied to the theatre of Epidaurus, which is surrounded by a forest of coniferous trees. Diffusion can equally be observed, when the sound wave impinges on the vegetation and is then reflected back [Kang, 2007]. Still, tree and shrub arrangements are important.

2.5 SUBJECTIVE EVALUATION AND TERMINOLOGY

In the 1960's, based on a study that examined 54 concert and opera halls all over the world, Beranek introduced a series of subjective acoustic attributes, which would help for the evaluation of every hall, and presented them in his book *Music, acoustics and architecture* [Beranek, 1962]. In his new book *Concert and opera Halls: How they sound* [1996] Beranek presented 76 halls, reviewed the previous terms and defined some new, as an attempt to find a common language for musicians and acousticians. These covered all the important aspects of music in an enclosed space. This section briefly reviews Beranek's subjective attributes of musical-acoustic quality, as an introduction for later references on the characterisation of ancient theatres.

Table 2.1 presents the definitions of the attributes, emphasising on the similarities or changes in Beranek's old [1962] and new [1996] book. The majority of these terms have been repeated in his new book, including 'intimacy', 'warmth', 'loudness', 'brilliance', 'balance', 'blend', 'ensemble', 'immediacy of response' (attack), 'freedom from echo' and 'uniformity'. Some of the original definitions have been enriched or reconsidered with different names. 'Liveness', which is related to reverberation time, is presented as 'reverberation or liveness'. 'Definition or clarity' is replaced by 'clarity'. 'Loudness of the direct sound' and 'loudness of the reverberant sound' are joined and replaced with the general term 'loudness'. Likewise, the 'dynamic range' and the 'freedom from echo' are replaced by 'dynamic range and background noise level' but the meaning is the same. Moreover, the importance of 'tonal quality' and 'uniformity' are signified by the titles 'extraneous effects on tonal quality' and 'uniformity of sound' respectively.

However, some original terms have been modified and presented with different attributes (Table 2.1). 'Diffusion' was discussed in the first book [1962] as spatial orientation of reverberant sound. The new book introduces the 'acoustic glare', which can be produced by early sounds created by smooth and flat surfaces, and can be prevented by fine-scale irregularities although the term 'diffusion' has not been mentioned. Furthermore, 'spaciousness' is a new term, divided to 'apparent source width' (ASW) and 'listener envelopment' (LEV). ASW is created when sound appears to emanate from a source wider than the visual width of the actual source. LEV is high when the reverberant sound seems to arrive to the listener from all directions-forward, overhand and behind.

The literature that relates Beranek's attributes to ancient theatre acoustics is limited [George, 1997]. Some of these terms can be assigned to a hall through computer simulation. These depend on acoustic indices, like RT, and on measurable constants like distance and hall dimension. However, the majority of the terms is determined by the listener's impression and experience, or by on site measurements. Due to this reason, in this study only a small number of Beranek' terms are used.

Table 2.1. *List of Beranek's subjective attributes: A comparison between 1962 and 1996 versions.*

Music, acoustics and architecture (1962)	**Concert and opera halls: how they sound (1996)**
Intimacy or presence	
A hall has acoustical intimacy if music played in it sounds as though it is being played in a small hall. An intimate hall has presence.	
Liveness	***Reverberation or liveness***
A hall that is reverberant is called a live hall. Liveness is related to reverberation times at the middle and the high frequencies (above 350Hz).	
Warmth	
Warmth in music is defined as liveness, or fullness of the bass tone (75-350Hz) relative to that of the mid-frequency tone (350 -1,400Hz).	
Loudness of the direct sound ***Loudness of the reverberant sound***	***Loudness***
Loudness is made up of the loudness of the direct and the reverberant sound.	
Definition or clarity	***Clarity***
A hall is said to have definition when the sound is clear and dinstict	Clarity is the degree to which the discrete sounds in a musical performance stand apart from one another.
Brilliance	
It is defined as bright, clear, ringing sound rich in harmonics.	
Balance	
Good balance entails both the balance between sections of the orchestra and the balance between orchestra and vocal or instrumental soloists.	
Blend	
Blend is defined as a mixing of sounds form the various instruments of the orchestra so that the listener finds them harmonious	
Ensemble	
Ensemble refers to the performers' ability to play in unison, to initiate and release their notes simultaneously so that many voices sound as one.	

continued...

Table 2.1.....continued from page 28.

<table>
<tr><th colspan="2">Immediacy of response (attack)</th></tr>
<tr><td colspan="2">Immediacy of response is related to the manner in which the first reflections from surfaces in the hall arrive back at the musician's ears.</td></tr>
<tr><th colspan="2">Texture</th></tr>
<tr><td colspan="2">Texture is the subjective impression the listeners derive from the patterns in which the sequence of early ound reflections arrive at their ears.</td></tr>
<tr><th colspan="2">Freedom from echo</th></tr>
<tr><td colspan="2">Echo describes a delayed reflection sufficiently loud to annoy the musicians on stage or the listeners in the hall.</td></tr>
<tr><th>Tonal quality</th><th>Extraneous effects on tonal quality</th></tr>
<tr><td colspan="2">Tonal quality is beauty of tone. A fine instrument has a fine tonal quality, and similarly a concert hall can have a fine tonal quality.</td></tr>
<tr><th>Uniformity</th><th>Uniformity of sound</th></tr>
<tr><td colspan="2">Another requisite of a god hall is uniformity of sound. The quality of a hall suffers if part of the audience is subjected to inferior sound, for example, under a deep overhanging balcony, or at the sides of the front of the hall, or if in certain locations reflections produce echoes, or muddiness, or lack of clarity.</td></tr>
<tr><th>Dynamic range</th><th>Dynamic range and background noise level</th></tr>
<tr><td>A concert hall must be free of extraneous noise from traffic, from adjoining halls or practice rooms, from subways, airplanes, ventilating systems, and movement of late-comers on stairways and in passageways.</td><td rowspan="3">Dynamic range is a spread of sound levels over which music can be heard in a hall. This range extends from the low level from background noise produced by the audience or the air-handling system to the loudest levels produced by the performers.

All extraneous sources of noise- traffic, aircraft noise- must be avoided.</td></tr>
<tr><th>Freedom from noise</th></tr>
<tr><td>Dynamic range is a spread of sound levels over which music can be heard in a hall. This range extends from the low level from background noise produced by the audience to the loudest levels produced by the performers.</td></tr>
<tr><td rowspan="2"></td><th>Apparent source width (ASW)</th></tr>
<tr><td>A concert hall is said to have one of the attributes of spaciousness if the music performed in it appears to the listener to emanate from a source wider than the visual width of the actual source. This attribute is called "apparent source width" (ASW).</td></tr>
<tr><td rowspan="2"></td><th>Spaciousness: listener envelopment (LEV)</th></tr>
<tr><td>Envelopment describes a listener's impression of the strength and directions from which the reverberant sound seems to arrive. "Listener envelopment" (LEV) is judged highest when the reverberant sound seems to arrive at a person's ears equally from all directions.</td></tr>
<tr><th>Diffusion</th><th>Acoustic glare</th></tr>
<tr><td>Diffusion concerns the spatial orientation of the reverberant sound. The diffusion is best when the reverberant sound seems to arrive at the listener's ears from all directions in bout equal amount. Diffusion is lacking when a hall has smooth side walls and ceiling which carry the sound directly from the stage to the audience without encouraging cross reflections or scattering of the sound waves.</td><td>If the side walls of a hall or the surfaces of hanging panels are flat and smooth and are positioned to produce early sound reflections, the sound from them may take on brittle or harsh or hard quality, analogous to optical glare. "Acoustic glare" can be prevented by adding fine-scale irregularities to these surfaces or by curving them.</td></tr>
</table>

2.6 Presentation and Comparison between Software for Simulating Ancient Theatres

With the advance of computer techniques, a number of computer simulation software has been developed. For ancient performance spaces, it is essential to use computer aided design tools for the construction of the space and acoustic software for the reproduction of its acoustic environment. In this section some commercial software for acoustic simulation, including CATT, ODEON and Raynoise, are briefly reviewed and compared. Details on the algorithms the software are based on are presented in Section 2.7.2.1.

2.6.1 RAYNOISE, CATT AND ODEON

Raynoise is an advanced computer program, designed to simulate the acoustic behaviour of any arbitrary enclosed volume, any open space or a combination of both: half open/half closed [LMS Numerical Technologies, 2001]. The application of the software includes industrial noise control, room and environmental acoustics, reverberation time assessment in churches, acoustical design of sound recording studios, speech-intelligibility assessment, acoustic layout of office environments, etc. Raynoise models the physics of acoustic propagation, including specular and diffuse reflections against physical boundaries, wall and air absorption, diffraction across screens, and transmission through walls. The core of the model is a hybrid algorithm combining the mirror image source method (MISM) and the ray tracing method (RTM). Since the software is based on the principles of geometrical acoustics it is subject to restrictions. Geometrical acoustics assume that sound waves behave as sound rays, exactly as in geometrical optics light waves behave like light rays. Acoustic rays are reflected by solid surfaces and lose part of their energy at each rebound. This approach is only valid at medium-to-high frequencies as it partly neglects the wave aspect of sound behaviour. In fact, this is also the restriction for other software packages, like CAAT and ODEON, as discussed below. Nevertheless, software developers are integrating wave motion in their software. Detailed description of Raynoise will be presented in Section 2.7.

CATT Acoustic was originally developed by an independent company called CATT (Computer Aided Theatre Technique) in 1986. The software is used for acoustic simulation and is compatible with the Windows user interface. CATT Acoustic is a program, based on the image source model (ISM) for the early part qualitative detail; on the ray-tracing for audience area colour mapping; and on randomised tail-corrected cone-tracing (RTC) for full detailed calculation, which enables auralisation. The main program integrates prediction, binaural post-processing, multiple sources, source directivity, surface properties library, sequence processing and convolution. WAV files can be produced and played and files can be converted, printed or plotted [CAAT, 2006].

ODEON was originally developed in 1984 by the Department of Acoustic Technology in Demark and six Danish consultant companies. The purpose was to provide reliable prediction software for room acoustics. Later versions allow prediction of acoustics in both auditoria and industrial environments. The software provides interface in Windows and multi-document processing function. It is based on the ISM and the RTM, while for noise prediction a special ray-tracing algorithm allows the modelling of surface and line sources [ODEON, 2007]. The graphical environment is easy to use. The main feature is allowing the aural evaluation and presentation of the predicted room. It includes the tools for the prediction of room acoustics and the creation of the aural demonstration of a room. The calculation principle is to create a binaural room impulse response (BRIR), which is the key to auralisation. The calculation carried out during the creation of the BRIR includes full filtering of each reflection in nine octave bands and applying a set of head related transfer function (HRTF) for each reflection [ODEON, 2006]. A method that combines diffusion caused by diffraction due to typical surface dimensions, angle of incidence and incident path length with surface diffusion was recently developed for ODEON and included in the newest version [Christensen and Rindel, 2005a; 2005b].

2.6.2 Comparison between Software and Discussion

To validate the accuracy of Raynoise for the acoustic simulation of ancient theatres, a comparison has been carried out between software CATT and Raynoise by simulating a simplified form of the Classic theatre type. It needs to be noted that information about ODEON is based on previous studies [Sanmartin *et al*, 2002], since it was not available for comparison. Figure 2.6.1 illustrates the plan of the model, with 7 rows of seats extended in an angle of 240°, with almost 32.5m diameter, divided into 9 wedges with total height of 3m.

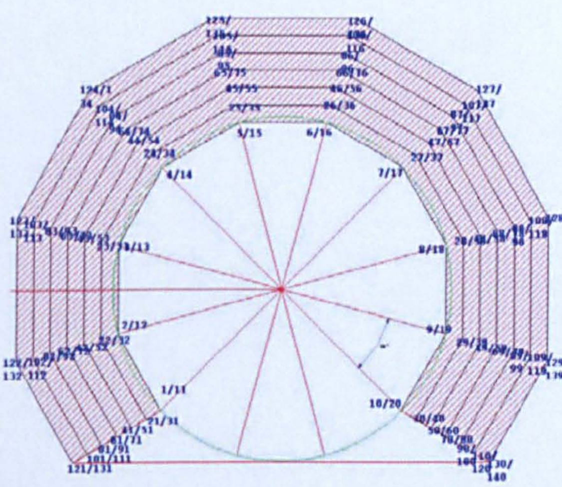


Figure 2.6.1. *Plan of the model used for the comparison between CATT and Raynoise.*

With coordinate system originating at the centre of the orchestra, the source is located at coordinates (x, y, z) = (-1, -1, 1.6), with power level at 72.9dB at125Hz, 74.9dB at 250 and 500Hz, 70.9dB at 1kHz, 65.9dB at 2kHz and 45.9dB at 4kHz. To test several parameters, both 20,000 and 200,000 rays have been used, with and without diffusion, and edge diffusion has been also used, since it is automatic in CATT. The absorption coefficients for marble have been used, at 0.01 across the frequency range, and diffusion coefficients, when applied, at 0.5 for the frequency range.

In terms of the model preparation, Raynoise is compatible with CAAD software, which makes it more user-friendly than CATT. The user can import the *DXF file of the model in Raynoise, where it can be further modified and adjusted. On the other hand CATT cannot import *DXF files. The only way to import a model is by using Autolisp, peripheral Autocad software, where the coordinates of each point/node and surface of the model is translated into a text file, which is then used by CAAT to create the model. Alternatively, the user can manually create *GEO files in CAAT. In this case the complexity of the model is usually compromised, because of multiple point coordinates that need to be entered, which is time consuming. From these it is obvious that for a simple room calculation CAAT is very useful, where for an ancient theatre it is usually prohibited. In future versions of the software the user will be able to import 3D models with details and textured graphics [Dalenbäck and Strömberg, 2006]. The results regarding Raynoise and CATT are compared in terms of SPL, reflection paths and impulse responses, due to the fact that the latter cannot calculate reverberation in open-air theatres, which consequently affects the other indices. Figure 2.6.2 illustrates the SPL for the software.

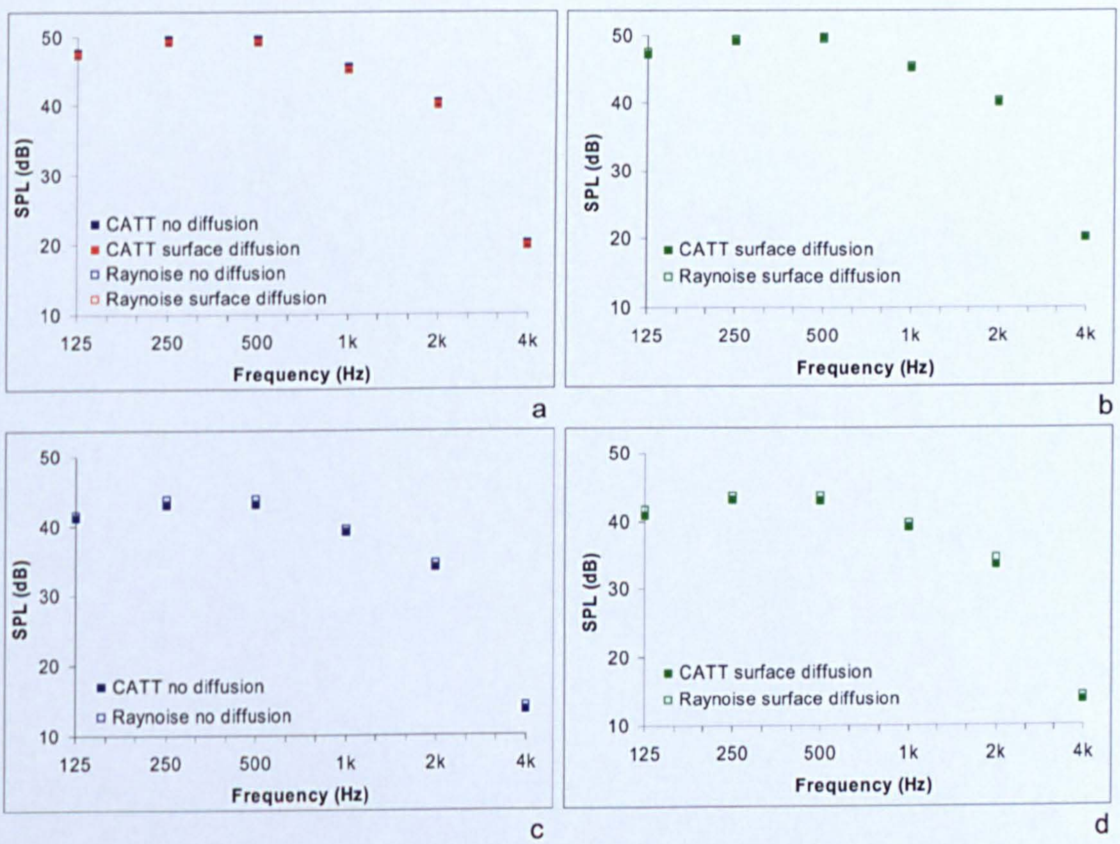


Figure 2.6.2. *SPL (dB) results in Raynoise and CATT for two typical receivers. a) Row 2 with 200,000 rays, b) Row 6 with 200,000 rays, c) Row 2 with 20,000 rays and d) Row 6 with 20,000 rays.*

There was an attempt to use a ceiling and assign 100% absorption in order to obtain RT30 results, as has been previously used in other open-air theatres with ODEON, but after discussion with the developer of CAAT it was decided not to follow this method with CATT because of the risk of inappropriate reflection path calculation [Dalenbäck, 2006]. In Figure 2.6.2 the SPL results are shown, indicating that in terms of sound distribution no particular difference is observed between the software. The maximum difference appears at Figure 2.6.2d for the receiver at row 6, where SPL is overestimated in Raynoise compared to CATT, at low frequencies in particular, by 0.9dB.

Figure 2.6.3 shows the impulse responses for the receiver in row 2 in Raynoise and CATT respectively. For the comparison it needs to be noted that in Raynoise time starts when sound is emitted, thus the direct sound reaches the receiver at 34.4ms, whereas in CATT it starts when the direct sound reaches the receiver. Therefore there is a time difference of at least 34.4ms in the two impulse responses. Also, Raynoise's amplitude scale is from 0 to 50dB, while for CATT it is -20 to 50dB. It can be seen that the impulse response reflections are similar with only some alteration especially in late reflections, after 500ms. In this way for the receiver at row 2 there are additional reflections at around 900ms after the direct sound, whereas for the receiver at row 6 there are two reflections at around 350 and 450ms. However, as far as the early reflections are concerned, they seem to be identical for both CATT and Raynoise. Moreover, in Figure 2.6.3b, which illustrates the impulse responses for the receiver at row 6, it is pointed out that the reflection pattern is dense for the first 200ms in Raynoise, while CATT provides two extra reflections between 300 and 500ms after the direct sound. Similarly, for the receiver at the side of the audience area late reflections appear after 750ms. In general though, the reflections that are produced either by diffusion or by the high reflection order seem to be more in Raynoise. Further investigation needs to be carried out concerning this part of the comparison by presenting the reflection paths of at least one receiver point. This will be examined later in this section.

Moreover, both CATT and Raynoise provide the user with the central gravity time (Ts for the former and TCG for the latter). The comparison shows that although CATT is unable to produce reverberation for open models, the distribution in TCG is similar, maintaining the same levels as well. The times are at around 30ms for the central part of the theatre and at 50ms at the sides, pointing out that reverberation must be higher towards the sides of the theatre area.

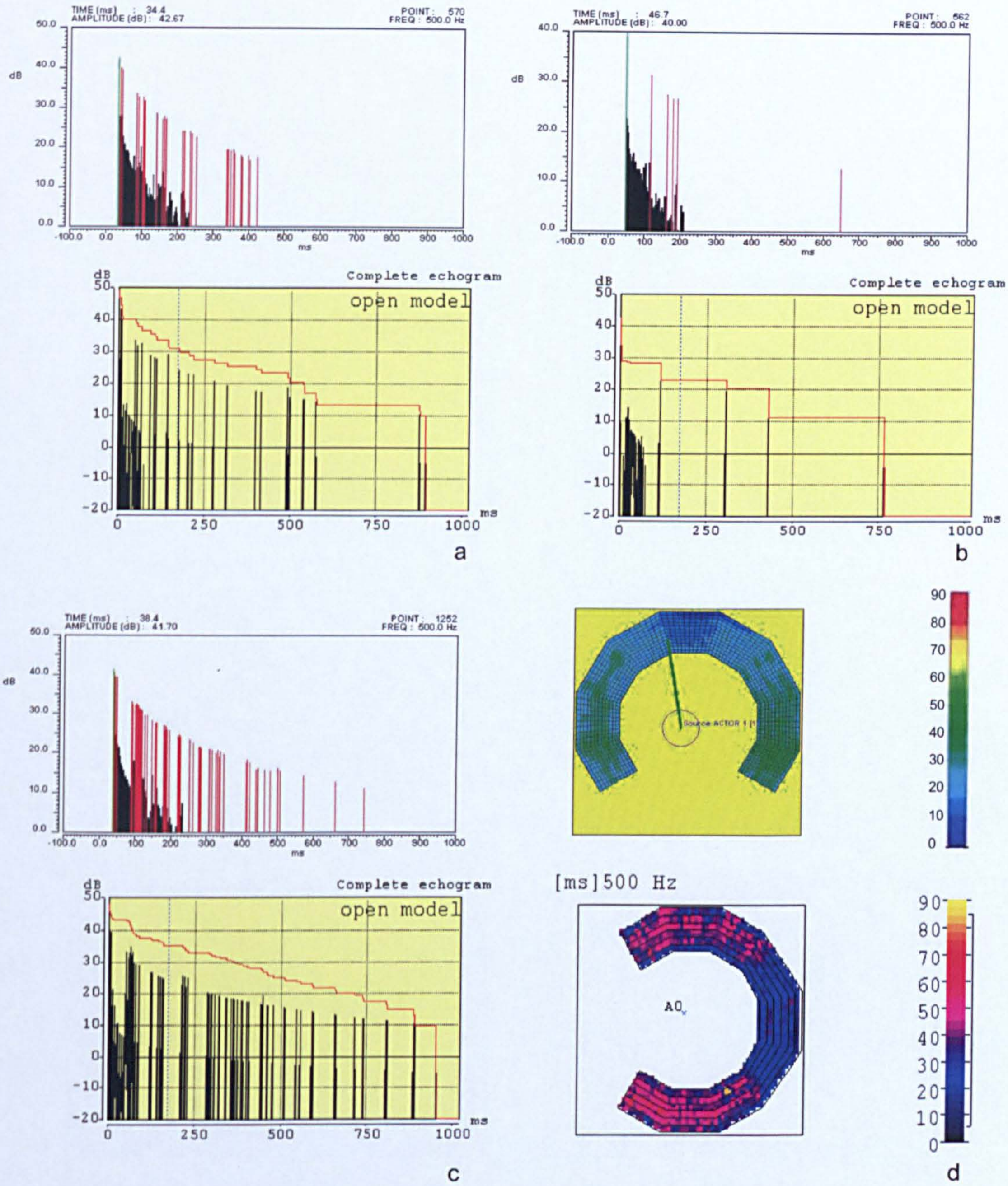
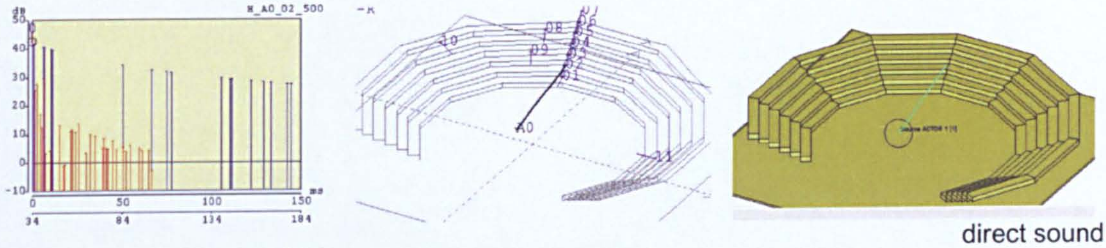
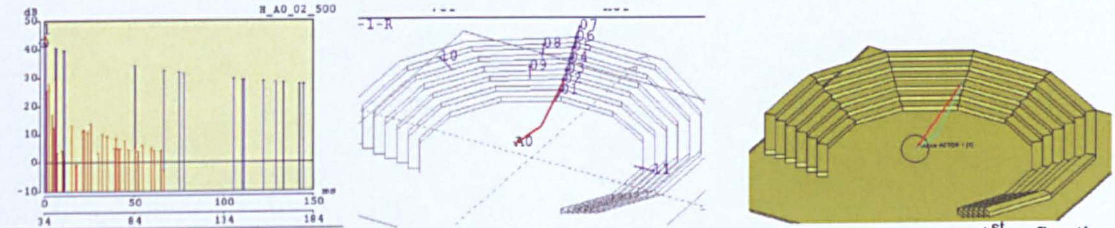


Figure 2.6.3. *Comparison between Raynoise and CATT. Impulse responses for receiver at a) Row 2, b) Row 6, c) Side of the audience area and b) TCG (ms) colour map.*

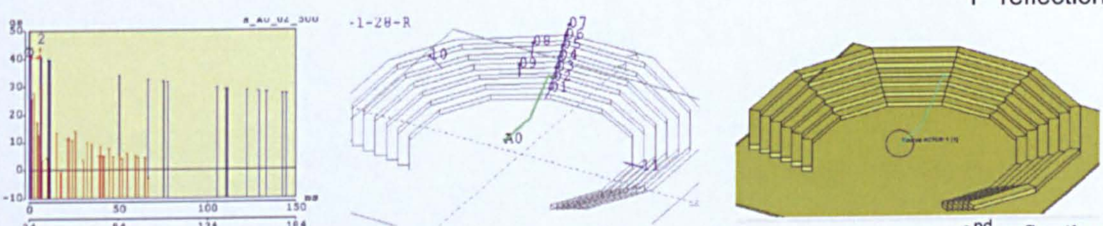
In Figure 2.6.4 the difference in the way the software handles the reflections in the first 150ms in CATT, hence 183.4ms in Raynoise, is shown. As can be seen, between the 9th and 10th reflections in CATT there are three more reflection paths in Raynoise. Similarly, a reflection at 168ms after the direct sound is provided by Raynoise, which is the last reflection. However, in CATT there are additional reflections, named 13-16, as seen in Figure 2.6.4. The small differences in the reflection path may have been caused by slight alterations in source/receiver positions, or by the small number of rays.



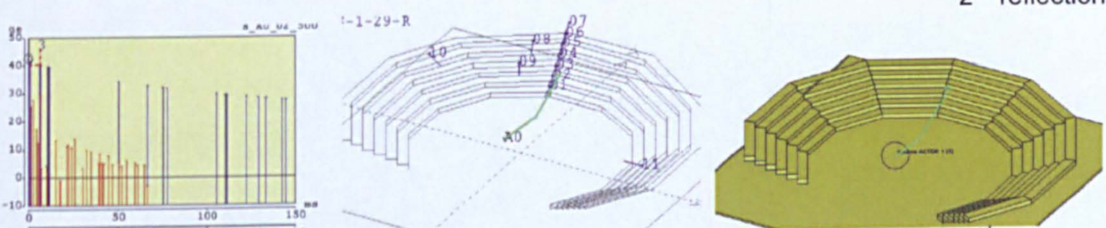
direct sound



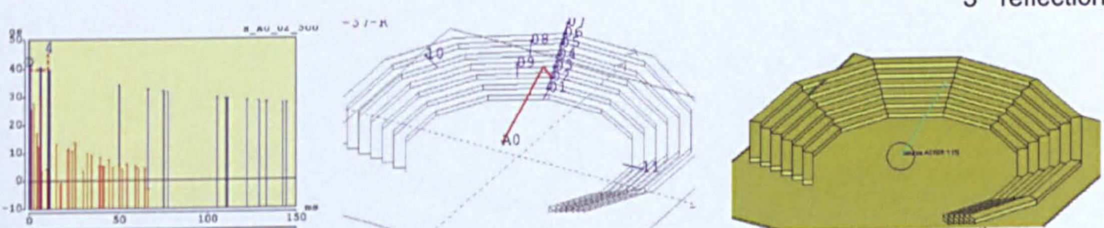
1st reflection



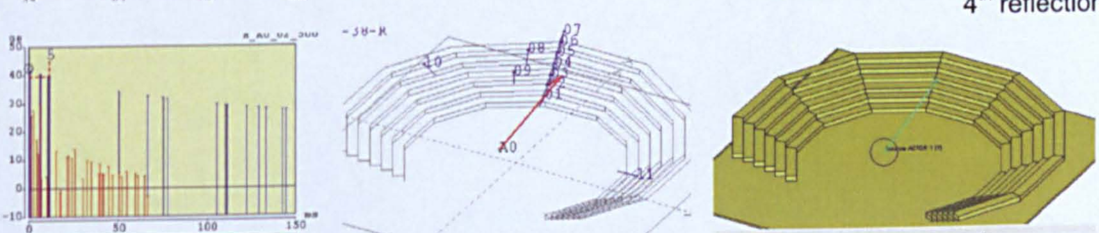
2nd reflection



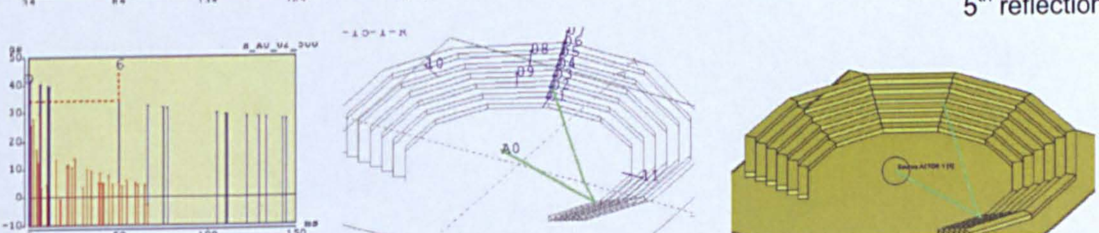
3rd reflection



4th reflection



5th reflection



6th reflection

continued...

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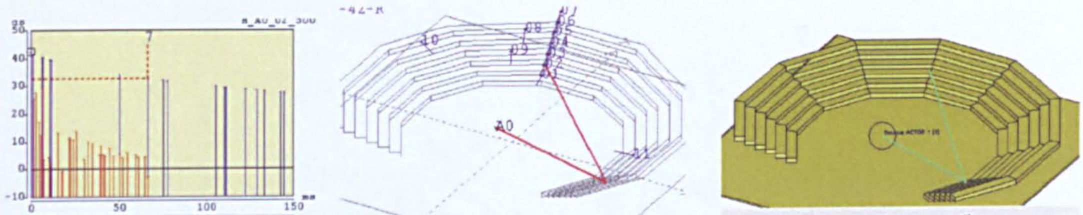
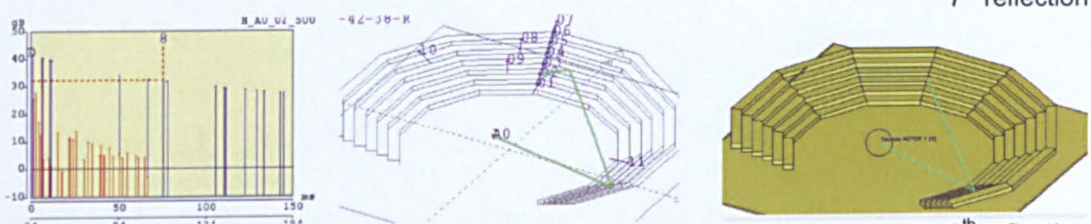
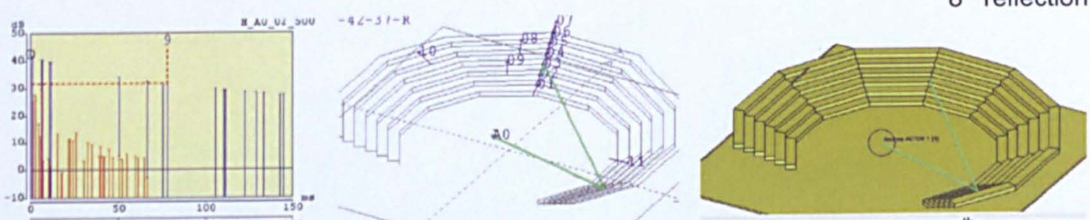


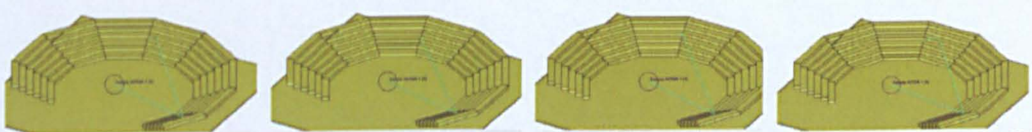
7^{th} reflection



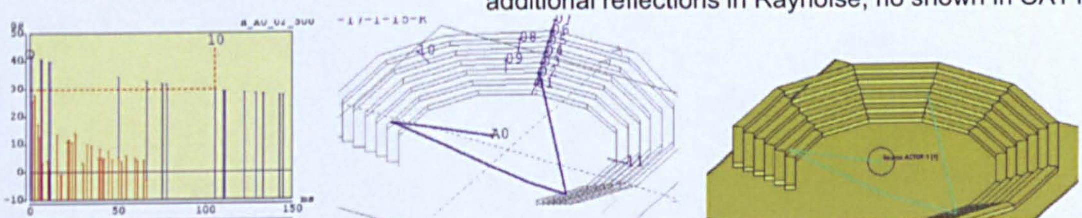
8^{th} reflection



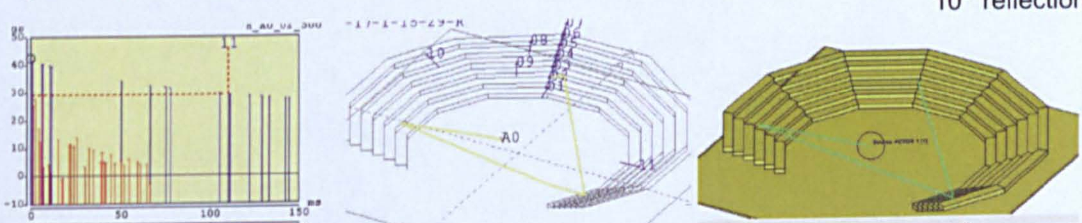
9^{th} reflection



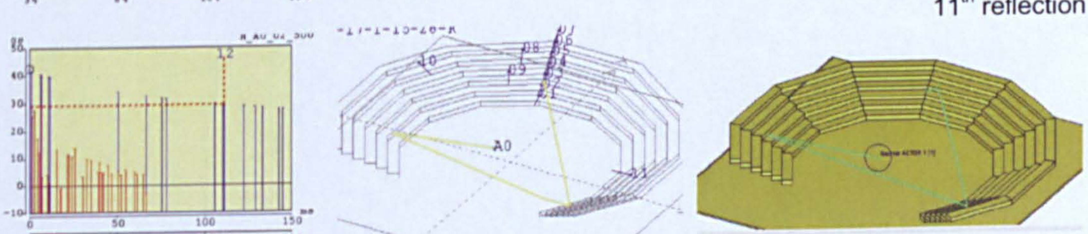
additional reflections in Raynoise, no shown in CATT



10^{th} reflection



11^{th} reflection



12^{th} reflection

continued…

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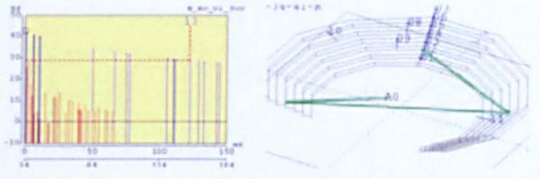
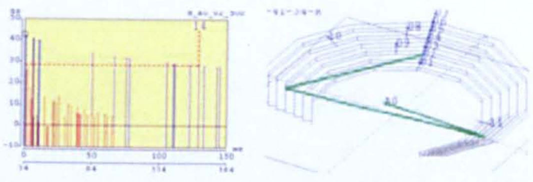
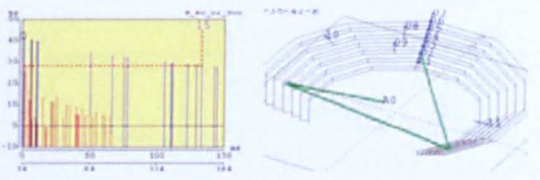


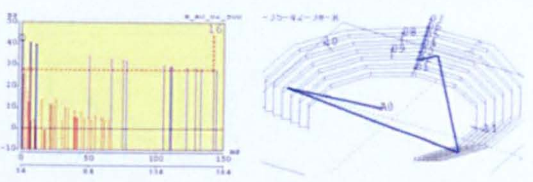
13th reflection in CATT



14th reflection in CATT



15th reflection in CATT



16th reflection in CATT

Figure 2.6.4. *Detailed reflection paths of early reflections for the receiver at Row 2 with CATT and Raynoise. CATT, white 3D model; Raynoise, Coloured 3D model.*

Furthermore, edge diffusion has been applied to the simulation in CATT, since the software allows the user to select the automatic calculation. Compared to the above simulations without considering edge diffusion, it is shown that the result of edge diffusion is a small increase in SPL, and enhancement of STI, C80, D50 and LEF.

In conclusion it needs to be pointed out that there is some inconsistency between the results in terms of impulse responses of the software. Although the tendency in the overall decay curve is similar, there are specific points where the reflection patterns are different, especially in terms of diffused sound. In terms of SPL and TCG the results are almost identical. However, the software needs also to be compared from the viewpoint of the user, its requirements, and the produced indices. From this viewpoint a very important advantage of Raynoise in the specific research area is the ability to produce RT results, which in some cases of outdoor spaces would be of less importance. However, as will be stressed in later chapters, namely Chapters 7-10, ancient theatres can formulate significant values of RT, thus simulation software that calculates reverberation in outdoor spaces is needed.

As indicated earlier in this section a difficulty in using CATT is its incompatibility with CAAD software. Hence, creating a model in any architectural software and then retrieving all coordinates to be entered in CATT is time consuming. However, once a model has been created and the requirements in terms of parametric selection have been met, the calculation time in CATT is especially low, at the range of a few minutes, compared to a few hours in Raynoise. This comparison has been carried out with the use of the model of ancient theatre type with 200,000 rays. Fast calculation times can however be outweighed by a restrictive reflection order, at the range of 9; clearly lower than the viable 50 in Raynoise. Still, CATT allows more possibilities for receiver directivities, either facing a fixed position, the stage, or applying unique directions. Also, an automatic selection in CATT is the edge diffusion, which in no way can be applied in Raynoise, unless with a scattering coefficient, as will be seen in Chapter 6. Finally, the presentation of results and colour maps in CATT is less attractive.

A comparison has been also carried out between software Raynoise and ODEON [Sanmartin *et al*, 2002]. They were investigated in terms of calculation time, stability of the models, diffusion processing, convergence in the results and user interface facilities. The results showed that ODEON has interestingly short calculation time, without an exponential increase, due to the algorithm that involves secondary sources with Lambert distribution, and can be 10 times quicker than Raynoise. It was stressed that in terms of results there is no significant difference. However, when they were examined separately, Raynoise showed that ray tracing algorithms are much more depended on the number of beams than the number of reflections. For ODEON, it is recommended that small surfaces should be avoided, especially for the parts of the room that contribute to strong early reflections. Processing times are almost the same in ODEON, regardless of the number of surfaces in the model, while in Raynoise they increase considerably for accurate predictions.

As previously discussed for CATT, simulations of ancient theatres carried out in ODEON have used an absorptive ceiling instead of the open-air area [Lisa *et al*, 2004]. It is suggested that because of the ceiling, when the reflection order increases "*the image source reflections will not grow exponentially but decrease. This will result in a decay curve dominated by a few strong reflections and therefore a low correlation coefficient that can give misleading results when calculating acoustical parameters*" [Lisa *et al*, 2004], which is common for all software. Nevertheless, despite the unavailability of ODEON in this study, it is noted that ODEON is suitable for simulating ancient theatres and has been used in some studies [Gade *et al*, 2004; 2005; Gade and Angelakis, 2006; Lisa *et al*, 2004; 2005; Rindel *et al*, 2006].

2.7 Simulation Methodology using Raynoise

As mentioned in Section 2.1, in this study Raynoise has been used to simulate the acoustic properties of ancient performance spaces. Here an examination of the methodology of the acoustic simulation is presented.

To acoustically simulate a space Raynoise's user has to construct the 3D model, preferably using CAD software. The model can then be imported into Raynoise and a series of properties have to be assigned. Those include speed of sound, material properties, source characteristics, receivers and background noise. Regarding the calculation there are a lot of analysis parameters that need to be defined by the user, including level of detail in data storage and refinement of the calculation, in order to achieve high accuracy. Detailed investigation has been carried out by the author in a previous study [Chourmouziadou, 2002]; hence the methodology is briefly discussed here.

2.7.1 Preparation of Model and Appropriate Parameters

CAAD software that can be used to build 3D models, like Archicad, Autocad and 3D Studio, were chosen for this study. To construct a space, exact dimensions are needed, and the surfaces have to be carefully connected. The basic advantage of Archicad is that the 3D representation is available at any time. Instead of drawing lines, ellipses and arcs, the software constructs walls, windows, doors, floors, stairs and roofs. Archicad creates a central database that can simultaneously handle 3D model data with plan and section views, dimensions, material finishes, component lists and more [Graphisoft, 2006]. For this study, Archicad 8.0 was available, which provides *DXF files of the 3D model that can be easily imported into Raynoise.

2.7.2 Description of Raynoise

As mentioned in Section 2.6.1, Raynoise is designed to simulate the acoustic behaviour of any arbitrary enclosed volume, any open space or a combination of both: half open/half closed. In this section the basic features of the software are reviewed.

2.7.2.1 Basic Algorithms of the Software

MISM and RTM

The core of the model is a hybrid algorithm combining the MISM and the RTM. The MISM uses virtual mirror image sources, in order to trace back sound reflection paths from the receiver to the sound source. Figure 2.7.1 shows the reflection paths for a specific receiver in a model in Raynoise. When the space has an irregular shape, further visibility tests need to be done, thus, the computation time becomes long. This appears especially if there are a large number of surfaces, or when the mean absorption is small, thus the number of image sources that need to be taken into account is increased.

In the RTM, it is assumed that the energy emitted from the sound source is distributed into a discrete number of sound rays, each of them having an initial energy equal to the total energy of the source divided by the number of rays. Each one travels at the speed of sound and collides with the walls, floor, and ceiling etc., where it is reflected in accordance with the law of specular reflection. Their energy level decrease at reflections by means of wall absorption and progressively as it travels by means of air absorption. When the energy level falls below a user-defined threshold, the ray is abandoned and the next one is traced. Receivers are cells with finite volume and each ray is checked to see whether it crosses the receiver volume. The number of rays crossing a receiver volume and the energy contributions of those rays give a measure of the SPL. Obviously there are losses due to spherical divergence, which are included as a result of the increasing separation between the rays as they spread out from the source with increasing travel time [LMS Numerical Technologies, 2001].

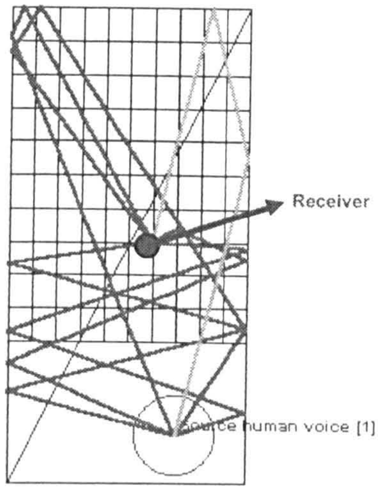


Figure 2.7.1. *Sound reflection paths.*

Conical and triangular beam method

The conical beam method (CBM) and the triangular beam (TBM) are two hybrid methods that can be selected for the calculation in Raynoise. The CBM emits a large number of cones with their vertices at the source. The propagation of the cones through the room is handled by applying a ray-tracing algorithm to the axes of the cones. Receivers are points. When a point lies inside a truncated cone, between two successive reflections, a visible image source has been found. Its contribution is easily calculated, using spherical divergence in the cone.

The TBM is similar to the CBM, but instead of emitting cones it uses triangular-based pyramids. The advantage is that no 'overlapping' takes place, thus, no weighting functions have to be applied. The results from this method are more accurate than those from the previous but its convergence rate is somewhat lower. It is recommended for exterior applications, where most reflections will have a low order and also the maximum order set for the calculation will usually be given a low value. Raynoise uses both the conical and the triangular beam method, combining the advantages of both MISM and RTM in one algorithm [LMS international, 2001].

2.7.2.2 Tail correction, statistical reverberation, diffraction, and diffusion

The statistical tail correction is mainly used when the cones or the pyramids reach their abandonment criterion and there is still some considerable energy left over. Although one has to make sure that the abandonment criterion is chosen such that there is no energy left, in cases of long reverberation times the statistical tail correction can be used to reduce the long computation times.

Sometimes the cross-section of the base of the cone becomes larger than the size of the room, and there is an underestimation of detected image sources. The continuous tail correction has the advantage that faster convergence can be obtained with less rays and that the transient behaviour is modelled correctly as well. It is necessary to choose a reflection order high enough to describe the echogram with reflections that reach the late part of the transient region.

Raynoise offers statistical reverberation time, calculated using Sabine, Eyring and Kuttruff's formulas from statistical acoustics, but this is less relevant to the simulation of ancient performance spaces. The program accounts for diffraction in an approximate way, computing the part of the diffracted waves that reach the shadow zone behind an object. This is possible either behind a surface, or with a curved object. The sources can be coherent and incoherent, depending on whether a lot of interference is expected or not. This is particularly interesting in cases of several sources (some of them producing noise) when STI maps are needed.

The surfaces in a model are sometimes attributed with diffusion coefficients. Raynoise handles diffuse reflections initially by using a beam-tracing method to find the specular parts of all reflections, and secondly, by handling the missing reflections by a method that uses rays as transporters of energy. This allows two possibilities, depending on the software's design. The results determine the distribution of sound and their differences can be identified in the echo/histogram.

It needs to be noted that auralization, "*the process of rendering audible, by physical or mathematical modelling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modelled space*" [LMS Numerical Technologies, 2001] enables the recreation of the aural impression of the acoustic characteristics of a space, whether it is outdoors or indoors, and has been previously used for ancient performance spaces [Chourmouziadou, 2002; Chourmouziadou and Kang, 2002; Rindel *et al*, 2006] although it will not be used in this study.

2.7.2.3 Simulation Procedure in Raynoise

This section describes the process of simulation, starting with the import of the model and concluding with the results' enquiry.

Model

Raynoise's main window, as can be seen in Figure 2.7.2, contains a Menu bar for activating the commands and dialogs, a Tool bar with a row of graphic buttons for applying the most frequent graphic commands, a graphic window for displaying the model and a keyboard input area for typing the commands using the Raynoise 'Command Language' syntax. Following the Menu bar step by step, there are a number of commands that lead to the last part of the simulation, which is when the user derives the results.

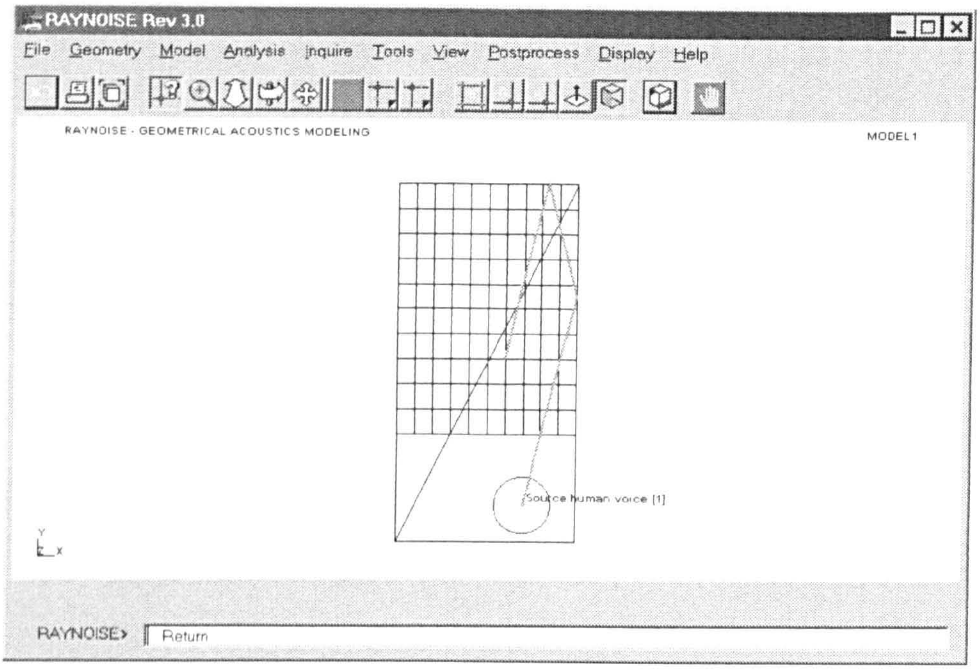


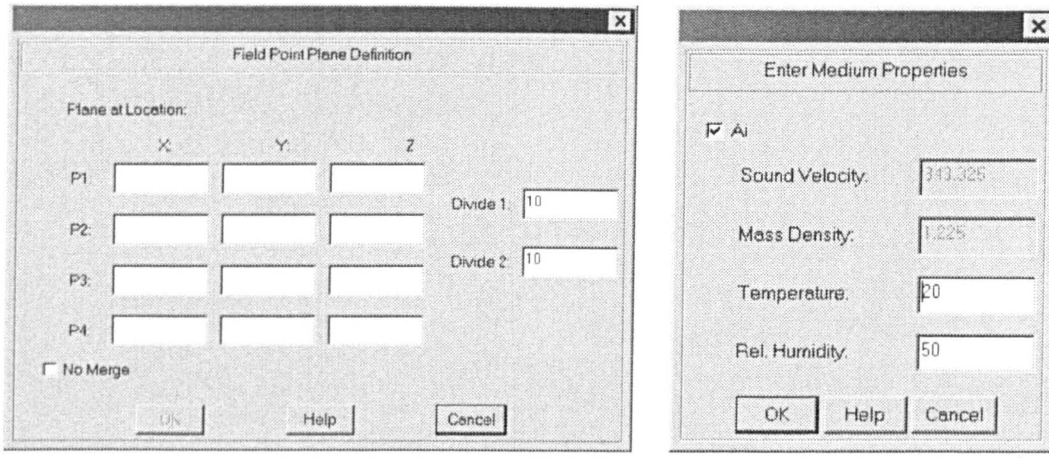
Figure 2.7.2. *Raynoise's main window.*

After importing the model, as described earlier, the points where the sound field needs to be calculated have to be created, in Geometry Menu. They are named field points and can be individual, creating a line, a 3D shape or a surface. The latter is called field point mesh and can be imported as a *DXF file or created in Raynoise from the Geometry Menu. For example, the surface that the preferred field points form can be created by the coordinates of four points, as shown in Figure 2.7.3a. Raynoise identifies the volumes as groups of elements and nodes. First, there is the possibility to divide these elements or nodes into sets, mostly if there is a need for attributing the same characteristics to them. This can be easily done through the Geometry menu. The sets can be imported or exported.

After the model is created in terms of volumes, field point mesh and sets, there is a number of data in the Model Menu that need to be defined. The user has to enter the properties of the medium through which the acoustic wave fronts propagate, such as sound velocity, mass density, temperature, relative humidity and air absorption, as shown in Figure 2.7.3b.

The materials can be defined and assigned directly to the surfaces or the sets. There are databases for the common materials that include absorption, diffusion and transmission loss coefficients, although the user can create new tables for materials that are not included in the database. A material can easily be edited or deleted and the assigned materials can be viewed from the View Menu.

A source is defined as a point, line, area, panel, or transmission source. The user has to choose the type, the position and the source's sound power. Orientation of the source, emission angles, directivity, alignment, and emission zone can also be used. The choice of a coherent or incoherent source is given, which can influence the results, mostly if STI is necessary and the source signal needs to be distinguished from the noise signal – this can be easily assigned through Background Noise. The source can be edited or deleted by the user at any time. Diffraction edges are then defined, if necessary, and this can be achieved by picking the faces, which are the edges of the element. After completing this, the model fulfils all the requirements for the calculation to begin.

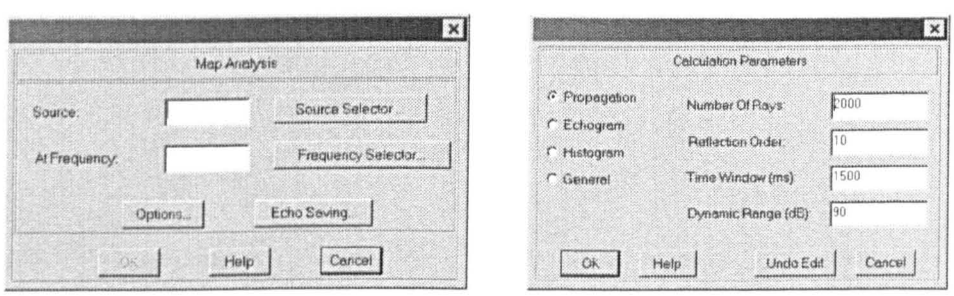


a b

Figure 2.7.3. *Raynoise Menu. a) Window used to create the field point mesh from Geometry Menu and b) Window for medium properties from Model Menu.*

Calculation parameters

The calculation parameters have a great effect on calculation accuracy. The results can only be acquired after performing the Mapping and the PostProcess calculations. Figure 2.7.4 shows the main window of the mapping analysis and the propagation parameters. The selection of large number of rays per source in the propagation parameters reduces errors, and the higher the reflection order the more accurate the results. This particularly applies to hard boundaries, because then the energy content of high order reflections (for example 50) can still be very significant. The time window and the dynamic range in Figure 2.7.4b determine when to abandon the propagation of a cone/pyramid so as to begin a new one.

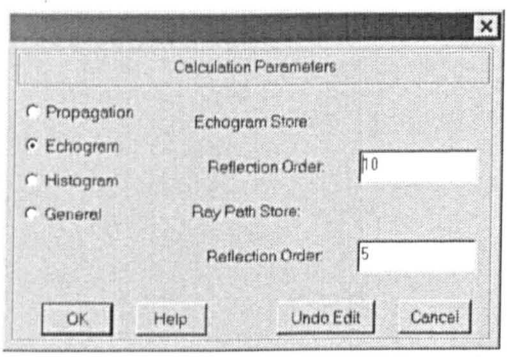


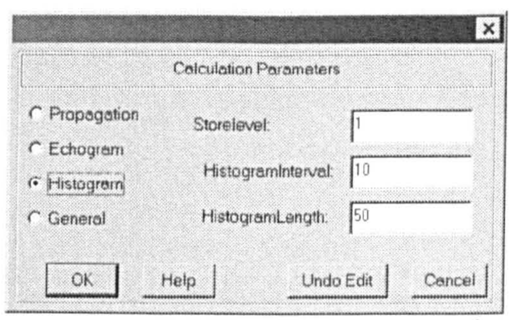
a b

Figure 2.7.4. *Mapping analysis. a) Main window of mapping calculation, b) Propagation parameters.*

The effect of the Echogram parameters, which can be seen in Figure 2.7.5a, is relevant to the echo saving procedure. The Echogram Store Reflection Order has a smaller value than the Reflection Order, giving the reflections which have an arrival time less than the time window, stored as discrete reflections in the echogram. The Ray Path Store Reflection Order indicates up to what reflection order the ray trajectories are stored individually with their arrival times and their amplitudes in the echogram. The reflections that arrive after the reflection order the user defines for the Echogram Store are added to the histogram bars that are displayed in the echogram.

The Histogram parameters relate to the histogram dimensions during the calculation, so the interval defines the width in milliseconds, while the length defines the number of time intervals that cover the full length of the response. If there is a need for assessing STI, the store level has to be defined with a value of 2, which allows modular transfer functions (MTF) to be calculated, with the prerequisite that there is at least one coherent source. The accuracy of the predicted reverberation time and other results derived from the impulse response results at a local receiver depend also on the settings of the Histogram Interval and Histogram Length, as shown in Figure 2.7.5b. The General parameters relate to optional procedures, such as diffuse reflections, diffraction, tail compensation, and conical or triangular beam method. These are shown in Figure 2.7.5c.





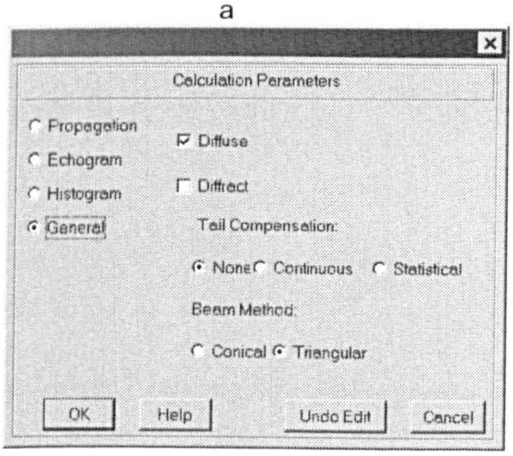


Figure 2.7.5. *Calculation parameters. a) Echogram parameters, b) Histogram parameters and c) General parameters.*

Extracting the results

The mapping calculation provides pressure contributions on field points at a number of chosen frequencies, for a specified source. For detailed analysis at a point, the Echo Saving is used. The mapping will then enable the PostProcess, from which the user will finally derive results of SPL, RT, EDT, STI, D50, C80, and much more, described in Section 2.2.2. It needs to be noted that Raynoise does not calculate G. The frequency response calculation, which considers a specific field point number that represents the receiver, is a narrow band computation of the frequency response function (FRF).

2.8 CONCLUSIONS

This chapter briefly reviewed the literature on the theory of sound, sound propagation and basic acoustic indices used for evaluation in room acoustics. The development of the science of sound from antiquity until today was also examined, particularly the application to room acoustics and the first evidence of architectural and applied acoustics. Moreover, it described basic identifiable characteristics of the nature of sound in ancient theatres as well as the acoustic conditions, as pointed out by previous research on the subject. Effects of temperature, relative humidity, wind, ground, trees and planting were also discussed. The chapter also briefly reviewed Beranek's subjective attributes, which were first introduced about half a century ago. Finally, it provided an introduction of the acoustic simulation software, namely CATT, ODEON and Raynoise, a detailed comparison between CATT and Raynoise, presenting each software advantages, and a brief discussion on the differences between Raynoise and ODEON. The selected software, Raynoise, was then described, including the basic algorithms, the simulation process and the appropriate calculation parameters.

Based on the review on the knowledge of sound and acoustics in antiquity, it was found that although the hearing mechanism was not clearly understood, auditory judgement, mathematics and logic had been criteria for interpreting acoustic phenomena, like the principle of equal angles of incidence and reflection, the speed of sound, the decrease in sound energy with the increase of distance, and the inverse proportionality between pitch and the length of the vibrating string. The observations in the field of architectural acoustics, which are related to theatre design, are of much interest in this study. These include the decrease of the chorus' voices in an ancient theatre when the orchestra was spread with straw, which was an indication of material absorption, and comments about wall reflections in a house. Also, Vitruvius' writings on theatre design, both in terms of layout and acoustics can be related to modern acoustics.

Regarding sound propagation outdoors there are several parameters, either architectural or environmental. Ancient theatre layouts create focus areas and multiple reflections between parallel sides. It has been demonstrated by modern acoustics that, in an outdoor performance space, reflective boundaries can improve the listening conditions for both performers and audience, and steeply raked seating is better for acoustic conditions, since both the direct sound and the angle of reflection is not parallel to the seating plane as with a horizontal layout. Ancient Greeks and Romans built outdoor performance spaces with the seats sloping upward or raked, and evolved their design by adding a stage building for the performers, possibly driven by optical lines, which may be in indication of fundamental acoustic design. The use of some kind of background or enclosure also provides a protection against background noise, which is identified today, especially due to traffic. Diffusion from destroyed edges or people's heads in the occupied condition allows a more even distribution. Moreover, the audience is usually very dense; hence the difference between the unoccupied reflective seats and the closely seated audience is large, opposite to an enclosed space.

Optimum RT values for theatres have only been suggested for indoors and, although recent research in ancient theatre reveals rather long RT there is still discussion about its significance outdoors. In this study RT30 and EDT are used to compare simulation with on-site measurements, in Chapters 7-10, acknowledging the fact that the subjective feeling of reverberation could be different in indoor and outdoor spaces, because of the absence of a diffusive field and the ceiling, which allows unique distribution patterns. Their use in relation to other acoustic parameters, such as the SPL, D50, C80, STI, G, and LEF are found sufficient for examining the acoustics of open-air performance spaces, while auralization can also be used.

As mentioned above the climatic and environmental conditions are also very important. Temperature and wind gradients affect the acoustic conditions like fog and snow affect background noise. Bending sound waves due to temperature changes can be taken into account both for the design of the theatre and the season/time chosen for a performance to take place, while the direction of the wind can be used for the orientation of the audience area. The influence of the ground material, like the orchestra in some cases of ancient theatres is also important. As expected, grass and shrubbery result in higher excess attenuation. Trees can also affect the acoustic conditions, through absorption, reflection and diffusion or even the edge effects of a forest, since most ancient theatres today are surrounded by them.

Furthermore, this chapter briefly discussed the subjective attributes that were used by Beranek for the evaluation of a hall, to introduce possible similarities with the subjective evaluation carried out for this research and presented in Chapter 8. Although these terms can be a common language for musicians and acousticians, their use for ancient performance spaces is less feasible due to the difference in perception outdoors.

Regarding Section 2.6 of this chapter it was noted that CATT, ODEON and Raynoise, which are widely used for the acoustic simulation of ancient theatres, are fundamentally based on similar algorithms. Their comparison showed that Raynoise is compatible with CAAD software, which makes it more user-friendly in terms of the model preparation, while CATT provides the user with more possibilities regarding calculation, required results, receiver directivities and automatic edge diffraction, and has comparatively short calculation times. Acoustic simulation of ancient theatres in CATT has not presented RT values, due to its inability to produce reverberation for outdoor spaces. ODEON, which was not available for comparison, has interestingly short calculation time, even 10 times quicker than Raynoise, and recommends avoiding small surfaces, especially for the parts of the room that contribute to strong early reflections. It is suitable for ancient theatre simulation and has been used in some previous studies. Based on the review and ODEON's unavailability, Raynoise will be used to simulate open-air performance spaces.

CHAPTER 3

THEATRE ARCHITECTURE, DRAMA AND ACOUSTICS IN ANTIQUITY

"I can take any empty space and call it a bare stage. A man walks across this empty space whilst someone else is watching him, and this is all that is needed for an act of theatre to be engaged".

Peter Brook (1968) The Empty Space, London

3.1 INTRODUCTION

This chapter is organised in a way that reflects the interdisciplinary nature of this research, in the fields of drama, architecture, archaeology and acoustics. Greek performances are said to have been created within and in response to a network of pre-existent spatial relationships [Wiles, 1997]. Contemporary theatre theorists suggest that the Greek theatre was not an empty space, but rather a part of a city's spatial and cultural organisation. This chapter presents a review on ancient Greek and Roman drama, performance spaces as well as town planning that allowed the construction of ancient Greek theatres. The evolution of the layout, materials and usages during the centuries is also briefly reviewed. The study attempts to form a connection between drama, architectural space and sound, through the performances and the human experience.

The study of a play is subject to understanding the original conditions of the performance. In the same way, the study of the acoustics of the performance space is subject to understanding the space in relation to the play. This is a rule that can be applied to either historic performances in antiquity, later types as the medieval or Victorian drama in Great Britain, or contemporary plays. Beckerman [1970] suggests that only the knowledge of the elements of the play can allow dramatic criticism and that its medium is not only language, but human presence, and one must return to the source of drama, the theatre itself. The activity of the theatre addresses an audience, or a society, thus it must be partly controlled by this audience. Drama can give a lot of information about the people who visit the theatre, the reason for attending a performance and their experience after that. The audience's experience during and after a performance is determined by several parameters. The plot is an important part of it and the basic component in provoking feelings like excitement, relief, sadness etc. However, the stimulation of the senses can be particularly related to the 'sound' of the performance [Mounajjed and Chourmouziadou, 2007]. Words, songs and music constitute that and should be experienced as appropriately as possible. Therefore the acoustic environment of each performance space is significant for the play itself and the audience that attends it.

The main purpose of this chapter is to review and relate the different disciplines of this study in order to identify the basis of the methodology and the simulation planned. The play, the space, the sonic environment and their interconnection are of main interest. Factors affecting acoustic indices are: sound source and amplitude, reflection patterns, temperature, relative humidity, as seen in Chapter 2. The elements that influence the layout of the performance space are material characteristics, temporary structures that can function as boundaries, positioning of actors and percentage of occupation, which will be examined in detail in Part 3.

The first part of this Chapter is a description of the Minoan period, the architecture in the forms of palaces, as well as the characteristics of the performance spaces, called 'Minoan type' in this study. Town planning in the Classic period in Greece is then briefly discussed and the first forms of theatre are analysed. Theatre development is also shown during the Classic and Hellenistic times and conservatories, or *odeia*, as they are called in Greek, are presented shortly. Greco-Roman and Roman theatres are introduced. To relate theatre architecture and development with drama itself, a presentation of the types of Greek Drama is carried out, in relation to the festivals and the audience's experience. Costumes and masks, important parts of ancient drama are described. The stage building and scenery in antiquity is also mentioned briefly, since they are extensively presented in Chapter 4. Finally, the types of drama and theatre architecture after the Roman period and until the 19th century are depicted.

3.2 Pre-Hellenic Architecture in the Aegean – Minoan Art and Architecture

This section refers to the earlier recorded performance spaces in Greece. At the beginnings of the 20th century the results of archaeological excavations in Crete were revealed to the public, of the existence of a widely spread Aegean civilization at the same period as the Bronze Age. Although the civilization evolved in the island of Crete in Greece, and was to some extend in contact with Egypt and with the mainland on the east and west, its characteristics were rather peculiar, but very important for the evolution and history of the European culture.

The Greek theatre as a concept had come through many types, following the cultural development of the civilisation from its peak to its decline. The first examples of rituals in ancient Greece appeared at the same time as the creation of the first organised societies during the Neolithic times. Later, there were rites that took place in palace courtyards, at the peak of the Minoan civilization.

In this study it is considered that the first phase of succession the theatre went through is the Minoan theatre. The excavation in Knossos and Phaestos brought the form of theatre of that period into light. According to Cailler [1966] they must have been the oldest theatres in the world. These theatres were used for holding contests, ceremonial rites, called *ταυροκαθάψια*, and other rituals and were the major public entertainment [Kontogiorgi, 2000[12]]. They differ little from the present day conceptions with their rectangular tier disposition and geometrically shaped orchestra and they are considered as brilliant examples of architectural design. Similar rites were performed at the Mycenaean civilization.

The art of moulding clay into objects, which were hardened with heat to produce utensils for domestic use or figures of primitive gods, was the first index of culture [Bell, 1926]. These objects were found in excavations in Knossos by Sir Arthur Evans and helped not only to reveal the growth of a single settlement, but a series of successive archaeological periods, and

[12] pp.15

sometimes by recognizing the specific dates of construction. In this way Evans gave the name Minoan to the prehistoric Aegean era. The Minoan period could be divided into Early, Middle, and Late Minoan, which are subdivided into three more.

Excavations revealed several scenes of dramatic and mimetic art through grotesque semi-human monsters on seals. Also, religious scenes, ceremonies and rites, were found in wall decorations and other smaller works of art. Furthermore, contests of strength and dexterity were often held, as well as boxing, wrestling and a sport dealing with the mastering of a bull, in which both men and women took part. It is unknown whether these kinds of contexts were held in the area described above, but it is certain that it was used for public spectacles [Bell, 1926].

3.2.1 THE PALACE AND THE THEATRE OF KNOSSOS

It is supposed that the hill of Knossos was one of earliest sites occupied in Crete, evident from the Neolithic deposits. In the Middle Minoan period the summit of the hill was levelled and the houses that were already there were cleared out, so that the new palace could be built. The palace occupied the summit of the hill and the east side, while the people were housed in the neighbourhood on the west. Figure 3.2.1 illustrates the plan of the palace. At some point in the history of the Minoan civilisation a fire destroyed the palace and the upper buildings were reconstructed from time to time.

An element of originality of the palace is an important feature near the north-west corner, behind the foundations of a long building. It is a paved area bounded on the east and south by wide flights of low and broad stone steps (Figure 3.2.1, no 25). The angle in which the lower steps of the two flights intersect is partly covered by a raised square platform, at the same level as the uppermost step on each side. At the outmost of the lateral flight on the south side were the footings of a low parapet with an interval in the middle for access to a paved causeway between the palace and the long building mentioned above. These imposing stepped ascents seem like part of the entrance to the palace. However, there is no frontage or gate (*propylaeum*) at the top of either flight, which would indicate a grand entrance. Therefore, these steps are not an architectural effect [Bell, 1926], but probably intended for the accommodation of spectators at athletic displays or possibly religious functions in the paved space below. This area has been described as the 'theatral area'. The steps overlooking the court may be regarded as an early equivalent of the Greek and the Roman theatre, especially since it was the slope of a hill that provided amphitheatric space both in the Minoan and the Greek Classic theatre [Bell, 1926]. In Section 8.4 the results of on-site measurements carried out in the performance space of Knossos are presented.

Figure 3.2.1. *Plan of the palace of Knossos. The theatre is shown at the north-western part, under the number 25 [source: Bell, 1926].*

3.2.2 The Palace and the Theatre of Phaestos

A similar type of outdoor performance space can be found in the ancient town of Phaestos, at the south-west of Knossos. The highest point of the spur was the acropolis of the former town, while the palace lay at the lower eastern end. It may have been the site of a chieftain's dwelling in Early Minoan times, although there is not enough evidence. The palace was built in the Middle Minoan Period, at the same time as that at Knossos, but at a smaller scale.

At the north end of the west court of the palace a wide flight of steps, with rises higher than that at common stairs can be found. At the top of the flight there is a wall or barrier. The court below is traversed diagonally by a slightly raised stone causeway leading from a side door in the palace to these steps, up which it is continued by a line of superimposed threads forming a more convenient stairway. This graduated platform was used as a theatre, or place for spectators during the existence of the earlier palace, and corroborates the significance assigned to the corresponding area of Knossos [Bell, 1926]. Figure 3.2.2 presents the plan of the palace of Phaestos, as well as the theatre, marked with *A*.

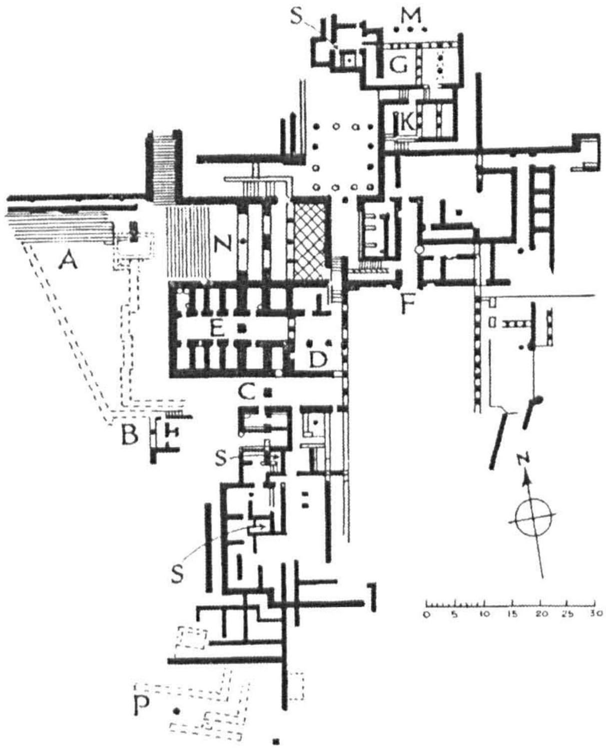


Figure 3.2.2. Plan of the palace of Phaestos. The theatre is shown at the north-western part, under the letter A [source: Bell, 1926].

3.2.3 Acoustic Evaluation of the Minoan Type of Performance Spaces

The outdoor performance spaces found through excavations at the palaces of Knossos and Phaestos can be considered primitive types of Greek and Roman theatres, as Allen [1963] has suggested. Although the layout of these spaces is somehow angular, as opposed to the circular layouts of later theatres, the acoustic can be considered acceptable, due to their small sizes. Direct sound, through speech and other sources was the means of an appropriate acoustic environment, where the facade of the adjacent building had possibly provided helpful reflections. A visit to the site revealed that the inclination of the audience area is hardly steep, and there is limited number of seats, which means that this area addressed only people from the palace, in a more intimate relationship between them and the performers. Moreover, the material is mostly local stone, which must have certainly helped in providing high-amplitude reflections.

Due to the importance of these findings, particularly as part of the evolution of the theatre in antiquity, a simulation will be carried out later in this study, in order to provide clear information about the sonic environment of the Minoan performance spaces, also validated by on-site measurements. In Chapter 7 a systematic examination of the Minoan and the other types of ancient theatre is carried out, for the evolution in theatre layout from the acoustic viewpoint. This is of equal importance since contemporary outdoor performance spaces are sometimes built based on rectangular layouts [Varopoulou, 1991].

3.3 GREEK AND ROMAN THEATRES

This section will present the basic layouts of the performance spaces used for ancient drama in antique Greece and Italy, namely theatres, mostly created after the 6th century B.C. in relation to the town planning, evolution, performance type and acoustics.

3.3.1 TOWN PLANNING, BUILDING SCALE, AESTHETICS, PERFORMANCE SPACES

The structures of the Classic period were the results of many different experiments and formulae in Greek architecture. The architects subdued their materials to the needs of the technique and conceptions before creating their final forms and styles. The conquest of plans and forms occurred in two stages. Available materials did not suit the early conceptions of the late 7th century, and until 600 B.C. no large project was created. From 800 B.C. and for two centuries many attempts were made with the use of wood, clay and marble but the most creative surge of forms and styles began at the turn of the 6th century B.C. with the use of marble, limestone and porous stone. Accordingly, the permanent theatres started to be constructed at that period. The buildings of balanced harmony that were constructed in the Classic period were in accordance with rules and standards, applied to architects through restrictions of both financial and architectural aspects.

Architects submitted their work for the approval of the bodies appointed by the state in models. Regional influences, choice of architectural order, requirements of the site in order to have a relationship between the building and the landscape, design details, proportions and decorative elements influenced the architect's originality. Greek architecture was simple in form and construction with the strict geometrical lines, thus it was important to have high standards in preparation and construction, in terms of workmen skills [Rolland, 1967]. The materials were often found on site. At Epidaurus, the contractors and workmen from Argos and Corinth provided and worked on tufa and porous stone from the Peloponnese, while the Athenians were responsible for the delivery and cutting of the Pentelic marble for the Tholos [Tomlinson, 1983]. The use of local materials for the construction can be attributed to high transport expenses.

The inspiration and interpretation of the Greek architecture can be found in the political and historical background it reflected. Architecture expressed unity and group life. The need for autonomy, the expansion of the group's political conscience and the development of institutions that ensured the independence of the *polis* (city), its community and its autonomy led to the erection of the city walls (late 6th century B.C.) and influenced the layout and construction of the first architectural centres. Neighbouring buildings were grouped around a public square, *agora*, which became the symbol of autonomous city states.

In the 5th and 4th centuries B.C. theatres and gymnasia, which were the settings for performances and games closely linked with religious life, became separated from the original centre. They gained individual architectural characteristics but still remained basic elements of the Hellenic town planning. Historical notes refer to the acropolis, the agora the theatre and the market as necessary elements of every Greek city [Rolland, 1967]. Figure 3.3.1 illustrates the plan and the model of the Akropolis at Athens. The theatre and the concert hall (*odeion*) are under the numbers 25-26 and 31 respectively.

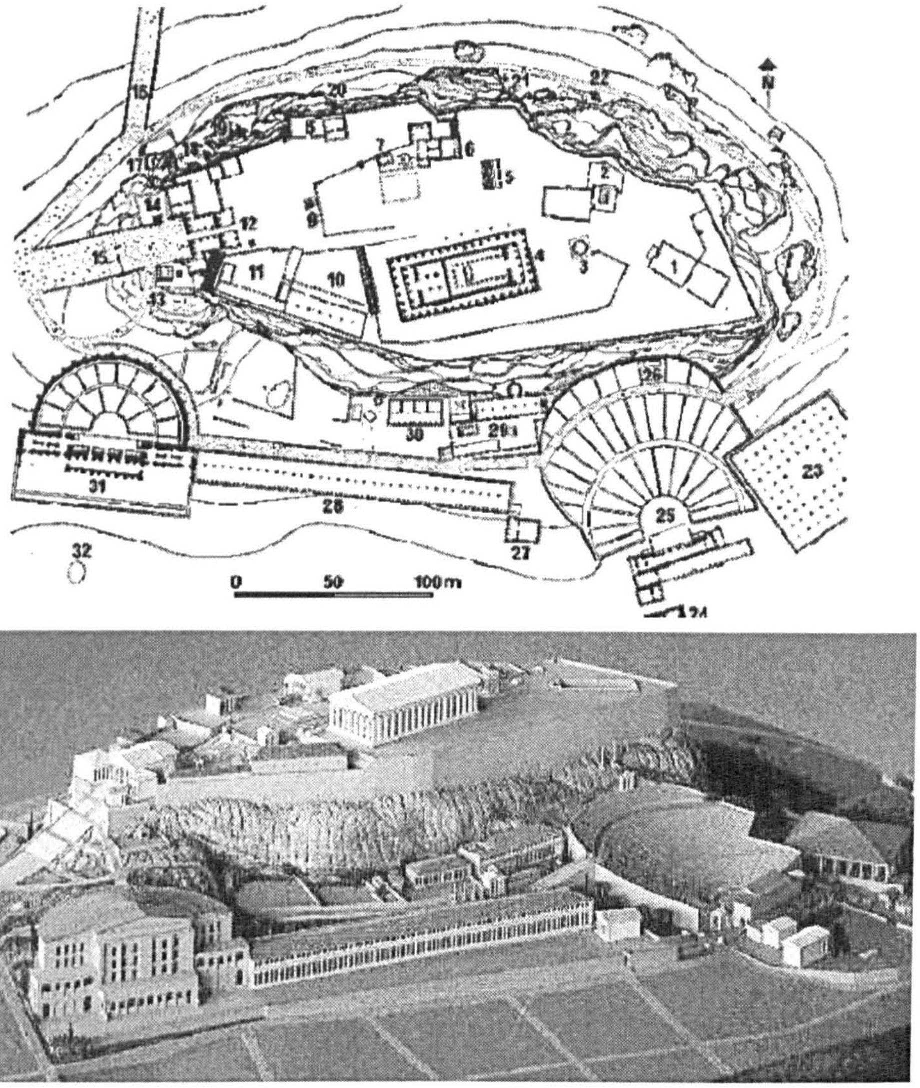


Figure 3.3.1. *Plan and model of Akropolis Athens. The theatre and the odium are at the south part, under the numbers 25-26 and 31 respectively [source: http://www.gottwein.de/Hell2000/athakr002.htm].*

Between the 4th and 3rd centuries B.C. the architecture of the city states was modified. The architecture as a whole and the principles of composition resulted in buildings that were not only group expressions but symbolised princely power as well. Large-scale prestige architecture developed, with plans and buildings in monumental scale and new aesthetic standards were applied, in terms of street facades, colonnades, flanking porticoes and decorated buildings [Rolland, 1967].

Festival, ritual, private rites and other aspects of intellectual and artistic life influenced the architecture of ancient Greece. Public readings, songs inspired by choral poetry, musical competitions and theatrical performances were very popular [Baldry, 1971]. The theatre played an important part in the citizens' life. The custom in Athens allowed even the poor citizens to attend performances and contests between the dramatists of their time. The theatre became a basic element of the city's architectural layout and an essential part of the community's life, since competitive theatrical performances were religious, literary, and even political in character.

During the Hellenistic period, buildings related to intellectual life, like schools of philosophy and academic teaching and gymnasia, were connected. Theatre design in this period was developed and divided into categories. Odeia and miniature theatres were established as part of the architectural layout of gyms and arenas, *gymnasia* and *palaestra*, and were erected in public squares and small temples [Rolland, 1967].

3.3.2 Greek Theatres

This part of the study examines ancient Greek theatres, from the Classic to the Hellenistic period. Several characteristics of the theatre will be presented and related to the acoustic environment of such spaces. This section will initially examine the early forms of the Classic theatre. It will then present the basic components of the development of the theatres, the orchestra, the audience area, namely the *koilon*, and the general layout, followed by possible irregularities that occurred in specific theatres. Moreover, seating systems, entrances and exits, stage buildings and materials will be discussed. Furthermore, this section will end with a brief acoustic evaluation of the theatres.

As mentioned before, the custom of holding *comuses*, early forms of comedy, in an orchestra arose, probably introduced at Icarion, a village of Attica, which was a centre of Dionysian religion. During the 6^{th} century a cult of Dionysus was introduced in Athens and his statue was brought and set up in a small temple erected on the south-eastern slope of the Acropolis. An orchestra was established, adjoining the temple, which was the beginning of the construction of the theatre of Athens. Generally ancient Greek theatres were not exactly alike and the various forms were the result of gradual changes and repeated readjustments [Allen, 1963]. However, they were the most original creations of civil architecture and their development continued into the Roman period. Theatres stemmed from rudimentary plans and represented a basic feature of the life of the city states. Theatrical performances were integrated with Greek manners and customs and became essential part of life.

3.3.2.1 Early forms of Theatre: Pre-Aeschylean and Classic theatre

Early forms of theatre consisted of simple flat spaces, sometimes paved, but more often of beaten earth, rolled or pounded according to Marquand [1909], where the chorus and dancers associated with the ceremonies of the cult of Dionysus could perform. This treatment of the performance area, which was later called orchestra, was altered in many performance spaces later, either by coating it with plaster, like in Delos, or by covering it with a marble and mosaic pavement like in Athens during the Roman period. When the orchestra was covered with sand for gladiatorial contests, it was known as the *konistra* [Marquand, 1909]. An altar to the god, the *thymele* (θυμέλη), stood in the center, which remained in the orchestras of later theatres, although it lost its central significance. In Priene it was relegated to the periphery of the orchestra and in later theatres it was totally omitted [Marquand, 1909]. The spectators sat around this dancing area, either on naturally sloping ground or on wooden stands.

The first performances took place in the agora in Athens, the central commercial, social and political part of the city, but, due to the fact that the wooden stands collapsed during a performance in 498 B.C., the Athenians transferred to the south side of the Acropolis where the audience was accommodated on the slopes at the foot of the cliff. According to fairly new research, it is possible that the theatre was always at the same place, on the Acropolis and never in the agora [Scullion, 1994]. The ground was levelled to form the orchestra and at its edge a few flimsy buildings were probably constructed off wood or canvas, known as *skene*, a building set at the tangent of the orchestra, containing properties and boxes. Its facade formed a background against or before which the simplified decors were arranged [Rolland, 1967]. A small temple dedicated to Dionysus was near. The architectural development started in the late 5^{th} century B.C. with the long porticoes and a few rows of stone seats, and continued until the Roman times. Stone constructions came in general use at the beginnings of the 4^{th} century B.C.

Several theatres were at first arrangements that suited a rectangular plan, similar to those used for assembly halls (like in Syracuse). The two basic elements were the orchestra and the koilon or *cavea*, as it was called in Roman times. According to Pöhlmann [1995], only lately it has become clear that theatres of the 5^{th} century B.C. outside Athens could be rectangular. Especially for the theatre of Dionysus at Icarion he suggests that it was rectangular, as well as the theatre of Euonymon. The latter had a quadrilateral playing space, but the auditorium was constructed in a rough curve around it [Wiles, 1997], although with an inclination that provided poor sightlines. Also, Pöhlmann [1995] implied a development from the rectangular to the round shape of the theatre, due to the problem of providing all spectators with the same visual and acoustic conditions, since the round form of the koilon was superior to the broad rectangle. In this study the early theatres with rectangular of trapezium layout are called the 'Pre-Aeschylean type'.

3.3.2.2 Discussion on Evolution

Another study that supports an evolution from the rectangular to the circular theatre shape was carried out by Gebhard [1974]. Wiles [1997] commenting on her study supports that an evolution cannot be proved, since both rectangular and circular layouts were constructed at the same time, and suggests that the rectilinear and circular shapes were created for different functions. However, since Roman theatres, which were certainly influenced by Greek design, were constructed in semicircular shape, it is not entirely wrong to suggest a process of transformation from the rectangular to the circular and then to the semicircular. It needs to be noted that this study does not particularly deal with the evolution of a specific theatre, like Dionysus, but rather with the general conceptions in design in the Greek and the Roman world.

3.3.2.3 Orchestra- Koilon-General Layout

The form of the orchestra was in most theatres nearly, or entirely circular, although at Thorikos it was almost a rectangle with rounded ends, built in the 5th century. The shape of the orchestra and the auditorium was possible predefined, due to the temple and the altar on the sides of the auditorium [Wiles, 1997]. However, it needs to be mentioned that there was no stage in the theatre, so it is probable that temporary facades were erected. Also, it lacked visual focus, due to the long orchestra and auditorium area. The theatre of Dionysus in Athens suffered many changes and still shows some of the blocks of the retaining walls of a circular orchestra dating as early as the 6th century B.C. The disagreement between researchers on its initial form is rather confusing. It has been mentioned that the seats could have been arranged in long parallel rows, in an analogy with Thorikos [Scullion, 1994]. In Epidaurus, which will be further described in Chapter 8, the circular form of the orchestra is emphasized by a ring of porous stone, which was decorated by a rounded moulding on the half of the circle towards the auditorium and has not been found elsewhere [Marquand, 1909].

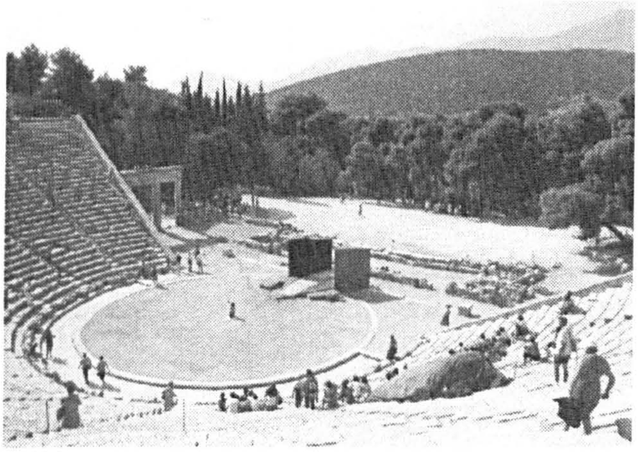


Figure 3.3.2. *Photo of the orchestra of the theatre of Epidaurus.*

The plan of the koilon followed that of the orchestra. In the theatre of Thorikos it was rectangular with irregularly rounded extremities, but elsewhere followed a circular plan. In Athens it resembled the end of a stadium and in Epidaurus it followed the line of a three-centred circle, which widened the passageway without sacrificing the continuous curvature in plan. Underneath this passageway, in Epidaurus and in other theatres, there was a channel which carried off the surface drainage of the orchestra and the koilon [Marquand, 1909].

The koilon in most theatres was subdivided in proper *theatron* and *epitheatron* (επιθέατρον, upper theatron), by means of *diazomata*, or horizontal passageways. There was one *diazoma* in most theatres, like in the theatre of Epidaurus before its extension, although in Megalopolis and Argos there were two, one usually narrower than the other. The upper part of the theatre was sometimes semicircular and concentric to the lower part, although in Delos it terminated in a pointed arch and in Athens in a horse-shoe arch, as shown in Figure 3.3.1, illustrating the plan of the theatre of Dionysus in Athens. There were stairways, known as furrows (*ολκοί*), radiating from the same circle, which subdivided the seats into wedge-shaped sections (*κερκίδες*). When there was an epitheatron, intermediate stairways were constructed [Marquand, 1909]. Vitruvius generalised this by the rule that above every diazoma the number of stairways should be doubled.

3.3.2.4 Irregularities

In terms of the aesthetics experiments must have been made for the plan of the koilon and its placing in the landscape, which aimed at achieving a balanced harmony between them. Not all of the theatres were planned and built with the same geometrical exactitude as in Epidaurus and other sites. In the latter the curve of the koilon was slightly irregular; it exceeded an exact semicircle and opened out at the ends to permit interior movement, as will be seen in Chapter 8. It was designed with a single radius directed from a single centre. As a rule, the middle section has its corresponding centre in the centre of the orchestra, but the end blocks have a more open circumference with longer radiuses extending from centres that do not correspond with that of the orchestra. These details, not obvious to the eye, only by measurements, resemble the optical corrections of the Parthenon and help to turn the theatres of Dodona, Epidaurus and Segesta into splendid geometrical compositions, perfectly set in the landscapes. The subordination of a theatre to the amenities of a site did not preclude its orientation to the south whenever possible [Rolland, 1967], although other orientations are found.

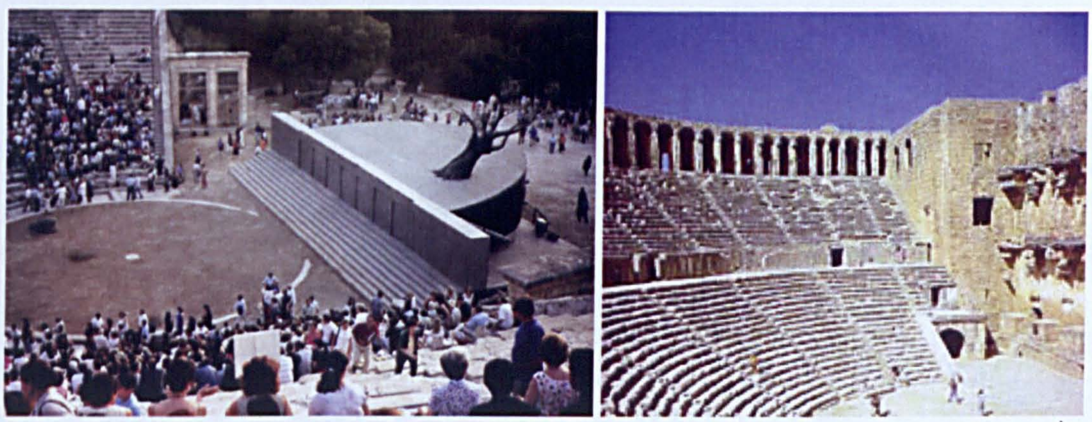
3.3.2.5 Seating System, Entrances and Exits

The seats of the theatres consisted of the thrones (*θρόνοι*), marble seats with backs, reserved for archons and honoured guests and the ordinary rows of benches. The thrones were either placed on the edge of the orchestra, in front of the passage at the base of the theatre, like in Priene, on the orchestra's level or slightly higher, like in Megalopolis and Athens respectively [Marquand, 1909]. However, in the theatre at Epidaurus there is an additional row of curved and decorated thrones at the base of the epitheatron. Moreover, the decoration of the ordinary benches differed in every theatre although most of them had a depression in the face and the top to accommodate the feet of the person seating above. Figure 3.3.3 shows the details of the seating system in the ancient theatre of Dionysus.

a b

Figure 3.3.3. Detail of the seating system at the theatre of Dionysus. a) Archons' seats and b) Typical seats.

The entrance to and exit of the theatre was possible through side passageways (*πάροδοι*, *parodoi*), placed between the koilon and the stage, which were usually closed with doors. In Roman theatres the parodoi became vaulted passages below the theatre, while the use of more exits was possible through the multiple passageways that their honeycomb structure allowed. These are illustrated in Figure 3.3.4.



a b

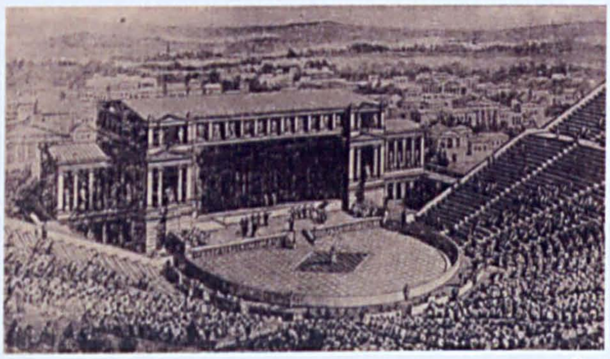
Figure 3.3.4. The entrances at the Greek theatre of Epidaurus and the Roman theatre of Aspendus.

3.3.2.6 STAGE BUILDING

In the early theatres the actors and chorus were performing on the orchestra, while a tent was sufficient for dressing purposes. Later a small wooden platform, called *logeion*, was created for the actors, separated from the orchestra by a few steps. According to Rolland [1967], it was the result of the interaction between actors and chorus during the play, while Marquand [1909] suggests that although the actors were distinguished from the chorus by the costumes, they could also elevate themselves above the chorus by standing on the steps of the altar platform, or above a temporary stand. In the Classic times the skene was built of wood, marble or stone.

The general notion is that at a point the actors were performing on the stage and the chorus on the orchestra. However, as Wiles suggests [1997], the fact that attention was transferred from the chorus to the actors, by the creation of the stage building, the latter changed the focal point of the performance, which used to be the centre of the orchestra. At the same time the stage building signified a hierarchy. Theatre theorists, based on this separation between the actor and the chorus, usually hesitate to verify the presence of the permanent low stage during the Classic times, unless it was just a platform, raised by a few steps [Wiles, 1997].

In the early 4^{th} century B.C., when the logeion was raised to form a proper stage, built of stone, it was supported by Doric or Ionic columns. The orchestra was enclosed by tiers of seats, until a point just beyond the diameter. In the late Hellenistic period, when the chorus had been given a reduced part in current plays, the stage building started to enter the orchestra, so that it did not form a complete circle. The Roman architects worked on this basis, using it as a model for their theatre plans [Rolland, 1967]. The advanced design of the stage building of the Hellenistic theatre of Dionysus and the Roman theatre of Aspendus is shown in Figure 3.3.5.


a


b

Figure 3.3.5. *Stage buildings of a) The Hellenistic theatre of Dionysus and b) The Roman theatre of Aspendus.*

The geometrical rules that Vitruvius laid down for Greek theatre planning were based on the design of Greco-Roman theatre type, seen in Section 3.3.4. In Roman theatres the extended logeion occupied half the orchestra circle [Marquand, 1909]. In the luxurious theatres of late Greek and Roman periods the stage facade was decorated with polychromatic marbles, bronze, silver, gold and ivory. A special device was sometimes used, when the actors had to appear or disappear suddenly. This was a subterranean passage (*κρυπτή είσοδος*), connecting the orchestra and the skene with steps at either side, probably closed with trapdoors [Marquand, 1909]. A detailed description of the stage/skene and the scenery used will be presented in Chapter 4.

3.3.3 Odeia

The *odeion* (*ωδείον*) or music hall was designed for musical contests and rehearsals of plays. The odeia were buildings that resembled the theatres, although they were smaller and covered with a roof (*θέατρον υπωρόφιον*). They were created in Roman times, although a similar type must have been constructed in earlier times. This kind of building is represented by the Odeion of Herodes Atticus at Athens, shown in Figure 3.3.6 in its present state. Recently, studies have been carried out for the acoustics of odeia [Rindel *et al*, 2006; Vasilantonopoulos *et al*, 2006]

Figure 3.3.6. *The odeion of Herodes Atticus.*

3.3.4 GRECO-ROMAN THEATRES

This section refers to two types of theatre that could be found in ancient Greece. The theatre of Dionysus was considered the most important of the Greek world in the 5th century B.C. and there is little evidence in the form of descriptive texts about the other theatres. All Greek theatres were similar in type, in terms of general layout, although not exactly identical. Many theatres were remodeled under the Roman influence, like the theatre in Athens, in order to resemble the Roman style of structure. However, since every theatre is unique and the remodeling different, it is difficult to categorise them.

The most famous Greek theatre, which never suffered any remodeling, and retained its Hellenistic type, found in excellent condition and still used nowadays for revivals of ancient Greek drama, is the theatre of Epidaurus, further presented later.

It has been suggested that a Hellenistic theatre could not be converted into a pure Roman theatre, in the process of modernisation [Allen, 1963]. Therefore a compromised form was adopted, which involved three fundamental changes: a deep stage was erected, the wall at the rear was made higher and ornamented, in conformity with the Roman style, and, with a few exceptions as in Athens and Priene [Allen, 1963], vaulted passageways (*vomitoria*) replaced the open parodoi. The stage was either at the same height as the proscenium (προσκήνιον, *proskenion*), the front of the stage building or *skene-building*, as it is usually called, or low like a Roman stage, as will be seen in Section 3.3.4, as a result of the reconstruction. The auditorium was altered either by adding, removing or replacing new seats of honour, adding few steps on the orchestra, or converting the orchestra into a pit. In these converted spaces the koilon was usually exceeding a semicircle, and the stage building was relatively small.

3.3.5 ROMAN THEATRES

The Roman theatre, like Roman drama, was Greek in origin [Robertson, 1979], although it differed in several respects from all Greek theatres of Classic or Hellenistic times. Many historians have dealt with the differences between the Greek and the Roman theatre, as examined below and in Section 3.3.6.

In ancient Rome drama was hardly regarded with the religious seriousness of the Greeks. Popular plays had neat plot and the chorus could be omitted. Many new theatres were erected and older Greek theatres altered for the performance of this type of play [Simpson, 1956].

According to the literature [Robertson, 1979], up to the early 3rd century B.C. there were no theatres in the Roman state. There were only some wooden stages-cum-scaffolding used for the performances of the popular farces or for productions of Etruscan drama. It is believed that the first Roman stage, made of wood, was erected in 364 B.C. at the Circus Maximus for the appearance of a troupe of Etruscan performers [Athanasopoulos, 1983]. Later, after Tarentum was captured, Romans came into contact with the advanced forms of Greek theatres, both in colonies of southern Italy and in metropolitan Greece. An interest in everything connected with letters, art and architecture was developed, and particularly in theatre architecture [Athanasopoulos, 1983]. It is worth mentioning that the Greek plays were adopted in Rome long before the first known Roman theatres were built.

The Roman theatres were initially constructed in wood. There is no evidence regarding their shape, but there is an assumption that the first structure Romans built for the purpose of the performance was a simple wooden stage, in front of which the spectators stood [Robertson, 1979]. It is noted that the early forms of theatre were common for several civilisations. There was an attempt in 150 B.C. for the construction of a permanent wooden theatre, but the Senate raised an objection for the use of seats, probably because an establishment of this kind would pose a serious threat to the militaristic way of life and would endanger the strict self-discipline and ascetic self-denial demanded of its populace by the developing state. Vitruvius [1st century B.C.] has also mentioned many wooden theatres, which were built every year in Rome, without providing any details of their form.

In the early days of theatre construction in Rome and the surrounding areas there was the *pulpitum*, a wooden platform with a structure at the rear to represent a stage building. Most of the theatres were wooden and the cavea, which is the equivalent of the Greek koilon, had no seating for the spectators.

The Roman theatres present many differences when compared with the Greek. It seems that some characteristics of Roman theatres were not the result of a steady evolution of the Hellenistic theatre [Robertson, 1979]. In the 2nd century B.C. the Large Theatre of Pompeii was built in purely Greek plan. During a period that commenced from the late Republican period many theatres, including the Large Theatre of Pompeii, were wholly or partly Romanised. This always consisted of drastic remodelling of a theatre and may have resulted from the earlier use of wood and the influence on stage construction of the farces from south Italy. As Robertson [1979] mentioned:

"In 58 B.C., the aedile M. Scaurus was allowed to build a wooden theatre of unprecedented magnificence, and three years later Pompey, inspired, it is said, by the Greek theatre at Mytilene, gave Rome her first stone theatre".

The same view is presented by Allen [1963], according to Plutarch's writings. The Roman theatre is said to be larger and more imposing. However, it was difficult to identify the resemblance, since the theatre at Mytilene was repeatedly restored and rebuilt, and became a typical Roman theatre. Today the theatre can no longer be seen, since, during the Medieval Times, most of the material was stolen to build the large castle of the area.

It is evident from the above that there were several innovations in theatre in Roman times, mostly related to the architectural construction of the space, rather than the plays or the scenery. Seats were added to the orchestra – a discrimination that would never happen during the Classic times of democracy in Greece, when the theatre was an educational institution. The orchestra and the main auditorium became semicircular, and peripheral corridors were created for the audience at the top of the cavea. The two or three-story stage building was established, depending on the need of every play, reaching the summit of the theatre, the parodoi were replaced by the vomitoria and staircases were constructed at the two sides of the stage for the viewers, leading to the architectural unity of the building. There was definitely a curtain at those times. However, the decline of the theatre leaded to low quality and rude performances, which was the main reason for the opposition of the Christians later [Kontogiorgi, 2000[13]].

3.3.6 Comparison between Greek and Roman Theatres

A fundamental difference between the Greek and the Roman theatre is the fact that the Greek theatre emerged from the orchestra, whereas the Roman theatre stemmed from a rectangular stage [Athanasopoulos, 1983].

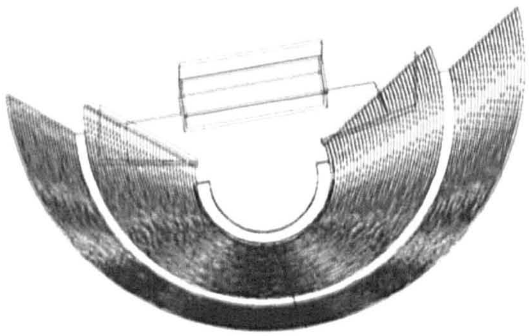
[13] pp.20

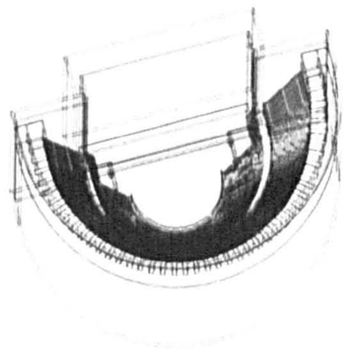
A basic principle of the Greek theatre was that the spectators' area 'embraced' the orchestra, the acting area, functionally uniting the one with the other. However, the Roman theatre preferred this relationship to be a confrontation [Athanasopoulos, 1983]. In this way, they placed the action opposite the audience thus the two actions were separated. The Romans retained the general shape of the cavea, but for functional and structural purposes abandoned the extended segment in favour of a strictly semicircular section. Architecture in Rome was generally massive; implying the power of the Roman law, while in Athens architecture was light, implying the triumph of *logos* (speech). Hence, whereas Roman architecture was based on the facade and the controlling gate, in Greek architecture columns were preferred to walls [Wiles, 1997].

Vitruvius [1st century B.C.] indicated that the architect should initially examine the site, the orientation, and the foundations of the theatre. He also suggested that Greek and Roman theatres could be designed based on a circle. For the Roman theatre, four equilateral triangles are designed in the circle, at same distances, having the same centre. The line that comes from two angles and the centre defines the skene from one side, and the seating area from the other. The angles of the triangles give the directions for the flights of steps. In this way there are five passage-ways, one of which runs directly opposite the skene, hence, in Roman theatres the line of perfect vision is taken by a passage-way. For the Greek theatre, three squares are designed in the circle. One of them determines the limits of the proscenium, while the ascending flights are directly opposite to the angles of the squares. Unlike Roman theatres, in the original form of Greek theatres there was no passage-way opposite to the stage. Therefore, corresponding to the literature, the Greeks built Epidaurus with a centre passage-way probably because of their dislike of the axial viewpoint [Simpson, 1956], and not following specific rules.

Moreover, the Greek theatre consisted of three parts, the auditorium with a great height, which exceeded a semi-circle, the orchestra, and a lower stage building [Robertson, 1979; Simpson, 1956; Athanasopoulos, 1983]. These parts were separated and the curve of the lowest seats of the koilon could be completed, or nearly completed as a circle, without cutting the front line of the skene, or even that of the slightly projecting proscenium, when there was one. Figure 3.3.7 shows the axonometric view of the Greek and the Roman theatre.

The auditorium or cavea of the Roman theatre on the other hand was semicircular and it was united as a single structure with the stage building, as illustrated in Figure 3.3.7b. There were vaulted passages at the point where the orchestra was connected to the cavea, to make the orchestra accessible. The important spectators were watching the performance from 'boxes' placed over these passages. The walls of the stage building had the same height as the cavea. The stage was low in height, and it usually had a solid front wall, though sometimes it had doors leading to the space underneath. It was projecting much further than the proscenium, affecting the shape of the orchestra, which was reduced to a semicircle. Although the stage was low, its depth was increased because all the actors performed there. The proscenium was high enough for actors to walk beneath it to the orchestra, and its front was treated as a colonnade, closed only with wooden panels and doors.





a b

Figure 3.3.7. *Axonometric views of the a) Greek theatre of Epidaurus and the b) Roman theatre of Aspendus.*

The orchestra in Roman theatres was part of the auditorium. It was often arranged in broad steps, for the accommodation of moveable chairs for important spectators. The skene with the proscenium was not longer than the orchestra's diameter, but the pulpitum usually had the double length. The front stage wall was simple in design, but the rest of the stage building was decorated with columns and niches. The preferred site for the construction of the theatre was usually a hill, but the Romans, unlike the Greeks, built their theatres on flat ground, in their cities, developing and structurally supporting the cavea [Robertson, 1979].

Additionally, the trend towards uniformity of mass created an integral architectural whole. Vitruvius [1st century B.C.] suggested that the acoustics of the Roman theatre were improved for this reason. Moreover, the height of the stage building and the cavea made it possible for Roman architects to devise a form of roof, a tent or awning that was named the *velum* or *velarium*, to cover the entire theatre.

There is also an example of a rectangular Roman theatre, called the Small Theatre of Pompeii, built around 80 B.C. It is believed to be a compromise between a rectangular hall and a curvilinear theatre. The significance of this structure lies to the fact that it was covered with a roof. Fiechter [1914] indicated that this building supplies the key to the character of Roman theatre architecture and that it unveiled a tradition of rectangular wooden theatres. However, as Robertson [1979] stated, this theory explains the link between the cavea and the stage building in the Roman theatre, but there is no evidence that supported a tradition of rectangular theatres. Additionally, there are a few earlier Greek constructions that had fitted the curvilinear auditorium into a rectangular building, such as the Bouleuterion of Miletus (2^{nd} century B.C.) and the Thersilion of Megalopolis (4^{th} century B.C.).

The Roman playhouse diverged from the purpose for which it was created, just as drama itself lost its meaning. The principal function of the theatre was not to satisfy the needs of culture and education any more but to entertain [Athanasopoulos, 1983]. Because of the huge dimensions of the skene-building and its overpowering weight, the actor was 'diminished', but this was of no account at those days, when the actor was likely to be a slave or a prisoner of war. The impressive effects were of much more importance.

3.4 Previous Studies on the Acoustics of Ancient Theatres

The first thing that must be mentioned about the ancient Greek theatres is that the background noise was generally very low, which was important for the unassisted speech to be audible. On the other hand, the sound from the whispering audience was far more important than today's, since the audience could reach 30,000. Previous studies have systematically examined the effects that determine the acoustic environment of the ancient theatres and have created formulas that connect the dimensions of the theatre, the reflection paths, the direct sound and the inclinations. One of them was 'equation canonique', formulated by Canac, a complex trigonometric equation involving the inclination, the axial development of the koilon, the orchestra radius, the width and height of the proscenium and the position of the stage building [Canac, 1967]. However, much of discussion has been carried out for their accuracy.

In most cases the audience received the direct sound from both the actor and the chorus, followed by a reflection of the orchestra floor. The more the actor approached the audience, the smaller the part of the audience that received the direct sound, due to the propagation of sound at nearly grazing incidence. Some studies referred to a useful acoustic zone, the 'Haas zone', a narrow space created by the tangent of the orchestra, the *paraskenia*, the sides of the stage building, and the stage building facade [Canac, 1967; Mparkas, 2004a]. Also, the centre of the orchestra was important from the acoustic, the visual and the focal viewpoint. Direct sound was good for all positions, sound travelled back to the performer, increasing his confidence, while the audience was focusing on his appearance. The centre of the orchestra was a good position 'not to see but to be seen' [Wiles, 1997], "*the strongest acting area, and we find evidence in the tragedies themselves that the 5th century (B.C.) playwrights recognised this fact*" [Rehm, 1992].

A fan-shaped theatre, with an angle of 210°, such as the theatre of Epidaurus, implied poor visual and acoustic conditions in the extreme seating areas at the sides of the orchestra. The ancient Greeks, who had probably observed this, solved that problem by reserving these seats for foreigners, latecomers and women [Barron, 1993].

Knudsen's measurements in the Mohave dessert showed that normal speech in a quiet location with no wind could be heard satisfactorily at a distance of 42m in front of the speaker, 30m at the side and 17m behind [Knudsen, 1932]. In Epidaurus the furthest seat after the extension of the koilon in the second century B.C. is around 100m from the stage. The early reflection increases the energy of the direct sound and in the case of a single early reflection off a hard surface the sound energy gives a 3dB increase [Barron, 1993]. At the same time, sound is reduced by 6dB for every doubling of the distance and the net effect of a single reflection is to increase the distance limit of satisfactory listening by a factor of $\sqrt{2}$. In the case of Epidaurus the reflection off the orchestra increases the distance from 42 to 60m. With the addition of the reflections from the skene-building, even if their energy was small, since the skene-building was behind the speakers, the speech transmission over 70m seems realistic. Moreover, the orientation of the theatre could have influenced the acoustics, in terms of temperature gradients and wind direction, as analysed in Sections 2.4.2 and 2.4.3. The audience's presence however would cause alterations in the reflection pattern and also absorption. It has been suggested that, regarding the reflection from the orchestra, the angle that the koilon inclination and the reflection are creating should be larger than 4° [Canac, 1967].

Since the acoustics in these spaces depended largely on the direct sound, the fact that the audience absorbed more sound energy by sitting on steeply raked rows of seats, thus being exposed to the sound [Kuttruff, 1973], was less important. Opposite to a horizontal layout where the sound path would be parallel to the audience plane, the steep seating area provided good conditions, because larger angles of incidence to the seating area were beneficial, and reduced the attenuation caused by the seating audience. Shankland [1973] supported that the unoccupied seats, with backs or risers sloped backward by about 10°, and the heads of the audience also scattered the sound to adjacent areas.

It has been suggested by Pöhlmann [1995] that the acoustic conditions, especially at the upper rows of the spectators, were improved by the appearance of the actors on a higher platform, especially since the upper level of the skene served as a sound reflector. On the other hand, the use of theatre buildings as a place for assemblies might have contributed to the development of the skene, because an individual speaker stood at the proscenium, so he was clearly visible and audible [Pöhlmann, 1995]. Arguments for a stage on acoustic grounds are based on the fact that the rear of the stage acted as a reflector [Wiles, 1997].

It is believed that the acoustic environment created in the Roman theatre was better than the Greek, because of the enclosed space it provided. The acoustics of the Roman theatres are certainly different from the Greek types, due to the layout and architectural characteristics of the stage building [Chourmouziadou and Kang, 2002]. The raised stage wall, as mentioned earlier, contributed to the increase of reverberation, due to the multiple reflections between this and the audience area [Chourmouziadou, 2002]. Also, the peripheral corridors, with low absorption, directed the reflections back to the stage building, and sometimes the centre of the 'imaginary' circle, the one the plan of the theatre was based on, which coincided with the central axis of the stage building. Hence the reflections were repeatedly sent back and forth, resulting in long RT values. The velarium, the fabric covering most of the audience part, was also hanging with ropes between the stage building and the audience perimeter [Izenour, 1977]. Although the absorption coefficients of the velarium are not known, it has been recently pointed out that similar fabric structures in an outdoor theatre were reflective at high frequencies, affecting both speech transmission and intelligibility [Mapp, 2000]. The hyperbolic paraboloid of the theatre in Rutland was causing focusing effects and this may have been the case in the Roman theatres. Nevertheless, their layout approached the later indoor theatres.

In the last two decades many studies have focused on the acoustics of ancient theatres, based on theoretical analysis, simulation and the comparison with on-site measurements, aiming mostly to identify the acoustic conditions of the theatres in antiquity. Mparkas [1992] and Goularas [1995] have analysed the acoustic environment and the methods used for the evaluation of ancient Greek theatres including Epidaurus, based on previous studies, especially Canac's [1967]. The former has also published a paper on the effect of the acoustics on the design of ancient theatres [Mparkas, 1994], focusing on Greek theatre types. A detailed study on the acoustics of ancient monuments in Greece by Vasilantonopoulos and Mourjopoulos [2001], mainly ritual and public spaces, was published later that showed the rather long reverberation values that were purposely created in specific public spaces in Athens.

A study on the simulation of ancient theatres was carried out by Chourmouziadou and Kang [2002], which mainly focused on the design and materials of Classic, Hellenistic, Roman and Chinese theatres, and the performance perception through the new method of auralization, provided by simulation software. Actors were invited to perform ancient Greek, Roman and Chinese drama in anechoic chambers, and the signals were imported in Raynoise. Part of it is presented in Chapter 7. This study was followed by a dissertation, presenting methods for simulating outdoor performances spaces, used for Greek, Roman and Chinese drama, as well as the comparison between them in terms of architecture and acoustics [Chourmouziadou, 2002]. It revealed that, opposite to the Mediterranean, the performance spaces in Asia developed in a manner that exemplified temporary structures and the surrounding area with the use of water, hills, etc, while the more permanent structures gained a strict rectangular layout. The basic differences between the circular, semicircular and rectangular layouts in terms of distribution and reflection patterns were pointed out in a later study by Chourmouziadou and Kang [2003], where material properties and simulation parameters were of major concern, seen in Section 7.7. At the same time, Vasilantonopoulos and Mourjopoulos [2003] carried out acoustic simulations for the ancient theatres of Epidaurus, Dodoni and the Roman Odeion of Patras, revealing that the excellent acoustics of Epidaurus were possibly related to the increased diffusion, that the reverberation was below 0.20s and that there were important differences between the three theatre layouts in terms of acoustics. Later, the same authors [Vasilantonopoulos and Mourjopoulos, 2004] as well as Vasilantonopoulos *et al* [2004] presented a comparison between acoustic simulation and detailed on-site measurements of the theatre of Epidaurus, validating the previous results on the acoustic indices. At that time, the study carried out by Chourmouziadou and Kang [2004] focused on the present use of ancient theatres and the application of temporary scenery design. By examining the recently excavated theatre of Mieza, as will be presented in detail in Section 9.2, the effect of scenery constructed for ancient drama performances on the acoustic environment of the theatre was identified. Also, Mpakas [2004a] studied the acoustic comfort in ancient Greek theatres, in relation to their present day function and possible applications of reflecting boundaries.

During this time, a European Commission funded project on the identification, evaluation and revival of the acoustical heritage of ancient theatres and odeia (ERATO) had started, by several countries in the Mediterranean and Europe[14]. One of the teams involved in this project, from the Technical University of Denmark, published the first part of their research that involved the comparison between acoustic simulation and measurements of the theatre of Aspendus in Turkey [Gade *et al*, 2004], revealing that the RT of Roman theatres is at the range of 1.40-2.0s. They carried out their study in relation to the development of ODEON software and later presented ways of representing the ancient theatres and selecting calculation parameters [Lisa *et al*, 2004], as well as comparing and matching the simulation and measurement results [Gade *et al*, 2005]. Through the latter the importance of the effects of diffraction in the acoustics of ancient theatres was indicated. They also studied the acoustics of the Roman odeion of Aphrodisias to indicate the differences between the layouts of Roman theatres and Odeia [Lisa *et al*, 2005], and to virtually reconstruct the sound [Rindel *et al*, 2006].

The effect of scenery on the acoustic performance of ancient theatres, and the avoidance of background noise coming from external sources was also investigated regarding the theatre of Philippi [Chourmouziadou and Kang, 2005], as seen in Section 9.3. Moreover, recent studies focused on the increase of reverberation in ancient theatre due to the installation of temporary scenery [Chourmouziadou and Kang, 2006a], verified by on-site measurements and subjective evaluation tests, discussed in Section 8.4 and 8.5, and the detailed investigation of the effects of diffraction and diffusion in open air theatres [Chourmouziadou and Kang, 2006b], investigated in Chapter 6. Furthermore, studies on Roman odeia reveal the acoustics in indoor ancient performance spaces [Vasilantonopoulos *et al*, 2006], while more attention is paid to performance types and conditions, as well as the use of the theatre area and the ancient stage building by the actors [Mparkas, 2006]. The latter has indicated that when there is no boundary at the back of the actor, the sound reaching the audience is less intense.

Overall, it has been shown in this section that the interest in the acoustics of ancient theatres is currently growing, while the performance styles are also receiving attention. The development in technology through simulation methods and virtual reconstruction allows for more detailed

[14] The countries participating are: Denmark, Turkey, Jordan, Italy, France and Switzerland.

examination, though always with the parallel use of measurements and other research methods.

3.5 PERFORMANCES

3.5.1 GREEK DRAMA

Prior to the creation of drama ancient Greece had cultivated melic poetry, intended to be sung to instrumental accompaniment, which in its choral forms was accompanied by dance movements. The choral odes of tragedy are believed to have derived from this type of art. Choric dithyrambs – improvised chants that evolved into a medium of poetic and literary expression – sung in honour of god Dionysus, the epic, like Homer's Iliad and Odyssey and, during the 7th and 6th centuries B.C., poems of iambic and trochaic verse-forms contributed to the growth of drama [Allen, 1963]. Figure 3.5.1 illustrates members of the chorus during a performance. Three forms of drama were created in Greece, tragedy, comedy and satyr-play [Bieber, 1939]. The essence of dramatic art was mimesis, representation and impersonation.

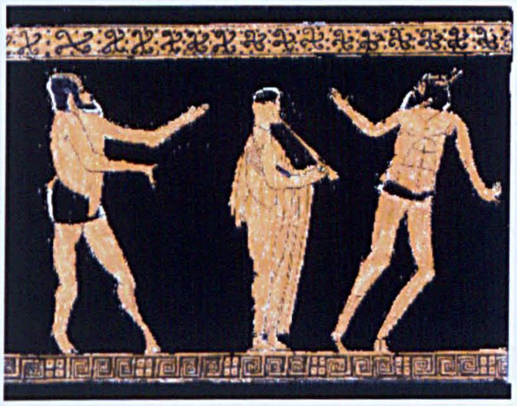


Figure 3.5.1. *The chorus singing in honour of Dionysus [source: http://www.richeast.org/htwm/Greeks/theatre/actors.html].*

However, the way drama evolved was through rude performances in the countryside and villages in connection to religious festivals and rites. The plays that developed had different names in different areas [Allen 1963]. Between 580 and 560 B.C. the semi-dramatic choral performances were brought to Athens and became a regular feature of the old 'Lenaean' festival. Later they were added to the 'City Dionysia' festival.

3.5.1.1 TRAGEDY

The word tragedy (τραγωδία) means goat-song (τράγος, goat; ωδή, song). Tragedy was born during the late 6th B.C. Thespis, who lived in that century in Icarion, was the poet that introduced an actor who addressed the chorus, engaged in dialogue with their leader and by changes of costume and mask impersonated different characters [Allen 1963]. Although Thespian drama's *choreutae* (chorus' members) and choral songs may have resembled those of satyr play, the addition of an extra performer, the actor, completed the foundations of Greek dramatic art.

Aeschylus (525-456 B.C.) introduced the second actor and made many improvements in the substance and the form of drama and in external elements, such as costumes and settings. Sophocles (496-406 B.C.) introduced the third actor [Baldry, 1971], portrayed the characters and gave complexity to the plot-construction [Allen, 1963]. Euripides (485-406/5 B.C.) universalised dramatic art and his plays were the most popular in all Greek civilization for hundreds of years after the 5th century B.C.

After the death of Sophocles and Euripides Athens was defeated by her enemies (404 B.C.), and the tragedy began to decline. During the 4th and 3rd centuries B.C. tragedy of inferior quality was produced in many centres of the Hellenic and Hellenistic culture even until the reign of Hadrian (117-138 A.D.). Old plays, especially the tragedies of Euripides were performed in dramatic festivals, and this custom of repeating ancient dramas survived with less frequency and popularity until the 5th century A.D. of the Christian era.

The relation between the play, the space and the acoustics is of great importance. Wiles [1997] refers to the careful design of the theatres of the 5th century B.C., so that they would be of superior quality. Tragedy was a performance that involved a lot of emotion and the audience was moved by the plot. The Greek theatre brought together the performers and the audience due to its shape, and the direct sound was the basic means of sound distribution. However, the audience's response to the play would have been very intense, since the direct sound of maybe 15,000 surprised people reached the performers at the same time. Thus, the actor's experience was also of great importance. Moreover, Aeschylus' improvements in costume and stage design may have changed the sonic environment of the theatres, in terms of absorption, reflection and diffusion, as will be seen later in Chapters 6-10.

3.5.1.2 COMEDY

The early history of comedy is very obscure and it is not until as late as 486 B.C. that it received official recognition in Athens. Comedy was also based on the worship of Dionysus. Masked and cloaked citizens sang derisive and ribald songs in honour of Dionysus. The chants of the chorus in comedy were often satiric lines addressed to the audience evoking a response. This became part of the ritual and later led to the form of a second chorus, which distinguished comedy from tragedy [Cartledge, 1999].

The first form that developed was Old Comedy, the comedy of the 5th century, complex in structure and local in colour and theme, known from the plays of Aristophanes (around 446-385 B.C.). According to Allen [1963] "*it was an exuberant, choral and dramatic extravaganza in which satire and burlesque accompanied by political and personal invective and acting of the* *slap-stick variety predominated*". Although it was complex in structure and local in colour and theme, it didn't survive the downfall of Athens after the Peloponnesian war (404 B.C.).

New Comedy, a new type, more refined and less local in colour, aroused about three quarters of a century later; around 330 B.C. Middle comedy was a transitional stage between the two, which flourished for about three quarters of a century, from the decline of Old Comedy, to the rise of New Comedy in the days of Alexander the Great.

Comedy's spatial meaning can be regarded more complex that tragedy's. First of all, comedy had usually two choruses, which immediately raised/doubled the number of performers. Because of its nature, comedy was very popular, dealing with either historic and fictional tales or contemporary political events. The actor provoked the audience and the response was immediate. The atmosphere was lighter than in tragedy, since songs, text and even visual effects evoked joy and laughter.

3.5.1.3 SATYR PLAY

One of the sources of satyr play, and probably of tragedy as well, is found in certain phallic mummeries, in which the performers imagined themselves to represent nature sprites, vegetation spirits and animals and were popularly known as *sileni* or *satyri*. The characters were the chorus of satyrs and an actor who impersonated a *Silenus*, the father of the satyrs. The subject was usually a humorous story taken from mythology or legend, treated in "*a vein of sportive and even obscene gaiety*" [Allen, 1963]. Although until the end of the 19th century it was supposed that tragedy was a refined kind of satyr-drama, today it is believed that they are related but separate in origin. Tragedy exercised considerable influence on this species of drama, but the tone was far from tragic.

3.5.2 GREEK DRAMATIC FESTIVALS

The oldest festival held in the city of Athens was the Lenaea. Its importance as a dramatic festival began in the early 6th century, between 580 and 560 B.C. when voluntary performances of comuses were made part of the program. There is no information from that period and until sometime after the middle of the 5th century B.C., when a contest of comic and later a contest of tragic poets were established. The records indicate that two poets competed for the tragic prize, each with a trilogy, a group of three plays, and five poets, each with a single play, competed for the comic prize.

The City Dionysia, or Great Dionysia, was another festival, far more important for the history of drama, which was celebrated in honour of Dionysus Eleuthereus since the 6th century B.C. The first contest in tragedy was held on the occasion of the City Dionysia and Thespis was awarded the prize. From that time and until the 2nd century A.D. tragedy was the main feature of this festival [Allen, 1963]. Before the close of the 6^{th} century satyr-drama was introduced, while at about 508 B.C. a contest of dithyramb choruses of men was added, from which comedy developed. In the 5^{th} century B.C. three poets were competing for the tragic prize, each with three tragedies and a satyr-drama, and five for the comic prize. The group of four dramas was called *didaskalia* [Allen, 1963]. The evidence has shown that the audience was composed by men, women, boys and even slaves.

In the 4^{th} century B.C. some changes were introduced, such as the performance of an old tragedy as a start of the regular competition, while after the close of the 4^{th} century B.C., the production of new tragedies diminished, so old plays were repeated. Also, instead of presenting a satyr-play, each tragic poet had to present a satiric play at the beginning of the program. This arrangement lasted several hundreds of years. Moreover, in 339 B.C. the contest between the comic poets was preceded by the reproduction of a comedy previously exhibited. These plays were merely chosen from New Comedy.

Another important ceremony was held in the odeion a few days before the start of the City Dionysia, which was called the *Proagon*. The tragic poets, the *choragus*, the person that provided the finances, the actors and the *choreutae*, the chorus, presented themselves to the audience, in order for the people to remember names during the contests.

3.5.3 The Audience's Relation to the Performance

Ancient drama is believed to be a reactive act. The spectators, as seen in Section 3.5.1 usually replied, or at least reacted to the questions imposed to them by the chorus. However, how can a theatre of such vast size, as the theatre of Dionysus in Athens with 17,000 spectators, or the theatre of Ephesus with 56,700 spectators, could allow the audience have a 'conversation' with the chorus? The visual details were diminishing as the distance was increasing, although the scale still remained [Styan, 1975]. The number of chorus was far greater than that of the actors and their songs and dance must have dominated the static actors with *cothurnus* (shoes that aimed to increase the actor's height) on their feet, which remained remote and impersonal. Also the chorus, due to its position in the theatre, was closer to the audience and may have expanded its visual and aural impact.

Moreover, the question that was applied previously in regard to the relationship between the audience and the play in such a big theatre can be partly answered by the theatre's layout. The almost circular shape, as opposed to later shoebox theatres, allowed the audience to surround the core of a play, which psychologically and visually improved their relationship [Styan, 1975]. Moreover, the effect of the audience in a performance space has been stressed in many previous studies [Beranek and Hidaka, 1998; Bradley, 1991; 1992 and 1996; Davies *et al.*

1994], particularly regarding reverberation. This will be further discussed in Part 3 of the overall study.

3.5.4 The Actor

The actor was, above all that he impersonated, the voice that reached out, over the orchestra, the most remote rows of the auditorium. He was trained to have a strong voice, so that he could be heard throughout the theatre without shouting. As Baldry [1971] has mentioned:

"There was no reason to suppose, as was once thought, that the mask did anything to enlarge it. But other qualities were equally necessary: clarity, correctness of diction (the comic playwrights never tired of making fun of one notorious mispronunciation), fineness of tone, adaptability to character and mood".

It was important for the actor to have the ability to change his voice, as well as his mask, from young to old and from man to woman. Argument and narrative were the two uses of spoken word in both theatre and every day life and the actor had to be equally effective. He had a good knowledge of music, while sometimes during the performance he sang a lyric solo or stanzas in alteration with the chorus. The chorus was facing towards the actors with their backs towards the audience, turning round only for the performance of their choric odes.

3.5.5 Costumes and Masks

The costumes were also of great importance. Luxurious fabrics and several accessories were used. In Roman performances the costumes were highly decorated. However, the important part of the costume in Greek theatre was the mask (προσωπείο), which specified the role and had practical use of relieving the actor from exhaustion, since the same actor performed several parts in the same play [Alexiou, 1994[15]]. Figure 3.5.2 illustrates a female and a male mask from the performance of 'Prometheus Bound' in 1927.

Both the chorus and the actor(s) wore masks. It has been suggested that the masks were partly derived from the drama's religious origins [Arnott, 1959]. It is said that Thespis experimented with painting his face. The mask could accentuate the face as an idealistic character, made of linen, or occasionally of cork or wood, by using a marble or stone face as a mould. It covered the whole head or most of it and had hair attached [Baldry, 1971]. Masks were necessary in the Dionysian religion and also helped the male actors impersonate female characters. The chorus wore masks, usually similar to each other but completely different from the leading actors. In the actor's case, the mask in ancient Greek performance exaggerated his expressions, maybe because of the size of the theatre. Also, it provided height to the actor. It is believed that it had

[15] pp.68-72

characteristics that influenced the acoustics. The open mouth of the Greek theatrical mask provided the requisite passage for the actor's voice, but it also symbolised tragedy's need to "*bear spoken witness to the unspeakable, to keep talking in the face of horror*" [Rehm, 2002]. According to Egan [1998], it reinforced their voices since conical-shaped megaphones were built into the mouth. Therefore, it is possible that the facial characteristics of female masks provided not only optical recognition but also a difference in the voice, although the actor was trained, so that, above all that he impersonated, he would be the voice that reached out, over the orchestra, the most remote rows of the auditorium.

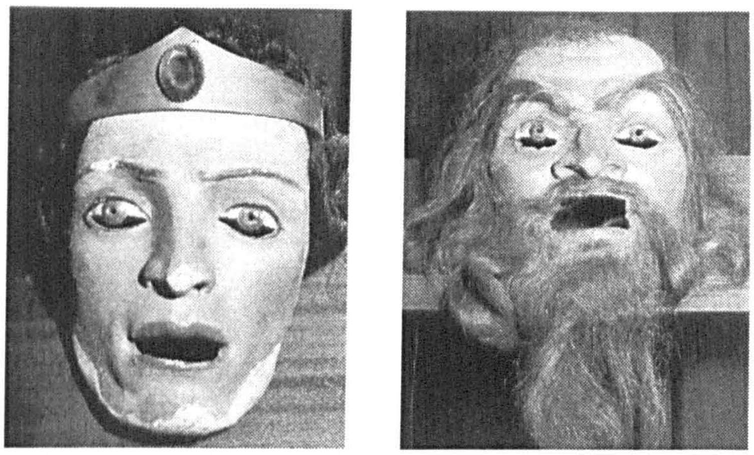


Figure 3.5.2. *Masks used at the performance of Prometheus Bound in 1927 [source: Kontogiorgi, 2000, pp. 58].*

3.5.6 The Role of the Chorus

The chorus existed before the tragic plays. The chorus in ancient Greek drama was usually leading the performance. The number of the members of the chorus is another subject of ancient Greek theatre that is in dispute. Fifteen is the number Sophokles is said to have used, while the text of 'Agamemnon' was written for twelve chorus members. Vases illustrate groups of six dancers and inscriptions refer to fourteen chorus-men [Wiles, 1997].

This section describes the chorus' role, based on the performance of 'Thesmophoriazousai', the Athenian women celebrating *Thesmophoria*, used for the subjective evaluation of the acoustics of the ancient theatre of Epidaurus, which will be discussed in Chapter 8. There were many women actors impersonating the Athenian women. In this comedy their presence was taken from everyday life and integrated into the plays. As Seidensticker [2003] mentioned, there are many important aspects on the chorus' presence in the play; initially its appearance, then its size, which could fluctuate from 5 to 12 people and even more, its dramatic role, the choral odes, the dancing and its general function. Choumouziadis [2003] referred to the tragic chorus as an important part of drama, the mode of the performance, and to the actor as the function of the performance. There was a leader in the chorus, the person that discussed with the actor, the representative of the chorus, the one who described the myth. Very important points were the formation of the dialogue and the treatment of the myth. The performers of the chorus were never equal to the actors, the *protagonists*. They acted as a unified voice, a net group of individuals. The practical role/function of the chorus and the difference between them and the actors was that they entered the theatre from the parodoi, not the skene-building. Moreover, their presence was important from the acoustic viewpoint since it was a unified voice, with high amplitude, resembling an area source. Their position was always in the orchestra, although in recent performances the members of the chorus can climb on top of the scenery, like in 'Eleni' and 'Iphigeneia en Taurois', performed in the summer 2006 and illustrated in Table 4.1.

3.5.7 Roman Drama

In ancient Rome drama was not related to religion, and Greek plays were imported and adopted, preventing the flourishing of Roman drama. This happened long before the first known Roman theatres were built. The influence of the Greek culture and civilisation began around 272 B.C. with Tarentum succumbing to the power of Rome.

Tragedy and comedy were Greek in subject and form although performed in Latin language, and the performances were modelled in Greek originals. In addition to the tragedies translated and adopted from Greek originals, a modified form was created that dealt with episodes in local history and legend, known as the *fabulae praetextae*. There were two types of comedy as well. Those of Greek origin were called *fabulae palliatae*, whereas the new type that referred to the Roman and Italian life of middle classes was known as *fabulae togatae*. However, although tragedy and comedy became a regular feature of Roman games and festivals, they disappeared in the 1st century B.C. The Roman theatres were dedicated to tragedian's solos, farces, pantomimic performances and vulgar variety shows [Allen, 1963].

The *versus Fescennini* and the *satura* were two forms of native entertainment, while the *mimus* and the *fabulae Atellana* were mainly imported from the Greek colonies of southern Italy and Sicily. Many new theatres were erected and older Greek theatres altered for the performance of this type of play [Simpson, 1956]. Masks were not always used during the performance. For example, the *Atellanae* required the use of masks, while the actors in *mimus* never wore them. Drama in Italy lived until the 6th century A.D., when the *mimi* were driven out of theatres.

3.6 Vases

There is a general belief that the ancient theatres were excellent from the acoustic viewpoint due to the presence of the vases, which functioned as resonators. This was based on the Roman writer on architecture, Vitruvius [1st century B.C.], who described a primitive amplification system for use in theatres. In niches, at specifically determined points in the auditorium, vessels of different sizes should be placed, designed to reverberate to various pitches of the human voice or provide low frequency absorption. According to Arnott [1959], there is no evidence that this ingenious device was ever used in Classic times, and there was certainly no need of it. However, George suggested that these vessels would function as 'Helmholtz Resonators', *"acoustic resonators in the form of an air cavity contained in a spherical or cylindrical bulb, connecting with the atmosphere through a neck whose length is negligible compared with its diameter"* [George, 1997]. He suggests that the vessels were an attempt to add resonance to an essentially non-resonant structure, emphasising the 'warmth' of the theatre.

Relatively recent papers dealt with the placement of vases both in outdoor theatres and Danish churches [Brüel, 2002]. The studies were carried out with the use of models of vases, as described by Vitruvius in Rome in about the year 70 A.D. for outdoor theatres, and of sound vases (lydpotter) placed in Danish churches from 1100 to 1300 A.D. Measurements of vases' resonant frequencies and re-radiation were performed showing that the model vases obeyed expected physical rules. However, it was found that the acoustic quality of many ancient Greek and Roman theatres cannot be ascribed to the vases placed under their seats and that sound vases placed in Nordic churches could not have shortened the reverberation time because of their number. Moreover, they could not have covered a broad frequency range.

3.7 CONCLUSIONS

Drama was born of dance and its origin can be found in religious rituals. This chapter focused on the spatial aspect of performance spaces and theatres in antiquity, the forms of drama performed in them and the acoustic environment according to previous research. It particularly discussed the 'evolution' this study will investigate from the acoustic viewpoint. Then the types of drama in the Greek and the Roman world, the audience's part and the chorus's role in the sensory experience of a performance were discussed.

In the initial forms of performance spaces in angular layouts and small sizes, the acoustics depended mostly on direct sound and adjacent buildings provided useful reflections, especially since the material used for the construction was stone. In later times drama was performed on a wooden platform in the agora (6th century B.C.). The Classic theatres were created in the 5th and 4th centuries B.C. and could only provide reflections from the orchestra and the back stage wall, which was not of great importance according to the literature. The construction of theatre buildings was related to material use, while the transformations in their layout were related to performance types and innovations in drama. The Hellenistic type, at around the 2nd century B.C., was a consequence of changes in the performance style. Architectural orders, relationship between the building and the landscape, design details, proportions and decorative elements due to regulations and restrictions influenced the architect's originality. The materials were often found on site. The best position for the actor on the orchestra was at the centre, for visual and focal purposes, while acoustically it was better than when the actor approached the audience. The low background noise level in antiquity also played an important role in the acoustic conditions. Nevertheless, from the visual and acoustic point of view, in Greek performance spaces, there were different seats, usually the best in the theatre, reserved for important spectators, while the Romans created the first 'boxes' in the history of Western theatre. This suggests that the ancients were aware, by experiment, of the specific seats that provided good visual and possibly acoustic conditions.

Despite the fact that the acoustic theory was not well developed, the ancient theatres seem to have been rather successful for their purposes, as will be also seen in Chapter 7. The steep seating area provided good conditions, because of larger angles of incidence to the seating area, while the unoccupied seats, with backs or risers sloped backward by about 10°, and the heads of the audience also scattered sound to adjacent areas. Moreover, the appearance of the actors on a higher platform possibly improved the acoustic conditions. Generally, the almost circular shape, as opposed to later shoebox theatres, allowed the audience to surround the core of a play, which psychologically and visually improves their relationship.

The Roman theatres, probably evolving from the Greek by increasing the height of the back wall of the stage, acquired unity of mass, which influences acoustics, as will be further examined in Chapter 7. It is believed that the acoustic environment created in the Roman theatre was better than the Greek, because of the enclosed space it provided. The multiple reflections between the stage building and the audience area contributed to the increase of reverberation. The 'evolution' of theatre layout in antiquity is a subject that will systematically be examined, mainly for acoustic purposes, although rectangular and circular layouts were simultaneously constructed.

Finally, recent studies have shown that the acoustic quality of many ancient Greek and Roman theatres cannot be ascribed to the vases placed under their seats. They have also indicated that there is measurable reverberation in Roman theatres, while with the use of computer simulation the interest in ancient theatres and their virtual reconstruction is growing. From the above it is clear that an extensive examination of the acoustics of the theatre spaces in antiquity would be particularly interesting, both from the evolution's and material use viewpoint.

CHAPTER 4

STAGE BUILDING AND SCENERY – PAST, PRESENT AND FUTURE

4.1 INTRODUCTION

Previous research on ancient theatres has mainly focused on their original forms in terms of layout, especially for the Hellenistic and the Roman types, including the stage building, as well as contemporary conditions with the destroyed stage buildings. However, the first excavations of representative theatre forms from these periods in the 19th century were the driving force for the revival of ancient Greek drama, the didaskalia. Drama festivals were established and have since evolved into social summer events. The scenery, part of the theatre architecture, has become an ephemeral structure with short but profound presence, moving from one theatre to another to attend different festivals. Inspired by the myth and the historical events, the stage designer is called to interpret the play through designs, adaptable to many open-air theatres, both ancient and contemporary. Many writers of antiquity have used the verb *σκηνογραφώ*, for the action of creating the stage design, the noun *skenographer* (σκηνογράφος), for the stage designer and *skenography* (σκηνογραφία), to characterise the sight of a theatrical performance [Kontogiorgi, 2000]. Previous semiotic approaches to theatrical space have been used to identify categories like: 'theater space' (the architectural givens); 'stage space' (stage and set design, costumes, actor's bodies, makeup, etc.); and 'dramatic space' (created by the 'stage-world') [Rehm, 2002]. Since theater space cannot be altered and dramatic space is determined by each scene of the play, the only category that can be manipulated is the 'stage space'.

The overall investigation of the acoustics of ancient theatres spans the historical scale from the Minoan Crete to the Roman times, as seen in Chapter 3. This chapter is mainly focusing on the Classic, Hellenistic and Roman types, when scenery was of major importance. These types are nevertheless the ones that are still used for ancient drama performances. Previous research has shown that the differences in the acoustic environment of Greek and Roman theatres are based particularly on the shape and volume of the stage building [Chourmouziadou and Kang, 2002; 2007a]. This creates the hypothesis that scenery can significantly alter the acoustics of an open-air theatre, since it can be absent or enclose the area.

Although previous research has mainly focused on the acoustics of the ancient theatres in antiquity or their contemporary condition, recent studies have shown that the effect of temporary scenery design is very significant for acoustic purposes [Chourmouziadou and Kang, 2004]. It has been indicated that sound was studied in antiquity [Hunt, 1978]. However, the layout and the capacity of the ancient theatres present several acoustic deficiencies, like the quality and the amplitude of sound at the extremities of the theatre, because of the directivity of the human voice, the focus areas due to the concave shape, the noise produced by the large number of audience and the distances from the last rows. In the meantime there is no consideration for the impact of the scenery design on the acoustics of the theatre.

In Chapter 3, the stage building in antiquity was briefly described. However, this chapter presents a systematic review of the stage building and scenery, their basic characteristics and the interrelation between them and the acoustics of ancient theatres. It discusses the creation of the stage building in antiquity, its original form and its development. Properties, or 'props', which is the term used for the necessary accessories for each play, are also discussed, especially regarding the overall performance perception and the different positions of the actors during the performance. An investigation of the forms of past and contemporary scenery designs is then presented, both from the aesthetic viewpoint but also in terms of identifying parameters and variables that formulate generic scenery designs, with different attributes to the acoustics. Hence, the aim of this chapter is to review trends in scenery design, to create categories and classify scenery design with the purpose of examining its effect on the acoustic environment of the theatre.

4.2 Stage Building in Antiquity

Following the description in Chapter 3, it is evident that the human need of theatre creation, or at least one form of a theatre, appeared early in the history of civilization. Excavations brought clear indications, not of theatres with the contemporary meaning, but of ritual and recreational spaces, used by the whole community. For centuries theatre was always connected with religious festivities. Almost identical is the meaning of *skenography* (σκηνογραφία), the sight of a theatrical action, which will be used throughout this study.

4.2.1 Creation of the Stage Building

The first examples of rituals in ancient Greece appeared at the same time as the creation of the earliest organised societies during the Neolithic times [Kontogiorgi, 2000[16]]. Later, at the peak of the Minoan civilisation there were rites, called *ταυροκαθάψια*, and other rituals that were taking place in palace courtyards and were the major public entertainment. Similar rites were performed at the Mycenaean civilization. As previously mentioned, there was no scenery or skene-building in the theatre at first. The first attempts for creating a specific architectural form were pointed out during the excavations at Poliochni in Lemnos, where a rectangular stage was added to a circular orchestra made of soil. Behind the stage there was a simple structure that was used for changing costumes. In front of the stage they put some form of painted scenery [Tsouchlou and Baharian, 1985[17]].

Also, skene-building is said to be erected at the theatre of Dionysus in Athens, certainly earlier than 458 B.C., due to the need of a palace for the Orestean trilogy of Aeschylus [Allen, 1963]. For the action of one of the tragedies ('Choephori') it was necessary to use several doors. Thus, the skene-building was a substantial structure of considerable size. The addition of such an important feature was very significant for drama.

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[16] pp.15
[17] pp.12

4.2.2 DESCRIPTION AND DEVELOPMENT OF THE SKENE-BUILDING

The skene-building or *skene* (σκηνή) was rectangular in plan, with or without projections (at the front, sides or rear). The central part was called *mesoskenion* (μεσοσκήνιον), whose length was usually equal to the orchestra's diameter with the surrounding passageway. In later theatres there were no lateral projections but the length of the skene was increased to one and a half orchestral diameters, while in Roman theatres it was double the diameter of the orchestra [Marquand, 1909].

The mesoskenion was subdivided by cross walls in three rooms, each of them having one door for access from the orchestra. Originally the skene consisted of one story, although in Classic times it had two stories, the *hyposkenion* (υποσκήνιον) and above it the *episkenion* (επισκήνιον). In later Greek theatres the hyposkenion lost its value and was merely the support for the actors' platform above, but retained its three doors. On the other hand, the episkenion increased in importance and was further decorated with columns and entablatures. As mentioned before, the facade of the stage building was usually decorated by one or two architectural orders and in some cases by three, the Doric, the Ionic and the Corinthian. Also, in Roman times the height of the stage building was equal to the roof of the portico at the summit of the theatre. Figure 4.2.1 illustrates the evolution of the stage building of the theatre of Dionysus in antiquity according to Fiechter [1914].

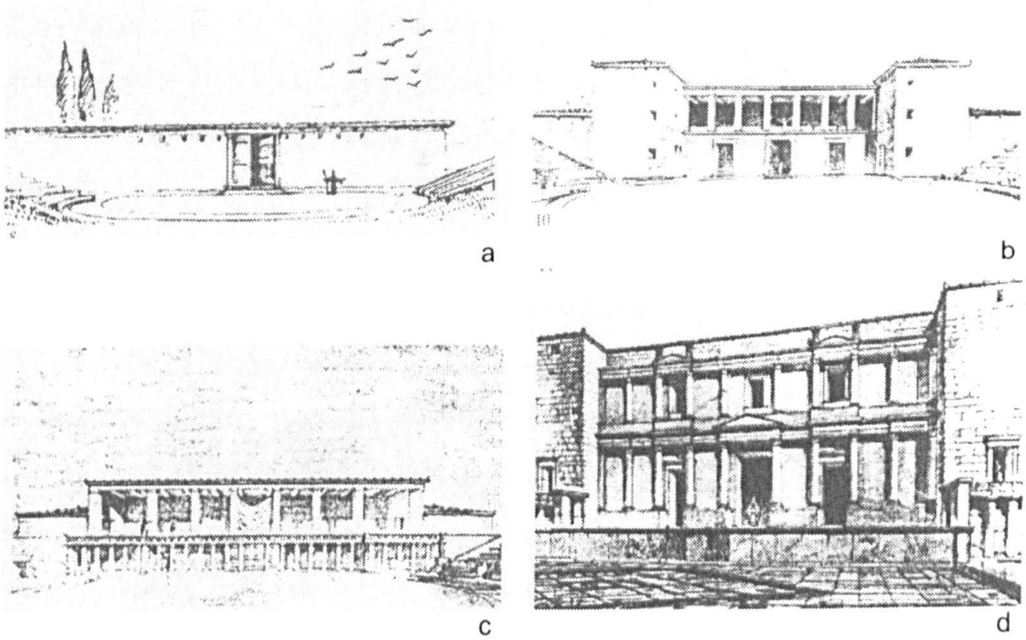

Figure 4.2.1. *Representation of evolution of the stage building of the theatre of Dionysus in antiquity. a) First stage building, b)Evolved stage building of the Classic period, c) Stage building of the Hellenistic period and d) The Roman times [source: Fiechter, 1914].*

A further development of the stage building was the projection of wings on one or more sides. The front wing was named proskenion (προσκήνιον), the same as the logeion according to Marquand [1909], which was the one of major importance; the lateral wings the *paraskenia* (παρασκήνια) and the rear wing the *opisthoskenion* (οπισθοσκήνιο). In the Classic period the proskenion consisted of a narrow projection with its length equal to the diameter of the orchestra, depth that varied from two to three meters and height from 2.5 to 4m [Marquand, 1909]. Originally the entire proskenion was made of wood and later its supports were made of stone or marble, decorated as to resemble a colonnade, while the intercolumniations were covered with *pinakes* (πίνακες) and movable wooden panels. Such a proskenion was usually narrow and high and was used both as a background for the performance that took place at the orchestra but also for performing, since it was accessible from the orchestra through the subterranean passage, mentioned in Section 3.3.2.6, from the mesoskenion, from the parodoi and from the paraskenia.

The logeion was widened in the Roman times to accommodate both the actors and the chorus and lowered to provide a better view to the audience at the front seats. From the mesoskenion there were three doors that opened to the logeion, the central or royal door (θύρα βασιλέως), from which the leading actor appeared, and the side doors, which were used by strangers (θύραι των ξένων). The paraskenia, mentioned above, were projecting wings, although in some cases, like in Epidaurus, they did not project from the mesoskenion wall but were accessible by lateral ramps. The latter were used by actors who were supposed to have arrived from the city or the country. At Priene this was achieved by continuing the logeion partially around the sides of the mesoskenion, which can be called *paralogeia* (παραλογεία). The rear part of the stage building varied, since there were no specific requirements for the opisthoskenion. It was sometimes decorated, the number of doors varied and it was at times replaced with a portico [Marquand, 1909].

Regarding the development of the stage building it needs to be mentioned that the changes may have been important for the acoustic evolution of the theatre types. Hence, a simulation carried out in Chapter 7 entails some characteristics of the stage buildings of different periods.

4.3 SCENERY IN ANTIQUITY

Theatre history started in Attiki, at the middle of the 6th century B.C. As mentioned previously, Thespis, a poet, actor and skenographer radically changed the form of the theatrical performance by introducing an actor that would address with some words the chorus (or choruses). At the same time the use of costumes and scenery started. Historical notes refer to Thespis' troupe, living and touring in some kind of a wagon loaded with costumes and sceneries, which was also used as a mobile stage for the actors. This indicates the separation of the actor and the chorus from the spatial viewpoint of the performance [Kontogiorgi, 2000[18]]. It is said the Frinichos, at the beginnings of the 5th century B.C. undertook the coordination of the two choruses, in order to specify the role of the chorus and the actor [Tsouchlou and Baharian, 1985[19]].

Agatharchus is said by Vitruvius to be the first professional skenographer (the one that created painted scenery), the one that dealt exclusively with the scenery of the Aeschylus' plays, while Aristotle supports that the first tragic poet that used scenery was Sophocles [Kontogiorgi, 2000]. It is still not clear what the skene-painting was. Perhaps not with the modern use of the term, it was just adornment of the skene-building [Allen 1963]. From several plays a variety of surroundings is suggested, although it may not be a representation through skene-painting, but with the use of the imagination. There were many professional painters, like Appolodoros, Anaxagoras, Dimokritos, and Kleisthenis, that dealt exclusively with skenography [Photopoulos, 1987[20]]. Between them, Apollodoros was famous for introducing shading on scenery, succeeding in accentuating the plasticity of the volumes and the space, while Kleisthenis for the perspective. However, the problem with a single focused perspective for ancient skene-painting is precisely that, given its size and shape, the ancient theatres offer anything but a single, frontal point-of-view. It is suggested that the natural background of the city and landscape makes painted perspective irrelevant; moreover, the bodily motion of characters entering and leaving by the central entrance and the parodoi are far more important than the effects painted on the facade [Rehm, 2002].

4.3.1 Types of Scenery

Before the end of the Hellenistic era the art of skene-painting had made great progress, while during the Roman period there was a high degree of realism, especially in the representation of architectural features. The settings for Greek and Roman plays have been divided by certain scholars into four classes [Allen, 1963]. In the first there was either no back stage, or if present it was used for entrances and exits, represented a hill or it was entirely ignored. In the second type the skene was a stretch of a wild country with rocks, trees and bushes, and a simple entrance at the rear represented the mouth of a cavern or hollow rock. In the third the skene represented a building, a palace, a temple, or a house, depending on the text. Usually one door was required, although in a few instances two or three doors were used. Finally, the set could also be a series of houses or other structures, two or tree in number, ranged side by side. In general, the range of choice appeared to be greater in the 5th century B.C. than in the 3rd and later.

[18] pp.16
[19] pp.12
[20] pp.11-17

Whenever the setting was altered between or within plays, this was done in front of the audience, since they were no curtains. However, from about 100 B.C. the Roman theatre had a curtain, which was rolled about a cylinder in a slot or deep recess that extended across the front of the stage. The change of settings in the Roman theatres was done by either shifting painted screens, like the pinakes, mentioned earlier, or turning about a pivot screens or panels with pictures on both sides. At the theatre of Euonymon there is a stone foundation 2m forward of the stage wall that supported a colonnade and slots at either end could have been designed for tablets or for removable scenic panels [Wiles, 1997]. Also, it is suggested that they used revolving prisms, *periactoi* (περίακτοι), which were triangular pieces of machinery that revolved, each having three decorated faces. Moreover, the *ημικύκλιο*, a board in semicircular shape, was placed on the orchestra to present scenes from the city or the sea.

4.3.2 Standardised Scenery

Except for the professional skenographers, a number of tragic poets dealt with skenography. Sophocles was the first to use periactoi, and Euripides the machines for the appearance and disappearance of gods. It was then that the scenery for the three different types of drama was standardised. A sight of a palace or a temple was presented in tragedy, a square in front of a house in comedy and a waterfront or a small forest in satyr drama.

It has been mentioned that despite the fast development of theatrical speech and scenery, the buildings retained the initial wooden form of the 6th century B.C., which involved the stage, a rectangular wooden structure where the actors performed, the orchestra, the circular area used by the chorus, and the wooden benches for the audience [Alexiou, 1994[21]]. This form of the theatre of Dionysus in Athens for example, was replaced only later in the 4th century B.C. by a permanent stone building. However, it has been suggested earlier in this study that several theatres evolved through the centuries. Therefore, it is possible that the theatre buildings were not significantly altered during the 5th century and the peak of Greek drama, and attention was mainly paid to the scenery creation for the performances in the festivals. During the Hellenistic times stone theatres were established, with ornamented stage, like the theatre of Dilos in the 2nd century B.C., which had a stone proskenion with columns, while the depth of the stage was ornamented with columns of two styles [Kontogiorgi, 2000].

4.3.3 Basic Scenery – Conventional Use

Following the previous descriptions, in the 5th century's Classic theatres there was a low platform that served as a stage, although some non-dramatic performances or old dramas were occupying the orchestra of the theatre, until late in Hellenistic and Greco-Roman theatres. However, some scholars support that the orchestra was the area that accommodated the

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[21] pp.68

performers, even after the erection of the skene-building, throughout the 5^{th} century and possibly until the beginning of the Hellenistic period, or even the Roman times [Allen, 1963]. Both actors and chorus (in cases where there was a chorus) were performing on the stage of the Roman theatre.

The basic scenery was the facade of a palace or temple, represented by the skene-building. It had three doors, the central or king door, which was rich and the most ornamented for the use of the protagonist, and two more on its sides, for the other actors, as mentioned also in Section 4.2.2. The doors at the sides are said to have conventional significance, although not clear. It is stated that the entrance on the left of the actor led to the centre of the city or the city as a whole, while the entrance to the right to the harbor or the country [Allen, 1963]. The fact that the position of the actors and the chorus were strictly predefined is of great importance. There is said to be a kind of silent agreement between the theatre group and the audience, so that everybody understood the role of every actor, by only looking at the door he used to enter the stage.

There is still discussion about whether a curtain (αυλαία) was used at the beginning and the end of a play. Historical notes refer to a curtain, used not only during the Hellenistic and Roman times, but at Classic times as well [Kontogiorgi, 2000[22]]. It is said to be an expensively embroidered textile, which was hidden in a slot and could have also been used for scenery changes.

4.3.4 'Properties' and Mobile Objects

Properties, or 'props', the necessary accessories for each play, can be objects like chairs, tables, household items, or other elements, like special lights etc. In ancient performances, like in contemporary performances, several 'props' were used that will be described below.

Apart from the thymele, the altar in the middle or at a side of the orchestra, there could have been other accessories required for the sets of different plays. On the upper part of the proskenion there was the *φρυκτώριον*, a sign with the title of the play and the name of the poet. Often, apart from the basics, additional scenery was needed, such as a cave, some houses, etc. In this case the *παραπετάσματα* or *καταβλήματα* were used [Kontogiorgi, 2000], which were movable decorated and painted boards, placed in front of the stage and made of wood and fabric. Sometimes they were structurally supported by the periaktoi, described in Section 4.3.2. The external facade of the palace (or temple) that was presented to the audience did not provide information about the action inside. Therefore, the *ekkyklema* (εκκύκλημα) was used, a platform on wheels that entered the stage and could rotate, slide or wheel, to present scenes from indoors.

[22] pp.17

The use of the 'machine' was frequent, especially in Euripides' plays. It was a combination of a crane, ropes and wheels on the upper and left part of the stage, and allowed the appearance of a god that would help the plot to evolve (*deus ex machine*). The frequent presence of gods established a number of stage accessories, placed on the upper part of the stage. Near the machine there was the *θεολογείον*, a narrow mobile platform, like the ekkyklema, where a god gave a speech without affecting the myth. In terms of acoustics the appearance of a god at a higher level has not, according to previous studies, enhanced the sound level since there was no background wall to reflect sound [Mparkas, 2006]. Hence, although the god had a lot of power, which was visually perceived, his position was rather weak from the acoustic aspect. Similarly the *στροφείο* was used, for the heroes that were transformed into gods or died during a battle. The presence of gods was usually accompanied by sound and visual effects, like the *κεραυνοσκοπείο*, from which painted lightning was thrown or rotated, and the *βροντείο*, a vase filled with pebbles and cobbles, thrown on a copper tray, creating the illusion of thunder.

Stage accessories were often used behind or at the sides of the skene-building. There was a high platform, like a balcony, behind the skene, called *διστεγία*, where the actors sometimes stood to view far away. Moreover, it is suggested that other high platforms must have been used by the critics that attended the performance.

Apart from the stage, accessories were placed on the orchestra, like the scenery described in Section 4.3.2. The simulations carried out in Chapters 9 and 10 involve similar scenery shapes. Next to the descendants of the seats, fall-ways were often constructed (χαρώνειος κλίμακα) for the appearance of people from the underworld. Statues of gods (ερμαϊκές στήλες) in honour of god Apollo and facades of graves where large parts of tragedies and comedies. In front of the thymele there sometimes was a table for offers. The creation of realistic skenography was a problem that troubled ancient skenographers. In some sources there are references of horses, carts and riders appearing during the performance.

4.4 Byzantine, Medieval and Renaissance

This section will present a brief discussion on the state of theatre and the scenery after the Roman Empire reached its decline and during the Byzantium, the medieval times and the Renaissance. The aim is to provide a brief summary of the development of the stage and scenery design, in the period between the Roman times and the revival of Greek drama in the 19th and 20th centuries, to relate the trends in antiquity and today. The information on these periods is not detailed, due to the absence of ancient Greek performances, extensive use of outdoor areas or purposely built indoor performance spaces. An exception is the Chinese opera that has been examined before from the performance viewpoint and in terms of architectural layout and acoustics [Chourmouziadou and Kang, 2003; Chourmouziadou 2003;

Chourmouziadou and Kang 2002]. However, it is not the aim of this research to examine other forms of drama at this point.

The turn from the Roman Empire to Byzantium brought the abandonment of Greek drama. The performances were related to the Church and formed the basis for medieval drama. In Medieval times there was a form of popular theatre, combining narrative speech, acrobatics, dance and song. The scenery was craftily decorated and the costumes were impressive, although made of cheap materials. The Mass (Liturgical Drama) was established in the 11th century A.D. with stories about the life of Jesus. It disappeared from the history of the western European theatre only with the invasion of Renaissance and the opposition to the Catholic Church by Reformation. At the end of the 15th century A.D. there were many innovations in the theatrical world. Religious plays were forbidden in Paris and the mixture of Roman-Catholic saints and elements of mythology were the most common theatrical repertory of propaganda.

This was followed, particularly in Italy, by 'Comedia del'Arte', based on the tradition of Roman Comedy, after the revolution in architecture and the study of Vitruvius, which also affected the form of theatre buildings. Medieval stages were abandoned and Vitruvius' drawings of Roman theatres were adopted. In fact, the arched proscenium and the development of painted scenery were established, the latter after the evolution of painting at that time [Kontogiorgi, 2000[23]]. These were radical changes that affected the evolution of west European theatre for centuries. Baldassare Peruzzi was the stage designer that used perspective drawing in scenery in 1518. However, Sebastiano Serlio (1453-1554) expressed ideas for scenery and costume design in 1545, while he suggested that there should be three basic scenery types for the popular kinds of drama at that time: tragedy, comedy and satyr drama [Kontogiorgi, 2000]. The 'Comedia del'Arte' was the most significant attribute of Italian productions in Renaissance.

Its decline started in the 17th century, when Baroque was introduced. The use of the term 'Baroque' in theatre was used in 1950-60, only for the 'new' theatrical forms that appeared at the end of the 16th and the beginning of the 17th century in order to distinguish them from the 'classic' theatre of Renaissance. Initially these were the plays with plots that did not follow the structure of the ancient Classic theatre. A great contributor in the 17th century theatre in France was Jean-Baptiste Poquelin, or Molieros, (1622-1673), whose innovation was the abandonment of multiple sceneries and the establishment of one. This allowed uniformity of space, while painted scenery and mechanical tricks had the purpose of impressing the audience.

The Elizabethan theatre, at around the 16th-17th century was based in England, while theatre in the rest of Europe started by performances of Comedia del'Arte and later of English and Spanish Productions (in the 19th century) [Vakalo, 2005]. Theatre has also been characterised

[23] pp.24-26

according to different periods in European history, like the French Baroque theatre, the Italian theatre of the Renaissance, the Rococo theatre, and the Romantic theatre [Patrikalakis, 1992].

Theatre in the 18th century was very popular in most European countries. In England the novelty was the separation of the orchestra and the stage. During the 19th century a significant change in Germany was introduced by Richard Wagner (1813-1883). Wagner specified the distance between the stage and the audience, creating a special space for the orchestra. There were no textiles for the background, while the first boxes that architecturally entered the stage, mostly used in opera, were abandoned. General lighting was replaced by light focused on the stage. He cooperated with important painters of that time. However his plays were not appreciated, since the audience was in favour of bad taste comedies and melodrama.

Cretan theatre, the only form of theatre in Greece during this period, was developed during the end of the Renaissance, when Crete was occupied by Venetians [Patrikalakis, 1984]. This allowed the Italian influence, although with Greek expression and characteristics of the popular theatre.

4.5 Scenery Design in Contemporary Adaptations of Ancient Plays

4.5.1 Greek Theatre Productions in the 19th and 20th Centuries

In Greece mainland, after four centuries of Turkish occupation, theatre started to blossom. In 1860-1870 there were several attempts for the revival of ancient Greek drama, between Eclecticism and Neoclassicism. Some of the performances took place at the Odeum of Herodes Atticus in Athens, previously seen in Figure 3.3.6. One of them was 'Antigone' by Sophokles performed for the wedding of George the First and Queen Olga. The scenery was archaic but neo-classicist at the same time, while the play was performed during the day.

In the decade between 1880 and 1890 theatrical scripts in Greece started evolving. This was accompanied by improvements in stage designing. In 1889 there was an attempt of 'teaching' ancient tragedy (didaskalia), due to the marriage of successor Konstantinos and Princess Sofia. The play 'Persians' of Aeschylus was performed and each actor was responsible of making his/her own costume, as mentioned in the issue of newspaper 'Akropolis' [Kontogiorgi, 2000[24]]. By that time there were evening performances with artificial lighting, with the use of candles and oil lamps. In 1894 the performance of 'Prometheus in Olympus' by Dimitris Kotopoulis was highly discussed for its scenery, a circular curtain made of white cloth, where projections with shadows were made.

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[24] pp.24-26

The beginning of the 20th century was very important for the technical characteristics of the theatres: oil lamps were abandoned and electrical lighting was established. All troupes at that point were font of the revival of ancient drama, and many plays were performed. Two important occasions in 1901 were the institution of the 'King theatre' and the 'New Scene'. The latter performed ancient drama and a monumental performance was that of 'Antigone' with the use of naturalistic scenery.

However, the public did not seem to enjoy these performances. Instead it preferred popular theatre, farces and melodrama. During the 1st World War many good writers following either the naturalistic theatre or the social aspects of Ibsen and Strinberg, attempted the representation of contemporary Greece that was particularly favoured by the public. However, most of the plays were performed with a great delay, due to the political situation. Aravantinos and Armenopoulos were two new artists that dealt with stage design at that period. The latter was distinguished for his talent and his ability to use the same worn-out scenery, due to economical problems of the theatre producers [Tsouchlou and Baharian, 1985]. The first post-war performance of ancient drama was that of 'Oedipus Tyrant' in 1919, although in an indoor space, as can be seen in Figure 4.5.1. In the same year 'Iphigenia' was performed and a three dimensional architectural scenery was used. Moreover, the stage design of 'Agamemnon' performed in the Odeum of Herodes Atticus was rather criticised as inadequately poor and modern.

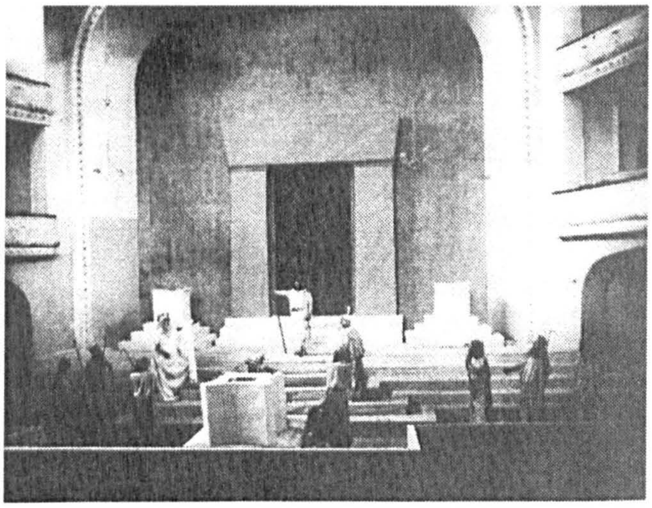


Figure 4.5.1. *Oedipus Tyrant, directed by Politis in 1919 at theatre 'Olympia [source: Kontogiorgi, 2000, pp. 56].*

In 1927, during the celebrations in Delfoi, 'Prometheus Bound' was performed, with direction, choreography and costumes by Eva Sikelianou. Although her contribution to the performance is still greatly recognised, the critics were highly negative [Department of Theatrical Studies, University of Athens, 1999]. While the use of masks was appraised, their design, shown in

Figure 3.5.2, was regarded extremely realistic, not an artistic expression but a poor mimesis of the reality [Kontogiorgi, 2000[25]].

Figure 4.5.2 shows the stage design, created by the sculptor Foskolos. Influenced by Appia – a pioneer in skenograghy with emphasis in sculptural scenery and lighting [Patrikalakis, 1984] – the scenery was characterised as melodramatic, a resemblance of the mountain of Caucasus, made of painted cardboards with staircases and several levels that was unsuccessful both aesthetically and functionally [Department of Theatrical Studies, University of Athens, 1999]. It was regarded baroque expressionism, which did not fit in the landscape, was very oppressive and diminished the actors. Although the photos of the performance are in black and white and the chromatic aspect cannot be seen, they are still useful for the investigation of the stage design from the acoustic viewpoint. The irregular shape and relatively hard material for the background allowed sound diffusion for most of the theatre area, which was very significant for a relatively even sound field. These effects of scenery design will be further examined in Chapter 10.

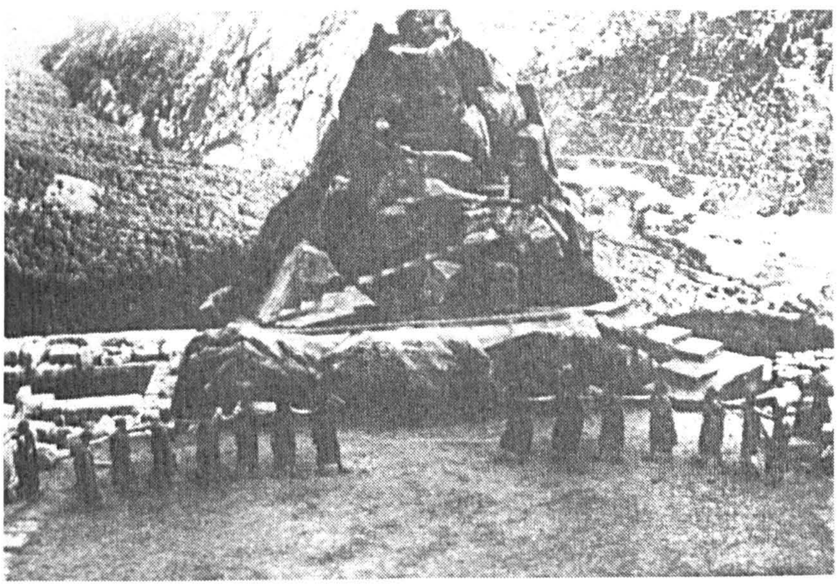
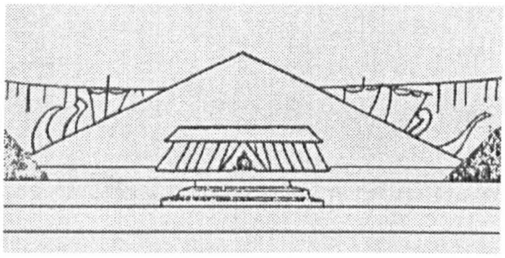


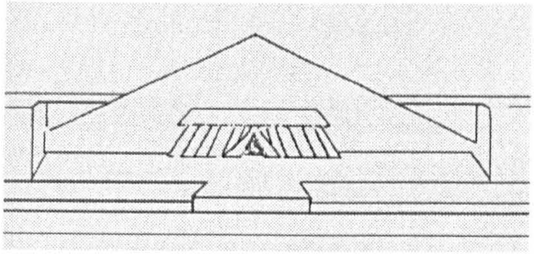
Figure 4.5.2. *Prometheus Bound in Delfoi, directed by Eva Sikelianou in 1927 [source: Kontogiorgi, 2000, pp. 57].*

In the same year, 'Ekabi' was performed in the stadium in Athens. Although the scenery was initially designed by two painters, Kastanaki and Spahi, as shown in Figure 4.5.3, it was changed many times and finally Kontoglou decided to create the one shown in Figure 4.5.4. The director supported that there must be architectural volume in outdoor theatres, instead of painted two dimensional designs. However the simple, primitive image of the 'Greek country' scenery that Politis, the director, referred to was regarded poor and miserable, with a roof 'that resembled storage buildings in Piraeus' [Tsouchlou and Baharian, 1985[26]]. It must have been a

[25] pp.24-26
[26] pp.65-66

rather hard material that reflected sound and maybe with better programming it could be useful from the acoustic viewpoint.





a b

Figure 4.5.3. *Models created by a) Kastanaki and b) Spahi for the scenery of 'Ekabi' in 1927.*

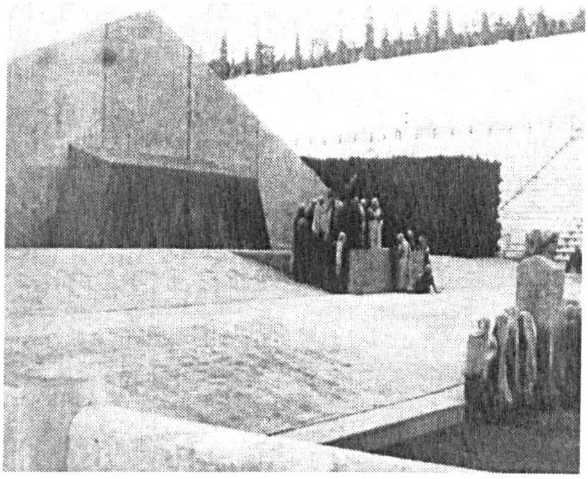


Figure 4.5.4. *Photo from the performance of 'Ekabi' in 1927 [source: Kontogiorgi, 2000, pp. 59].*

In the 30's the 2nd Celebrations of Delfoi were organised, and 'Prometheus Bound' and 'Iketides' were performed. Kontoleon designed the scenery, which was simple and 'classically modern', functionally and aesthetically effective, combining the abstract ideas of Appia with the landscape of Delfoi [Department of Theatrical Studies, University of Athens, 1999]. Figure 4.5.5 shows Kontoleon's scenery design for the two performances. Kleovoulos Klonis was another stage designer that put the ideas of symbolism, of Appia and of Craig – also emphasising on the relationship between architecture, plasticity and lighting – into practice, creating big architectural volumes, eliminating the painted scenery and using new materials and techniques, with respect to the actor.

Karolos Koun directed school performances of Aristophanes in the same decade. He created the 'Popular Stage' while Karantinos created the 'New Dramatic School'. The ideas of Karolos Koun about ancient theatre were its diachronic revival, as a part of Greek tradition. He imported contemporary elements to each performance. Both Koun and Karantinos employed many young people for the scenery creation, not only painters but architects as well [Kontogiorgi, 2000[27]].

[27] pp.62

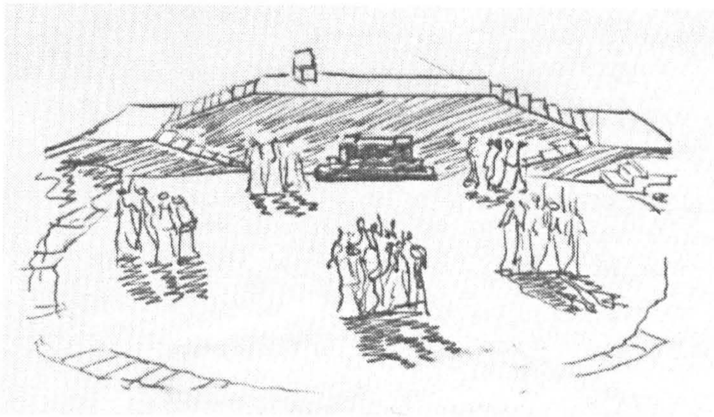


Figure 4.5.5. Kontoleon's scenery design for the performances of 'Prometheus Bound' and 'Iketides' in Delfoi in 1930 [author's drawing].

However, the 'Popular Stage' closed down in 1936, due to economic problems that did not allow its maintenance. Koun established the 'Theatre of Art' in 1942. He achieved overcoming the economic problems and obtained their own building in 1948 [Kontogiorgi, 2000[28]]. It was a novelty in terms of theatrical space for its time, not the usual box-set but an amphitheatre. This prohibited 'simple' scenery solutions and created problems in the movements of the actors. He regarded the placement and movement of the actors in *X* shape on the stage as the appropriate solution in this space. The background scenery was replaced by a stage environment, and within it the actors moved. Props and common objects were also used.

Meanwhile, the National Theatre with Fotis Politis as a director, Klonis as the scenery designer and Fokas as the costume designer performed 'Agamemnon' by Aeschylus in 1932 in the indoor space of the theatre. Due to the small size of the theatre, when compared to the outdoor ancient Greek theatres, Klonis tried to take advantage of every square meter by creating light coloured architectural volumes at the two sides of the stage. In between them there was a crooked staircase used by the actors for the entrance and exit from the stage, while the chorus entered from the sides [Tsouchlou and Baharian, 1985[29]]. Figure 4.5.6 illustrates the model for the scenery and one of the costumes.

The same group performed the 'Persians' by Aeschylus in 1933 with a more conservative scenery design, representing the front of a palace. Three layers were created for the performers. The lower level was occupied by the chorus, while at about 1.8m and 3.6m above the protagonists and some less important actors performed respectively. The epilogue was a satyr play – the first performance of this kind of drama for this century in Greece – and the palace front was replaced by a vast painted background.

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[28] pp.104
[29] pp.153

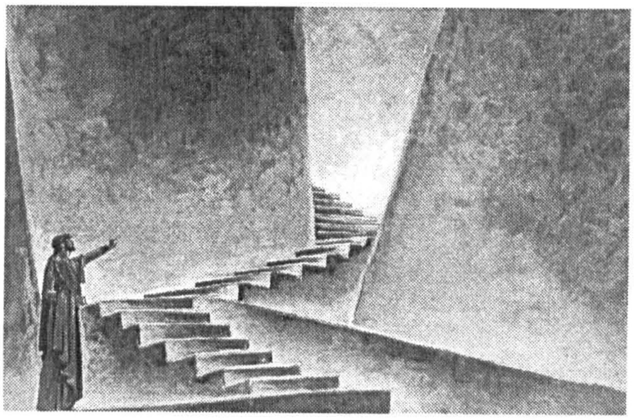


Figure 4.5.6. *Model for 'Agamemnon' in 1932 [source: Tsouchlou and Baharian, 1985, pp. 153].*

It needs to be mentioned that the inspiration for both scenery and costume designs usually came from the Classic period, the period that ancient drama was first presented. However, the sceneries used referred to the Cooper Age, not the Classic times, which can sometimes create confusion, but was far easier for the designers, since they had far more historic information.

There is a suggestion in the literature review that director Politis was troubled by the problem of presenting ancient drama in outdoor theatres [Kontogiorgi, 2000[30]]. His death did not allow him to participate in the performance of 'Electra' by Sophokles in the Odeum of Herodus Atticus and the theatre of Epidaurus in 1938. By then, Rontiris had become the director of the National Theatre. The latter performance was probably the first in the ancient theatre of Epidaurus after its excavation. Due to the fact that an ancient theatre can exemplify both the advantages and the disadvantages of a stage design and possibly ridicule it, Klonis decided to minimise it as much as possible. As can be seen in Figure 4.5.7, he used the remains of the ancient stage and the thymele, adding only some necessary for the performance objects, like vases. It is obviously expected that this scenery did not contribute to any acoustic improvement in comparison with the contemporary state of the theatre.

The years that followed were the most difficult in terms of theatre performances, due to the beginnings of the 2nd World War. Not only were performances unachievable for curfew and economic reasons, but people of theatre were arrested and murdered as well. The decade of the 40's began with the performances of 'Antigone' and 'Oedipus Tyrant' in the Odeum of Herodus Atticus. Both performances had the same concept of stage design, since they used the multilayered stage for the appearance of the actors. Nevertheless, it was the layout of the performance space with the high proscenium that allowed this decision. The first performance used different levels; the lower for the chorus, the second used an alteration of the scenery of 'Agamemnon', seen in Figure 4.5.6, without architectural volumes but with the proscenium of the Odeum and a wide staircase for easier access by the actors.

[30] pp.74

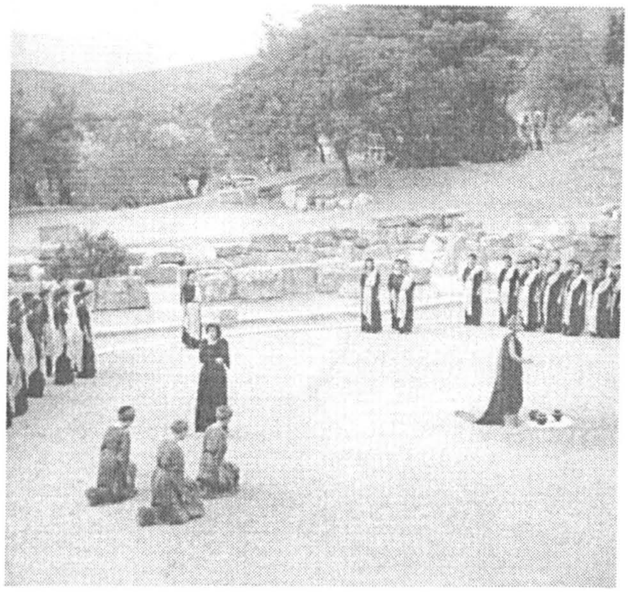
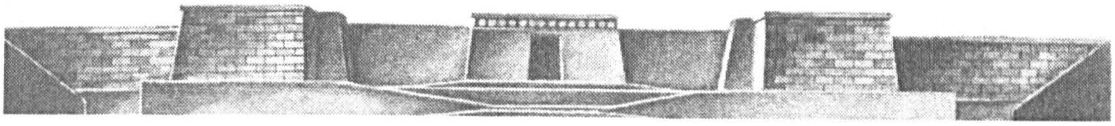


Figure 4.5.7. *Performance of 'Electra' in 1938 in Epidaurus [source: Kontogiorgi, 2000, pp. 75].*

After 1950 a wide variety of ancient plays was and still is performed in ancient sites. The most important change though is the institution of the Festival of Epidaurus in 1955 by the National Theatre. This allowed Klonis to use an almost permanent stage design that represents the front of an ancient palace or temple, with a central and two side entrances, like it is described in ancient texts [Kontogiorgi, 2000[31]]. In front of it extra architectural parts were added or taken away, like columns, openings, stairs, according to the needs of each performance. This is shown in Figure 4.5.8, which represents the models of two performances that took place in the ancient theatre of Epidaurus in 1955. The 'Ekabi', shown in Figure 4.5.8a, was performed in front of a simple structure in trapezoid shape, having one entrance. At its right and left side there were two architectural volumes that referred to the wall of Troy, while there were some gradual planes descending to the orchestra. Figure 4.5.8b shows the model for the second performance, the 'Oresteia', with the central entrance covered by a colonnade that runs up to the side volumes. In this case the walls imply the ancient Greek city, while the planes had been replaced by an imposing staircase. In this way he succeeded in applying the ideas of Appia, without forgetting the tradition of the ancient theatre [Kontogiorgi, 2000[32]].

Kleovoulos Klonis did not attempt to create the scenery of any comedy. Two of his later sceneries are illustrated in Figure 4.5.9. They were designed for the performances of 'Alkistis' and 'Andromahi' in 1963, for the theatre of Epidaurus and the Odeum of Herodus Atticus respectively.

[31] pp.80
[32] pp.80



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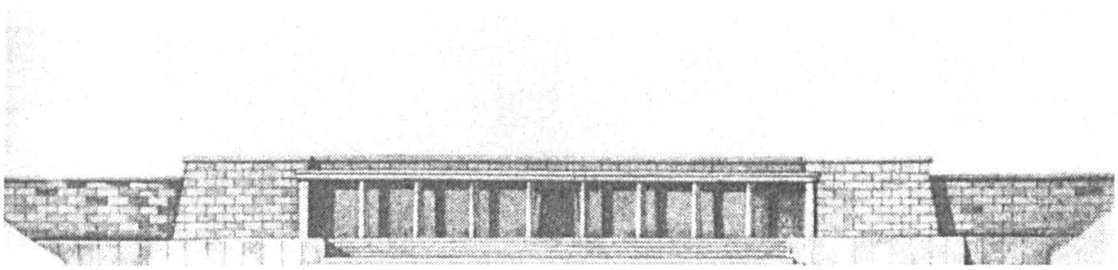
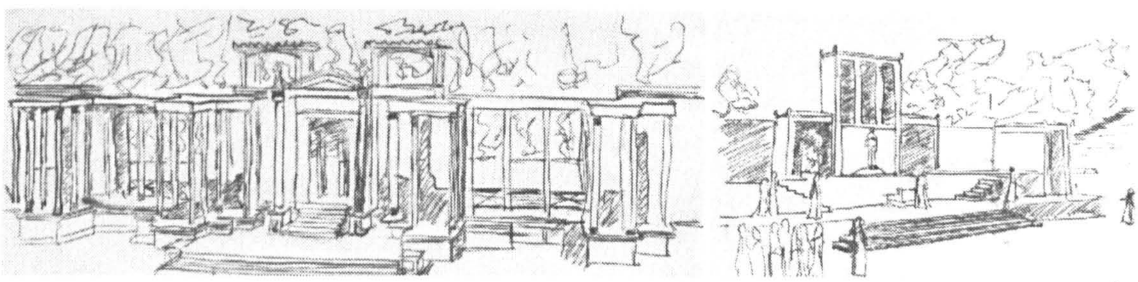


b

Figure 4.5.8. *1955 was the first year of the Festival of Epidaurus. a) Model of 'Ekabi', b) Model of 'Oresteia' [source: Kontogiorgi, 2000, pp. 75].*



a b

Figure 4.5.9. *Sceneries designed by Klonis for the performances of a) 'Alkistis' in Epidaurus and b) 'Andromahi' in Odeum of Herodus Atticus in 1963 [author's drawings].*

However, Giorgos Vakalo was regarded as the most important skenographer that worked for the National Theatre in the stage design of Aristophanes' comedies [Kontogiorgi, 2000[33]]. The 'Ecclesiazousai' were performed in 1956 in the Odeum of Herodus Atticus and in 1957 in Epidaurus. Following the first period of surrealism, he was charmed by the combination of irrelevant objects, especially those that had a 'Hellenic' character. He believed in a balance between painted and architectural scenery and in the wide use of colour. He supported that the extreme realism could destroy the magic of the theatre. In 1956 it was the first time he was asked to work for an outdoor theatre. The distinctiveness of each theatre was apparent and, especially in the case of Epidaurus, he faced the sacredness of the space. He suggested that the scenery should never obstruct the surroundings, while a skenographer should not radically interfere with the orchestra, since it is the part of the theatre that a large part of the performance traditionally takes place. Therefore, he proposed the maintenance of three architectural openings and low height buildings that will allow the audience view the surrounding space. The

[33] pp.82

architectural form of the theatre, the circle that is created by the landscape, the scenery and the koilon, needed to be kept, according to his opinion. On the other hand the Roman stage of the Odeum of Herodus Atticus was regarded inadequate for Greek drama, since it absorbed the viewer by its size. In this case he suggested using bright colours on the staircase that connected the stage with the orchestra.

The audience was probably impressed by the sceneries created by Vakalo, a pandemonium in construction and colour opposed to the strict, simple and colourless sceneries by Klonis. The former followed the same principles in 'Lysistrati' that was performed in Epidaurus in 1957. After many years of cooperating with the National Theatre, Vakalo finally designed 'Ecclesiazousai' in Epidaurus in 1981.

Gkikas was a painter that successfully translated cubism in Greece, after embracing the 'Hellenism' of Greek painting. He combined paint and architectural volume in the sceneries he created for ancient drama, to give not only decorative, but conceptual aspect to colour as well, to accomplish the atmosphere of the play and the characters.

4.5.2 Tendencies of contemporary scenery

During the history of theatre, scenery was connected with the architectural layout of the stage. This principle was apparent in the ancient theatre, where the architecture determined the placement of all parts of the theatrical event. Even before Greek drama was developed, the existence of some kind of scenery was important, in order to separate the performers from the audience. The first ideas about scenery were three dimensional, mostly architectural rather than a painting. The painted background became important later, when the plot and the space became more 'relaxed' and the viewer needed to be notified about the different spaces the play referred to [Kontogiorgi, 2000[34]].

This practice was common from ancient times but it was not until the creation of the enclosed stage during the renaissance that it blossomed. It helped the audience get into the mood of the play and it lasted until the end of the 19th century, when the naturalism established the box-set that represented scenes of every-day life and ended up to a mimesis of reality. The skenography returned to its initial goal because of the movements of the beginnings of the 20th century. The dimension of the stage space or 'scenic space' is determined by the stage, the scenery and the actor's movement. In contemporary theatre the painted scenery is not only the background but it participates in the theatrical act, emphasising on its illusionist character. The space affects and is affected by the actor's movement around or in it [Tsouchlou and Baharian, 1985[35]].

[34] pp.65
[35] pp.153, and pp.82-85

The turn of skenography into the painted background was sometimes characterised 'abstract and meaningless' for the non-realistic appearance. The polymorphic reality led to different styles, although all had the same initiatives. Cubism created new problems in space representation with its crooked perspectives, while constructivism used new stage mechanisms and established the idea that the actors should move freely, without any limitations [Chourmouziadou and Sakantamis, 2006]. Today an actor has to be familiar with dance and kinesiology, in order to perform [Kontogiorgi, 2000[36]].

New tendencies in the theatrical space, as described earlier, created a variety of forms that re-identified the relationship between the performers and the audience. The skenography is now the visual language of the performance and the audience's first impression. The contribution of skenography to the theatre is the aesthetic aspect of the action and the meaning of the play, which, if added to the speech, the music and the movement of the body, leads to the accomplishment of the play.

A catalogue of several scenery types, from performances of ancient plays that took place in the last 40 years is presented in Table 4.1. The scenery designs are illustrated either with photographs or drawings. The name of the play, the date and the skenographer are also shown. Based on these sceneries and the identifiable characteristics that relate them, generic categories will be created. The acoustic impact of each category will be presented through acoustic simulation. In Table 4.1 it can be seen that, according to the database of photos and drawing material or models, there are few characteristics that can define the sceneries and arrange them into groups. These are background, foreground, object, size and orchestra. It can be seen that most of the scenery designs are composed by several elements, hence by more than one identifiable characteristic, either in terms of the background, an object, many scattered objects or a combination of these.

4.5.3 Classification of Scenery Design for Acoustic Examination

According to the previous review on ancient, past and present scenery designs, as well as the art movements, the contemporary trends allow the architect/designer/acoustician to classify them into four generic categories, each of which has subdivisions due to the characteristics of the scenery layout in space [Chourmouziadou and Sakantamis, 2006]. The sceneries should be adaptable to many theatres, as if they were transparent objects. The results show that the architecturally apparent and aesthetically impressive scenery can, through its acoustic attributes, become a determining factor for the sensory success of the performance.

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[36] pp.67

Table 4.1 presents relatively recent scenery designs, divided according to the major characteristics, as explained in Section 4.5.2. Due to the fact that more than one categories can be found in a scenery design, the reader should follow both the vertical and horizontal classification. The classification of the scenery needs to be rather detailed, especially for the purpose of the acoustic simulation, since it is important to identify the boundaries, objects and other characteristics that will mostly influence distribution of sound and acoustic indices one by one. The categories are investigated from the acoustic viewpoint in Chapter 10. The four generic categories are determined as sceneries that are:

1. Visually created by a background wall, with a variety of materials and heights (Bacchae, 1993; Medea, 1997; Prometheus Bound, 1983 in Table 4.1).
2. Represented by one large-size object, placed on the orchestra. This can partly create a background without interfering with the surroundings, and can be in several shapes and volumes (Oedipus Tyrant, 1985; Eleni, 2006).
3. Composed by many small objects. These can be scattered in several places on the orchestra, or lined up to create the image of a wall. The variables that are highly affective in this case are the objects' width and density, which in their combination may either provide a transparent effect, allowing the actors to move in-between them, or create the sense of an impenetrable boundary [Chourmouziadou and Sakantamis, 2006]. Several combinations in width and distribution can be used (Trojan Women, 1985; Iketides, 1964; Ecclesiazousai, 1993).
4. Concentrated on the orchestra's floor. There are two variables, the material, and in the case of a raised orchestra level, the height from the original orchestra's floor (Ploutos, 1985; Rhesus, 1981; Iphigeneia en Taurois, 2006).

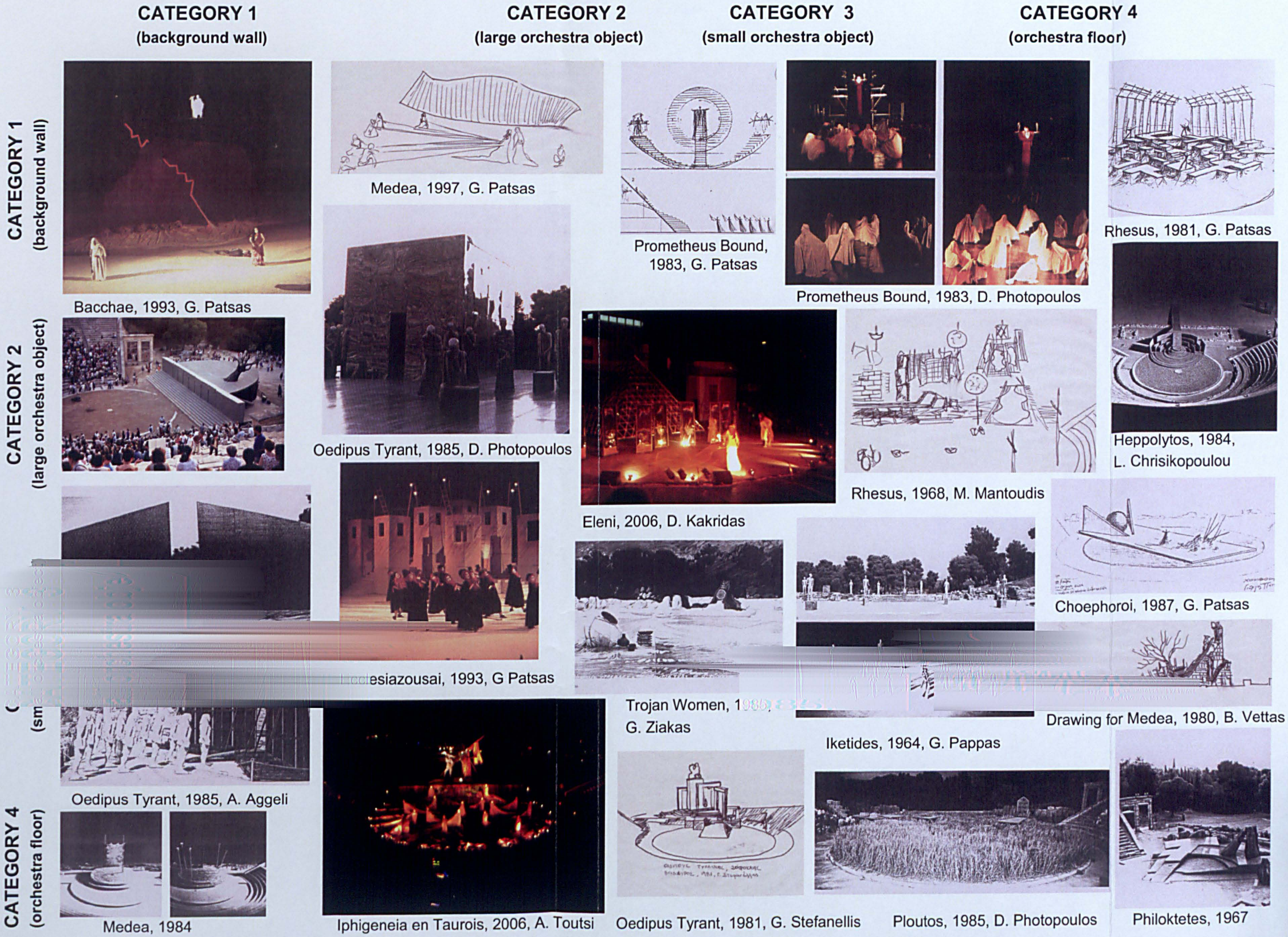
4.6 Conclusions

This chapter, the last component of Part I of this PhD research, namely the literature review, was mainly focused on the layout, creation and development of the stage building in antiquity, as well as on the productions of ancient performances in the last century, with temporary scenery design. The need for a scenic space allowed the designers to create spaces that communicated the play to the audience, usually adaptable to many open-air theatres. The adaptations of ancient Greek drama were examined from the viewpoint of performance and theatre organisation in the 20^{th} century. Innovative scenery designs were discussed, and a classification to identify variables that formulate generic scenery designs was achieved through the investigation of past and present scenery designs.

Regarding the development of the stage building, from a wooden platform to a permanent stone construction that provided an enclosed space, the changes were important for the acoustic evolution, as seen in Chapter 7. Conventional scenery use in antiquity and today, like entrances, exits and positions of actors can also be taken into account in the scenery design and consequently affect the acoustics.

In recent performances the scenery followed several trends in art and architecture, like constructivism, symbolism, abstract art and modernity. This allowed the skenographers to create sceneries that apart from a simple background formulated spaces that had three-dimensional characteristics and the actors could move in, out and in between them. The trends in scenery design constituted its classification, according to characteristics in terms of architecture, in four groups: the scenery in the form of a background, a large object, a combination of small objects and an alteration of the orchestra floor, which will be extensively investigated in Chapter 10. This will allow the acoustic investigation corresponding to the questions/objectives of the whole study. Parametric examination in terms of materials, heights, shape and arrangement will also be studied, as well as actor's positions.

Table 4.1. Photos and drawings from scenery designs in the last 40 years (the one or more categories every scenery design belongs to are found both horizontally and vertically) [sources: Patsas,1995; Photopoulos, 1987; Photopoulos, 1995; and personal archive of drawings and photographs].



PART 2

RESEARCH METHODS

CHAPTER 5

RESEARCH METHODOLOGY AND ACOUSTIC SIMULATION

5.1 INTRODUCTION

This chapter discusses and describes the methodology followed throughout the research study. The methodology has been tested in this part of the research as well as in previous pilot studies [Chourmouziadou, 2002]. The models of the theatres are generic layouts of Greek and Roman theatres. The aim is to identify the appropriate parameters for the acoustic simulation, in order to acquire accurate results and to describe other research methods.

Following the software package description in Chapter 2 regarding open-air theatre simulation, namely CATT, ODEON and Raynoise, this chapter initially discusses the model preparation. Based on the pilot study, appropriate simulation parameters are suggested, including number of rays, and reflection order. Background noise and source directivity are also examined, because of the fact that most of the simulations in later chapters will not include them for the sake of convenience. Moreover, the effects of an area source representing the chorus, a vital part of the performance of ancient drama, as mentioned in Chapter 3, is briefly discussed. It needs to be noted that the way the software handles diffusion will be further investigated in Chapter 6.

Furthermore, this chapter examines the optimum representation of the theatre model, so that the acoustic simulation will provide accuracy of the soundscape, the acoustic environment of the theatre, with short calculation times. Finally, to introduce other means of methodology that will be used in Chapter 8, it describes the processes of absorption coefficient measurement, of on-site measurements and of subjective evaluation tests.

5.2 METHODOLOGY OF ACOUSTIC SIMULATION

With the advance of computer techniques, a number of computer simulation software has been developed, including CATT, ODEON and Raynoise, as shown in Chapter 2. The methodology regarding appropriate parameter selection, used for the acoustic simulation of ancient performance spaces in the latter, is discussed in this section, following the simulation process described in Chapter 2.

To acoustically simulate a space the user of Raynoise has to construct the 3D model, preferably using CAD software. The model can then be imported into Raynoise and a series of properties have to be assigned. These include speed of sound, material properties, source characteristics, receivers and background noise. Regarding calculation there are a lot of analysis' parameters that need to be defined by the user, briefly discussed in Chapter 2, including level of detail in data storage and refinement of the calculation, in order to achieve high accuracy. Detailed investigation has been carried out in previous studies [Chourmouziadou, 2002].

This section starts with a description of the model preparation. Three case studies are then presented, which show the parameters that need to be assigned to the simulation, for accurate results and relatively short calculation time.

5.2.1 PREPARATION OF MODEL

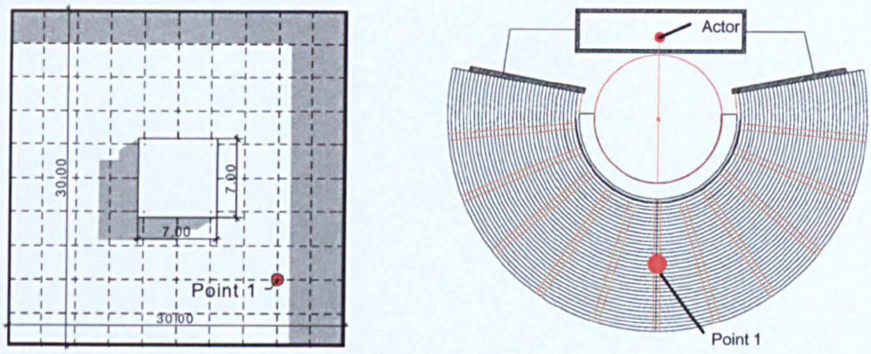
CAD software that can be used to build 3D models, like Archicad, Autocad and 3D Studio, were chosen for this study. To construct a space, exact dimensions are needed, and the surfaces have to be carefully connected. The basic advantage of Archicad is that the 3D representation is available at any time. Instead of drawing lines, ellipses and arcs, the software constructs walls, windows, doors, floors, stairs and roofs. ArchiCAD creates a central database that can simultaneously handle 3D model data with plan and section views, dimensions, material finishes, component lists and more [Graphisoft, 2006]. For this study, Archicad 8.0 was available, which provides *DXF files of the 3D model, easily imported into Raynoise.

5.2.2 SELECTION OF APPROPRIATE PARAMETERS IN SIMULATION

As mentioned in Chapter 2, calculation parameters can influence the accuracy of the model, like number of rays and reflection order. The results of three case studies in a rectangular and a semicircular open-air theatre are briefly presented in this section [Chourmouziadou, 2002]. For the rectangular open-air theatre a Chinese performance space was used. It is noted that a common form of historic Chinese theatre was courtyard-type space with a rectangular stage installed [Chourmouziadou and Kang, 2002; 2003]. Because of the long calculation times in Raynoise, especially for ancient theatre that involve thousands of surfaces, a number of simulations have been carried out for the model of the ancient theatre of Philippi, to identify the minimum required number of rays and reflection order. Furthermore, since the distribution of diffused sound is random in Raynoise, repeated simulations have been made for a Classic Greek theatre to identify possible differences in calculation results.

5.2.2.1 RECTANGULAR AND SEMICIRCULAR OPEN-AIR PERFORMANCE SPACES

This section presents three case studies on the effect of simulation parameters on the acoustic indices. The models used are shown in Figure 5.2.1. For the first case study [Chourmouziadou, 2002] the results derived from 10 simulations of a rectangular open-air performance space with the number of rays ranging from 1,000 to 100,000, reflection order of 10 to 50 and a variety of choices for different parameters like time window, histogram interval and length and tail compensation have shown that although SPL slightly decreased with the increase of the number of rays, the variation was insignificant, while RT30 and EDT were decreasing noticeably. Also, tail compensation has not shown any significant change in results, while the reflection order affected reverberation. When the number of rays exceeds 10,000 the results vary only for STI, hence appropriate parameters suggested were 10,000-20,000 rays, echogram store 10 and histogram store 8. The second case study involved further investigation of the reflection order [Chourmouziadou, 2002], revealing that with reflection orders above 50 the SPL is stable and RT30, EDT and STI increase. In the third case study the model used was an early form of the circular shaped Greek theatre. The parameter investigated was the number of rays. The simulation results showed that RT30 becomes longer and EDT shorter when the number of rays increases. Hence, for this performance space suggested parameters are 10,000-20,000 rays with a reflection order of 50.



a b

Figure 5.2.1. *Plan of the models used. a) Case studies 1 and 2, b) Case study 3.*

5.2.2.2 Number of Rays

This section refers to a comparison between 10,000 rays and 5,000 rays for the simulation of the theatre of Philippi, as illustrated in Figure 5.2.2, with the typical receiver and receiver line positions. The detailed representation of the theatre is presented in Section 9.3. The number of rays was determined after the results of the third case study presented in Section 5.2.2.1. It needs to be noted that, due to the complexity of the ancient theatres, simulations with more than 10,000 are impossible to be carried out in Raynoise, either because of the extremely long calculation times (3-4 days each) or the error messages that cause failure to the software.

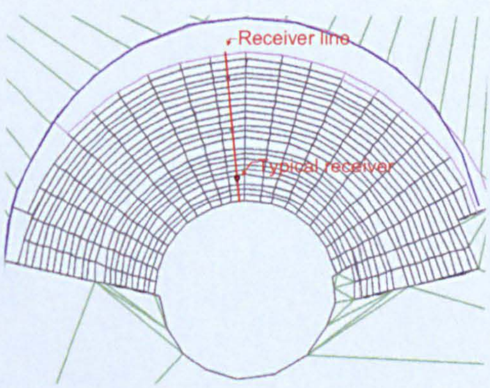


Figure 5.2.2. *Plan of the theatre of Philippi.*

The calculation has been run with 20 reflection order, time window of 2,000ms and dynamic range of 90. Diffusion has been applied to the surfaces, while diffraction and tail compensation have not been calculated. The SPL and RT30 results regarding the comparison of the ray number are illustrated in Figure 5.2.3, while the energy responses are shown in Figure 5.2.4. The SPL for three receiver points on the receiver line on rows 2, 10 and 12, at distances of almost 15, 24 and 26m from the source respectively, points out that only at large distances from the source there is a variation between the two numbers of rays, at a maximum of less than 1dB. The low values are found with 5,000 rays, since they do not formulate appropriate early reflection distribution to the receivers high on the koilon to enhance SPL. RT30 results reveal the same tendency for the range of frequencies. In Figure 5.2.3b the RT30 for the whole receiver line at 500Hz is shown. The simulation of 10,000 rays produces a rather smooth RT30 curve, due to the better disperse of sound in terms of the beam method and the receiver points.

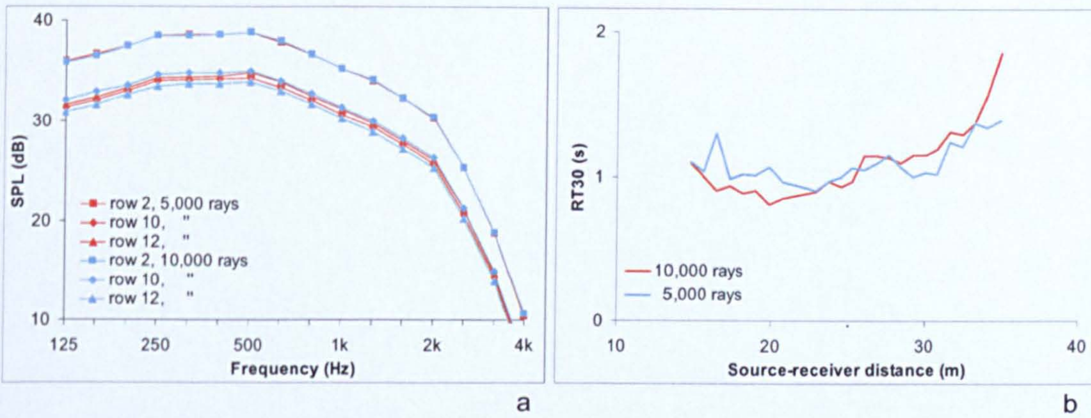


Figure 5.2.3. Comparison between 5,000 and 10,000 rays in the simulation of ancient theatres a) SPL (dB) for the frequency range at three receiver positions, b) RT30 (s) for the receiver line at 500Hz.

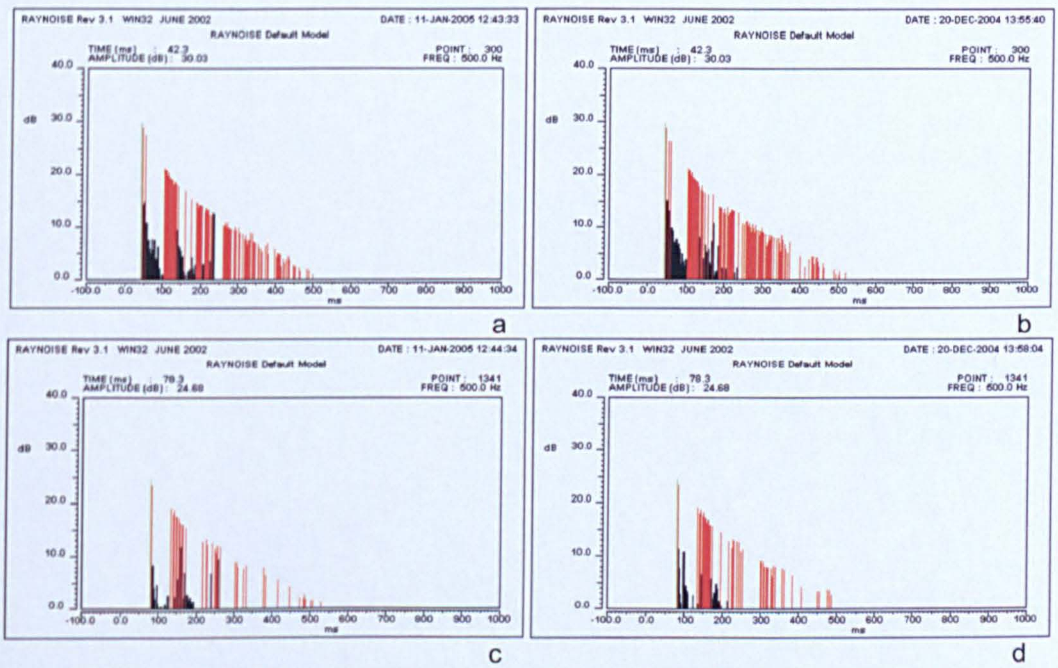


Figure 5.2.4. Comparison of the energy responses. a) Receiver at the front with 5,000 rays, b) Receiver at the front with 10,000 rays, c) Receiver at the back with 5,000 rays and d) Receiver at the back with 10,000 rays.

The values of STI and D50 are almost the same for the two cases, showing that no particular difference occurs for speech evaluation. The energy responses presented in Figure 5.2.4 further demonstrate the above discussion. Although the general layout of the impulse responses of the receiver at the front of the theatre, in Figures 5.2.4a and b do not particularly differentiate for the 5,000 and 10,000 rays, Figures 5.2.4c and d show that the large number of rays produces more specular reflections, shown in red, as well as high order reflections and diffused sound, shown in black. As far as the rest of the indices are concerned, distinguishable variation is found in LEF, which seems to be slightly improved with large number of rays. From the above it is obvious that, as discussed in Section 5.2.2.1, the maximum number of rays possible is preferred in the simulations.

5.2.2.3 Reflection Order

This Section, like Section 5.2.2.2, presents a comparison of different values in reflection order for the simulation of the theatre of Philippi. The reflection order varies between 5, 10 and 20. Figure 5.2.5 illustrates the SPL, RT30 and D50 for a receiver line off the central axis of the theatre at 500Hz, and the RT30 for two receivers, at 15 and 26m from the source.

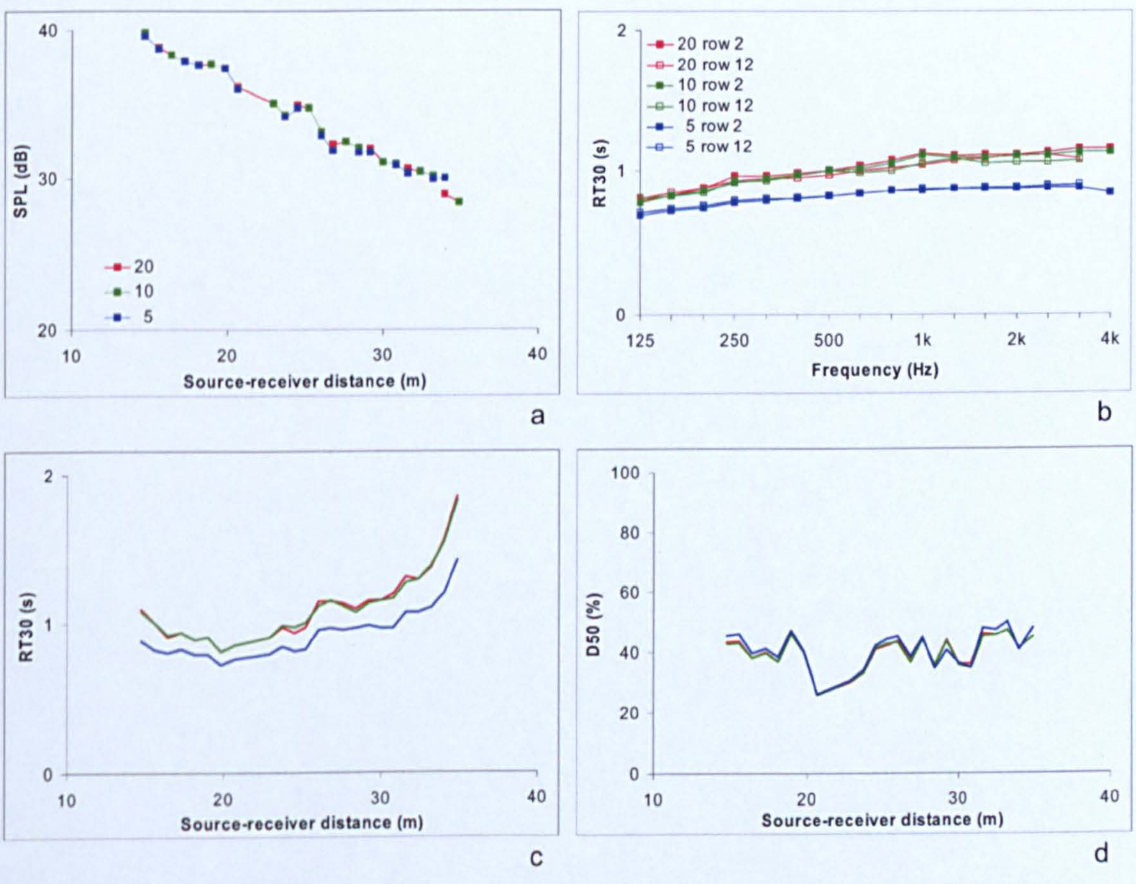
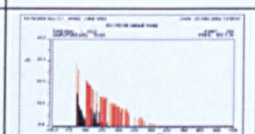
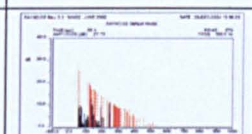
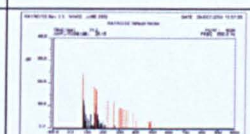
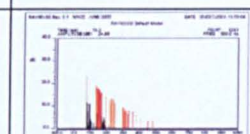
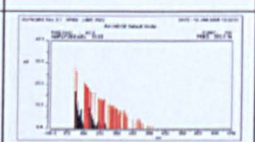
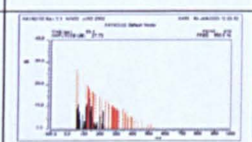
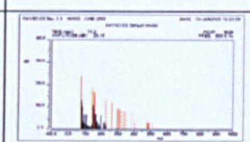
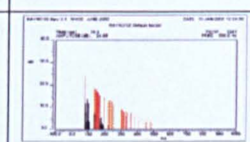


Figure 5.2.5. Comparison between 20, 10 and 5 for the reflection order. a) SPL (dB) for the receiver line at 500Hz, b) RT30 (s) for the frequency range at two receiver positions, c)RT30 (s) for the receiver line and d) D50 (%) for the receiver line.

All the indices shown reveal that there is no prominent dissimilarity between 20 and 10. However, when the reflection order is further reduced RT30 is decreased by 0.11-0.43s. SPL and D50 are not altered in a great degree.

Further comparison between reflection orders 20 and 10 is carried out in Table 5.1, where the energy responses for four receivers are illustrated, showing that sound distribution and reflection are not influenced by the difference between the two reflection orders. Hence, considering the above results, both in terms of the acoustic indices and reflection distribution, the simulation of ancient theatres is possible to be carried out with reflection order of 10.

Table 5.1. *Impulse responses for reflection orders of 20 and 10.*

		Receiver			
		1	2	3	4
Reflection order	20				
	10				

5.2.2.4 Diffusion

As mentioned previously, in Raynoise diffused sound is randomly distributed in the simulated space. Hence, to test the effect of diffusion on the acoustic indices, simulations of ancient theatres were repeatedly carried out. However, the repeated simulations revealed that the final values for most indices were approximately the same in all simulations [Chourmouziadou, 2002]. Therefore, variation in the indices due to random diffusion distribution was negligible.

5.2.3 Background Noise

Background noise can be applied in Raynoise either as a constant sound, where the user determines the sound power level for each frequency, or by determining a source, either point, area or line that produces the noise. In the first case the acoustic environment is influenced by both the main source and the background noise. For the former case the test was performed by applying wind noise as background noise to the simulation of the theatre of Mieza in its original condition, as will be further examined in Section 9.2. The sound power level of wind was: 0dB at 125-250Hz, 33dB at 500Hz, 35dB at 1kHz, and 37dB at 2-4kHz, according to Egan [1988], while the main source was human speech. Raynoise calculates the effect of the background noise automatically, by applying it to the final results. Figure 5.2.6a illustrates the SPL for two receivers on the receiver line, at the low and the high part of the audience area, as shown in Figure 9.2.2a. Due to the fact that the wind's sound power level corresponds to frequencies above 500Hz, its values are significantly higher than the SPL in the theatre with no background noise, since the speech SPL attenuates considerable with increasing distance. The effect is more obvious above 2kHz for the receiver at the low part of the koilon and above 1kHz for the high part of the koilon, with differences increasing with frequency, at 0-27.6dB and 6.4-34.3dB respectively. Hence, for the part of the performance that corresponds to high frequencies, either speech or music, the acoustic conditions are poor, especially for the audience high at the koilon. The impact on STI is shown in Figure 5.2.6b, with extremely low values above 500Hz. Obviously, reverberation cannot be measured in these conditions, while definition is also decreased with the addition of background noise, by 13% at the front and 52% at the back of the audience.

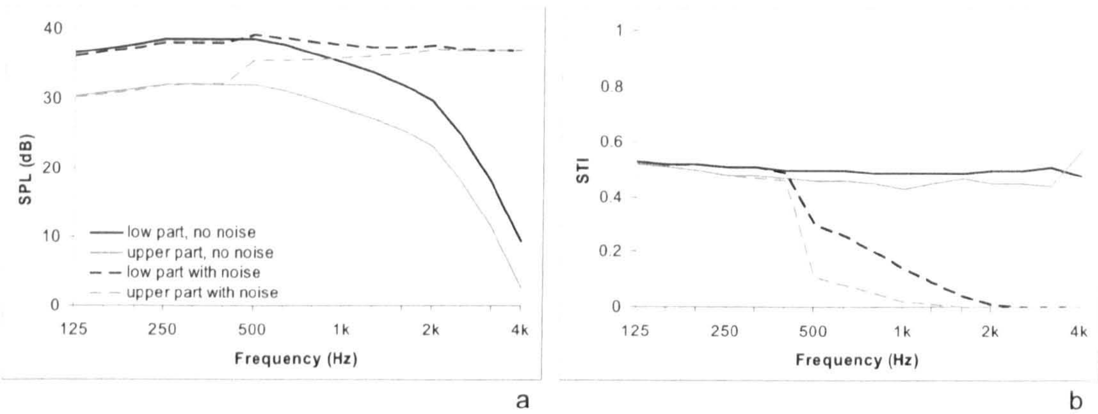


Figure 5.2.6. *Effect of background noise in the ancient theatre of Mieza for two receiver positions. a) Comparison between SPL (dB) with and without noise for the frequency range and b) Comparison between STI with and without noise for the frequency range.*

In the second case, the user has to identify one source for the acoustic simulations. Since two sources cannot emit sound simultaneously, only the source that produces the noise will be calculated. This has been carried out for the theatre of Philippi in Section 9.3, because it is located next to a motorway. Hence, the effect of the traffic has been calculated as a line source. It is clear by the above discussion that, since this study is mainly focused on the comparison between different configurations of the ancient theatres, regarding original, present and restoration conditions, material properties and effect of scenery design on the acoustic environment, the evaluation of acoustic indices in terms of differences in architectural layout are of major concern. The application of background noise is used in several instances, when it is considered very important, but would otherwise complicate the purpose of this study. It is acknowledged that the presence of background noise due to the large number of audience, external factors, insects and animals are harmful for the acoustic environment during a performance. However, as will be seen in Section 8.6, the audience is mostly irritated by mechanical devices rather than animals and insects.

5.2.4 SOURCE DIRECTIVITY

The simulations carried out throughout this study are based on an omni-directional source, except where indicated otherwise. Lambert distribution and semi-point sources have also been compared in Chapter 6, Section 6.7, while a source with human directivity characteristics is presented in this section, mainly to show the differences in sound distribution.

It has been previously mentioned that because of the fact that power level of the human speech is reduced at the back of the head compared to the front, sound amplitude and distribution are weaker at those areas in the ancient theatre, than at the axis, and consequently, background scenery would slightly affect the acoustics [Barron, 1993]. However, the prerequisite for this argument is that the actors are always facing forward, while performing in an ancient theatre. Ancient drama is a combination of voice, dance and movement, and this claim would be unrealistic. Rarely are the actors facing the axis of the theatre. It is also unlikely for an actor to be standing at a fixed position. Therefore, a difficulty of using a directional source in the simulations is its orientation.

To examine the effect of source directivity, a comparison is carried out between an omni-directional source and a directional source for the Hellenistic theatre type in the original condition, in terms of the distribution of direct sound only, SPL with reflections, RT30 and STI, at 500Hz. Figure 5.2.7 illustrates the source and receiver positions.

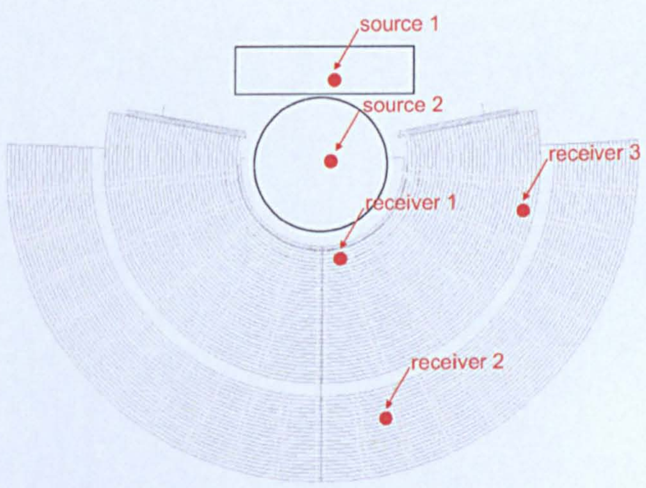


Figure 5.2.7. *Plan of the Hellenistic theatre of Epidaurus with source and receiver postiions.*

The directional source considers both horizontal and vertical directivity, based on directivity tables of human voice from the literature, shown in Table 5.2 [UK Department for Education and Skills, 2004].

Table 5.2. *Directivity tables for horizontal used for the directional source [source: UK Department for Education and Skills, 2004].*

HORIZONTAL DIRECTIVITY

Azimuth (°)	125	250	500	1k	2k	4k	8k
	Octave band centre frequency (Hz)						
0 (front)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	-0.2	-0.3	0.3	-0.7	0.3	-0.6	-1.1
60	-0.7	-1.2	0.2	-0.5	-1.8	-2.0	-4.4
90 (left/right)	-1.5	-2.8	-1.8	-0.3	-5.6	-5.5	-8.9
120	-2.3	-4.2	-3.8	-3.0	-6.3	-10.0	-13.3
150	-2.8	-5.3	-5.3	-7.1	-10.4	-14.4	-16.8
180 (back)	-3.0	-5.9	-6.1	-5.0	-10.9	-16.6	-18.9

VERTICAL DIRECTIVITY

Elevation (°)	125	250	500	1k	2k	4k	8k
	Octave band centre frequency (Hz)						
0 (front)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.3	-1.0	-0.2	2.4	0.3	-2.1	0.5
60	-0.3	-2.3	-1.7	1.6	-0.1	-2.3	-1.1
90 (up)	-1.7	-3.3	-3.7	-0.2	-3.4	-5.8	-4.6
120	-2.2	-3.8	-3.4	-3.6	-4.7	-8.1	-9.4
150	-2.5	-4.8	-3.9	-1.2	-7.8	-13.3	-16.6
180 (back)	-3.0	-5.9	-6.1	-5.0	-10.9	-16.6	-18.9
210	-3.3	-6.6	-7.6	-8.9	-13.0	-18.6	-18.5
240	-3.0	-4.7	-6.3	-7.5	-15.4	-17.6	-16.9
270 (down)	-2.2	-4.0	-2.8	-3.7	-10.7	-11.0	-9.5
300	-1.3	-3.2	0.7	0.1	-6.0	-4.4	-2.1
330	-0.4	-1.6	3.2	-2.6	-1.2	-0.5	2.2

The source is positioned both on the stage building and the orchestra, representing two possible performance conditions in antiquity, with its central axis parallel to that of the theatre. It is noted that for the convenience of relative comparison, the sound pressure levels of the two sources are set to be the same on the central axis. In other words, the overall sound power level of the directional source is less than that of the omni-directional source. Consequently, the comparison between the two sources would mainly be for distribution patterns, rather than absolute values, especially for SPL. Figure 5.2.8 presents the direct sound distributed in a semi-free field, both from the directional source with the characteristics of Table 5.2 and from the omni-directional source.

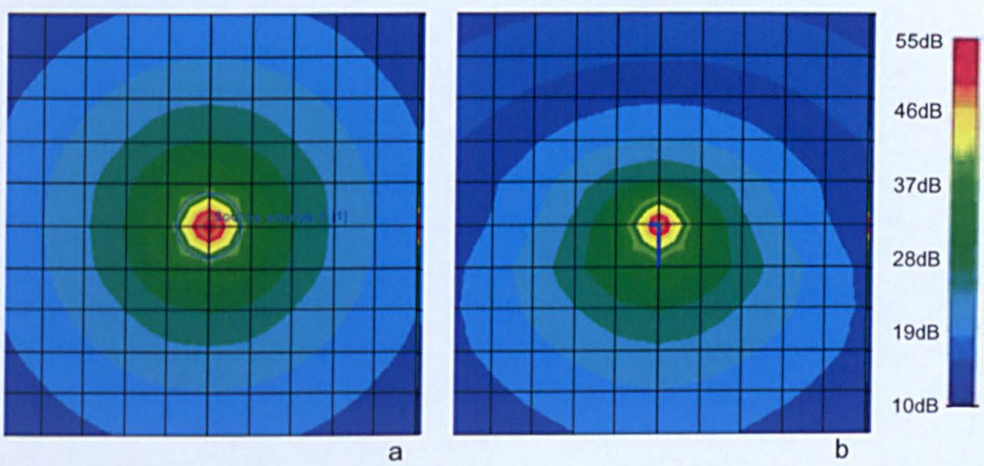


Figure 5.2.8. *Colour maps of direct sound. a) Omni-directional source and b) Directional source.*

From Table 5.3, presenting the results with the source on the stage building, namely source 1, it can be seen that, with direct sound only, on both sides of the audience area the SPL with the directional source is lower than near the axis, which corresponds to its directivity. With reflections being taken into account, the SPL in the audience area is greatly enhanced for both sources. With the omni-directional source, the enhanced SPL on the sides is greater than that with the directional source by 1-3dB. In terms of the reverberation distribution, there are some variations between the two sources, but the difference on average is generally insignificant.

More obvious is the difference between the two sources, when these are placed in the orchestra at coordinates x= -1m, y= -1m and z=1.6m (x=0m and y=0 is the centre of the orchestra). Table 5.4 shows the colour maps of the acoustic indices. The SPL and direct sound differences are almost the same as in the previous case. However, RT30 values show that the sides of the koilon have longer reverberation than the rest of the audience area, when the simulation is carried out with the omni-directional source. A rather more even distribution can be seen with the directional source. As far as definition and clarity are concerned, it is found that, corresponding to previous observations, the conditions at the sides are worse than in the middle of the theatre. However, because the directional source seems to provide better D50 and C80 conditions in general, the results of the directional source indicate better conditions for speech. Therefore, the omni-directional source used in the simulations would possibly point out the defects of the theatre's layout.

Table 5.3. *Colour maps with the acoustic indices for directional and omni-directional sources with the actor on the stage building.*

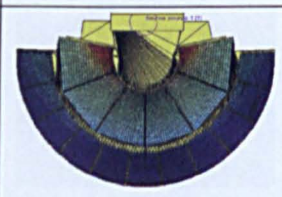
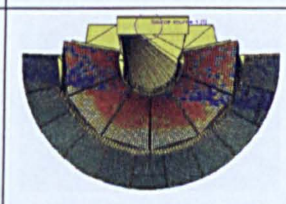
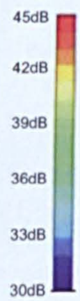
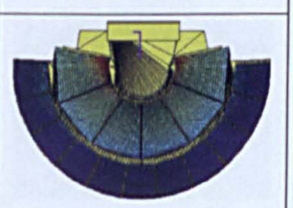
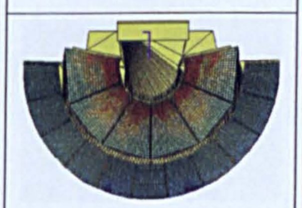
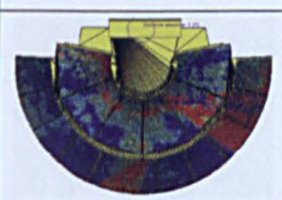
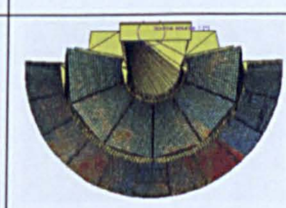
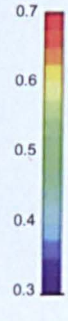
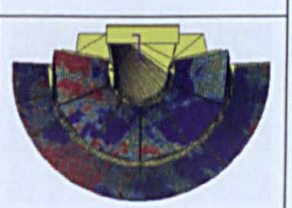
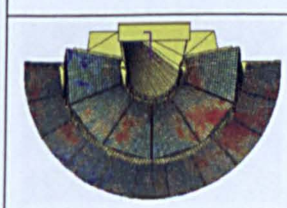
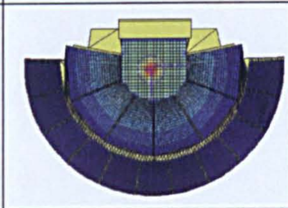
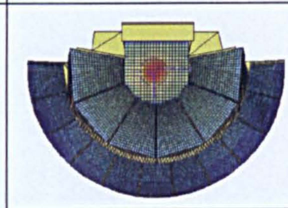
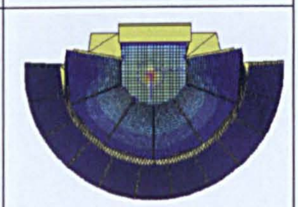
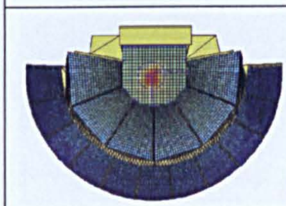
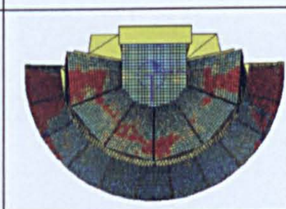
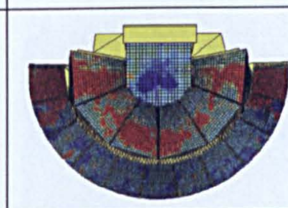
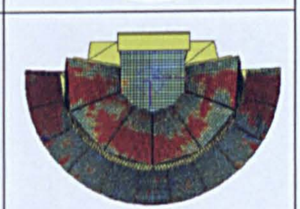
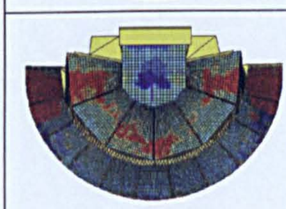
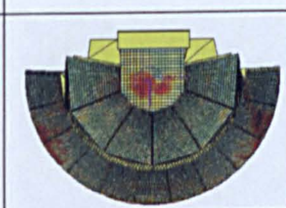
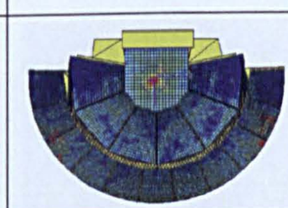
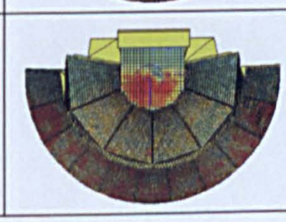
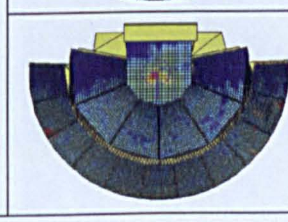
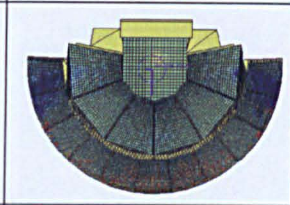
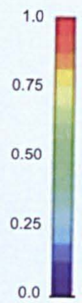
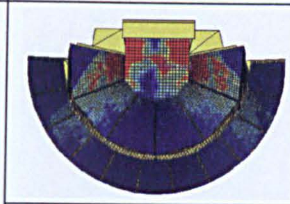
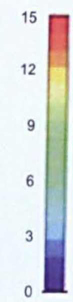
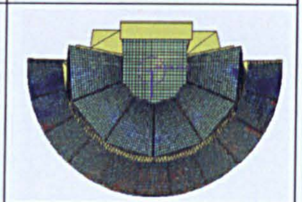
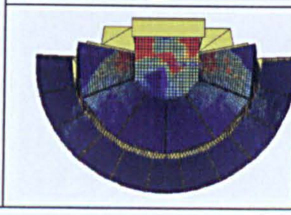
	Direct Sound	Range	SPL	Range
Omni-directional source		 40dB 38dB 36dB 34dB 32dB 30dB		 45dB 42dB 39dB 36dB 33dB 30dB
Directional source				
	RT30		**STI**	
Omni-directional source		 2.0s 1.8s 1.6s 1.4s 1.2s 1.0s		 0.7 0.6 0.5 0.4 0.3
Directional source				

Table 5.4. *Colour maps with the acoustic indices for directional and omni-directional sources with the actor in the orchestra.*

	Direct Sound	**Range**	**SPL**	**Range**
Omni-directional source		50dB 44dB 38dB 32dB 26dB 20dB		50dB 44dB 38dB 32dB 26dB 20dB
Directional source				
	RT30	**Range**	**EDT**	**Range**
Omni-directional source		3.0s 2.4s 1.8s 1.2s 0.6s 0.0s		3.0s 2.4s 1.8s 1.2s 0.6s 0.0s
Directional source				
	D50		**C80**	
Omni-directional source		100 75 50 25 0		20dB 16dB 12dB 8dB 4dB 0dB
Directional source				

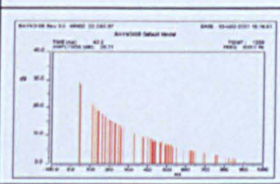
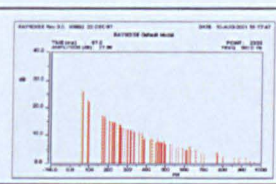
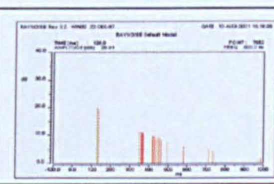
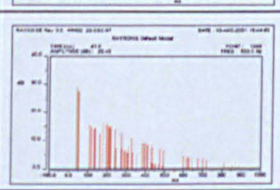
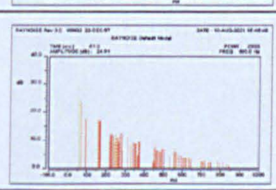
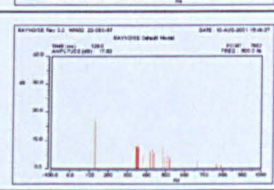
continued…

Table 5.4.*....continued from page 115.*

	STI		LE%	
Omni-directional source				
Directional source				

By examining the energy responses at three typical receivers, one at the low part, one at the high part and one at the sides of the koilon, shown in Figure 5.2.7, Table 5.5 shows that with the directional source there is a small decrease in the number of reflections as well as the amplitude, although the decay process is generally the same. In terms of STI, the directional source seems to provide better speech intelligibility, since it is basically related to RT. However, the difference between the two sources is not radical. Overall, considering the general differences between the two sources in terms of sound distribution, but also the fact that a directional source will only provide a fixed position of the actor, the simulations in this study have been carried out with the omni-directional source for the sake of convenience. More calculations have been carried out in a previous study, both for the unoccupied and occupied conditions of the theatre [Chourmouziadou and Kang, 2007a].

Table 5.5. *Impulse responses for directional and omni-directional sources with the actor in the orchestra.*

	Receiver 1	Receiver 2	Receiver 3
Omni-directional source			
Directional source			

5.2.5 Model Layout, Impulse Response and Reverberation

Basic characteristics of the ancient theatres, especially after the Classic period, are their shape, either in 180° angle or more, their inclination, which is constructed with rows of seats instead of one inclined surface, and the lack of a ceiling.

In Chapter 2 it has been pointed out that in the simulation procedure it is important to use software that accurately represents and calculates the model of the theatre. The application of an absorptive ceiling to represent the sky could sometimes result in unrealistic distribution patterns. Moreover, the exact representation of the model regarding the audience area, namely the stepped area instead of the widely used inclined surface, is also needed to ensure accurate reflection paths. This has initially been stressed out by Chourmouziadou and Kang [2002] and by Lisa *et al* [2004]. With accurate representation the sound coming from the actor will be repeatedly reflected from the audience area and from the stage wall, arriving at the listener's position with large delay and attenuation and contributing to long reverberation time. The effect of this phenomenon is more obvious in Roman theatres that have high stage walls. On the other hand if the representation of the audience area is simplified, the reflection will be directed to the sky.

Another peculiarity of the simulation is that, since specular reflections determine impulse responses and consequently RT30 values, significant variation between two adjacent points can be often observed, due to the differences in reflection paths. In cases where this is observed the user could calculate and use average values.

Additionally, the diffraction and scattering effect from the empty seats is important in open-air theatres because of the small number of strong reflections in the impulse responses. By comparing the measurement and simulation results, as will be seen in Chapters 6-8, the gaps between the strong reflections have to be filled in with scattered energy [Lisa *et al*, 2004] for a smoother decay curve. Nevertheless, due to the size of ancient theatres the reflection paths are usually long; hence the impulse responses present only few reflections with large gaps.

With reference to this, the impulse responses of several layouts of ancient theatres are illustrated in Figure 5.2.9, corresponding to typical receivers in the Classic, Hellenistic, Roman and Chinese theatre types. The Chinese type is used only for comparison. It is a rectangular open-air performance space, surrounded by 10m high walls, similar to the one shown in Figure 5.2.1a. The effect of the layout on the impulse responses is obvious, as will be also discussed in Chapter 7. The Classic theatre, in Figure 5.2.9a, with low stage building provides small numbers of reflections, clearly identifiable, with relatively large delay gaps due to long reflection paths, when sound is reflected many times between the surfaces of the theatre. The reverberation time in this type is 0.40-0.70s. In the Hellenistic type, in Figure 5.2.9b, the reflections have been increased, still without a smooth decay, with RT30 around 0.80-1s. The software calculates reverberation in these cases irrespective of the gaps in these impulse responses, by calculating the decay curve. Therefore, even small numbers of reflections can produce reverberation. In Figure 5.2.9c the echogram in the Roman theatre layout shows the improved reflection distribution, due to the raised stage building. It is noted that the RT30 is around 1.70s. Finally, the echogram of the Chinese theatre, shown in Figure 5.2.9d, shows a smooth decay curve with RT30 values at around 1s, produced by multiple reflections between parallel surfaces. In the two last cases the gaps have been filled, although it is revealed that Figures 5.2.9b and d, corresponding to the Hellenistic and the Chinese layout respectively, produce the same reverberation. It is noted that the Hellenistic theatre is significantly bigger than the Chinese.

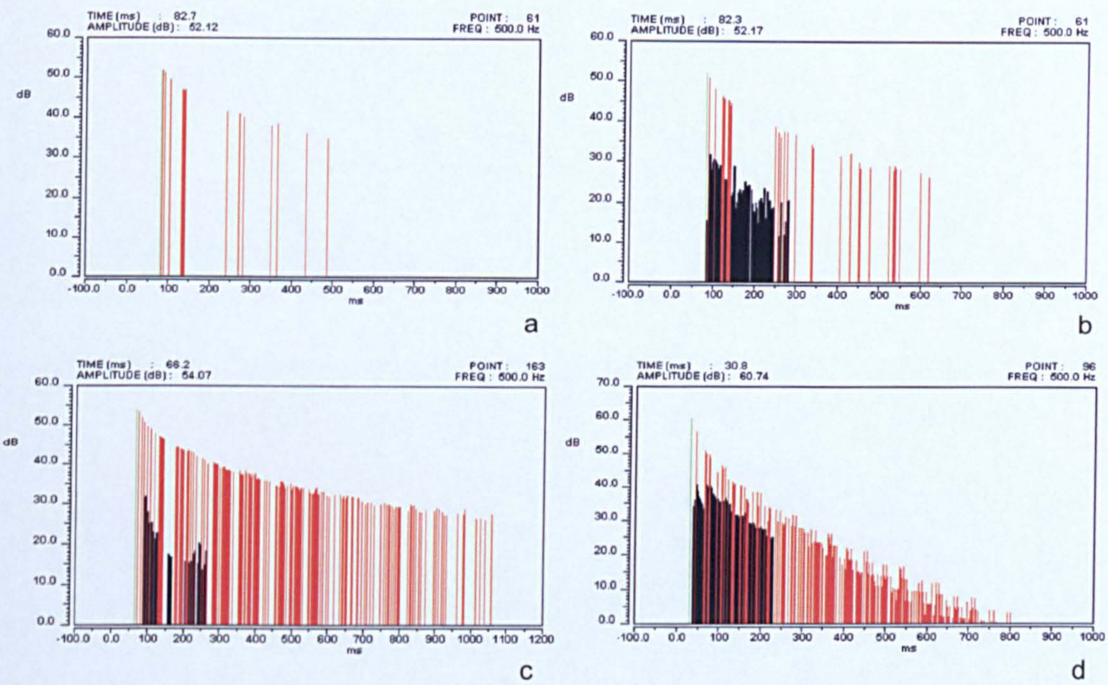


Figure 5.2.9. *Impulse responses of different theatre layouts. a) Classic Greek theatre type, b) Hellenistic theatre type, c) Roman theatre type and d) Rectangular Chinese theatre type.*

5.3 Representation Methods for Outdoor Ancient Theatres with Concave Shape

The overall research on the acoustics of ancient performance spaces is nowadays based on the simulations with the use of commercial software. One of the requirements is the 3D model, which often needs to be simplified, especially in Raynoise. Complicated models of ancient theatres, which consist of hundreds of thousands of surfaces, are extremely time consuming. The simulation of the theatre of Epidaurus, presented in Chapter 8, with 55 rows of seats, and 36 staircases is an example of the complicated and time consuming simulations. Figure 5.3.1 illustrates the original plan of the theatre after its excavation [Müller-Wiener and Gerkan, 1961]. In this case a method of simplification of the 3D model needed to be invented, in a way that would not interfere with the basic acoustic indices, as for example by altering the reflection paths. Although the audience area of the ancient theatres has been previously represented by inclined surfaces [Barron, 1993], the method lacks consideration of major reflections of the theatre's koilon [Chourmouziadou and Kang, 2002]. Therefore, for each row of the 12 lower and 22 upper wedges of the audience area a rectangular object was selected, to replace the concave segment, namely the step of the koilon.

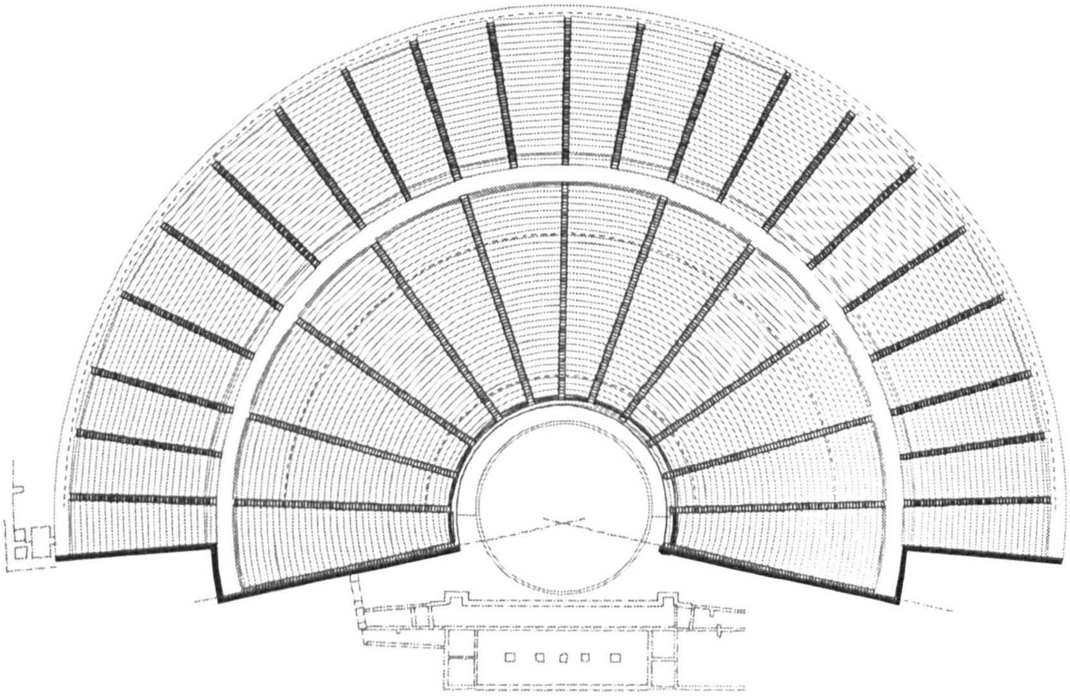


Figure 5.3.1. *Plan of the theatre of Epidaurus according to the drawings by Von Gerkan.*

CAAD software are usually constructing circles with poly-lines, so the problem of altering the reflection patterns would be eliminated if the appropriate number of lines was selected for each concave part of the theatre. Thus, before the simulation of the whole theatre was carried out, tests needed be done with simplified models. This section presents a series of simulation results, with the use of software Raynoise, of four ways of representing semicircular enclosures, namely using 6, 12, 24 and 36 segments. Variables such as relative source-receiver heights, distances from the enclosure, enclosure heights, absorption and diffusion are taken into account.

5.3.1 Comparison between different Representations of Concave Shapes

This section involves all sets of enclosures, named after the number of linear segments representing a semicircle as: Set 6, Set 12, Set 24 and Set 36. For each set three sizes of enclosures were simulated, with radiuses selected in order to consider boundaries in several distances from the source and the receivers. For the radius of every element, distances from the source in the theatre of Epidaurus were selected, at 12.70m, 31.80m and 56.90m, with heights of 2m, 10.30m and 22.10m respectively. These are illustrated in Figure 5.3.1 by the red dashed lines. Figure 5.3.2 presents Set 12, where the semicircles are divided in 12 segments.

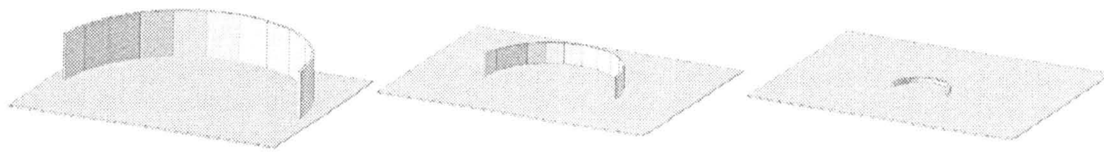


Figure 5.3.2. *The three sizes of Set 12 created for the simulation.*

Both the enclosures and the floor are simulated as marble surfaces in all configurations, since it was the most common material for ancient theatres, followed by porous stone. The absorption coefficients are 0.01 for all frequencies [LMS Numerical Technologies, 2001]. Flat panel diffusion coefficients are also applied, further investigated in Chapter 6. They are: 0.30 at 125Hz, 0.20 at 250Hz, 0.15 at 500Hz, 0.10 at 1kHz, 0.09 at 2kHz, and 0.07 at 4kHz. For this set of enclosures a point source is positioned at the centre of the circles, simulating a single actor at 1.7m above the ground floor. The receivers occupy a flat surface, positioned at the same height as the actor. The temperature for these models is at 20°C and the relative humidity is 50%. The frequency for the calculations is from 125 Hz to 4kHz in third octave. The triangular beam method is used and no tail compensation is applied, according to the discussion in Section 2.7.2 regarding outdoor spaces. The propagation parameters involve 20,000 rays, with 50 reflection order. The time window is 2,000 and the dynamic range is 90dB.

For the simulations that have been carried out with no diffusion applied to the model, the SPL and C80 are illustrated in Figure 5.3.3. It is indicated that with large radius, which corresponds to large boundary-receiver distance, the variation between the different representations is smaller. For 12.70m and 56.90m radiuses the maximum differences in SPL are 3dB and 1dB respectively, and in C80 6dB and 3dB respectively.

Especially for Sets 12 and 36 the SPL for the 12.70m radius between the simulations both with specular reflection only and with diffusion is presented in Figure 5.3.4a. The results show that shape hardly affects SPL, for the same receiver as in Figure 5.3.3, although small differences can be seen at low frequencies. In the most extreme case the difference in SPL reaches 2.3dB. The higher values are found when the semicircle is represented by 12 segments. This reflects a point positioned near the source. It has been observed that with bigger enclosures, which are far from the fixed positions of the source and the receiver, the differences are eliminated. This corresponds to the majority of receivers. Hence the variations are more obvious for the receivers close to the boundaries. The comparison between the two cases with diffusion has the same results.

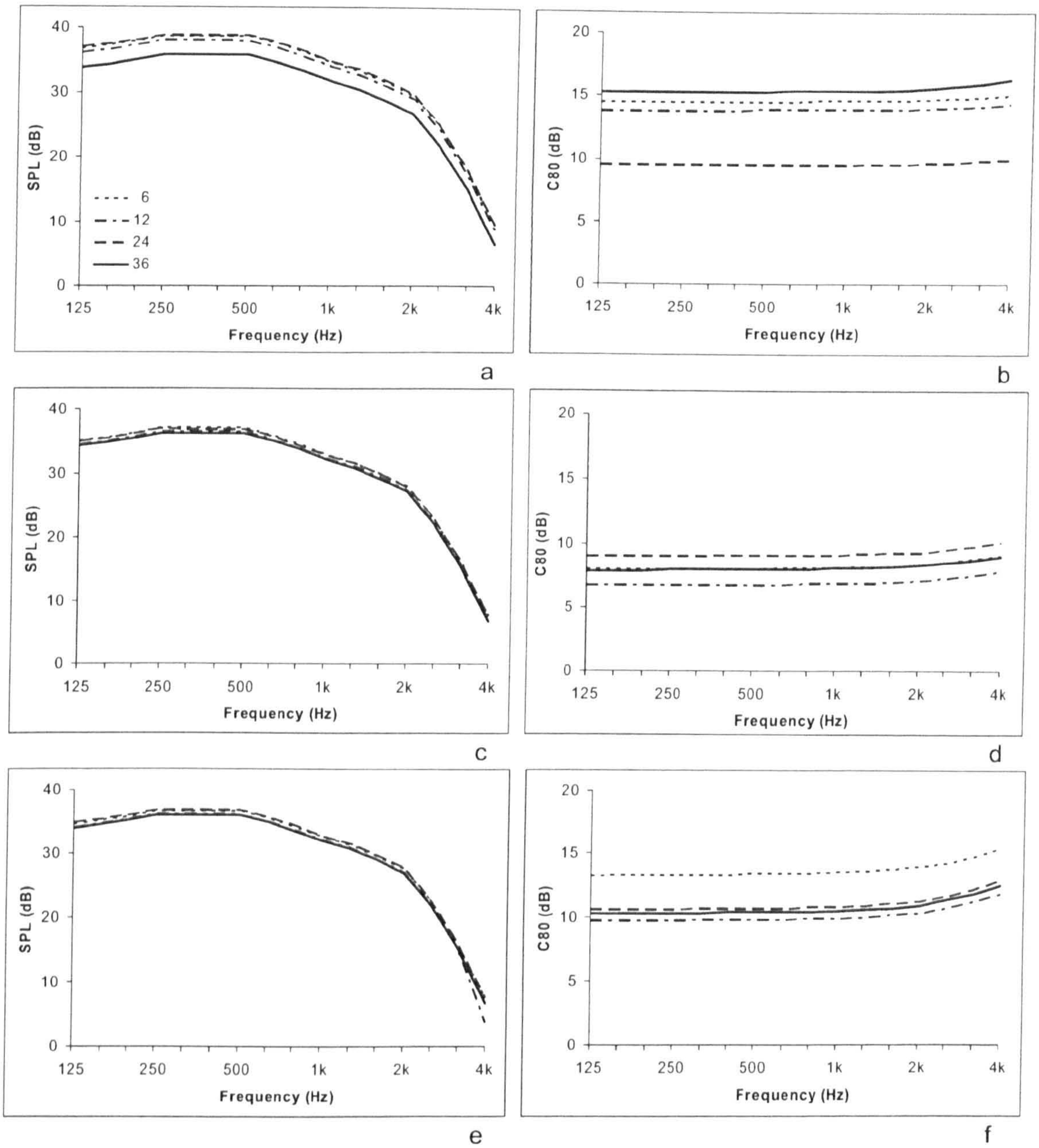


Figure 5.3.3. *SPL (dB) and C80 (dB) for the 4 sets of segments and the three enclosure sizes. a)SPL for 12.70m radius, b) C80 for 12.70m radius, c) SPL for 31.80m radius, d) C80 for 31.80m radius and e) SPL for 56.90m radius and f) C80 for 56.90m radius.*

The results regarding RT30 variations are shown in Figure 5.3.4b for the 56.90m enclosure. It is revealed that the increase in segment number, representing a semicircular enclosure, increases RT30 around 1s both with specular reflections only and with diffusion. At high frequencies variations are reduced considerably but are still significant. It needs to be noted that for receiver positioned near the centre of the semicircle neither the representation of the enclosure or the size/proximity of the boundaries affects the RT, since reflection paths are similar.

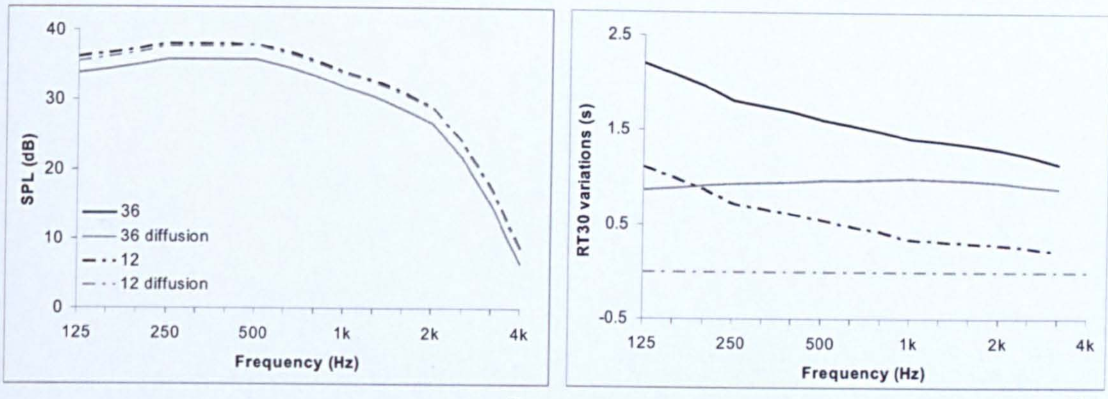


Figure 5.3.4. *Two enclosure sizes for specular and diffuse reflections. a) SPL (dB) with 12.70m enclosure radius and b) RT30 (s) variations with 56.90m enclosure radius.*

Sound distributions particularly regarding reverberation are shown in Figure 5.3.5 in the form of colour maps. Different patterns between Sets 12 and 36 are illustrated, which particularly affects small enclosures. The impulses responses and reflection paths at the receivers in Table 5.6 are presented to examine the reflection patterns that Sets 6, 12, 24 and 36 provide.

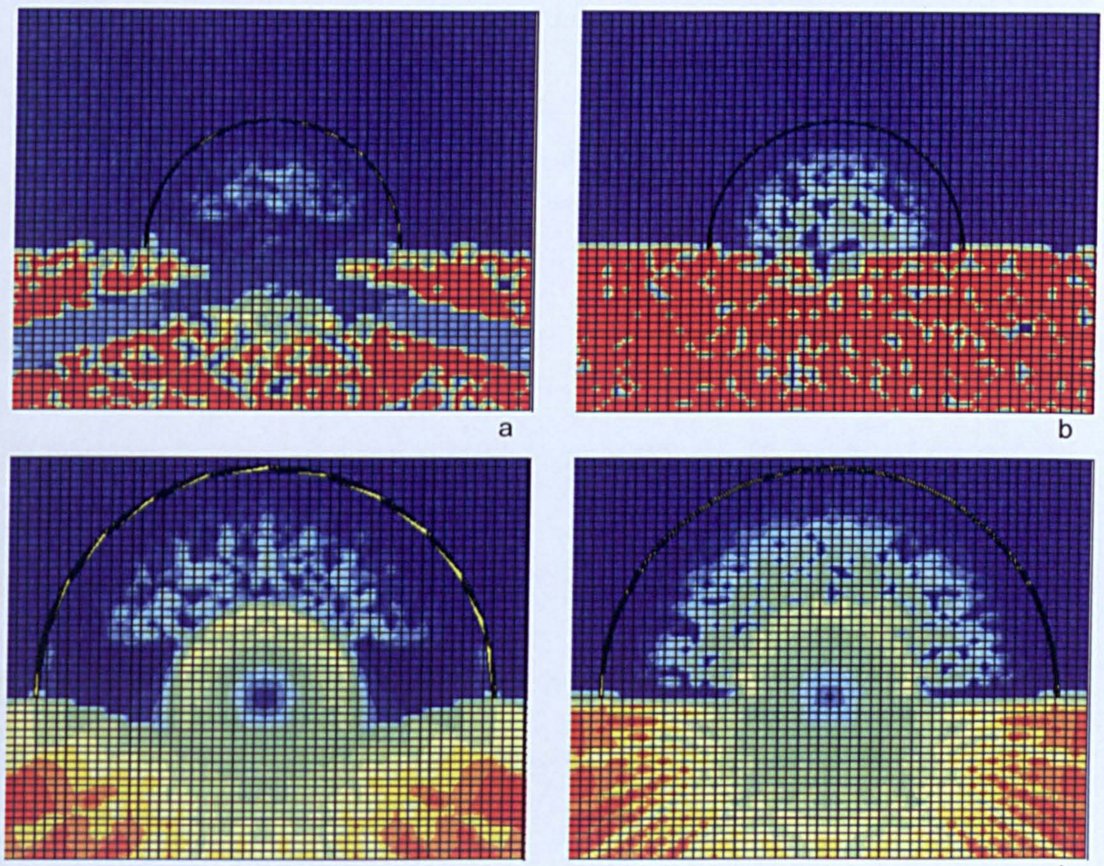
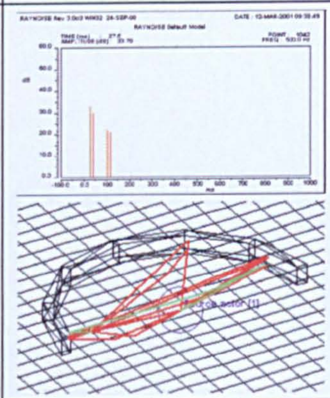
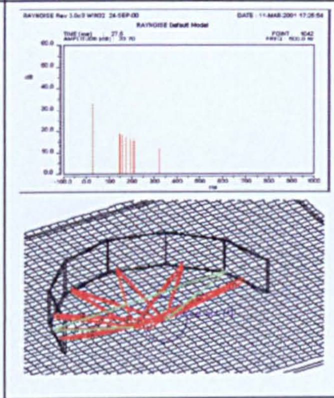
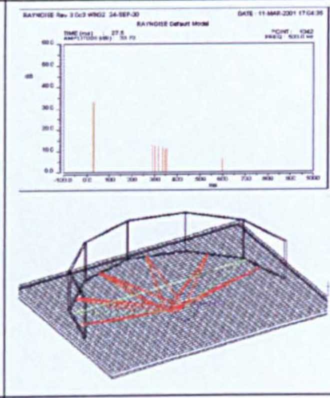
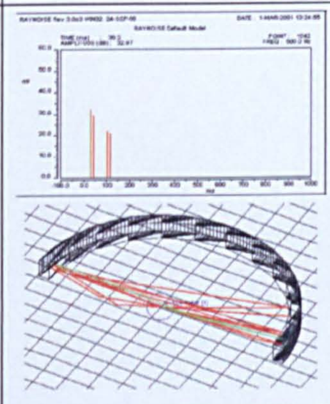
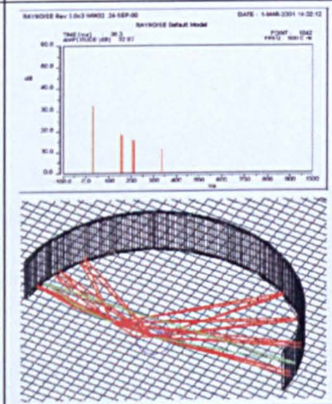
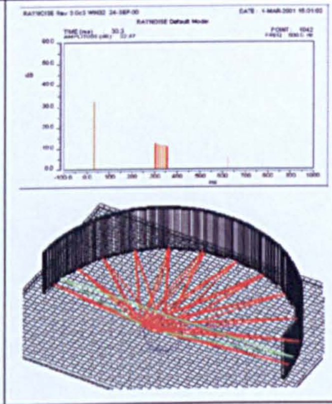
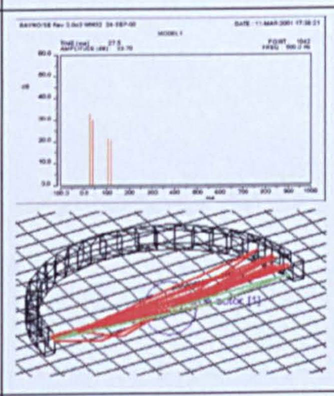
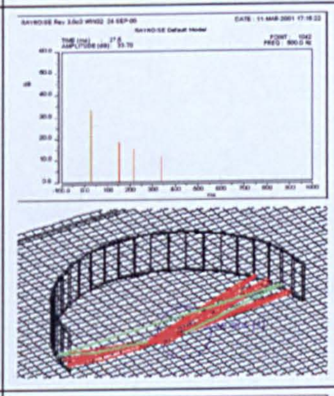
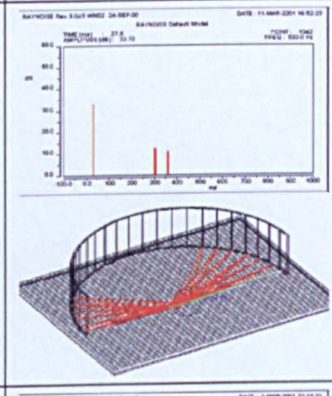
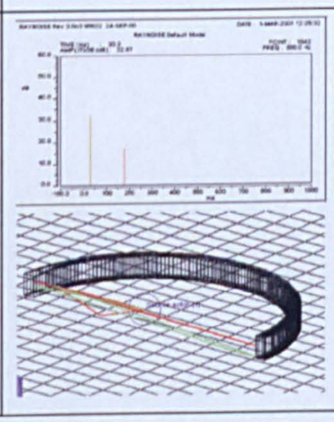
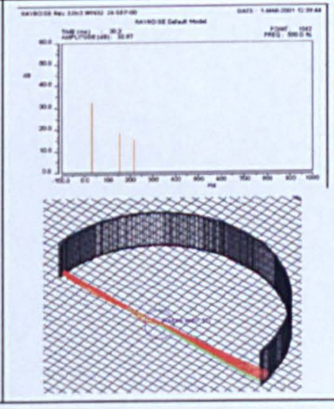
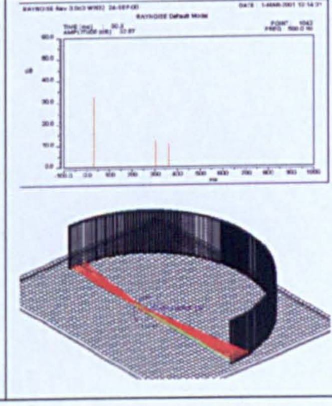


Figure 5.3.5. *RT30 (s) colour maps for the Sets 12 and 36. a) Set 12 with 31.80m radius, b) Set 36 with 31.80m radius, c) Set 12 with 56.90m radius and d) Set 36 with 56.90m radius.*

Table 5.6. *Impulse responses and reflection paths for all sets and enclosure sizes with geometrically reflective boundaries.*

		Enclosure Radius		
		12.70m encl.	**31.80m encl.**	**56.90m encl.**
Number of Segments	Set 6			
	Set 12			
	Set 24			
	Set 36			

It is shown that the enclosures represented with fewer segments provide more reflections, due to larger reflector areas, further explained in Section 5.3.2. In fact Sets 6 and 12 reduce the initial time delay gaps. It can be seen in the impulse responses that Set 24 resembles Set 36, which approaches the circular shape. It is nevertheless the intention of this section not to extremely reduce the number of segments but to search for the appropriate number that provides the accurate results and at the same time reduces calculation times. This brief investigation indicates that Sets 24 and 36 are more appropriate to use. However, further investigation is needed. In terms of reflection paths, patterns and numbers, it seems that regardless of the proximity to the boundaries the differences between representations are significant. However, it needs to be noted that these results correspond to geometrically reflective boundaries. As can be seen in more detail in Chapter 6, geometrical reflections from distant boundaries are less important in ancient theatres than from surfaces situated close to the receiver.

5.3.2 Further Investigation on Set 6 and Set 24

Following the findings of Section 5.3.1, Set 24 provides a rather realistic acoustic environment, even when no diffusion is applied, while Set 6, which is an extremely simple representation, could still be useful for boundaries at large distances from the source/receiver. As will be discussed in Chapter 6, in ancient theatres the receiver is usually close to the concave surfaces and the source far from it. This section presents the results of the simulations of Sets 6 and 24. The simulation is carried out with the same parameters as in Section 5.3.1 for 3 enclosure radiuses.

The results for the impulse responses and the reflection paths for a receiver far from the enclosure are shown in Figure 5.3.6. As previously seen, there are different reflection paths for Sets 6 and 24. Comparatively, Set 6 provides more reflections, which arrive to the receiver from different directions. When representing and simulating an ancient theatre with similar design these results can be misleading both in index values and in subjective impressions like 'texture', defined as 'the subjective impression the listeners derive from the patterns in which the sequence of early sound reflections arrive in their ears', 'listener's envelopment' etc [Beranek, 1996].

In order to explain this phenomenon, Figure 5.3.7 illustrates a drawing of some of the reflections. The floor area with Set 24 enclosure, the source and the receiver are shown. The reflection paths the simulation has produced are illustrated in black colour. By selecting parts of the enclosure, represented in red, one can find the image sources and provide reflections to the specific receiver. The latter are represented by the dashed blue lines. However, it is noted that the sound is reflected by the extensions of the actual segments, seen in red dashed lines. This indicates that the important prerequisite for multiple reflections is not only the complexity of the enclosure, but the width of each surface as well. This explains the reflection pattern of Set 6 in Figure 5.4.6b and leads to an unrealistic reflection pattern.

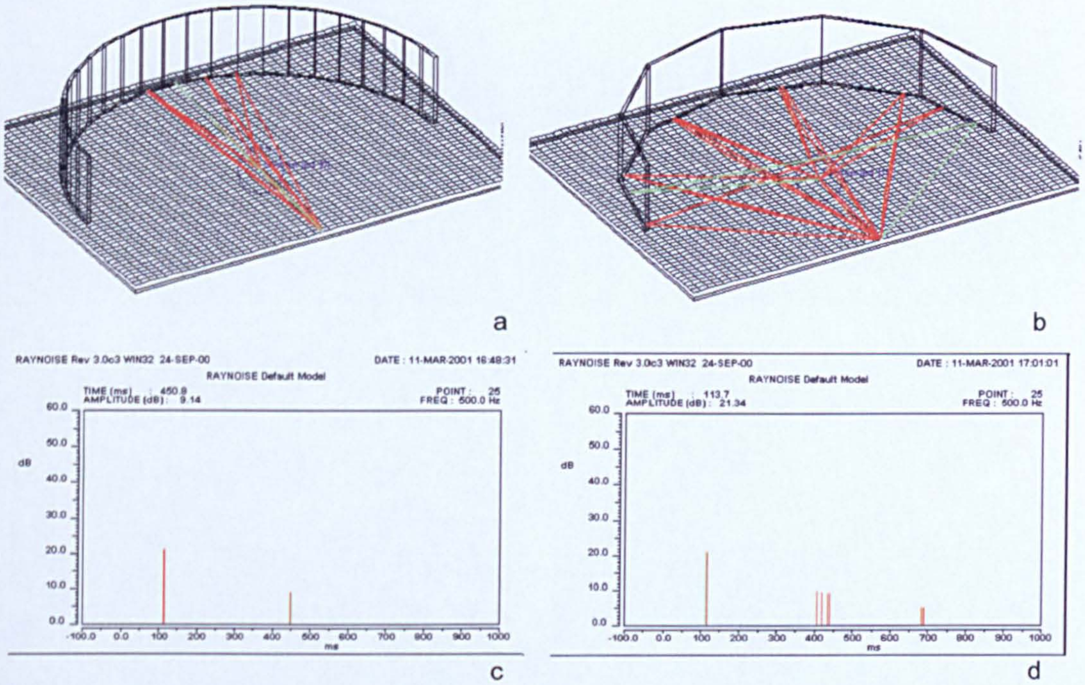


__Figure 5.3.6.__ Reflection paths and impulse responses with 56.90m enclosures radius. a)Set 24 reflection path, b) Set 6 reflection path, c) Set 24 impulse response and d) Set 6 impulse response.

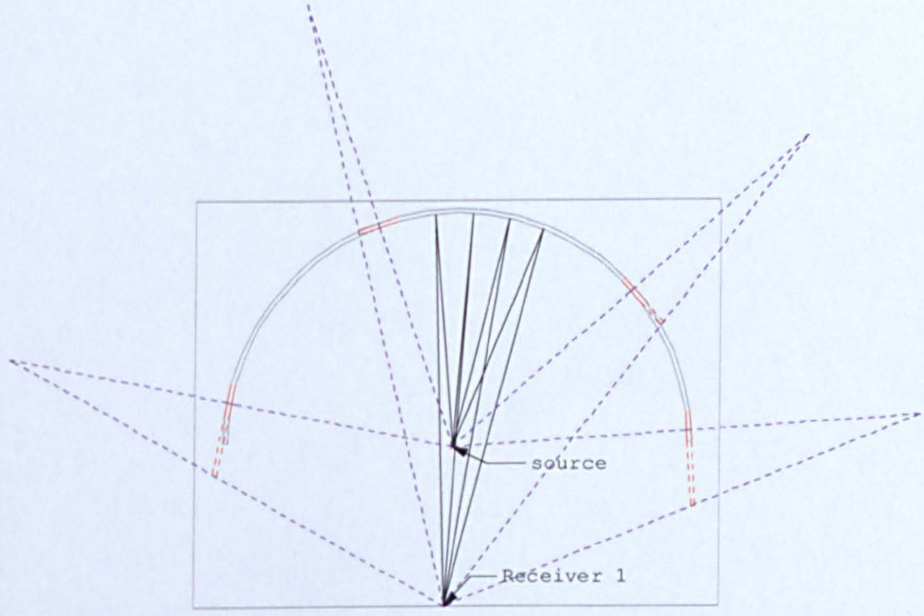


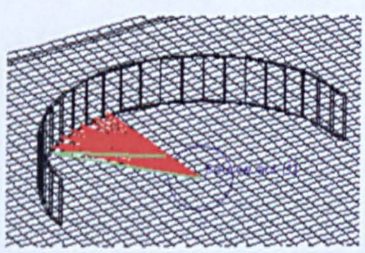
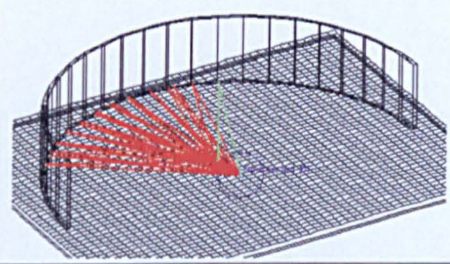
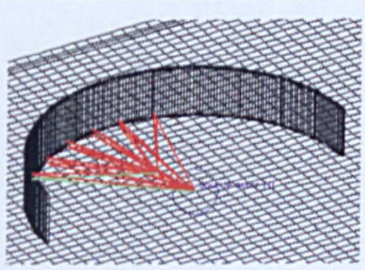
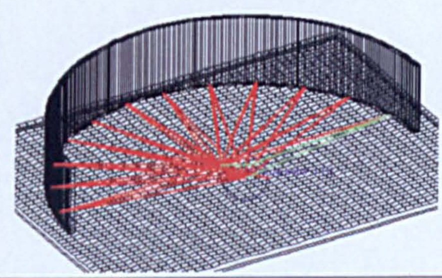
__Figure 5.3.7.__ Possible reflection paths for the 24-segment enclosure with 56.90m radius. Blue dashed lines represent the reflections and red dashed lines the extensions of the reflective surfaces.

Therefore it is still safer for ancient theatres to be represented as realistically as possible, hence with the maximum number of segments that also allows reasonable calculation times. In this case the results showed that Set 24 was the most appropriate. An inclined audience area was also simulated, to resemble real audience positions but also to allow spatial reflections, in opposition to a horizontal layout. It has shown that due to the relative source/receiver heights the reflection paths have changed, without causing any significant difference between representations though.

5.3.3 Comparison between 12 and 24-segment enclosures

To allow validation of Set 24, a comparison has been carried out between Sets 24 and 12, with diffusion of 0.5 and absorption of 0.5 or both applied to the enclosures. The point source is positioned off the centre of the enclosure. The reflection paths for two enclosure sizes are presented in Table 5.7 with no diffusion added. Corresponding to the previous conclusions, it can be seen that the difference is significant between the two sets, especially for the large enclosure.

Table 5.7. *Reflection paths for Sets 12 and 24.*

	Enclosure Radius	
	31.80m	**56.90m**
Set 12		
Set 24		

The need for simulating the same enclosures with increased absorption and diffusion initiated from the fact that occupied theatres are also of interest in this research, thus audience absorption would affect the results. Additionally, both from the audience and the partly destroyed seating system, sound would be diffused. Figure 5.3.8 presents three receivers in the audience area, for whom the acoustic indices will be briefly analysed.

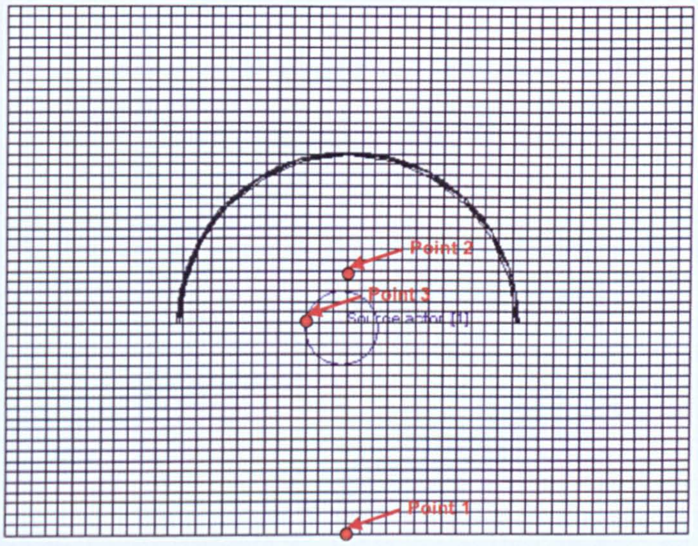
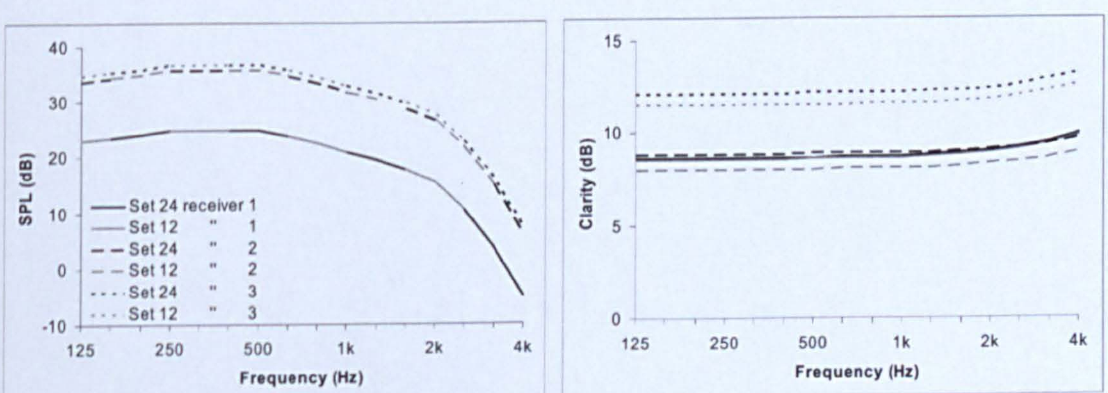


Figure 5.3.8. *Floor plan of the model and the audience area, showing three receivers for whom calculations are carried out.*

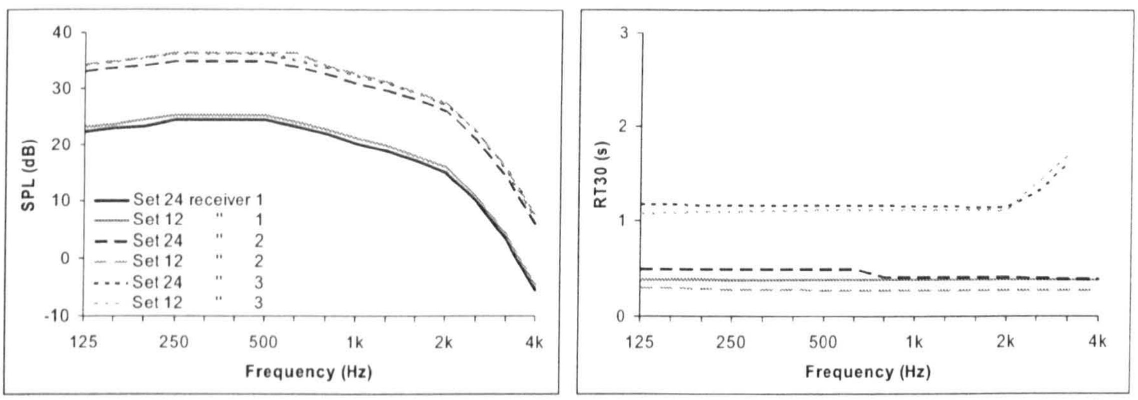
When absorption of 0.5 is applied to the enclosures the SPL results show that there is no identifiable difference between the two sets. Figure 5.3.9a presents the SPL for the three receivers. Although there is a difference in the amplitude, the SPL values are almost identical in both conditions. However, this is mostly due to the fact that SPL is mainly depended on the direct sound, so a few differences in reflection patterns would not alter it significantly. For reverberation, the fluctuation is more obvious, especially for point 1, situated far from the enclosure and the source. Regarding clarity, which is the ratio of the energy of the early sound to the late arriving sound and defines perceptibility [LMS Numerical Technologies, 2001], Figure 5.3.9b reveals good conditions at receiver point 3, compared to points 1 and 2. In terms of segment difference, both RT30 and clarity show that there is a characteristic dissimilarity, thus it would be incorrect to use less than 24 segments in the representation of the enclosure. Obviously, when the complexity of the model and the calculation time allow it, Set 36 can also be used, providing more realistic results.



a b

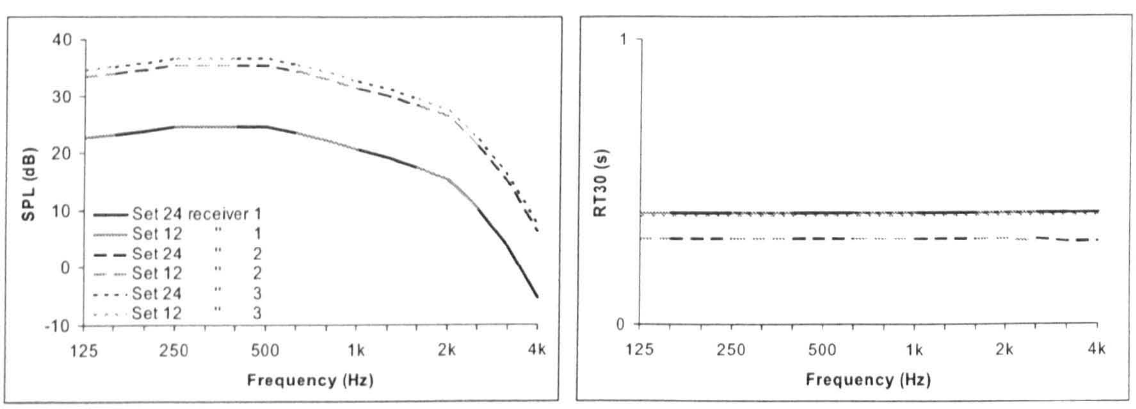
Figure 5.3.9. *Acoustic indices for 0.5 absorption in the 39.70m enclosure. a)SPL (dB) for points 1, 2, and 3 and b) C80 for points 1, 2, and 3.*

Below the results with 0.5 diffusion coefficient applied to all frequencies are presented. While some of the performance spaces have been restored, like the odium of Herodes Atticus and the theatre of Epidaurus, others produce diffusion due to the destroyed finishes of the koilon, even in the unoccupied condition. The SPL values for points 1, 2, and 3 are shown in Figure 5.3.10. The diffusion that has been applied to the enclosure has caused a reduction in the SPL, while a distinctive difference between point 1 and points 2 and 3 can be seen, mainly due to the distances from the source. Also, the SPL values are at similar levels as in Figure 5.3.9, which means that diffusion and absorption create the same effect. Set 12 causes an increment of about 1dB. The same applies to RT30 results, where there is variation among the two ways of the spatial representation of the model, depending also on the receiver position. For points 2 and 3 the variation is at the range of 0.1-0.2s. Consequently, with high diffusion it would be possible to represent the theatre with even less number of segments. The last comparison will be carried out between the same models, but both with absorption and diffusion applied, presented in Figure 5.3.11.



a b

Figure 5.3.10. *SPL (dB) and RT30 (s) results for 0.5 diffusion at points 1, 2 and 3. a)SPL and b) RT30.*



a b

Figure 5.3.11. *Index results for receiver points 1, 2 and 3. a) SPL (dB) and b) RT30 (s).*

The SPL in Figure 5.3.11 indicates the similarities between the two cases. In fact the SPL values in the graph are completely identical. The results regarding reverberation show that the

12 and the 24-segment enclosure lead to the same RT30 when both diffusion and absorption are applied. This means that there is a possibility that the occupied theatres, which allow sound diffusion caused by either the audience or the space itself, could be simulated even simpler than with 24 segments. It needs to be noted though that small variations should be allowed for STI and C80.

5.4 Research Methods – On-Site Measurements and Analysis

To validate the simulations on-site measurements were carried out at specific theatre sites, as will be seen in detail in Chapter 8. This section only describes the procedure followed for the measurement of the RT.

The reverberation measurements were carried out with simple equipment, namely balloon-popping used as a source and a SONY mini-disc for the recordings, mostly under the unoccupied conditions of the theatres. The measurements were usually taken at multiple receiver points, both situated on a receiver line, as well as for random receivers throughout the audience area and the orchestra. The results were analysed using Symphony 01dB software dBBATI32, both automatically and manually [01 dB-Stell, 2001]. The software procedure entails the analysis of the signal into the frequency range, the estimation of the decay for each frequency and the reverberation time estimation. However, the user can also calculate the RT manually, so that the results can be validated. The measurements taken at the theatres of Epidaurus, Philippi and Knossos used both the automatic and the manual analysis for the frequency range. The theatre of Epidaurus was briefly discussed in Section 3.3 both in terms of layout and acoustic environment, in Sections 5.2.4 and 5.3 in terms of simulation parameters and methods, and will be further described in Section 8.2. The theatre of Philippi was used for the methodology research in Sections 5.2 and 5.3. Its historic information, acoustic evaluation in the original and present condition and the effect of background noise will be provided in detail in Section 9.3, while it will be used for the application and evaluation of scenery in Chapter 10. The theatre of Knossos was depicted in Section 3.2.1, as one of the earliest examples of theatre architecture in Greece. The measurements for these theatres will be analysed in Sections 8.4.1. 8.4.2 and 8.4.3 respectively. The automatic analysis of the results is calculated twice, for 30 and 20dB decay, while the manual analysis is performed three times. From the results, standard deviation and averages are calculated, for the final values of reverberation to be produced. Figure 5.4.1 illustrates the main window of the software, after the signal has been imported.

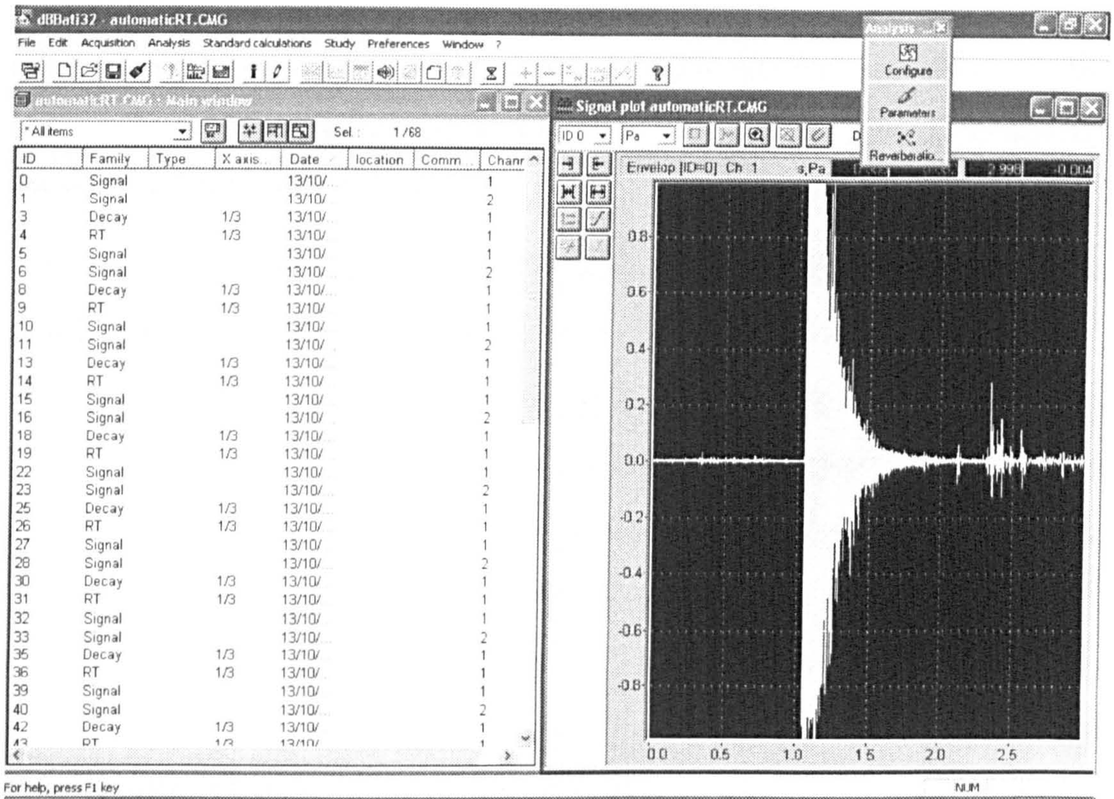


Figure 5.4.1. *Main window of dBBATI32 with signal files and plot.*

5.5 Research Methods – Subjective Evaluation and Analysis

This section briefly discusses the subjective evaluation method followed in this PhD study and presented in Chapter 8, in relation to acoustic simulation and on-site measurements. The research on the acoustics of ancient performance spaces, especially of the Classic and Hellenistic times, has to be carried out in consideration of the performance itself. It mainly corresponds to Greek theatres of Classic and Hellenistic times, which are still used for the revival of ancient Greek tragedies and comedies. As mentioned in the review in Chapter 3, ancient plays are performed every summer, usually organised by the Greek Ministry of Culture.

The usefulness of the subjective evaluation in a research study on acoustics lies on the fact that the audience perception is important for the acoustic evaluation of a space. Questionnaires are easy to be created and distributed before a performance takes place, although with the expense of limited replies. The subjective evaluations used in this study were carried out in summer 2003, in relation to the measurements described in Section 5.4. The survey was designed using simple terminology, with multiple choice answers. Table 5.8 illustrates the general layout of the questionnaire used. The subjects were asked to respond in terms of SPL, reverberation, speech intelligibility, delayed reflections and echo presence and encouraged to provide comments on their general impression in terms of acoustics.

Table 5.8. Layout of the questionnaire used for the subjective evaluation.

<table>
<tr><td rowspan="2"></td><td colspan="6">Personal details</td></tr>
<tr><td colspan="2">Sex</td><td>Age group</td><td>Profession</td><td colspan="2">Seating position</td></tr>
<tr><td rowspan="12">Multiple Choice Questions</td><td rowspan="2">1</td><td colspan="5">Actor's sound level</td></tr>
<tr><td>Very Loud</td><td>Loud</td><td>Medium</td><td>Faint</td><td>Very faint</td></tr>
<tr><td rowspan="2">2</td><td colspan="5">Reverberation time</td></tr>
<tr><td>Very long</td><td>Long</td><td>Medium</td><td>Short</td><td>Very Short</td></tr>
<tr><td rowspan="2">3</td><td colspan="5">Delayed reflections</td></tr>
<tr><td>Strong</td><td colspan="2">Not so strong</td><td colspan="2">None</td></tr>
<tr><td rowspan="2">4</td><td colspan="5">Echo</td></tr>
<tr><td>Strong</td><td colspan="2">Not so strong</td><td colspan="2">None</td></tr>
<tr><td rowspan="2">5</td><td colspan="5">Background noise</td></tr>
<tr><td>Very noisy</td><td>Noisy</td><td>Medium</td><td>Quiet</td><td>Very quiet</td></tr>
<tr><td rowspan="2">6</td><td colspan="5">Speech intelligibility</td></tr>
<tr><td>Very confusing</td><td>Confusing</td><td>Normal</td><td>Clear</td><td>Very clear</td></tr>
<tr><td rowspan="2">Other information</td><td colspan="6">Background noise sources</td></tr>
<tr><td colspan="6">General comments</td></tr>
</table>

5.6 RESEARCH METHODS – ABSORPTION COEFFICIENT MEASUREMENT

The simulation of the acoustics of ancient theatres is usually carried out with approximate material characteristics. It is difficult to determine the exact diffusion coefficients of the boundaries, either because they are not easily measurable in practice, or the theatres tend to diffuse more sound today than in antiquity, due to partly destroyed stone parts. Similarly, the treatment of the materials is unknown, although it seems that the stone was cut and hand-sanded before applied to its exact position.

Maekawa and Lord [1994] have briefly discussed the methods used for the measurement of absorption coefficients for the 'normal incidence absorption coefficient', the 'oblique incidence absorption coefficient' and the 'random incidence absorption coefficient' for zero, oblique and at all angles incidence respectively. There are several methods used for the measurement of the absorption coefficient. The most commonly used methods are (a) the reverberation chamber method, (b) the impedance tube method and (c) the site method.

Previous studies have analysed methods for the absorption coefficient measurement, like the free-field measurements [Jansens, 2002], the impedance tube method with one microphone

[Choy, 2004], with two microphones [Chu, 1986a], and compared the two latter methods [Esquivel, 2002]. As mentioned by Choy [2004], there are four methods to determine the in-duct acoustic properties, such as the reflection coefficient and absorption coefficient. The standing wave method uses a probe microphone to measure the ratio of successive maxima and minima of a standing wave pattern. The multi-point method uses one microphone to take measurements at multiple points, while the two microphones are placed at two different positions with a certain separation distance. The latter method saves time but requires the knowledge of accurate amplitude and phase relationships between the two microphones, so calibration is necessary before each measurement. To eliminate the calibration, Chu [1986b] introduced the one-microphone method in which a single microphone is used to measure sound at the two measurement points of an otherwise two-microphone rig. This method can eliminate the error of phase divergence between two microphones. In both two and one microphone methods, the two measurements become one when the separation distance between the two measurement positions is equal to an integer multiple of the half-wavelength. In other words, there are frequency blind spots in these methods. To overcome this problem, a third microphone position might be needed.

The method used in this study is the impedance tube method, with SCS9020 "Kundt Tubes", by S.C.S. Controlli e Sistemi s.r.l. [S.C.S. Controlli e Sistemi s.r.l., 2003], a two microphone method, which will be further described in Section 8.3. Moreover, the software used for the measurement analysis is dBAlpha test, part of the 01dB-Stell [MVI technologies group, 2002].

5.7 Conclusions

This chapter presented part of the methodology of this PhD study. It examined acoustic simulation parameters, representation and results in relation to the unique layout of open-air theatres of antiquity. The investigation involved number of rays, reflection order, background noise application, diffusion distribution, source directivity, reverberation and energy responses. Methods of simplified representation of ancient Greek theatres were also investigated. Apart from the acoustic simulation, other research methods were introduced, including on-site measurements, subjective evaluation, and absorption coefficient measurements.

From the analysis it was found that 10,000-20,000 rays and reflection order of 10 can be used in Raynoise for the simulation of complicated ancient theatres, to ensure accurate results and relatively short calculation times. Although the impulse responses do not particularly differentiate between the 5,000 and 10,000 rays, large numbers of rays produce more reflections, specular, high order and from diffused sound. For the reflection order, simulations with 10,000 rays and reflection orders of 5, 10 and 20 were compared, showing that there is no significant difference between 10 and 20. Hence, 10 was suggested for the simulation of ancient theatres.

The methods of considering background noise in the simulation were also investigated, especially for the simulation of the ancient theatre of Philippi, shown in Chapter 9. By separately simulating the primary source and the background noise, it is possible to identify the effect of background noise. By integrating background noise in the simulation the indices are much affected, while it is possible to obtain SPL and STI results. Obviously, reverberation cannot be calculated. For the theatre of Philippi, the former method will be used.

To validate the influence of source directivity on the acoustics of ancient theatres an omni-directional source and a source with human directivity were compared, positioned both on the stage building and the orchestra level. The aim was to show the differences in sound distribution. It is widely accepted that with human directivity the sound amplitude and distribution are weaker at the sides of the theatre than at the axis, hence these calculations were based on the prerequisite that the actor was facing the axis of the theatre. In general both the direct sound and the SPL are increased at the sides of the theatre with the omni-directional source.
Regarding the actor on the stage building it was indicated that:

- The difference in reverberation between the two sources is insignificant.

For the source near the middle of the orchestra:

- Longer reverberation and decreased definition and clarity are found at the sides with the omni-directional source.
- The directional source provides fewer reflections with better speech intelligibility.

From the above, using the omni-directional source for the simulations would stress out possible defects of the theatre's layout. Considering the differences between the two sources in terms of sound distribution, the simulations in this study have been carried out with the omni-directional source for the sake of convenience.

For the relationship between the layout of the theatre, the impulse response and reverberation, it is noted that the exact representation of the model regarding the audience area is needed to ensure accurate reflection paths. Long reflection paths produce large delays, enhanced by the layout of the ancient theatres. Diffraction and scattering effects from the empty seats are important because of the small number of strong reflection in the impulse responses of open-air theatres.

Moreover, the effects of the model representation in CAAD software, regarding circular shapes, on the acoustic environment of outdoor theatres were investigated. The comparison between 6, 12, 24 and 36 segments showed that:

- The choice in representation, namely Sets 6, 12, 24 or 36, hardly affects SPL, although small differences can be seen for some receivers

- Enclosures that are represented with fewer segments provide more reflections, from several directions.
- Diffusion and large source/receiver-enclosure distances reduce differences
- For the receiver close to the source, neither the representation nor the proximity of the boundaries affects the RT. This is the disadvantage of the circular shape that leads the reflections to its centre.
- For larger enclosures the effect of different Sets in RT is very important, by up to 1s.
- An important prerequisite for multiple reflections is the size of each surface.

By analysing the simulation results it is suggested that the representation of the theatre in the unoccupied conditions should be based on a minimum of 24 segments. By incorporating high absorption and diffusion in an attempt to represent the state of the theatres in an occupied condition it was shown that the difference in SPL with different model representation is almost eliminated. Although in terms of reverberation there is still variation, with both diffusion and high absorption applied SPL and RT30 values are almost identical. This means that there is a possibility that the occupied theatres, which allow sound diffusion caused by either the audience or the space itself, could be simulated with 12 segments instead of 24.

CHAPTER 6

PHENOMENON OF DIFFRACTION AND EFFECTS ON ACOUSTIC SIMULATION

6.1 INTRODUCTION

The uniqueness of the layout and the spatial organisation of ancient theatres relates to several characteristics of sound and the way it is distributed. One of them is diffusion. As briefly discussed in Chapter 5, the phenomenon of sound diffusion is considered in the acoustic simulation of ancient theatres by the application of diffusion coefficients that refer to surface roughness and surface size. However, the distinctive koilon area of the theatre provides further diffusion, due to the edges the stepped area formulates, namely edge diffraction, as well as due to the limited surface size. Although much attention is recently paid to the acoustics of ancient theatres, these phenomena were hardly considered in previous studies.

This part of the research focuses on diffraction, its effects on the acoustic environment of open-air performance spaces, and the ways it can be simulated. The effects of diffraction are analysed theoretically with the Kirchhoff-Fresnel approximation, producing a diffusion coefficient. Four mechanisms are considered (a) diffraction to the shadow zone behind a panel, (b) diffusion/diffraction due to limited surface size, (c) diffraction from a panel edge, and (d) diffusion effects due to the acoustic roughness of panel surface. (a) and (c) are analytically reviewed in Sections 6.2 and 6.3 respectively. (b), which is particularly important in ancient theatres with stepped koilon areas, and (d) are systematically examined in the methodology of Section 6.4 and further examined in Section 6.5.

This chapter initially refers to previous studies of diffraction around a barrier in both theory and experiment, followed by the phenomenon of edge diffraction, its effects on the acoustic environment, its treatments and diffusion due to surface size and acoustic roughness. Computer simulation methods that consider diffraction are briefly discussed. Because the scattering effect of diffraction has not previously been considered, two methods are described, tested and evaluated. Method 1 applies an increased diffusion coefficient to the audience area of the ancient theatre. Method 2 uses equations previously developed for specific receiver positions and reflection paths but modifies them to consider the layout and sound distribution of ancient theatres. First only a part of the ancient theatre is taken into account, while later 33 receiver positions are calculated. In the mean time, diffusion due to surface roughness has been taken into account. The three dimensional nature of ancient theatres is translated into the simulation with Method 2 by analysing the reflection paths in several ways, using horizontal and vertical components, normal vectors and the scalar product. The calculations are compared with measurements in the theatre of Epidaurus and diffusion/diffraction coefficient values are suggested. Moreover, a scattering method based on Lambert distribution law is discussed for the effect of edge diffraction, by comparing different reflection patterns. Finally, the conclusions about the simulation methodology regarding the effect of diffraction are presented. In this chapter, as well as throughout the PhD study, the term diffusion is related to the spreading of incident specular energy into non-specular directions. Scattering can also be used for the effect of a reflection off a profiled surface, while diffusion describes the condition of the acoustic sound field [Chourmouziadou and Kang, 2007a].

6.2 Diffraction Around A Barrier: Previous Work

Many theoretical and experimental studies of wave diffraction by a thin plane have been carried out in the last two centuries. Actually, the idea of wave diffraction was first suggested in the 18th century. The concept of diffraction is usually related to noise reduction and the use of noise barriers. A barrier, which intercepts the line-of-sight from source to receiver, is frequently used to shield receivers from transportation noise from highways, railway lines, industrial complexes and airports. When the receiver is in the shadow zone of a barrier, the sound is mostly a result of sound diffraction around it. The appearance of a diffraction pattern behind a half plane is a result of the superposition of scattered waves by the edge and the unobstructed portion of incident waves [Li and Wong, 2005]. The effect diffraction can cause in non-shadowed areas, through the scattering effect of a barrier edge, is called edge diffraction and will be discussed in Section 6.3.

The methods for evaluating diffraction extend the optical geometric theory of diffraction to that of acoustic waves. An exact approach to estimate the insertion loss of a barrier is with wave-based methods such as the Boundary Element Method (BEM) and the Finite Element Method (FEM). One of the simplest and most widely used is that of Maekawa [1968]. He introduced an empirically based diffraction model that provides the insertion loss due to a thin-walled barrier in terms of the Fresnel number. The insertion loss of a finite-length barrier could then be determined by applying this curve to the diffraction paths around the barrier and then summing the energy contributions of these paths. From his study it was established that the shorter the distance between the source and the barrier's base, the greater the decrease in sound level. Maekawa considered the effect of ground reflection negligible when the receiving point is higher than 2m from the ground. He also suggested considering the attenuation due to atmospheric conditions, i.e. wind, temperature gradients and ground effect when the distance between the source and the receiver is around 100m [Maekawa, 1968].

Regarding sound attenuation by barriers, Kurze and Anderson [1971] have examined attenuation due to diffraction of sound rays emanating from both a point source and a line source parallel to a barrier and developed the following equation:

$$\Delta L_b = 5 + 20\log\frac{\sqrt{2\pi N}}{\tanh\sqrt{2\pi N}}(dB) \tag{6.1}$$

where ΔL_B is the attenuation (dB) due to the screen obstruction, N is the Frensel number $N=2(\alpha+b-d)/\lambda$, where α, b and d are source-diffraction point, diffraction point-receiver and source-receiver distances respectively, and λ is the wavelength [Kurze and Anderson, 1971]. Their equation cannot be used for receivers close to the line-of-sight of the source, when the path length difference between the diffracted and the direct path is small, for large wavelengths or low frequencies.

The fact that wind, temperature gradients and ground effect are important when the distance between the source and the receiver is around 100m could possibly apply to some cases of ancient theatres, as for example the back rows of the ancient theatre of Epidaurus, as also discussed in Chapter 2. After Maekawa's study [1968] was published, his chart for the shielding effect of a thin screen was widely used to calculate sound attenuation by a barrier. His formulas were also pioneering work for other studies to follow. Lam [1994] used Maekawa's model to develop a formula to predict insertion loss using pressure summation. Lam's method was further extended by Muradali and Fyfe [1998] to include 2D and 3D modelling, parallel barriers, the effect of finite ground impedance and 3D coherent and incoherent sources. From their work it has been suggested that for large distances, where few reflections appear, the differences between the methods of evaluating diffraction are indistinguishable.

Pierce [1974] and Takagi [1990] regarded Maekawa's chart [1968] as inappropriate when the source and the receiver are near the ground, while Li and Wong [2005] also examined the case of the source or the receiver being close to the barrier. Pierce [1974] formulated an approximate solution to the wave equation for the single-edge diffraction by the semi-infinite wedge. His solution considers cases where the source and receiver are at large distances from the barrier in terms of wavelength. After examining Maekawa's [1968] and Kurze's [1974] methods, Takagi [1990] found the former insufficient in the case of a soft ground, introduced a way for the correct use of Maekawa's chart and proposed a method for considering ground effect. In ancient theatres, the ground effect is important since both the source and the receiver are close to it, especially in exceptional cases, where an actor is hidden behind a scenery panel, thus diffraction around a barrier applies. Also, if one considers the risers of the koilon as wedge-shaped barriers in order to calculate the sound that is scattered from its edge, the materials should play a determining role.

Moreover, diffraction of sound has been incorporated in studies about traffic noise propagation that take speed gradient into consideration [Defrance, 1999]. Previous work on noise reduction, although not of immediate interest for this study, involve various shapes of barrier [Yuzawa, 1981], multiple wedges and polygonal shapes [Kim, 2005] or inclined barriers [Jin *et al*, 2001]. The latter involved the actual width of the partially inclined barrier, including additional diffraction at edge points. These are all useful if one considers an actor performing behind a panel or an object. Also, works that investigate three sided enclosures that embrace the receivers, like Alfredson's and Seow's [1976] are interesting. In the latter the theoretical approach was applied to the far field at low frequencies and the enclosure and the receiver were at the near field, so they showed agreement between the measured results and the predicted results using diffraction theory at 1-2kHz. They used both lined and unlined enclosures showing that for unlined enclosures the influence of sound reflection from walls can be approximated using ray acoustics [Alfredson and Seow, 1976].

The above studies that refer to diffraction around a barrier, wedge or polygonal shapes are very important in several fields of acoustics, including some cases of open-air theatres where scenery panels have been applied and the actor is performing behind them. However, for typical source and receiver positions, namely near the centre of the orchestra and on the koilon of an ancient theatre respectively, the receivers are not in the shadow zone of any object, hence this phenomenon of diffraction cannot be applied. This has been indicated in previous studies [Chourmouziadou and Kang, 2004].

6.3 Edge Diffraction

6.3.1 Edge Diffraction and Its Effects

Edge diffraction is a fundamental component of the sound field around any finite reflecting surface. The concept of edge diffraction is used in many fields of acoustics. In room acoustics, apart from describing sound propagating around corners, it considers the scattering from wedges of any angle in all directions. In this study, the edges of the koilon of the ancient theatres and the 'knife-edges' of thin scenery panels and overhead reflectors can present the phenomenon of edge diffraction. As previously mentioned by Torres *et al* [2001], for frequencies low enough that small-scale surface roughness becomes negligible with respect to wavelength, a room's interior can be considered as a simple assemblage of various wedges that reflect and diffract.

Geometrical acoustic models can work well at mid-to-high frequencies in room acoustics, especially if surface scattering is included, as shown by Round-Robin comparisons between computer predictions and measurements [Vorländer, 1995]. At low frequencies, however, geometrical acoustics is insufficient for accurate predictions. Also, edge diffraction near balcony edges and seat edges may be significant at higher frequencies, as shown by Torres *et al* [1997] by using auralization. The basic problem in edge diffraction is that of the diffraction from an infinite wedge, which is irradiated by a point source.

It has been suggested that edge diffraction can be defined as the difference between the total scattered field and that given by geometrical acoustics in the presence of a wedge [Torres *et al*, 2001]. In their work, Torres *et al* have included diffraction in the early order impulse responses, excluding reverberation, which can be calculated with statistically based methods. They recommended identifying diffraction by comparing the measured and computed impulse responses in non-reverberant geometries, which can be applied to outdoor amphitheatres. In other calculations that involved subjective evaluations it was suggested that edge diffraction can be significant for auralization [Torres, 2000] and that the effect would be greater from small-scale diffracting surfaces at high frequencies. It was also suggested that 2nd order diffraction, if neglected, has no audible spectral effect, with a maximum difference of about 0.5dB in frequency response curves. In this paper by Torres edge diffraction was computed using a time-domain finite edge version of the exact Biot-Tolstoy [1957] solution, developed first by Medwin [1981], then Medwin *et al* [1982] and further discussed by Svensson *et al* [1999] when they proposed an approach in which directivity functions for the secondary edge source of Medwin are derived analytically from the IR solution for the infinite wedge.

However, the results in another Torres' and Svensson's study [2002] compared models that considered 1st and 2nd order diffraction with others that computed only direct sound and specular reflection. In their latter study [Torres and Svensson, 2002] it is shown that 2nd order diffraction should not be neglected as it could become important for lower frequencies and smaller surfaces, grazing angles, and shadowed receiver positions. Also, wavelengths longer than the dimensions of panels (in this paper 12cm panel width corresponded to 2900Hz) can cause differences of more than 6dB at low frequencies [Torres and Svensson, 2002]. This could possibly apply to ancient theatres for narrow/small scenery panels or the risers of the koilon, which are usually between 35 and 50cm. The characteristic frequencies for these dimensions are from 680 to 1kHz, the most important frequencies for this use (theatre and speech). Moreover, it is suggested that because the effects of edge diffraction increase with lower frequency, the perceivable difference would extend over a greater frequency range as the scale of the scattering facet decreased. Therefore for small facets (e.g., reflector panels) it would be appropriate to use 2nd order diffraction for accurate impulse responses at long wavelengths [Torres and Svensson, 2002].

6.3.2 Treatments of Edge Diffraction

The most approximate treatments of edge diffraction in room acoustics prediction use 'Lambert diffusion' methods. According to Torres [2000] an 'edge-diffusion' technique is usually being employed, which places Lambert-radiating sources on a strip along the perimeter of a finite reflector, for the decrease of the amplitude of specular reflections near the edges, approximately simulating the interference of edge diffraction in the specular direction. It has been suggested, however, that such energy-based methods neglect phase information and cannot replicate the correct interference effects of edge diffraction components from non-specular directions to the receiver [Torres, 2000]. Moreover, a Lambert edge source's lobe maximum is directed in the normal direction from the plane and does not reproduce the actual, more complex (diffraction) directivity, which varies with incidence angle and position along the edge. Furthermore, the selection of the appropriate Lambert diffusion coefficient is somewhat arbitrary or, at best, only roughly determinable.

According to Kuttruff [1973], totally diffuse reflections from a wall take place according to Lambert's cosine law. If an area element *dS* is 'illuminated by a bundle of parallel or nearly parallel rays, which make an angle θ_o to the wall normal, whose intensity is I_o, the intensity of the sound scattered in a direction characterised by an angle θ, measured at a distance *r* from the surface is given by:

$$I(r) = I_o \cdot dS \frac{\cos\theta \cdot \cos\theta_o}{\pi r^2} = B_o dS \frac{\cos\theta}{\pi r^2} \qquad (6.2)$$

where B_o is the energy incident on unit area of the wall per second, supposing that there is no absorption, thus the incident energy is totally re-emitted. Otherwise, $I\,(r,\,\theta)$ has to be multiplied by an appropriate factor, less than 1 [Kuttruff, 1973].

Other diffraction studies in room acoustics invoke the Kirchhoff Approximation (KA), which although can be useful near the specular scattering angle and sometimes at higher frequencies, it is not clear in predicting the diffracted component for all frequencies at certain incident and scattering angles [Torres *et al*, 2001]. The Biot-Tolstoy method that has been adopted for a point source irradiating an infinite wedge of an arbitrary angle seems more accurate. It has also been adapted to include finite-length wedges, second order diffraction [Medwin, 1981] and directivity for the edge sources [Svensson *et al*, 1999].

Torres' study [2001] examined a room's geometry with several wedge types of finite length incorporating 2nd order diffraction and three combinations of specular/diffracted components. It demonstrated the importance of edge diffraction as a type of scattering that affects all regions surrounding a wedge. As mentioned above, edge diffraction can become significant for geometries with small surfaces and/or several wedges and should be modelled. This applies to the scenery designs that involve several smaller objects/panels. Also, 2nd order diffraction seems negligible for non-shadowed conditions but could become important for long wavelengths (relative to edge separation) and grazing angles [Torres *et al*, 2001].

6.4 Diffusion due to Surface Size and Acoustic Roughness

As mentioned in Section 6.1, two phenomena of diffraction are diffusion/diffraction due to limited surface size and diffusion due to the acoustic roughness of panel surface. These have to be applied to the acoustic simulation of ancient theatres through diffusion coefficients.

Previous studies focused on the scattering effects of surfaces and have particularly developed diffusion/scattering coefficients, both for commonly used surfaces and for commercial diffusers. Cox has developed techniques for scattering prediction [1994; 1998]. Hargreaves *et al* [1998a; 1998b; 2000] have, by evaluating several diffuser types, developed an optimum diffusion coefficient [Hargreaves *et al*, 1998b; 2000] and carried out diffusion measurements in three dimensions [Hargreaves *et al*, 1998a]. Christensen and Rindel [2005b] suggested several diffusion coefficients for smooth surfaces, brickwork, bookshelves and audience (0.6-0.7) at mid-frequencies. Previous studies however have been carried out using a transition order for changing the calculation method from ISM to RTM, although it has no direct physical equivalent.

Moreover, Lam indicated that for the same material the diffuse-reflection coefficients required by all methods to produce accurate results in an auditorium (a space with these aspect ratios) remain constant. On the other hand, in cases with few early reflections, a higher diffuse-reflection (up to 100%) coefficient can be used to improve the accuracy of the predictions [Lam, 1996a].

It has been indicated that several parameters influence diffusion caused by diffraction. For example, oblique angles of incidence increase surface diffusion whereas parallel walls lead to low surface diffusion and sometimes flutter echoes [Christensen and Rindel, 2005a]. Also, if the source or the receiver is close to a surface, this may provide a specular reflection even if it is small, while if it is far it will only provide scattered sound [Christensen and Rindel, 2005b]. Usually in ancient theatres the source is far from the surfaces in question and the receiver close to them. This implies a combination of specular and scattered sound. However, both methods described below take all parameters into account, with consequences in the acoustic indices.

6.5 COMPUTER SIMULATION OF DIFFRACTION

As mentioned in Chapter 2, computer simulation is a room acoustic design tool very useful in predicting sound propagation and obtaining acoustical information in the design process. Conventional methods for computing room impulse responses usually neglect edge diffraction and rely on geometrical acoustics and methods, like the ISM, RTM or some variation of these. However, these models' predictions for a discontinuous field are not realistic, which is apparent in impulse responses that reflect only the individual geometric/specular reflections. The use of ISM or the RTM can result in errors, depending on the complexity of diffraction or diffusion and the excessive reflection sound energy, which occurs when the wall size is small compared with the wavelength. Some early studies incorporating diffuse reflections examined reflection by two sound components: the geometric reflection sound and the scattered sound [Nakagawa, 1993]. The geometric reflection coefficient was derived from the simplified diffraction theory for a finite free reflecting panel, so that the difference between the total reflection energy and the geometric reflection energy was assumed to be the scattered sound, proving that their model was useful in predicting clarity, definition and lateral efficiency.

Usually, room acoustics software considers surface scattering due to material roughness (diffusion) and limited surface (diffraction). Raynoise, which is mainly used in this study, accounts only for diffraction around a barrier, in an approximate way. It computes the part of the diffracted waves that reaches the shadow zone behind an object, typically a screen, by searching 1st order diffraction paths. A 1st order diffraction path is the shortest path between the source (or image source), the diffraction point, located on the barrier/screen edge and the receiver [LMS Numerical Technologies, 2001]. After the user defines the dominant diffraction edges in the geometry model, the software searches for diffraction paths as long as the diffraction point lies between the extremities of the edge, the receiver lies in the shadow zone of the screen and the first part of the diffraction path, which is source-diffraction point distance, is not intersected by other polygons. Raynoise uses Kurze-Anderson's [1971] equation (6.1) for diffraction (see Section 6.2). When more than one diffraction paths exist, all diffraction contributions accumulate to give the pressure at the receiver, including interference due to relative phases from path-length differences.

As mentioned in Section 6.1 diffraction effects, like diffusion/diffraction due to limited surface size, diffraction from a panel edge and diffusion due to the acoustic roughness of panel surface, are not always considered in computer simulations of indoor performance spaces, since the reflections from the ceiling and the side walls mask the energy that diffusion and diffraction create. However, outdoor performance spaces present fewer strong reflections, so even the weak scattered energy would influence results and form decay curves in impulse responses. As mentioned by Lisa *et al* [2004] the gaps between strong reflections have to be filled for the estimation of the acoustic parameters.

Surface diffusion coefficients of 0.2-0.5 are usually applied to simulations with the purpose of calculating the diffraction by reflector panels and coffered ceilings. Lam [1996b] has found that in auditoria diffusion coefficients of 0.1 are suitable for large smooth surfaces, and 0.7 for the audience area because of surface roughness. Other studies that examine the acoustics of ancient theatres and discuss diffraction have been presented for Roman theatres [Lisa *et al*, 2004]. They simulated the Roman theatre of Aspendus with the use of ODEON, adjusting the calculation parameters and surface characteristics in order to match the results of on-site measurements that were performed in the theatre. Lisa *et al* [2004] suggested that edge diffraction becomes more important for the late part of the energy, and was considered in the simulations by applying diffusion coefficients of 0.2-0.7 to the audience area.

Recently, a method that combines diffusion caused by diffraction due to typical surface dimensions, angle of incidence and incident path length with surface diffusion was developed for ODEON [Christensen and Rindel, 2005a; 2005b]. Later in this chapter the equations this method is based on will be compared with other methods of simulating diffraction. Christensen and Rindel [2005a; 2005b] proposed using the same frequency dependent diffusion coefficient for all surfaces (3-5% at 1kHz) in order to describe surface roughness, while the part of the diffusion that relates to surface size can be handled by the simulation program. This does not apply to the audience area and surfaces with details omitted from the 3D model. Suggested scattering coefficients are given by Christensen and Rindel [2005b] for mid-frequencies.

Recently published studies on geometrical acoustics take diffraction and edge diffraction into account and have developed a method that enables interactive updates of propagation paths from a stationary source to a moving receiver, although the application to ancient theatres is not possible due to shape limitations of the prototype [Funkhouser *et al*, 2004].

6.6 Methods of Diffraction Calculation

The diffraction effects that are relevant to ancient performance spaces are diffusion/diffraction due to limited surface size, diffraction from a panel edge, and diffusion effects due to the acoustic roughness of panel surface, simulated in this section.

6.6.1 Method Description

6.6.1.1 Method 1

Method 1 applies diffusion coefficients to the audience area in order to simulate diffraction, based on Lam's [1996a] comparison of three modelling methods of diffuse reflection, which has been used before [Lisa *et al*, 2004]. As mentioned in Sections 6.3 and 6.4 diffusion coefficients Lam suggested to be used in computer simulation include 0.1 for plain surfaces and 0.7 for seating in an auditorium. Based on the above, diffusion of 0.7 is attributed to the risers of the audience area, which reflect the direct sound effectively in the unoccupied theatre condition, while flat panel diffusion is applied to the rest of the boundaries, measured under reflection-free condition on sample areas of 64 square feet (5.95m^2), using the time-delay-spectrometry technique, with diffusion coefficients at: 0.3 at 125Hz, 0.2 at 250Hz. 0.15 at 500Hz, 0.1 at 1kHz, 0.09 at 2kHz and 0.07 at 4kHz [Everest, 1994; LMS Numerical Technologies, 2001]. Christensen [2005] has suggested accurate representation of the koilon, scattering coefficient of around 0.3 for other areas, transition order around 2, late decimation off, and number of rays and late ray density set to high values for accurate results.

6.6.1.2 Method 2

The second method, based on Christensen and Rindel [2005a; 2005b] briefly described in Section 6.5, uses equations developed by Rindel [1986; 1991] and has been applied to ODEON. It basically combines scattering and diffraction into one reflection based scattering coefficient and was developed after identifying problems in some acoustic indices when the coefficients were adjusted in order to obtain reasonable RT values [Christensen and Rindel, 2005a].

The basic equation that describes the relationship between the scattering coefficients is:

$$S_r = 1-(1-S_d)\times(1-S_s) \tag{6.3}$$

where S_r is the coefficient that combines diffraction and roughness, S_d is the estimate of the fraction of energy scattered due to diffraction and S_s is the surface scattering coefficient. In order to calculate S_r, S_s will be given according to ISO-17497-1 and S_d will be calculated as follows [Christensen and Rindel, 2005a]:

$$S_d = 1-K_w K_l \times(1-S_e) \tag{6.4}$$

where

$$K_w = \begin{cases} 1 & for\ f \geq f_w \\ \frac{f}{f_w} & for\ f \leq f_w \end{cases} \quad (6.5), \qquad f_w = \frac{c\cdot a^{*}}{2(w\cdot\cos\theta)^2} \tag{6.6}$$

$$K_l = \begin{cases} 1 & for\ f \geq fl \\ \frac{f}{f_l} & for\ f \leq f_l \end{cases} \quad (6.7), \qquad f_l = \frac{c\cdot a^{*}}{2l^2} \tag{6.8}$$

$$S_e = \begin{cases} 0 & for\ d_{edge}\times\cos\theta \geq \frac{c}{f} \\ 0.5(1-\frac{d_{edge}\times\cos\theta\times f}{c}) & for\ d_{edge}\times\cos\theta \leq \frac{c}{f} \end{cases} \quad (6.9), \qquad a^{*} = \frac{d_{inc}\cdot d_{ref}}{2(d_{inc}+d_{ref})} \tag{6.10}$$

where c is the speed of sound, l and w are the surface length and width respectively and θ is the angle of reflection.

6.6.2 Calculation and Comparison between Methods 1 and 2

In this section, two ways of simulating edge diffraction in an ancient theatre are being carried out and evaluated in order to select the appropriate way of representing the effects of diffraction. The 3D model that has been used for all simulations in this section is a simplified representation of an ancient Greek theatre with 8 rows of seating for the audience area, with 0.4m riser height and 1.8-3.2m riser length, as it is varying at each step. Figure 6.6.1 illustrates the model used in the simulations. The speed of sound for these calculations is 344.82m/sec for

22°C temperature, according to normal temperature and humidity conditions in Greece during the summer evenings.

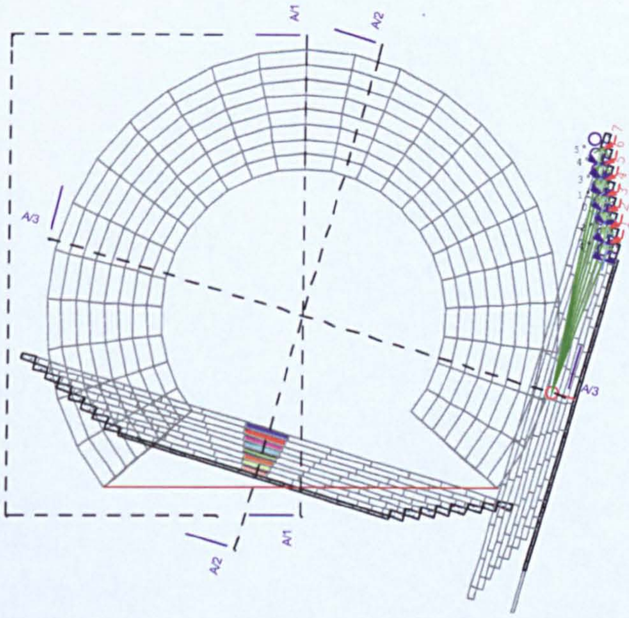


Figure 6.6.1. *Plan and two sections of the 3D model used for diffraction simulation.*

Method 1 and Method 2 will be used, as described above and will be compared with a simple model, named Model 1, where flat panel diffusion has been applied to the audience area, as described in Section 6.6.1.1. Model 1 has been used for comparison and to evaluate the flat panel diffusion characteristics, which have been used in many previous studies on ancient theatres [Chourmouziadou and Kang, 2002; 2004; 2005].

Calculations regarding Method 1 were carried out by assigning 0.7 diffusion coefficient to the koilon risers and flat panel diffusion to the rest of the theatre. The aim is to achieve diffusion caused by edge diffraction and due to limited surface size through simulation. For Method 2 only one receiver is used in the theatre, situated in Row 4, to calculate the combined coefficients with the use of equations (6.3) to (6.10). The combined scattering coefficients were calculated for one row of risers, shown in colour in Figure 6.6.1 Reflection path distances were measured for the receiver in the 4th row, as shown in Figure 6.6.2. The length, width, source-panel and panel-receiver distances, and angles of incidence and reflection were also measured and applied to the equations, each time for one riser and for one frequency, as shown in Table 6.1. The final scattering coefficients produced are shown in Table 6.2, with the colours indicating the corresponding to each value rows. In this way, each scattering coefficient is applied to only one row of seats of the theatre for one frequency.

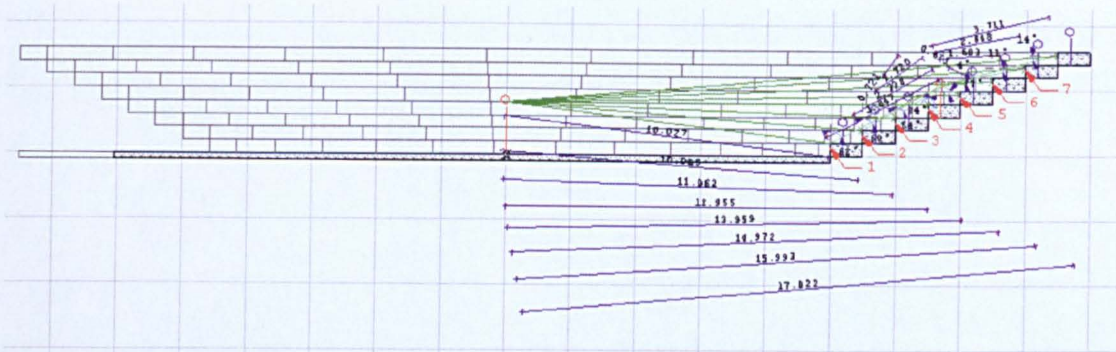


__Figure 6.6.2.__ Section of the model used for Method 2 of the diffraction simulation. The receiver in row 4 is indicated with red colour.

In Table 6.2 it can be seen that diffusion tends to decrease from Row 1 to Row 4 and then gradually increase again. This effect is analogous to the distance between the reflection point and the receiver. Obviously, closer to the receiver the specular reflections play an important role, thus the diffusion coefficients are decreased. Similarly, the coefficient values decrease with higher frequencies, since the K_w values of equation (6.5) are formed through the comparison between the reference frequency and the actual frequency. At high frequencies *Sr*, which is the final value of the coefficient, depends mostly on edge diffraction, thus the *cos* of the angle of reflection.

__Table 6.1.__ Table indicating calculations for the combined diffusion coefficient of Method 2 for 500Hz.

Equation\Row	1	2	3	4	5	6	7	8
$d_{incidence}$	10.027	10.985	11.962	12.955	13.959	14.972	15.993	17.022
$d_{reflction}$	3.847	2.778	1.72	0.721	0.671	1.603	2.648	3.711
angle θ (°)	62	60	54	34	27	4	11	14
cos (θ°)	0.459	0.5	0.588	0.829	0.891	0.997	0.982	0.97
Width (m)	1	1	1	1	0.4	0.4	0.4	0.4
Length (m)	1.888	2.078	2.267	2.457	2.647	2.836	3.026	3.215
a	1.390	1.109	0.752	0.341	0.320	0.724	1.136	1.523
f_w (Hz)	1089.6	764.6	374.9	85.6	434.5	784.8	1269.3	1744.6
f_l (Hz)	55.5	37.2	21.5	8.4	6.8	13.6	18.9	25.4
K_w	0.459	0.653	1	1	1	0.637	0.394	0.286
K_l	1	1	1	1	1	1	1	1
S_e	0	0	0	0	0.435	0.428	0.429	0.43
S_d	0.541	0.346	0	0	0.435	0.635	0.775	0.836
S_r	0.61	0.444	0.15	0.15	0.52	0.69	0.809	0.861

Table 6.2. *Diffusion coefficients of Method 2 for 8 rows.*

	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
1	0.92	0.91	0.61	0.59	0.54	0.53
2	0.88	0.87	0.44	0.55	0.54	0.53
3	0.77	0.73	0.15	0.55	0.54	0.53
4	0.3	0.6	0.15	0.55	0.54	0.53
5	0.9	0.75	0.52	0.43	0.31	0.07
6	0.94	0.86	0.69	0.42	0.28	0.07
7	0.96	0.92	0.81	0.54	0.29	0.07
8	0.97	0.94	0.86	0.67	0.29	0.07

In Figure 6.6.3a the SPL for Model 1 and Methods 1 and 2 for simulating diffraction is illustrated. The triangle represents the receiver for which the equations have been calculated (in Row 4), while the square a typical receiver seated close to the source (Row 3). Since SPL is determined by the early sound, any difference in the scattering coefficients has not affected the values. Possible variations are less than 0.5dB. In Figure 6.6.3b for the receiver line at 500Hz, both Methods create smoother curves than the flat panel diffusion, although the variation in scattering coefficients of Method 2 for this frequency fluctuated from 0.15 to 0.86.

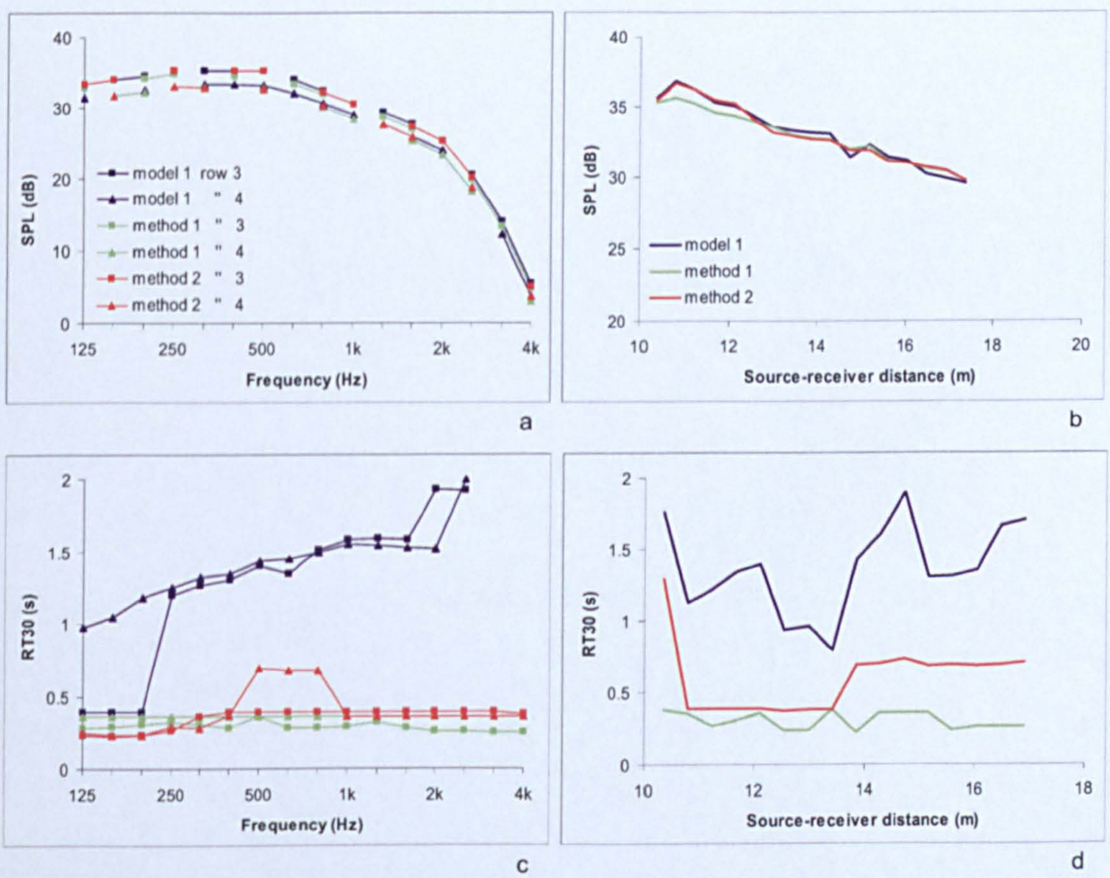
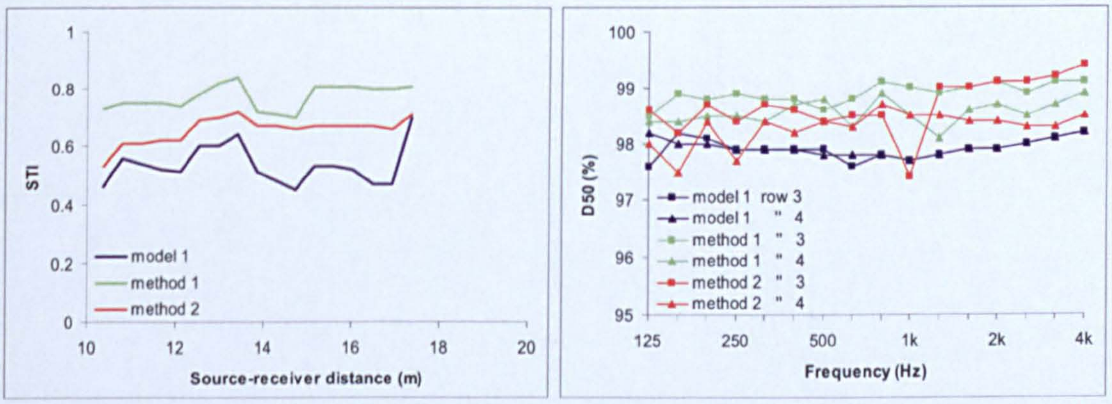


Figure 6.6.3. *Acoustic indices for the methods of simulating diffraction. a)SPL (dB) for two receivers at Rows 3 and 4, b) SPL (dB) for the receiver line at 500Hz, c) RT30 (s) for two receivers at Rows 3 and 4 and c)RT30 (s) for the receiver line at 500Hz.*

Reverberation is presented in Figure 6.6.3c and d[37]. Contrary to SPL, the RT30 is influenced by the altered scattering coefficients. For both receivers Methods 1 and 2 retain RT30 almost at the same values at low and high frequencies, as shown in Figure 6.6.3c, while at mid-frequencies, which are of interest, the differences are up to 0.31s. Both methods present short RT30 values compared to Model 1, which is obviously caused by high diffusion. In the mean time RT30 for Model 1 is around 1.5s. It needs to be noted that for Model 1 the values present a rather uneven curve for different source-receiver distances due to fluctuating diffusion coefficient values (0.3-0.07) and the distribution patterns. Method 1 uses high diffusion coefficients for the koilon for the whole frequency range (0.7) whereas for Method 2 the diffusion coefficients are lower at mid-to-high frequencies (0.15 as opposed to 0.8 at low frequencies).

STI and D50 results are illustrated in Figure 6.6.4a and b respectively. For STI Model 1 presents the lowest values around 0.5, while STI for Methods 1 and 2 is increased due to low RT30 (STI values reach 0.84 and 0.72 respectively). For definition, all results are above 95%, the highest values corresponding to Method 1. This emphasises the appropriate layout of the Greek theatre for speech but does not particularly distinguish between the methods.



a b

Figure 6.6.4. *Acoustic indices for the range of frequencies for the methods of simulating diffraction. a) STI for the receiver line and b)D50 (%) for the receivers at row 3 and 4.*

The impulse responses for 500Hz of a typical receiver are illustrated in Figure 6.6.5. Diffuse reflections for the first 70-80ms after the direct sound have considerably increased for both Methods compared to flat panel diffusion, particularly Method 1, since it is obviously characterised by higher diffusion at 500Hz (0.7 for Method 1 and 0.15 to 0.86 for Method 2, depending on the row). Accordingly, specular reflections disappear at 180ms after the direct sound for Method 1 and 300ms for Method 2, which corresponds to the short reverberation in Figure 6.6.3c and d. It is also noted that scattered sound is mostly gathered in the first 100ms, after the direct sound and together with the early reflections. In Method 2 however, high amplitude diffuse reflections appear at 100ms. Regardless of diffraction, the majority of the

[37] Invalid simulation results at 4kHz are not illustrated in Figure 6.6.3.

reflections in the impulse response reflection patterns are still specular. The gaps between the strong reflections are caused by the layout of ancient theatres, which creates large differences in path lengths (distances of incidence and reflection). Also, the simplified representation of the theatre, where a concave shape is represented by 24 linear segments (according to the representation method suggested in Section 5.3) allows for less reflections compared to reality, although in the figure with strong red colour more than one reflections are represented, that reach the receiver almost simultaneously.

The comparison shows the effectiveness of both methods in reducing RT, caused by increased diffusion and diffraction. However, further calculations need to be carried out for validation of the results. These will be carried out in Section 6.6.4, by comparing simulation results with measurements.

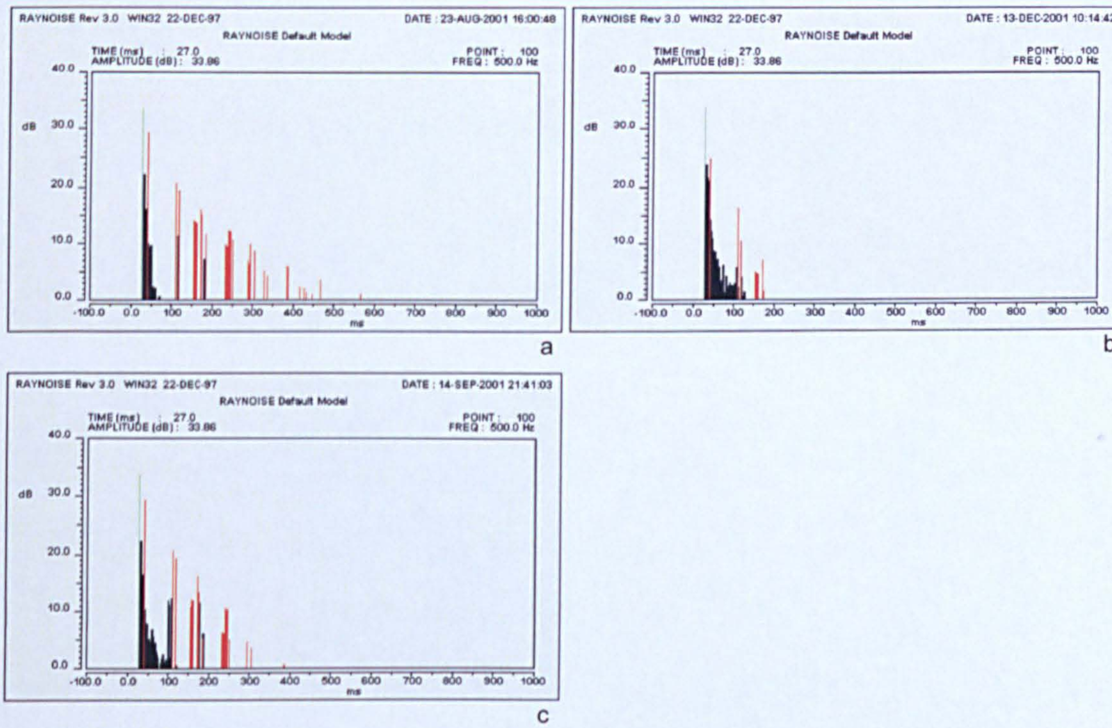
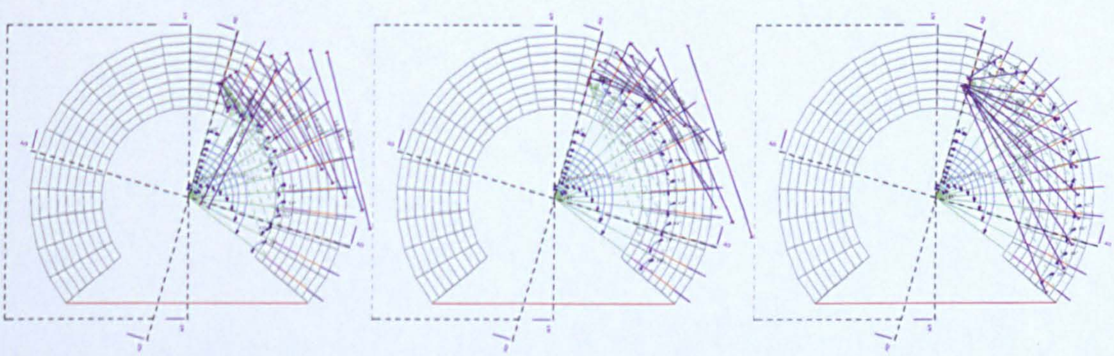


Figure 6.6.5. *Impulse responses for a typical receiver at 500Hz. a) Model 1 (no diffraction considered), b) Method 1, and c) Method 2.*

6.6.3 Extended Calculations for Method 2

The calculation of the combined diffraction/diffusion coefficients, based on equations (6.3) to (6.10) in Section 6.6.1.2, is further examined in this section. Using excel worksheets, the diffraction coefficients are calculated for the whole theatre. This is achieved by dividing the theatre into wedges of 10^{o}. In each wedge three reflection points are selected, in Rows 2, 5 and 8, shown in Figure 6.6.6a, b, and c respectively. In this way, 33 points have been calculated.

Initially, following the Method 2, described in Section 6.6.1, the width w and length l represent the height and length of the risers respectively. For the sake of convenience the new method developed here is named Representation 1. This results in very increased coefficient values, since, according to the equations, only dimension w is related to the angle of reflection θ. However, because the angle of reflection is almost parallel to the horizontal dimension, as shown in Figure 6.6.6, the horizontal dimension should be mostly linked to the angle, providing an interdependent value F_w and correspondingly the coefficient. Thus, Representation 2 is created and calculated, where w is replaced by l and l by w. Thus, in antithesis with Representation 1, in Representation 2 w stands for the horizontal dimension of the riser and l for the vertical.



a b c

Figure 6.6.6. *Plan of the theatre divided into wedges of 10° with angles of incidence and reflection at a) Row 2, b) Row 5, and c) Row 8.*

Figure 6.6.7 illustrates the coefficients for Representations 1 and 2 and for Rows 2, 5 and 8. In Figure 6.6.7a, c and e for Representation 1 it is shown that the combined coefficients are approaching 1, especially at low-to-mid frequencies for all reflecting surfaces. It is demonstrated that as the distance between the reflection surface and the receiver increases, the coefficients are slightly decreasing. This mostly applies to the 2nd row for Representation 1; this is not a common phenomenon, while for Representation 2 coefficients are low for the surfaces close to the receiver and tend to increase as the distance increases. F_w and F_l are the reference frequencies for which the width and length of panels are important respectively. Because only F_w is influenced by the angle of reflection, only one dimension is determining in each case. Consequently, for Representation 1 w, which is the small vertical dimension, influences F_w by substantially increasing it, although the horizontal distances are of interest. Therefore the increase in Representation 2 is more accurate, since scattering and distance increment are analogous phenomena, influenced by the dimension the angle of reflection corresponds to.

Also, as it is shown in Figure 6.6.7 for both the 5th and 8th rows in Representation 2, the coefficients are stable after 30° angle, at an average of 0.99 at 125Hz, 0.98 at 250Hz, 0.94 at 500Hz, 0.86 at 1kHz, 0.67 at 2kHz, and 0.25 at 4Hz and 0.99 at 125Hz, 0.98 at 250Hz, 0.95 at

500Hz, 0.87 at 1kHz, 0.70 at 2kHz, and 0.26 at 4Hz respectively. A similar tendency is observed for Row 8 for Representation 1, although the values are slightly more increased.

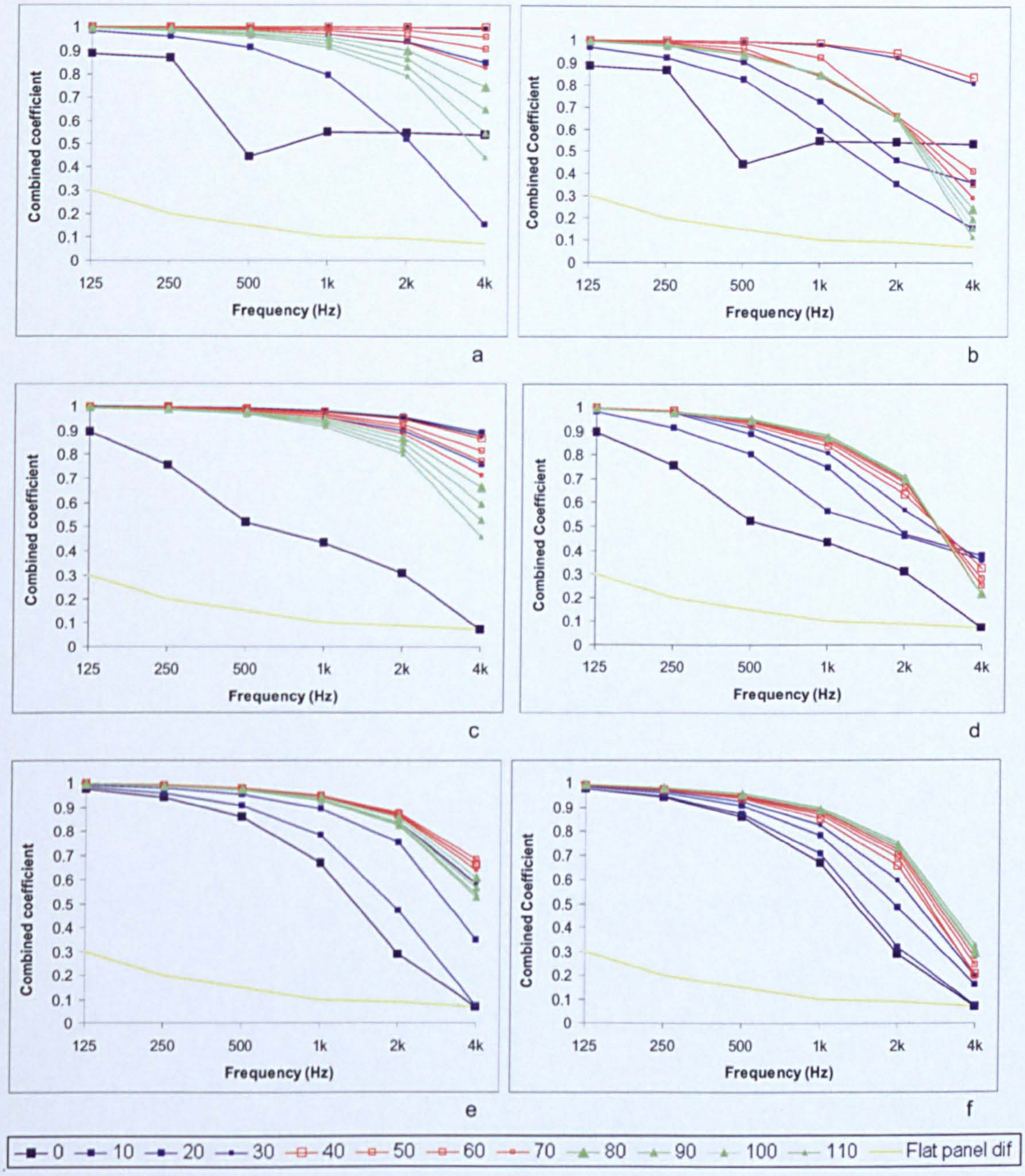


Figure 6.6.7. Combined scattering and diffraction coefficient versus frequency. a) Row 2 Representation 1, b) Row 2 Representation 2, c) Row 5 Representation 1, d) Row 5 Representation 2, e) Row 8 Representation 1, f) Row 8 Representation 2.

Based on Representation 1, which is the initial equations developed, the theatre of Epidaurus is used, once with the application of flat panel diffusion coefficients, shown in Figure 6.6.7 by the yellow colour and once with scattering coefficient 1 for all frequencies. It is shown that SPL is decreased by less than 1dB, STI, D50 and C80 are slightly increased, by about 0.05-0.10, 3%

and 2-5dB respectively, while RT30 is altered by 0.10-0.30s up or down, according to the receiver point, since the reflection distribution is random each time.

Figure 6.6.8 illustrates the impulse responses for two points, one with a reduction of 0.10s in RT30 and one with an increase of 0.30s when the scattering coefficient is 1. The specular reflections for the former are drastically reduced, and some early diffuse reflections appear, while only diffuse reflections are added to the impulse response of the latter, increasing RT30. The changes are quite reasonable since flat panel diffusion at 500kHz is 10%, which is far decreased compared to 100%. In Section 6.6.4 the theatre of Epidaurus is further discussed using Method 2, with simulation results compared to measurements.

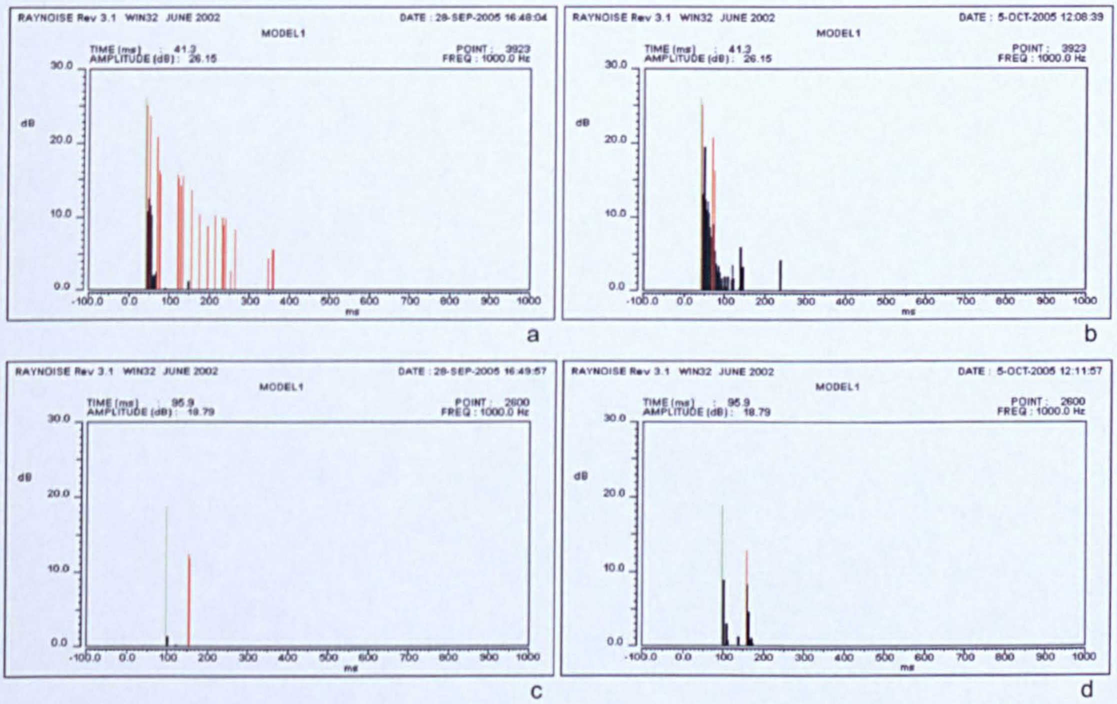


Figure 6.6.8. *Impulse responses for two receiver points at 1000Hz. a) Point 1 with flat panel diffusion, b) Point 1 with diffusion 1.0, c) Point 2 with flat panel diffusion and d) Point 2 with diffusion 1.0.*

6.6.4 Application of 3D Reflection Paths to Method 2

In real situations, the angles of incidence and reflection in an ancient theatre, as in any space, are three-dimensional, so Method 2 was further developed by the author in order to incorporate the three dimensions of the reflection paths for the calculation of the combined diffusion coefficients. The resulting coefficients were thus named 3D combined coefficients. The angles of reflection, previously named θ, were divided into their vertical and horizontal components and these were translated and applied to the equations. In this way, all coordinates are variables depending on the 3-dimensional reflection path. As a result, equations (6.6) and (6.8), presented in Section 6.5.1 are replaced by:

$$f_w = \frac{c \cdot a^*}{2(w \cdot \cos\beta)^2} \quad (6.11) \qquad f_l = \frac{c \cdot a^*}{2(l \cdot \cos\delta)^2} \quad (6.12)$$

where β and δ are the vertical and horizontal component of angle θ in equation (6.6) respectively. The coefficients produced according to this method are somewhat decreased, compared to Representations 1 and 2. Figure 6.6.9 shows the coefficients that were derived from the equations and applied to the whole theatre area at 500Hz. It can be seen that scattering increases as the distance of the reflection surface increases and mostly at the lower part of the theatre. However, from the practical point of view, the application of different diffusion coefficients to each riser of the koilon is both time consuming regarding simulation procedure and impractical since only one receiver has been taken into account. However, as can be seen in Figure 6.6.9, the lower part of the koilon, namely Row 2, should be assigned the highest coefficient values, from 0.95 to 0.99, while similarly, the 5th row with 0.84-0.96 and the 8th row with 0.88-0.95. It is thus possible to divide the koilon into areas, where average values of diffusion coefficient can be assigned. These averages have been calculated for the lower, middle and upper part of the theatre at the range of frequencies, and are shown in Figure 6.6.10. Similarly, one could calculate averages for several regions of the theatre koilon, like for example for 10^o to 30^o degrees, 40^o-70^o, 80^o-110^o.

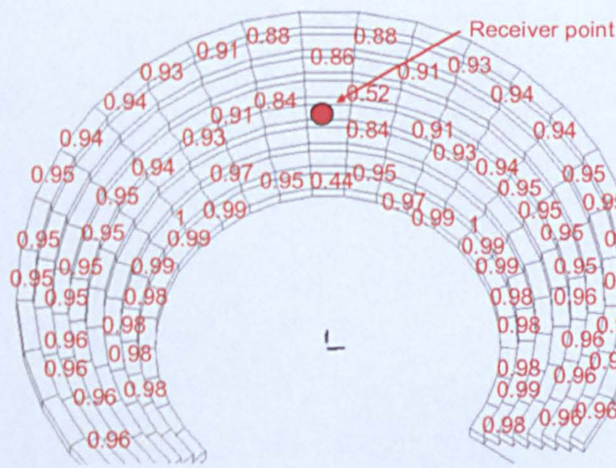


Figure 6.6.9. *3D model of the theatre with combined scattering and diffraction coefficients for the lower, middle and upper part of the koilon at 500Hz.*

From the above it is assumed that it is possible to use coefficients that combine diffusion and diffraction, especially when the receiver position is known. However, this method seems impractical to use for more than one receiver positions, since a different simulation needs to be run each time, with appropriate diffusion coefficients applied to the surfaces. As mentioned above, in order to validate this method, calculations were carried out for the ancient theatre of Epidaurus and a specific receiver position, for comparison with measurement results, described and presented in Sections 5.4 and 8.4 respectively.

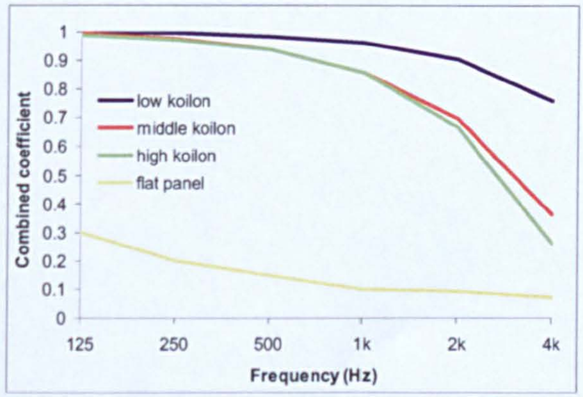


Figure 6.6.10. *Average values for combined scattering and diffraction coefficient from 125 to 4kHz.*

The equations were adjusted according to distances, source/receiver positions and angles of the theatre, and new values for diffusion coefficients were extracted for the theatre koilon, the orchestra and the temporary scenery that was sited in the theatre during the measurements, also presented in Section 8.4. Figure 6.6.11 illustrates part of the theatre plan with the reflection points, after dividing the theatre into wedges of 20° angle. The coefficients that were derived are presented in Figure 6.6.12. It can be seen that according to distances of incident and reflected sound, as well as reflection angles, there is a specific pattern followed in the formation of coefficient values [Chourmouziadou and Kang, 2006a].

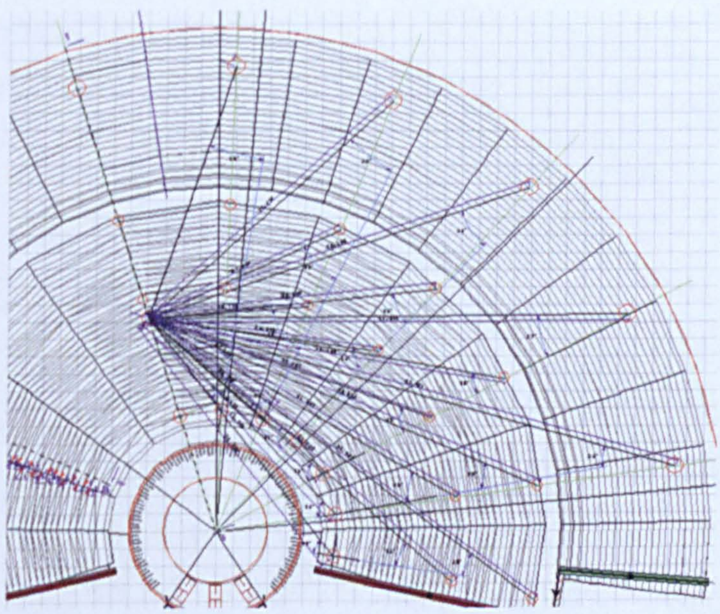


Figure 6.6.11. *Plan of the theatre of Epidaurus showing reflection points used for the calculation of diffusion coefficients.*

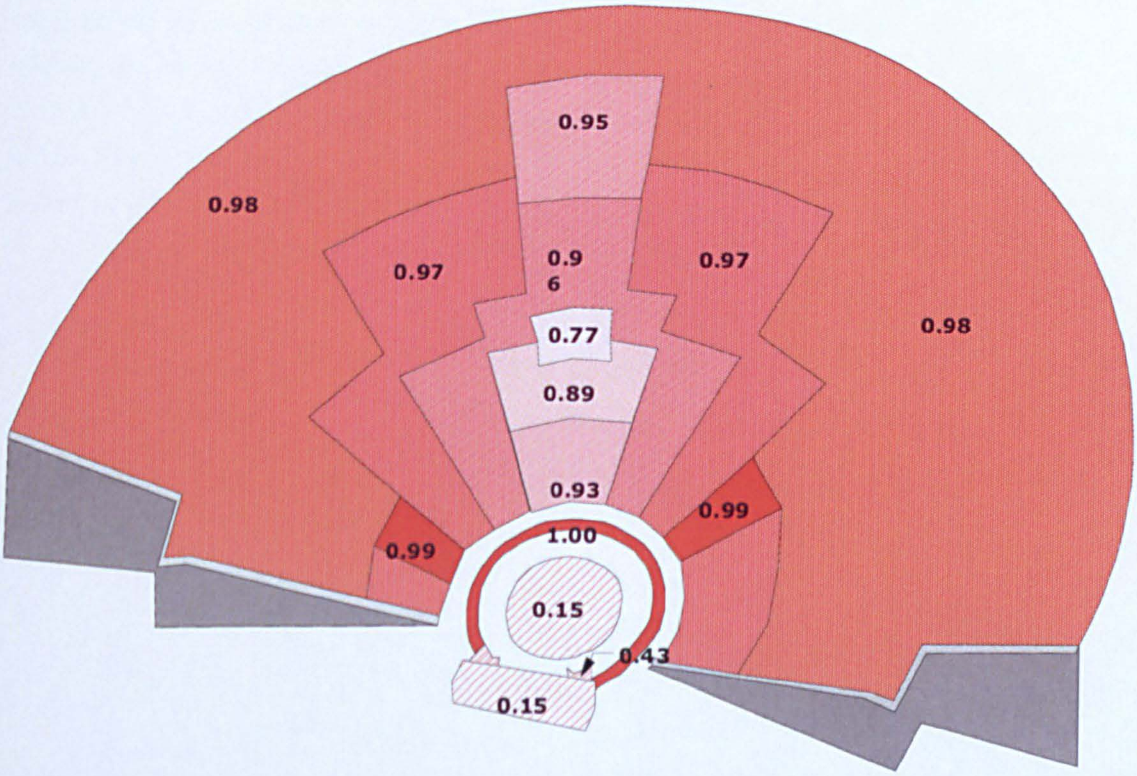


Figure 6.6.12. *The theatre of Epidaurus with the calculated values of the combined coefficient at 500Hz for the audience area, the orchestra and the scenery.*

The results regarding RT30 are illustrated in Figure 6.6.13, including two inclination possibilities. This was necessary because although the excavator and archaeologist indicates one inclination of 26° in the original drawings [Gerkan and Müller-Wiener, 1961], several sources suggest that the lower and upper part of the koilon have different inclinations, of 23° and 27° respectively [Dinsmoor, 1950; Canac, 1967]. As seen in Figure 6.6.13a the simulation values for the former possibility tend to match the measurements (0.95-1.2s) when flat panel diffusion is applied to the materials. Flat panel diffusion causes fluctuation in reverberation for the two inclinations as well, seen in Figure 6.6.13b from 0.7 to 1.6s. However, it is still possible that the values at certain receiver points match the measurements. The point of reference in these cases is the receiver at a distance of 27m from the source. The RT produced according to Method 2, seen in Figures 6.6.13a and b, are only between 0.51-0.61s in that area, 0.55s shorter than the measurements, while for the whole source-receiver distance is at least 0.33s lower. Therefore, in this case of ancient Greek theatres Method 2 is not to the most appropriate, since it produces very high diffusion that leads to relatively short RT results. In the case of scenery panels, situated far from the audience, it would be possible to apply the aforementioned method. Flat panel diffusion shows better agreement with the measurements.

It is noted that the method developed by Christensen and Rindel [2005a; 2005b] for ODEON was used for the simulation of the Roman theatre of Jerash in Jordan [Gade *et al*, 2005], indicating good agreement with measured data at middle and high frequencies. This is probably because the layout of Roman theatres creates multiple reflections between the high stage wall and the cavea (the Roman koilon) and thus a high diffusion/diffraction coefficient would be appropriate; whereas in ancient Greek theatres the reflections are not as many because the stage building is low and thus, a lower diffusion/diffraction coefficient seems to be more appropriate [Chourmouziadou and Kang, 2006b]. In addition, differences between software Raynoise and ODEON may result in some variations when applying diffraction/diffusion.

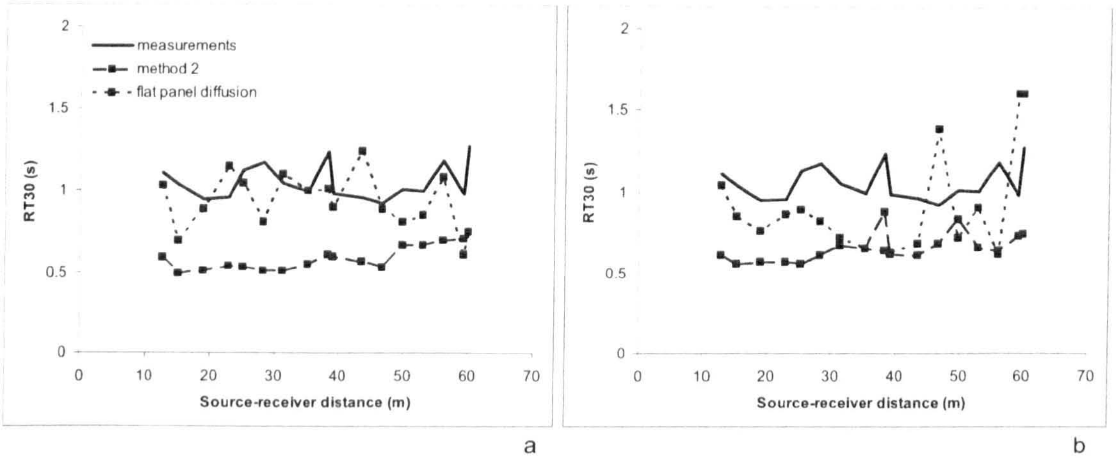


Figure 6.6.13. *Comparison between measurements and simulation results for the RT30 (s) at 500Hz of the theatre of Epidaurus. a) One inclination, 26°, and b) Two inclinations, 23° and 27°.*

6.6.5 FURTHER DEVELOPMENT OF METHOD 2 RESULTS

After discussions with the original developers of Method 2[38], it was decided to replace the angle of reflection, used in equations (6.6) and (6.9) and consequently in the final combined coefficient, by the angle of incidence [Christensen, 2005]. Although it was expected that the results would not be significantly altered, the new coefficients for Method 2, which could be used in Section 6.6.2, are presented in Table 6.3 for 500Hz. It can be seen that due to the change of the angle θ the final combined coefficient has been increased for rows 1-4, but remained the same for 5-8.

Regarding the frequency range the coefficients are illustrated in Table 6.4. By comparing them with Table 6.2 of Section 6.6.2 it can be seen that the combined coefficients have increased in most of the cases. Generally, for the rows in front of the receiver the increase is about 0.07-0.40 for Row 1, 0.12-0.55 for 2, 0.23-0.43 for 3 and 0.45-0.85 for Row 4. Rows 5-8 are attributed with almost the same coefficient values as before, with differences at the range of 0.08. Considering the previous results of the comparison of the two methods of diffraction, carried out in Section

[38] Method 2 was presented in the Auditorium Acoustics 2006 conference [Chourmouziadou and Kang, 2006a], where Prof. Rindel and Dr. Christensen provided feedback.

6.6.2, it is suggested that the new coefficients would only increase the differences between the two methods and Model 1.

Table 6.3. *Table indicating calculations for the combined diffusion coefficient of Method 2 for 500Hz.*

Equation\Row	1	2	3	4	5	6	7	8
$d_{incidence}$	10.027	10.985	11.962	12.955	13.959	14.972	15.993	17.022
$d_{reflection}$	3.847	2.778	1.72	0.721	0.671	1.603	2.648	3.711
angle θ (°)	83	86	88	90	1	3	4	5
cos (θ°)	0.123	0.07	0.036	0	1	1	0.997	0.996
Width (m)	1	1	1	1	0.4	0.4	0.4	0.4
Length (m)	1.888	2.078	2.267	2.457	2.647	2.836	3.026	3.215
α	1.39	1.109	0.752	0.341	0.32	0.724	1.136	1.523
f_w (Hz)	15946	38440	101841	92846060	345	782	1230	1654
f_l (Hz)	67.812	44.265	25.224	9.7523	7.877	15.52	21.388	25.41
K_w	0.031	0.013	0.005	5.3853E-06	1	0.639	0.406	0.302
K_l	1	1	1	1	1	1	1	1
S_e	0	0	0	0	0.427	0.428	0.428	0.428
S_d	0.969	0.987	0.995	1	0.427	0.634	0.767	0.827
S_r	0.973	0.989	0.996	1	0.513	0.689	0.802	0.853

Table 6.4. *Diffusion coefficients of Method 2 with the use of the angles of incidence.*

	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
1	0.99	0.99	0.97	0.97	0.94	0.88
2	1	1	0.99	0.99	0.98	0.95
3	1	1	0.99	0.99	0.99	0.98
4	1	1	1	1	1	1
5	0.87	0.69	0.51	0.42	0.28	0.07
6	0.91	0.86	0.69	0.42	0.28	0.07
7	0.96	0.91	0.8	0.53	0.28	0.07
8	0.97	0.93	0.85	0.65	0.28	0.07

Further calculations were carried out for the 3D representation of Method 2, like in Section 6.6.4. The results for the whole area of the koilon are presented in Figure 6.6.14. A comparison with Figure 6.6.9 reveals that the coefficients at 500Hz have retained the same values, which consequently means that the simulation will produce the same results in reverberation. Moreover, in Figure 6.6.15 the average values for the combined coefficients for the range of frequencies are shown. The curve approaches 1 for the front rows of the koilon, while it is reduced for the rest of the koilon, especially at high frequencies. Still, the simulation results would hardly be differentiated, except for high frequencies, where diffusion would be decreased, thus reverberation could slightly increase.

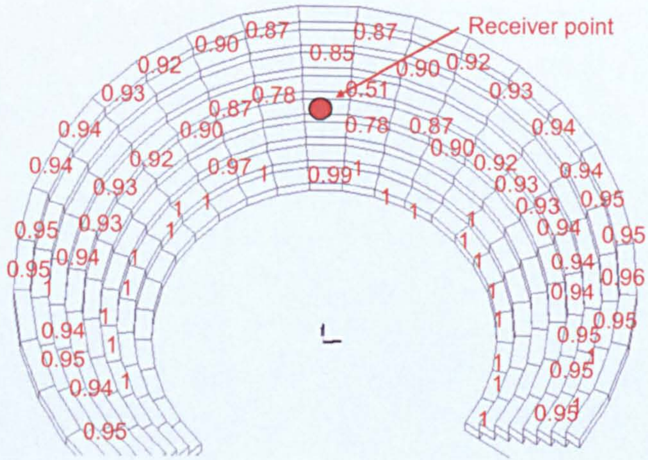


Figure 6.6.14. 3D model of the theatre with combined scattering and diffraction coefficient for the lower, middle and upper part of the koilon at 500Hz.

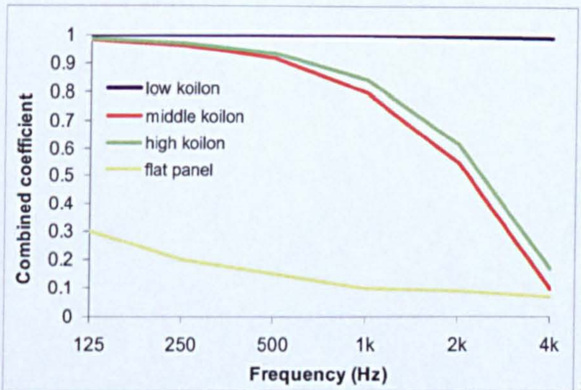


Figure 6.6.15. Average values for combined scattering and diffraction coefficient from 125 to 4kHz.

For comparison, and to examine all the possibilities of the representation of the 3D nature of the reflections, the combined coefficient was recalculated based on the equation known as 'scalar product' [Spiegel, 1999]

$$CosIncidence = A \cdot x + B \cdot y + C \cdot z \tag{6.13}$$

where A, B and C are the unit normal vectors of the wall and x, y and z are the unit vectors of the incidence vector. The coefficients derived from this method are presented in Figures 6.6.16 and 6.6.17, illustrating the perspective of the theatre with the coefficients for the whole koilon area at 500Hz and the average coefficients for the range of frequencies respectively. It is shown that the coefficients at 500Hz are decreased, at around 0.1 for the areas around the receiver. Across the frequencies the coefficients show a decline at mid-frequencies, although the high frequency diffusion has increased.

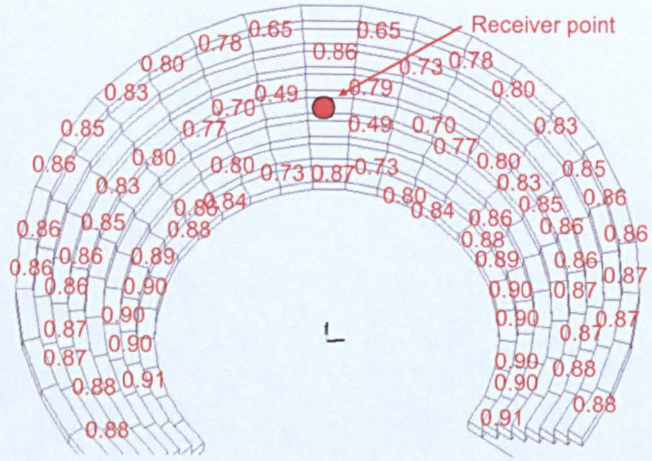


Figure 6.6.16. Perspective of the theatre with coefficient at 500Hz, with the use of unit vectors.

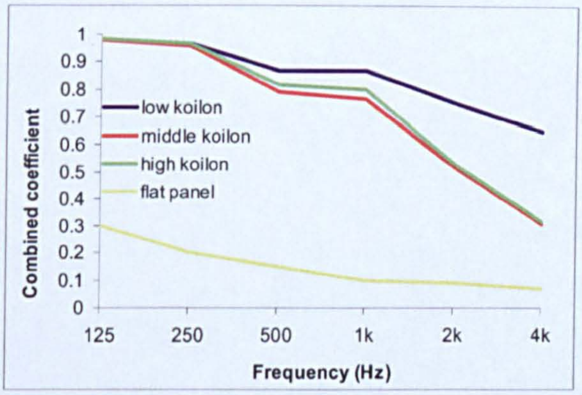


Figure 6.6.17. Average values for combined coefficients across the frequencies.

6.7 Comparison between a Lambert and a Semi-point Source

Regarding edge diffraction in ancient theatre acoustics a method had been previously suggested, based on secondary edge sources, as mentioned in Section 6.3.1. Extending Biot's and Tolstoy's [1957], and Svensson's and Torres' [2000] suggestions, a comparison is carried out between two sources applied to an edge of the ancient theatre koilon, to replicate scattering from an edge. The aim is to investigate the difference in scattering between the two sources, the one distributing sound in a semi-sphere and the other based on Lambert's law of distribution. The directivities in Raynoise were accordingly attributed. Figure 6.7.1 shows the two sources. The sound power level of the sources is 62dB at 125 Hz, 64dB at 250Hz and 500Hz, 60dB at 1kHz, 55dB at 2kHz, and 35dB at 4Hz. Flat panel diffusion has been applied to the surfaces of the koilon. A source is being placed at the edge of a riser of the Greek theatre koilon for each of the two cases. Although not a series of radiating sources is placed at the edge of the riser, since the software simulates only one source at a time, it is expected that the results will show differences in the interference of edge diffraction according to the two ways of distribution.

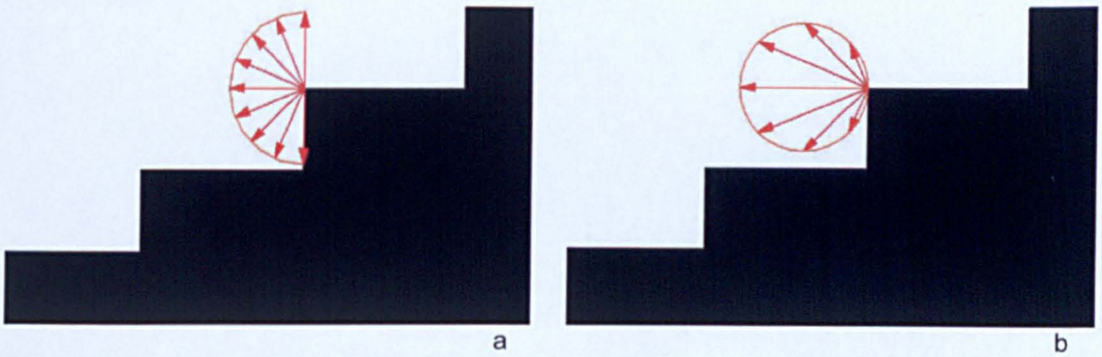
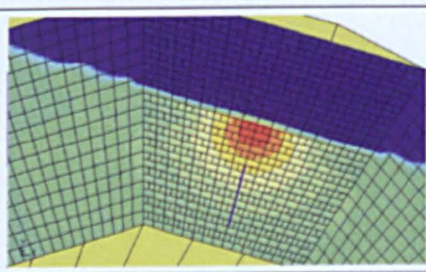
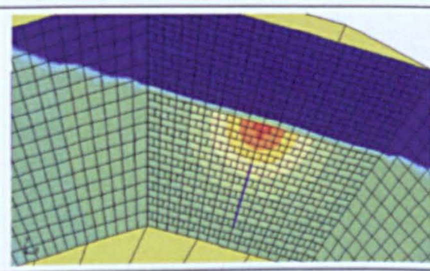
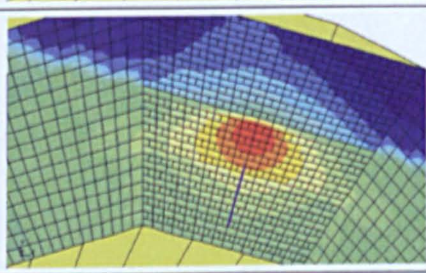
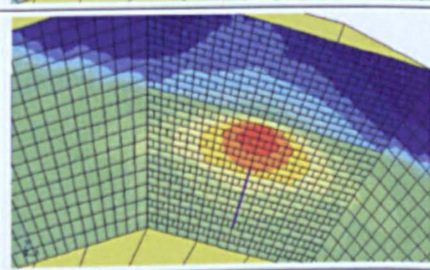
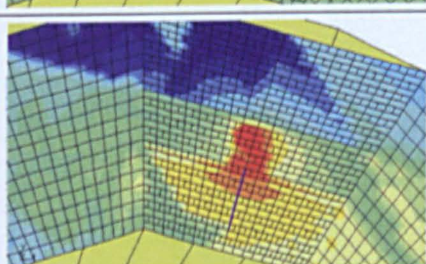
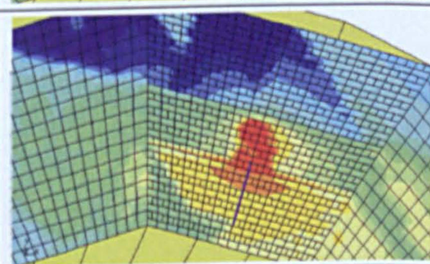
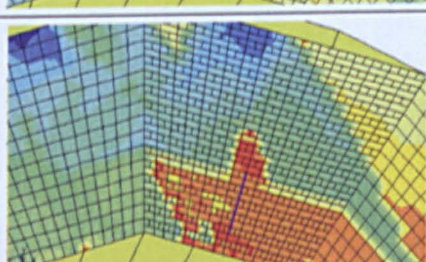
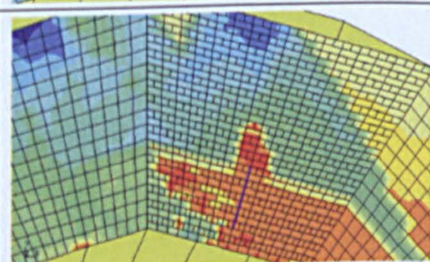
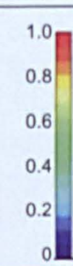
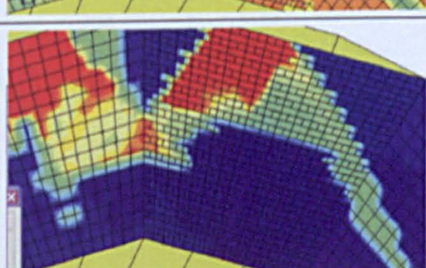
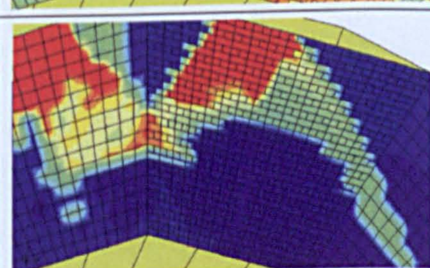
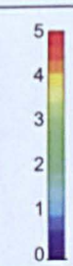
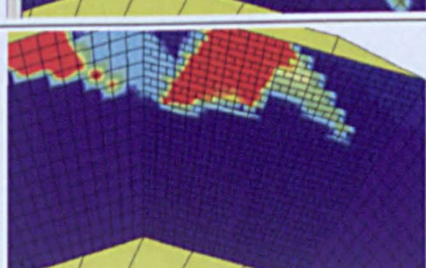
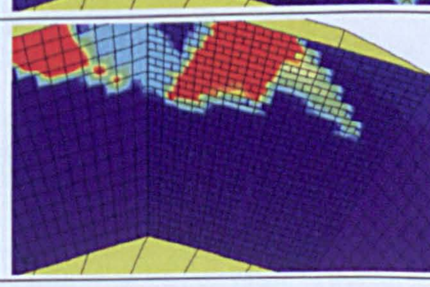
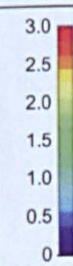


Figure 6.7.1. *Section of an ancient theatre with the two edge sources used for comparison. a) Semi-point source and b) Lambert distribution.*

The results for the audience area that surrounds the source are presented in Table 6.5 in the form of colour maps for SPL, STI, C80, RT30 and EDT. For each case one source is being calculated, applied to one of the edges of the koilon. As can be observed in the colour maps, there are small alterations in the indices, although of no obvious consequence to the acoustic environment. Figure 6.7.2 illustrates the SPL, RT60 and RT30 differences between the two types of sources used. The bigger variations can be found in the area behind the source, according to its directivity patterns. Generally the differences are at the region of 0-3.4dB for SPL, 0-0.34s for RT30, where 0.34 can be found only for selected receiver points, 0-0.14s for RT60, 0-0.04s for EDT and 0-0.09 for STI.

By analysing the results of SPL and RT in Figure 6.7.2 it can be seen that the maximum difference appears to be in the area behind the source, approximately after two risers. According to the sources' distribution patterns, seen in Figure 6.7.1, it is expected that a small difference will occur in that area. However, although both SPL and RT results suggest a small discrepancy between the two sources, Table 6.6 shows that the impulse responses of the adjacent receiver points are almost identical.

Table 6.5. *Colour maps of acoustic indices for a semi-point source and a Lambert distribution source.*

	Semi-point source	Lambert distribution source	Range
Direct sound (dB)			
SPL (dB)			
C80 (dB)			
STI(-)			
RT30 (s)			
EDT (s)			

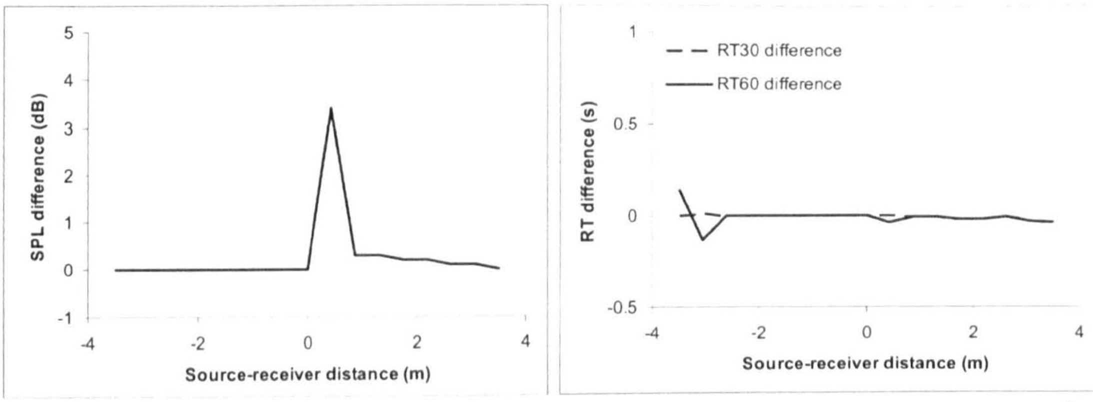
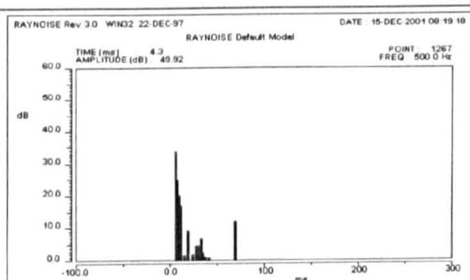
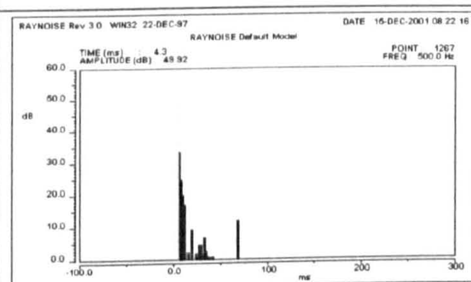
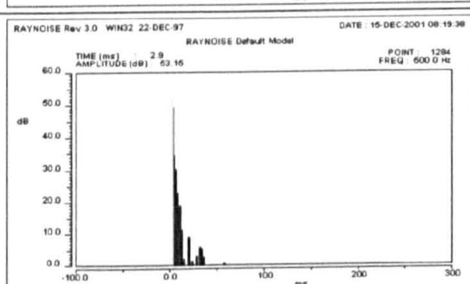
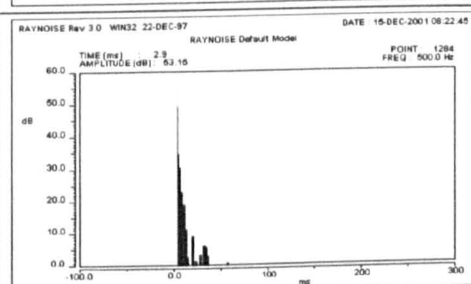
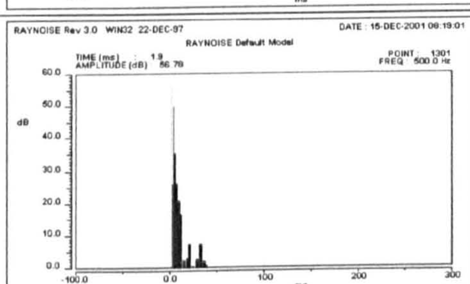
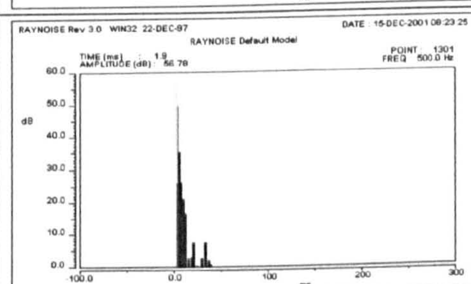
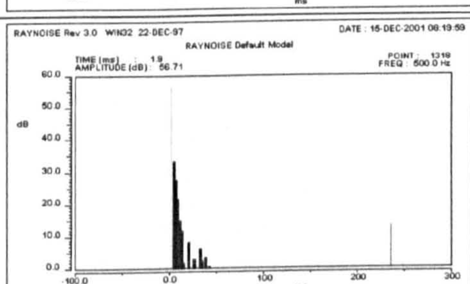
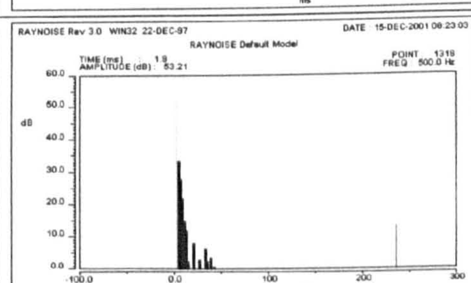


Figure 6.7.2. *Differences between a semi-point source and a Lambert distribution source at 500Hz. a) SPL (dB) and b) RT30(s) and RT60 (s).*

Table 6.6. *Impulse responses at four receiver points near the sources.*

	Semi-point source	Lambert distribution source
previous row		
in front of source		
at source		
behind source		

6.8 CONCLUSIONS

This chapter was focused on the effects of diffraction on sound distribution in ancient theatres, discussing (a) diffraction to the shadow zone behind a panel, (b) diffusion/diffraction due to limited surface size, (c) diffraction from a panel edge, and (d) diffusion effects due to the acoustic roughness of panel surface. Although the effects of diffraction are not always considered in computer simulations, outdoor performance spaces present few strong reflections, so even the weak scattered energy would influence results and form decay curves in impulse responses. Previous work on the effects of diffraction was examined and ways of simulating these acoustic phenomena were looked into. Diffraction around a barrier is relevant to ancient theatres only in cases of actors situated behind a scenery panel or object. Small-scale surface roughness becomes negligible with respect to wavelength at low frequencies, while edge diffraction may be significant at higher frequencies, especially for geometries with small surfaces and/or several wedges, like scenery designs that involve several smaller objects/panels.

Based on research on diffraction in computer simulations two methods were developed and tested in Raynoise. The comparison between Methods 1 (diffusion application) and 2 (theoretical approach on a combined diffraction/diffusion coefficient for reflecting panels) has shown that RT30 was the index mostly affected, compared to other acoustic indices, with maximum differences of 1s. For indication, the maximum variations in SPL were around 0.5dB. Both Methods underestimate reverberation, with a difference of almost 1s compared to flat panel diffusion, namely Model 1 in this chapter.

Especially for Method 2, the effect of each variable on the final coefficient values was examined. It was found that by increasing d_{edge} (the distance between the reflection point and the edge of the riser), the combined coefficient reduces. Increasing the length of the panel (which is around 2m) has no effect on the coefficient, but decreasing it ensues increased diffusion. By changing the panel's width the coefficients are mostly determined by surface roughness. In general the combined coefficients are stable after a specific distance (30° angle), at an average of 0.99 at 125 Hz, 0.98 at 250Hz, 0.94 at 500Hz, 0.78 at 1kHz, 0.68 at 2kHz, and 0.25 at 4Hz.

The equations of Method 2 were developed in order to incorporate the 3D characteristics of the reflection paths, both by analysing each reflection path to its components according to x, y and z axis, and by using the normalised vectors, what is commonly known as the 'scalar product'. It was shown that scattering increases as the distance from the reflection surface increases. Since the final values of the coefficients show a pattern as far the theatre layout is concerned, it is possible to divide the theatre into zones and apply the same coefficient.

The three methods of considering diffraction/diffusion have been tested and compared with measurements in the ancient Greek theatre of Epidaurus. It is shown that the calculation by using the flat panel diffusion coefficients generally agrees well with measurements, whereas the other two methods tend to underestimate reverberation. Regarding Method 2 it has been indicated that it may be useful in the case of scenery parts and other objects that could determine the acoustic environment in relation to their dimensions and surface roughness. It is noted that, however, for other theatre layouts, such as the more enclosed Roman theatres, different diffusion/diffraction coefficients might be more appropriate.

Regarding edge reflection, a comparison between a Lambert and a typical distribution has shown that the effect of reflection pattern/directivity is not significant.