ACOUSTICAL PROPERTIES OF ANCIENT THEATRES:
COMPUTER SIMULATION AND MEASUREMENTS

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy.

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Doctor of Philosophy.

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ABSTRACT

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In this study, acoustical properties of ancient theatres have been examined by using the geometrical room acoustics approach. For this purpose, the theatres of Aspendos, Perge and Termessos in Pamphylia and Pisidia have been selected for measurements and acoustical simulations. Sound reflections from the orchestra surface and stage wall have been simulated on the computer by the ray-tracing method and method of the image sources. An impulsive sound source has been used to record sound at several locations in the theatres. These recordings have been later analyzed and compared to simulation results. Reflection patterns obtained from analytical and experimental studies are discussed and the receiver positions with and without echoes are determined. Surfaces that cause echoes are determined and preventive methods are proposed for their obstruction. The resultant evaluations prove that the splendid geometries of ancient theatres and their inclined auditoria have a significant role on their acoustics. Moreover, the acoustical importance of the stage-back wall and reflective orchestra surface are emphasized. It is proposed that the design-tradition of ancient theatres in terms of architectural and acoustical design principles be exploited in constructing the contemporary open-air theatres.

Keywords: Ancient Theatres, Open-air Theatres, Geometrical Room Acoustics, Acoustical Simulation Methods, Acoustical Measurements, Ray-tracing, Image Source Method.

ÖZ

ANTİK TİYATROLARIN AKUSTİK ÖZELLİKLERİNİN BİLGİSAYAR BENZETİMİ VE ÖLÇÜMLERLE BELİRLENMESİ

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Bu çalışmada, antik tiyatroların akustik özellikleri, geometrik oda akustiği yaklaşımı ile incelenmektedir. Bu amaçla Aspendos, Perge ve Termessos tiyatroları akustik ölçümler ve bilgisayar benzetimi için seçilmiştir. Orkestra yüzeyinden ve sahne duvarından yansıyan sesin bilgisayar benzetimi ışın izleme ve ayna görüntüsü yöntemleri kullanılarak gerçekleştirilmektedir. Tiyatroların birçok yerinde yapılan ölçüm kayıtları için patlayıcı bir ses kaynağı kullanılmıştır. Bu kayıtlar daha sonra çözümlenmiş ve benzetim sonuçları ile karşılaştırılmıştır. Analitik ve deneysel çalışmalardan elde edilen yansıma grafikleri üzerinde tartışılmış, eko oluşan ve oluşmayan izleyici konumları saptanmıştır. Eko oluşturan yüzeyler belirlenmiş ve bunların önlenmesi için yöntemler önerilmiştir. Yapılan değerlendirmeler sonucunda antik tiyatroların mükemmel geometrilerinin ve eğimlendirilmiş oturma alanlarının (kavea) akustikleri üzerinde olumlu rol oynadığı kanıtlanmıştır. Sahne arka duvarının ve yansıtıcı orkestra yüzeyinin akustik önemi de vurgulanmıştır. Yeni yapılacak açık hava tiyatrolarında, antik tiyatro tasarım geleneğinden, mimari ve akustik tasarım ilkeleri açılarından yararlanılması önerilmektedir.

Anahtar Kelimeler: Antik Tiyatrolar, Açık Hava Tiyatroları, Geometrik Oda Akustiği, Akustik Benzetim Yöntemleri, Akustik Ölçümler, Işın İzleme, Ayna Görüntüsü Yöntemi.

To My Parents

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RT	Reverberation time
V	Volume of spaces
A	Total absorption in m^2-Sabines
ε	Hearing angle
ω	Declination angle of cone or its complements
D_0	The length between the source and the first row of the auditorium
H	Height of receiver location
h	Total height of stage and actor's mouth level (height of sound source)
h_0	Height of stage
d_1	Length difference between direct and reflected paths of sound from orchestra surface
d_2	Length difference between direct and reflected paths of sound from stage building
Δ_1	Time difference between direct and reflected paths of sound from orchestra surface
Δ_2	Time difference between direct and reflected paths of sound from stage building
c	Speed of sound
d	Difference in path-lengths
D	Distance between the sound source and receiver
D_1	Distance between the sound source and receiver

CHAPTER I

INTRODUCTION

There are more than fifty ancient open-air theatres belonging to the Greek and Roman periods in Asia Minor. Some of these theatres are still being used. Most of the theatres were built in the Roman period. Even those theatres built during the Hellenistic era were later adapted to the Roman pattern. Only a few of the ancient theatres have kept their original Hellenistic type. These theatres are located in the southern and western parts of Turkey. At least eight months of the year are suitable for the use of these ancient theatres because of the moderate climatic condition of the regions.

Acoustics of ancient open-air theatres is said to be satisfactory for most seating places, although the seating capacity of most of them is very large. A search for the reasons of good acoustics, reveals only a few studies concerning the acoustics of ancient theatres. In these studies neither acoustical measurements nor detailed acoustical analysis for the theatres of Asia Minor and ancient theatres elsewhere were discussed. Moreover, existing studies were carried out at least twenty years ago. The lack of comprehensive research in this respect was the main reason to study the acoustics of ancient theatres by state of the art techniques involving computer simulations based on geometrical room acoustics. It is also believed that revealing the reasons for good acoustics will serve as a powerful tool in the design of new open-air theatres.

The most important and oldest extant scholarship on the acoustics of open-air theatres is found in the architectural treatise of M. Vitruvius Pollio. The main sections of this ancient text related to the theatres and their acoustics are excerpted and discussed in the first part of Chapter 2. Contemporary scholarship and relevant research is evaluated in the second part of Chapter 2.

In conducting the study, first of all, it was necessary to obtain the documentation on ancient theatres in Asia Minor. A historical survey was conducted in order to define the architectural characteristics and structural conditions of ancient theatres. In this respect the ancient theatres of Asia Minor are tabulated according to their location, construction period, seating capacity and structural condition which was the most determining factor to be considered in the selection of theatres for acoustical measurements. After the identification and classification of ancient open-air theatres, the theatres of Side, Aspendos, Perge and Termessos were chosen for acoustical measurements. The closeness of the theatres to each other and their well-preserved condition were the main factors which supported such a selection. However, measurements could not be performed at the theatre of Side because of the high background noise level from the bus depot.

The evolution of classical theatres from the ritualistic Greek celebration to Roman theatre building are explained in Chapter 3, and the main differences between the Greek and Roman theatre buildings are discussed in terms of their forms. This study concentrates on the conventional theatres designed for the acting of plays. However, the architectural development of the concert hall (odeion) which is a related building type is also dealt with briefly in this chapter.

Geometrical room acoustics approach has been selected for analyzing the acoustics of selected ancient theatres. Acoustical characteristics of ancient theatres have been examined on the basis of impulse response. The criterion of speech intelligibility in open-air theatres and the basic factors which affect the clarity of speech are also examined in Chapter 4. Effects of theatre geometry on the acoustical characteristics of theatres are discussed in this chapter. The importance of the hearing angle which depends on the theatre slope is emphasized. Principles of acoustical designing for direct sound, especially effects of shape and slope for open-air theatres are evaluated. In addition, the propagation of sound in open-air is also discussed in this chapter.

Geometric room acoustics and its two basic methods, namely methods of image sources and ray-tracing are examined in detail in Chapter 5. The importance of the two main surfaces of ancient theatres, namely, skene and orchestra, are analyzed in the latter part of the chapter.

The acoustical measurement technique, the positions of receivers and sound sources are described for the selected ancient theatres in Chapter 6. Impulse responses which are found by the analysis of acoustical measurements are given in this chapter for the specified sound-receiver configurations.

The method of image sources and ray tracing method have been used for simulating acoustical characteristics of theatres of Aspendos, Perge and Termessos. Speech Transmission Indices (STI) and impulse responses for theatres of Aspendos and Termessos are found by IMAGE program. However, the theatre of Perge could not be simulated by this method because of its very large and complicated form. Impulse responses for theatres of Aspendos, Perge and Termessos are found by RAYTR. Impulse response diagrams obtained from the RAYTR and IMAGE programs take place in

Chapter 7.

Impulse responses which are found from the acoustical measurements and simulation methods for selected theatres are compared and evaluated in Chapter 8. Critical echo regions of theatres and echo free positions are discussed in this chapter. Three-dimensional figures of some interesting receiver-source configurations which are the output of RAYTR show the surfaces that cause the echoes in the theatres. The role of the skene and orchestra surfaces which reflect and reinforce sound is also examined in these three-dimensional figures which show the paths of sound rays.

The importance of acoustical design in the re-use of ancient theatres and its application to contemporary open-air theatres is dealt with in Chapter 9. Criteria for the more conscious use of ancient theatres are discussed in terms of consolidation, sub-structure and comfort conditions of theatres and the kinds and frequencies of activities. A coordination model for conservation, use and control of theatres is proposed. Acoustical design criteria in the re- use of ancient theatres and new open-air theatres are recommended. The requirements of new open-air theatres for either music or theatrical performances in contemporary towns and their reasons are put forward in the last part of the chapter.

The studies which could be performed effectively or which were simply not possible in the context of this thesis are discussed in the conclusion. The importance of the study in its scientific scope is also evaluated in this section and proposals for future studies in this field are listed. Finally findings from the study are referred for the use of architects related with the subject and who may be in the position to design new open-air theatres.

CHAPTER 2

EVALUATION OF ANCIENT AND MODERN SCHOLARSHIP

The extant relevant research and scholarship on the acoustics of ancient theatres may be evaluated in two main parts; the ancient evidence and contemporary scholarship.

2.1 The Ancient Evidence

The most important and oldest extant scholarship on the acoustics of open-air theatres is found in the famous Ancient text of Marcus Vitruvius Pollio , De Architectura (The Ten Books of Architecture). This work consists of ten books. Especially Book 5, and its chapters 3, 4, 5, 6, and 8, have invaluable information about Greek and Roman theatres and harmonics. The most important paragraphs of these chapters have been excerpted below. Our discussion is based on the English translation of the original text.

Book 5, Chapter 3, (Vitr. 5.3)

THE THEATRE: ITS SITE, FOUNDATIONS, AND ACOUSTICS

4. The curved cross-aisles should be constructed in proportionate relation, it is thought, to the height of the theatre, but not higher than the footway of the passage is broad. If they are loftier, they will throw back the voice and drive it away from the upper portion, thus preventing the case-endings of words from reaching with distinct meaning the ears of those who are in the uppermost seats above the cross- aisles. In short, it should be so contrived that a line drawn from the lowest to the highest seat will touch the top edges and angles of all the seats. Thus the voice will meet with no obstruction.

5. Particular pains must also be taken that the site be not a "deaf" one, but one through which the voice can range with the greatest clearness. This can be brought about if a site is selected where there is no obstruction due to echo.

6. Voice is a flowing breath of air, perceptible to the hearing by contact. It moves in an endless number of circular rounds, like the innumerably increasing circular waves which appear when a stone is thrown into smooth water, and which keep on spreading indefinitely from the centre unless interrupted by narrow limits, or by some obstruction which prevents such waves from reaching their end in due formation. When they are interrupted by obstructions, the first waves,

flowing back, break up the formation of those which follow.

7. In the same manner the voice executes its movements in concentric circles; but while in the case of water the circles move horizontally on a plane surface, the voice not only proceeds horizontally, but also ascends vertically by regular stages. Therefore, as in the case of the waves formed in the water, so it is in the case of the voice: the first wave, when there is no obstruction to interrupt it, does not break up the second or the following waves, but they all reach the ears of the lowest and highest spectators without an echo.

8. Hence the ancient architects, following in the footsteps of nature, perfected the ascending rows of seats in theatres from their investigations of the ascending voice, and, by means of the canonical theory of the mathematicians and that of the musicians, endeavored to make every voice uttered on the stage come with greater clearness and the sweetness to the ears of audience. For just as musical instruments are brought to perfection of clearness in the sound of their strings by means of bronze plates or horn, ηχεια, so the ancients devised methods of increasing the power of the voice in theatres through the application of harmonics.

Chapter 4, (Vitr. 5.4)

HARMONICS

2. The voice, in its changes of position when shifting pitch, becomes sometimes high, sometimes low, and its movements are of two kinds, in one of which its progress is continuous, in the other by intervals. The continuous voice does not become stationary at the "boundaries" or at any definite place, and so the extremities of its progress are not apparent, but the fact that there are differences of pitch is apparent, as in our ordinary speech in sol, lux, flos, vox; for in these cases we cannot tell at what pitch the voice begins, nor at what pitch it leaves off, but the fact that it becomes low from high and high from low is apparent to the ear. In its progress by intervals the opposite is the case. For here, when the pitch shifts, the voice, by change of position, stations itself on one pitch, then on another, and, as it frequently repeats this alternating process, it appears to the senses to become stationary, as happens in singing when we produce a variation of the mode by changing the pitch of the voice. And so, since it moves by intervals, the points at which it begins and where it leaves off are obviously apparent in the boundaries of the notes, but the intermediate points escape notice and are obscure, owing to the intervals.

Modes and notes are defined in a detailed manner in Paragraphs 3-8. This section, which is rather technical, can be effectively analyzed with extensive musical knowledge. Therefore, it has not been included here.

9. For there can be no consonancies either in the case of the notes of stringed instruments or of the singing voice, between two intervals or between three or six or seven; but, as written above, it is only the harmonies of the fourth, the fifth, and so on up to the double octave, that have boundaries naturally corresponding to

those of the voice: and these concords are produced by the union of the notes.

Chapter 5, (Vitr. 5.5)

SOUNDING VESSELS IN THE THEATRE

1. In accordance with the foregoing investigations on mathematical principles, let bronze vessels be made, proportionate to the size of the theatre, and let them be so fashioned that, when touched, they may produce with one another the notes of the fourth, the fifth, and so on up to the double octave. Then, having constructed niches in between the seats of the theatre, let the vessels be arranged in them, in accordance with musical laws, in such a way that they nowhere touch the wall, but have a clear space all round them and room over their tops. They should beset upside down, and be supported on the side facing the stage by wedges not less than half a foot high. Opposite each niche, apertures should be left in the surface of the seat next below, two feet long and half a foot deep.

2. The arrangement of these vessels, with reference to the situations in which they should be placed, may be described as follows. If the theatre be of no great size, mark out a horizontal range halfway up, and in it construct thirteen arched niches with twelve equal spaces between them, so that above mentioned "echea" those which give the note nete hyperbolaeon may be placed first on each side, in the niches which are at the extreme ends; next to the ends and fourth below in pitch, the note nete diezeugmenon; third, paramese, a fourth below; fourth, nete synhemmenon; fifth, mese, a fourth below; sixth, hypate meson, a fourth below; and in the middle and another fourth below, one vessel giving the note hypate hypaton.

3. On this principle of arrangement, the voice, uttered from the stage as from a centre, and spreading and striking against the cavities of the different vessels, as it comes in contact with them, will be increased in clearness of sound, and will wake an harmonious note in unison with itself.

But if the theatre be rather large, let its height be divided into four parts, so that three horizontal ranges of niches may be marked out and constructed: one for the enharmonic, another for the chromatic, and the third for the diatonic system. Beginning with the bottom range, let the arrangement be as described above in the case of a smaller theatre, but on the enharmonic system.

5. No vessel is to be placed in the middle, for the reason that there is no other note in the chromatic system that forms a natural concord of sound.

In the highest division and range of niches, place at the extreme ends vessels fashioned so as to give the note of the diatonic hyperbolaeon; next, the diatonic diezeugmenon, a fourth below; third, the diatonic synhemmenon; fourth, the diatonic meson, a fourth below; fifth, the diatonic hypaton, a fourth below; sixth, the proslambanomenos, a forth below; in the middle, the note mese, for this is both the octave to proslambanomenos, and the concord of the fifth to the diatonic hypaton.

6. Whoever wishes to carry out these principles with ease, has only to consult the scheme at the end of this book, drawn up in accordance with the laws of music. It was left by Aristoxenus, who with great ability and labor classified and arranged in it the different modes. In accordance with it, and by giving heed to these theories, one can easily bring a theatre to perfection, from the point of the view of the nature of the voice, so as to give pleasure to the audience.

7. Somebody will perhaps say that many theatres are built every year in Rome, and that in them no attention at all is paid to these principles; but he will be in error, from the fact that all our public theatres made of wood contain a great deal of boarding, which must be resonant. This may be observed from the behavior of those who sing to the lyre, who, when they wish to sing in a higher key, turn towards the folding doors on the stage, and thus by their aid are reinforced with a sound in harmony with the voice. But when theatres are built of solid materials like masonry, stone, or marble, which can not be resonant, then the principles of the "echea" must be applied.

8. If, however, it is asked in what theatre these vessels have been employed, we can not point to any in Rome itself, but only to those in the districts of Italy and in a good many Greek states. We have also the evidence of Lucius Mummius, who, after destroying the theatre in Corinth, brought its bronze vessels to Rome, and made a dedicatory offering at the temple of Luna with the money obtained from the sale of them. Besides, many skillful architects, in constructing theatres in small towns, have, for lack of means, taken large jars made of clay, but similarly resonant, and have produced very advantageous results by arranging them on the principles described.

Chapter 6, (Vitr. 5.6)

PLAN OF THE THEATRE

4. The roof of the colonnade to be built at the top of the rows of seats, should lie level with the top of the "scaena," for the reason that the voice will then rise with equal power until it reaches the highest rows of seats and the roof. If the roof is not so high, in proportion as it is lower, it will check the voice at the point which the sound first reaches.

Chapter 8, (Vitr. 5.8)

ACOUSTICS OF THE SITE OF A THEATRE

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 κατηχουντεζ; the circumsonant, which with them are named περιηχουντεζ; again the resonant, which are termed αντηχουντεζ; and the consonant, which they call συνηχουντεζ. 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 in 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's 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.

The drawings of the plans may be distinguished from each other by these difference, that theatres designed from squares are meant to be used by Greeks, while Roman theatres are designed from equilateral triangles. Whoever is willing to follow these directions will be able to construct perfectly correct theatres.

2.1.1 Discussion

1. As it is seen in Book 5, Chapter 3, "The Theatre: Its Site, Foundations, and Acoustics", (Vitr. 5.3.4); we may infer that the ancient Roman and Greek scientists and architects had known about the principles of geometrical room acoustics. The ancient architects had applied the acoustical theories formulated by scientists in theatre design. The plans and sections of theatres had been designed according to acoustical considerations.

2. The selection of the theatre site is important acoustically. Possible echoes can be prevented by a correct selection of site. It is proposed that the site should not be a "deaf" one, but one through which the voice can range with the greatest clearness. (5.3.5)

3. The consideration that ancient mathematicians had adequate knowledge in sound theories (propagation of sound, sound waves, etc.), is apparent in the paragraphs (5.3.6-8). Ancient architects attempted to design acoustically excellent theatres by means of canonical theory developed by the participation of musicians. This informative interchange between the disciplines (music-mathematics- architecture) is very important for determining application areas to the theories. (5.3.6-8)

4. Chapter 5, "Sounding Vessels in the Theatre" is very revealing. It is proposed that bronze vessels be made which are proportioned to the size of the theatre, for high quality of sound. Particular pains must be taken that the vessels settle in accordance with the investigation on mathematical principles which are explained in Chapter 4, "Harmonics". It is stated:

For there can be no consonancies either in the case of the notes of stringed instruments or of the singing voice, between two intervals or between three or six or seven; but, as written above, it is only the harmonies of the fourth, the fifth, and so on up to the double octave, that have boundaries naturally corresponding to those of the voice: and these concords are produced by the union of the notes (5.4.9).

It is also proposed that; the vessels be so fashioned that, when touched, they may produce with one another the notes of the fourth, the fifth, and so on up to the double octave (5.5.1).

5. The places where sound vessels are arranged in the theatre, are defined in quite a detailed manner (5.5.2):

If the theatre is of no great size, mark out a horizontal range halfway up, and in it construct thirteen arched niches with twelve equal spaces between them, and so arrange the vessels which give the notes above mentioned correctly.

The arrangement of the vessels in larger theatres is described (5.5.3). The following information is given:

But if the theatre be rather large, let its height be divided into four parts, so that three horizontal ranges of niches may be marked out and constructed.... Beginning with the bottom range, let the arrangement be as described above in the case of a smaller theatre, but on the enharmonic system. (5.5.3)

After all these arrangements; it is said that, the voice, uttered from the stage as from a centre, and spreading and striking against the cavities of the different vessels, as it comes in contact with them, will be increased in the clearness of sound, and will wake an harmonious note in unison with itself. (5.5.3)

It is proposed that the use of the scheme at the end of this book, can be drawn up in accordance with the laws of music. (5.5.6).

It was left by Aristoxenus, who with great ability and labor classified and arranged in it the different modes. In accordance with it, and by giving heed to these theories, one can easily bring a theatre to perfection, from the point of the view of the nature of the voice, so as to give pleasure to the audience.

6. It is stated that all public theatres made of wood contain a great deal of boarding, which must be resonant. It is also proposed that when theatres were built of solid materials like masonry, stone, or marble, which could not be resonant, then the principles of the "echea" must be applied (5.5.7). Furthermore, Book 1, Chapter 1 (Education of the Architect), states:

> In theatres, there are the bronze vessels which are placed in the niches under the seats in accordance with the musical intervals on mathematical principles. These vessels are arranged with a view of musical concords or harmony, and apportioned in the compass of the fourth, the fifth, and the octave, and so on up to the double octave, in such a way that when the voice of an actor falls in unison with any of them its power is increased, and it reaches the ears of the audience with greater clearness and sweetness (1.1.9).

7. It (5.5.8) discusses the theatres in which the sound vessels have been employed. It is stated that none could be pointed to in Rome itself, but that examples existed only in the districts of Italy and in a good many Greek states. The following paragraph is about the evidence of Lucius Mummius who, after destroying the theatre in Corinth, brought its bronze vessels to Rome, and made a dedicatory offering at the temple of Luna with the money obtained from their sale. In the same paragraph, is a discussion on the evidence of the large jars made of clay, but similarly resonant, used by many skillful architects, in constructing theatres in small towns, for lack of means and added that they had produced very advantageous results in arranging them on the principles described.

We did not notice any evidence of these vessels and their corresponding niches in the theatres of Aspendos, Perge, Side and Termessos where we performed acoustical measurements in Turkey. Furthermore, further knowledge about the vessels could not be found in our survey of the literature. But, it can be supposed that these vessels were indeed used in certain periods because of the very detailed information about them and their placement principles in the theatre, given by Vitruvius. However, we did notice some niches which we originally thought may have been used for vessel niches in the theatre of Aspendos. We now assume that these niches were built for lighting the gallery behind the "diazoma". But it may be possible to consider that these niches could be used with a double function i.e. for lighting and sound.

8. It (5.6.4) states:

> The roof of the colonnade to be built at the top of the rows of seats, should lie level with the top of the "scaena," for the reason that the voice will then rise with equal power until it reaches the highest rows of seats and the roof. If the roof is not so high, in proportion as it is lower, it will check the voice at the point which the sound first reaches.

This indicates that ancient architects had great experience and knowledge about geometrical room acoustics. They had the ability to apply acoustical theories to the open-air theatres. (5.6.4)

9. Vitruvius states that it would be possible to build perfectly correct theatres provided that the directions are followed in both Greek and Roman theatre design tradition. Theatres were designed from squares by Greeks and equilateral triangles by Romans (5.7.2). Both architectural and acoustical design perfection may be considered here. Both our measurements and simulations as well as ancient scholarship seem to suggest that these ancient theatres performed perfectly from the viewpoint of acoustics.

Equilateral triangles and squares which were used as the basis of design are reflected in theatre plan geometry as the semi-circle and horse-shoe forms.

10. Consequently, the endeavors of ancient architects for increasing sound quality in the theatres and their scientific and technical knowledge are quite astonishing. Unfortunately, architects of the modern age cannot be said to approach the buildings like concert halls, which are considerable acoustical properties, with the same consciousness.

2.2 The Evidence of Contemporary Scholarship and Relevant Research

The contemporary scholarship and relevant research on the acoustics of ancient theatres may be evaluated in two sections: the acoustical aspect of open-air theatres and historical studies on the architectural development of the open-air theatre building. Unfortunately, there are only few studies directly related to the former.

The architectural characteristics of Greek and Roman theatre buildings are also important while analyzing their acoustical properties. Another significant topic involves acoustical simulation methods. A literature survey is included also on this subject.

2.2.1 Acoustics of Ancient Theatres

One of the most important works in this field is Canac's (1967) book <u>L'acoustique des Theatres Antique</u> where geometrical room acoustics approach has been applied to ancient theatres. In this study, a basic equation has been developed for the hearing angle and the relation between the slope of the theatre and hearing angle has been shown.

Papathanassopoulos (1959) has analyzed the distribution of sound from orchestra and stage wall in ancient Greek theatres. The results show that the geometrical characteristics of the theatre, especially, its conic form and slope, have affected its acoustical properties. Isophonic curves for several distances from the centre of the orchestra have also been developed and applied on Epidauros and Dionysos theatres.

The acoustical measurements have been done in order to obtain sound power level, speech intelligibility, and reverberation time in the Epidauros theatre (Papathanasopoulos, 1965). Only reflections from the orchestra surface have been analyzed because of the non- extant stage wall. Papathanassopoulos has concluded that the reasons for good acoustics in ancient theatres depend on their splendid design and achievement of the early architects on the theatre plan and section.

A technical report has been prepared for impulse measurements of open-air theatres at Heinrich-Hertz Institut fur Schwingungsforschung (Kürer, 1968). The report consists of theoretical study and measurements. An ancient Greek theatre (Epidauros) has been compared with a modern open-air theatre (Waldbuhne in Berlin) in terms of impulse measurements. Authors concluded that impulse measurements have been seen as an appropriate method.

Shankland (1973) studied the acoustics of ancient theatres in Italy in 1964 and 1966, in Sicily in 1968, and in Greece in 1972. The author claimed that, the acoustics of Epidauros theatre was superior to all the others. The excellent acoustics of the Epidauros theatre does not depend on a single factor, but involves many other factors such as design, construction and the excellent state of preservation that all contribute to its acoustical superiority, especially for speech intelligibility.

Knudsen and Harris (1978) have a chapter on the acoustics of open-air theatres where the propagation of sound in the open-air has been examined. They noted that the sound pressure of spherical waves originating at a point source decreases inversely with the distance from the source.

2.2.2 Development of Open-air Theatres

Knudsen and Harris (1978) give some valuable advice for designing open-air theatres. The selection and grading of the site is a very important factor. The design of the orchestra-shell and provision for a sound-amplification system, especially for large-capacity auditoria are other considerations in order to provide satisfactory acoustical properties for open-air theatres.

A Ph. D. Thesis prepared by Bledsoe (1971) is about investigations on design criteria for the ideal outdoor theatres.

'The History of Greek and Roman Theatre' (Bieber, 1961) is a very useful reference work in this field. In this book the development of theatre buildings, from the Classical to the Roman Period, is investigated in detail with a contextual approach.

Plans and sections of the theatres in Asia Minor are presented in Ferrero's works (1966, 1969, 1970). Plans of the theatres of Aspendos, Perge and Termessos which are used for acoustical analysis, have been adapted from this study.

Tidworth's (1973) work which investigates the development of the theatre is also very useful in this field. The author places the development of theatres in a historical frame-work starting from Greek drama until our time.

Izenour's (1977) work is very useful for the architects who are designing theatres. Criteria which are important for theatre design are discussed in detail. The author investigates many existing open and closed theatres and concert halls according to their typological characteristics and acoustical properties.

2.2.3 Geometrical Room Acoustics and Acoustical Simulation Methods

The geometrical room acoustics approach consists of two basic methods, namely methods of ray-tracing and image sources.

2.2.3.1 The Method of Image Sources

Allen and Berkley (1979) applied the method of images to a small rectangular room and simulated impulse response between source and receiver. The reverberation time of the room was calculated by the energy decay curve obtained from the impulse response. They compared the results of the applied theoretical analysis and the image modelling. They showed that the image solution for a rectangular enclosure rapidly approached the exact solution of the wave equation.

Gibbs and Jones (1972) employed the method to predict variation in sound pressure level in rectangular rooms having various absorption coefficients. The analysis results are compared to the ones obtained by the diffuse field theory and measurements.

Thompson and Zagar (1983) compared the method of image sources with the room acoustics equation and experimental data for rectangular rooms and showed that the method of image sources appears to be more accurate than room acoustics equation in predicting sound pressure level distribution inside such rooms.

Gensane and Santon (1979) compared the method of image sources with classical modal methods. It is reported that the image source method agrees better than the modal approach with experimental results.

2.2.3.2 Ray-tracing Method

Krokstad, Strom and Sorsdal (1968) used the ray- tracing technique for calculating the acoustical response of rooms. They also applied this technique in both research and implementation projects (1983).

Schoeder (1973) examined the ray-tracing method in order to design acoustically successful concert halls. It was shown that the computer model application of this method provided satisfactory data for such spaces.

Rietschote (1983) compared the results of ray- tracing technique and general room acoustics approach. He proved that room dimensions, distribution of absorptive surfaces and the shape of the room affected speech intelligibility characteristics of spaces.

Kulowski (1985) presented a ray-tracing algorithm developed for three dimensional spaces. Emitted rays from the sound source were generated randomly yielding favorable results over uniform ray generation scheme.

2.2.4 Acoustical Response

Allen and Berkley (1979) studied the impulse response of a rectangular room by using the method of image sources. The reverberation time was calculated by the energy decay curve obtained from the impulse response.

Schroeder (1980) indicated that the echoes in concert halls can be determined by impulse response. The author concluded that the concert halls having same reverberation times differ widely in audience acceptance because of the echoes present.

2.2.5 Speech Intelligibility

In a series of studies (Rietschote, Houtgast, and Steeneken, 1981 and 1983) an objective measure for speech intelligibility termed as the Speech Transmission Index (STI) was developed. Van Rietschote, Houtgast, and Steeneken (1983) used the ray-tracing technique to calculate STI for prediction of speech intelligibility.

Speech-articulation tests have been conducted on a level site to determine the percentage articulation of speech in the open air as a function of distance from the speaker (Knudsen and Harris, 1978).

Kleiner (1981) measured the speech intelligibility in a theatre. The effects of reverberation, direct listening, indirect listening and the background noise were analyzed. He also obtained impulse response of the theatre and analyzed the effects of echoes.

2.2.6 Miscellaneous

An extensive scholarly bibliography on theatres prepared by Howard (1982) is an important contribution in this field. A bibliography on acoustics and sound is also included in this study.

CHAPTER 3

EVOLUTION OF CLASSICAL THEATRES

3.1. Architectural Development of the Open-air Theatre Building

It is a widely held that the drama and the theatre building have a Greek origin. The art of the theatre has gradually developed from the primitive Greek celebration carried out during the Dionysiac rites.

The Greek word tragos means one who dresses up and performs as a follower of Dionysus. Therefore, tragedy is a song in honor of Dionysus. At the Attic rural Dionysia the *members of the joyous parade dressed up as animals, and from their song during the gay* Komos comedy developed. Drama is the latest of the three most important literary forms -epic, lyric, and drama- created by the Greeks and still fully active today (Bieber, 1961: 2).

There were theatral areas at Knossos and Phaestus in the period of the beginnings of Cretan palaces (Lawrence, 1962: 26-33). The construction of theatral areas just outside the palaces was probably an innovation of the Middle Minoan II period (2000-1700 B.C.). They are important as a pre-Hellenic construction. There is a space on the steps for 500 people at Phaestus. At Knossos, the theatral area occupied part of the north court, enclosed for the purpose by a wall; the five steps on the south side may be still older, but another flight of seventeen was added in Middle Minoan III period (1700-1380 B.C.) on the east side, together with a higher platform set behind the junction of the two flights as though to form a 'royal box'. The open space was then restricted to 12.94 by 10.16 m. (Figure 3.1).

All theatre buildings consist of two essential areas. The first one is the "auditorium", which is designed for the audiences, the other one is the "stage" which is designed for performances. The ancient Greek theatre has three main parts (Figure 3.2)

- orchestra
- skene
- theatron

The orchestra and the skene are the parts of the stage in the modern sense.

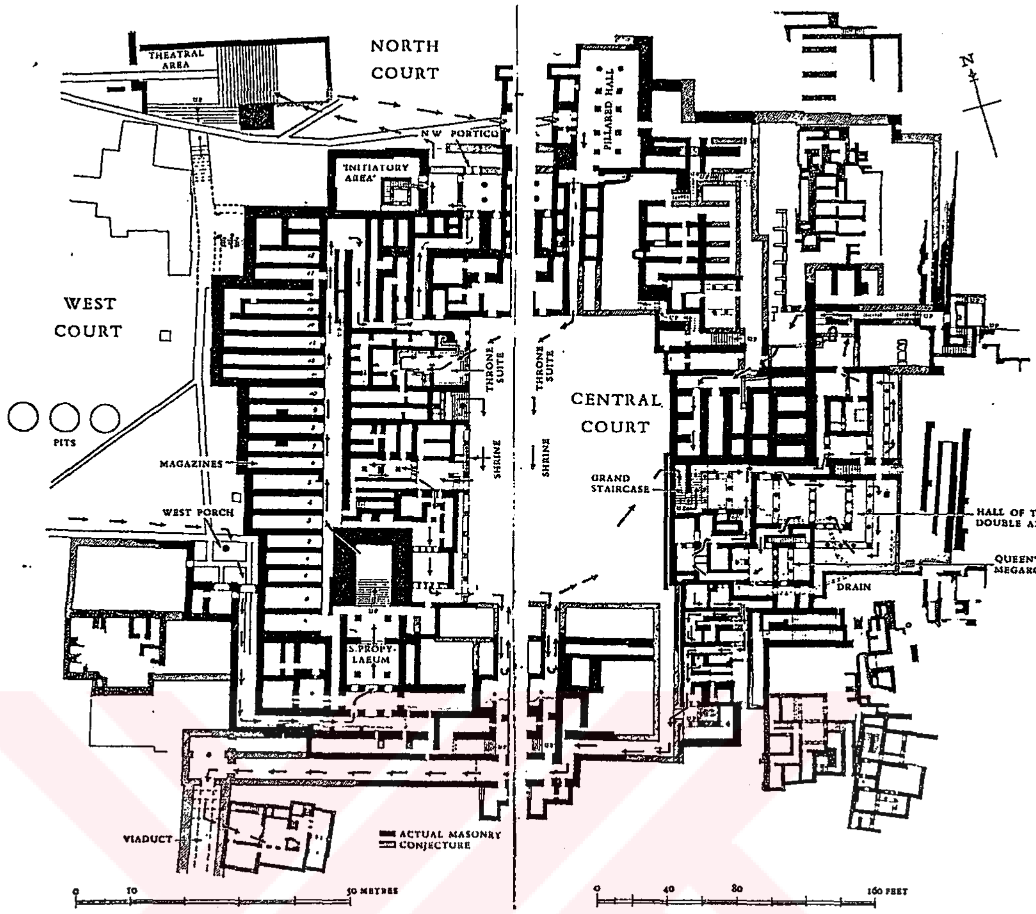


Figure 3.1 The Theatral Area on the Restored Plan of Palace, Knossos. (Source: Lawrence, 1962: 32-33)

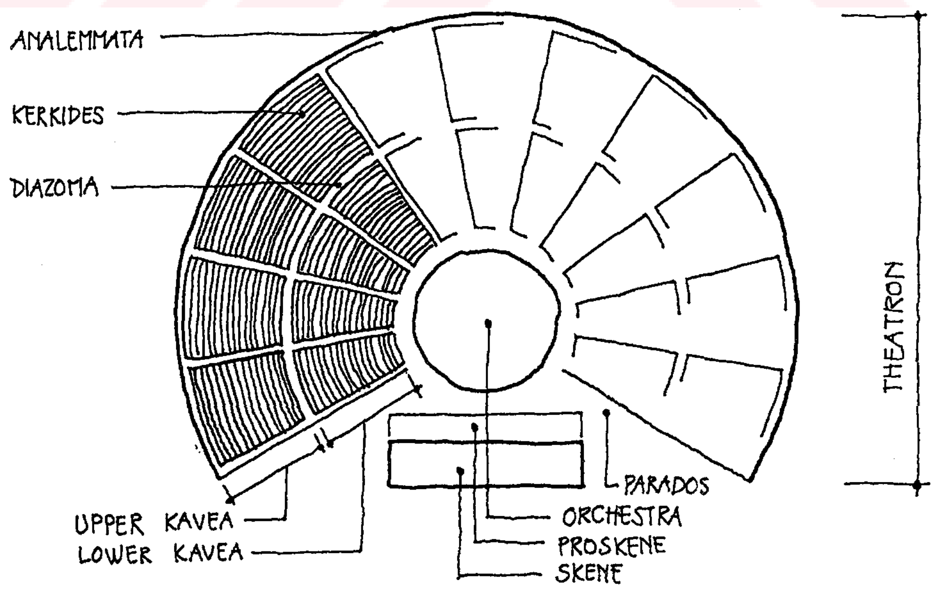


Figure 3.2 Schematic Illustration of an Ancient Greek Theatre.

Orchestra: The nucleus of the Greek theatre was its orchestra where dancing used to take place. There are different views about the earliest shape of the orchestra. The earliest Greek orchestras may have been rectangular in shape. The provincial theatre of Thorikos in Attica with its almost rectangular orchestra is a classical example (Figure 3.3). The ends of the parallel rows of seats in the theatron curve to enclose the orchestra. The orchestra is surrounded with spectators on one side, and the skene or proskenion on the other. The floor material of the orchestra might be earth, wood, marble or mosaics (Bozkurt, 1950: 11-12). The radius of the orchestra is 1/3 or 1/5 of the whole theatre building.

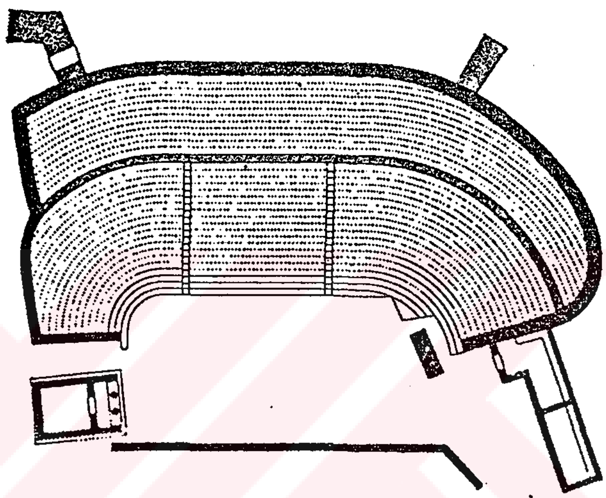


Figure 3.3 Theatre of Thorikos (Source: Bieber, 1961: 57).

Skene: Skene is the stage building which houses the dressing rooms. The materials used in the construction of the skene are wood, stone and marble (Bozkurt, 1950: 15). Proskenion is located, with its 3-4 m height, in front of the skene. The actors used to act in the proskenion. Proskenion was the stage in the sense of modern theatre terminology.

Theatron: Theatron is the place for spectators. Stairs divide the theatron into smaller parts. These parts are known as kerkides. The theatron is also divided in the horizontal plane by a corridor called diazoma. These divided areas constitude the cavea (Figure 3.2). (Technical terms are defined in Appendix B).

Ancient theatres can be classified in three groups according to their chronological and typological characteristics (Bieber, 1961; Bozkurt, 1950). These are as follows:

1. Classical theatre building
2. Hellenistic theatre building

3. Graeco-Roman theatre building and purely Roman theatre building.

The Roman theatre building follows on from the Greek tradition. For this reason, it is sufficient to indicate only the differences between the Greek and Roman theatre buildings after explaining the structural characteristics of the Greek theatre building (Figure 3.4).

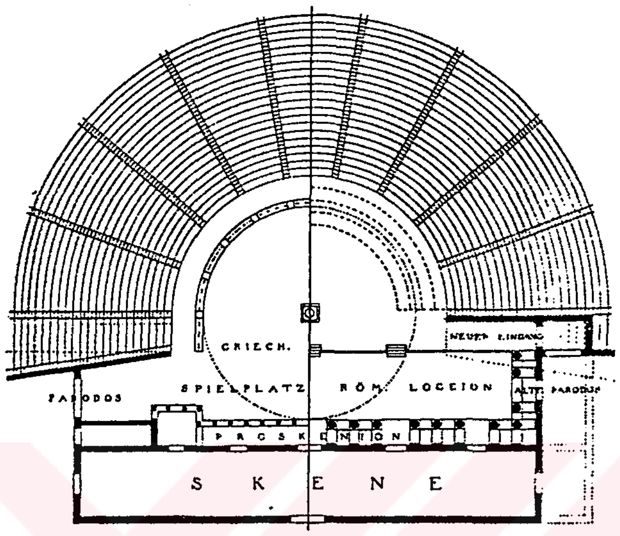


Figure 3.4 Differences between the Plans of the Greek and Roman Theatres, Dörpfeld (Bieber, 1961: 188).

The most important characteristics of the Greek- Hellenistic and Roman theatre building may be outlined as follows (Bieber, 1961: 189):

1. The orchestra is a circle in the Hellenistic type and the auditorium is horse-shoe in shape. In the Roman theatre the orchestra and auditorium were reduced to a semi- circle.

2. The depth of the stage was increased because the orchestras in the Roman theatres contained seats for senators.

3. In the Hellenistic theatre proskenion is decorated by columns. However a proskenion decorated with niches and a permanent scaenae frons is developed in the Roman theatre.

4. The auditorium, the stage building, and the orchestra are all separated in the Hellenistic theatre. In the Roman theatre the auditorium was supported by a substructure of barrel-vaulting.

everybody, but the Roman theatre has different seats for different classes in society.

6. Although the Greek performances are literary events, the Roman performances are for public entertainment (tragedy versus atellana, etc.).

7. Hillsides are preferred by Romans and Greeks, but this was not possible everywhere. Especially in large cities, Romans built theatres on level ground. Consequently, the structure of the cavea was developed.

Most of the theatres in Asia Minor are the typical examples of the Roman period. Some of them are Side, Sagalassos, Patara, Myra, Tralles and Aspendos. Priene is the classical example of the Hellenistic theatre building. Ephesus and Great Theatre in Acropolis in Pergamon are other examples of the Hellenistic type.

A historical survey for ancient open-air theatres in Asia Minor has been put together in order to define their locations, capacities and conditions (e.g. state of preservation). Compilation of such data is very important as far as the acoustical measurements are concerned.

The identification and classification of ancient open-air theatres were completed before the selection of theatres for measurements and simulations was performed. The results of this investigation given in Table 3.1 indicate that the number of theatres exceeds that of odea and that they are in better condition.

Consequently, it was decided that the work would be carried out on theatres for speech. In our time the functions of open-air theatres are both for speech and music. The theatres of Side, Aspendos, Perge and Termessos were selected for measurements. Side, Aspendos and Perge theatres are the examples of Roman theatre building in Pamphylia. Termessos theatre is a well-known example of the Hellenistic period in Pisidia. However, acoustical measurements could not be performed in Side theatre because of background noise which propagates from the bus terminal and parking area near the theatre.

A short history of Pamphylia and Pisidia and selected theatres (e.g. Aspendos, Perge and Termessos) is given in Appendix A.

Today, the open-air theatre design has followed the ancient design tradition. There is a large demand for open- air theatres in the world. Some contemporary examples of such theatres are given by Bozkurt (1950: 79-119). There are also some contemporary examples of

Table 3.1 Ancient Theatres in Asia Minor (1).

Name	Location	Period	Seating Capacity (2)	Condition (3)
TROY (Troy)	Hisarlık	Roman	D	-
ASSOS		Roman	B	***
NIKAIA	Iznik	-	B	-
PERGAMON	Bergama			
.Great Theatre		Hellenistic	A (10.000)	******
.Roman Theatre in Asklepieion		Roman	B (3500)	-
.Small Theatre in Middle City		Roman	D (Max. 1000)	-
.Amphitheatre		Roman	-	**
.Roman Theatre		Roman	-	**
AIZANOI	Çavdarhisar	Roman Period Hellenistic Type	B	-
NYSA	Sultanhisar	Roman	B	******
EPHOSOS				
.Theatre	Selçuk	Hellenistic+Roman	A (24.000)	******
.Odeion	Selçuk	Roman	C (1400)	******
MAGNESIA on the MEANDER				
.2 Theatres		Unknown		
.Odeion			-	**
PRUSIAS AD HYPIUM		Roman	B	**
PRIENE		Hellenistic	B	******
MILETOS		Hellenistic+Roman	B (5.300 in the Hellenistic Period) A (15.000 in the Roman Times)	******
ALINDA	Karpuzlu	Hellenistic+Roman	B	***
ALABANDA	Araphisar	Greek Type Hellenistic+Roman	B	***
HERACLEA under LATMOS		Roman	-	*
APHRODISIAS	Karacasu-Geyre	-	A (10.000)	-
HIERAPOLIS	Pamukkale	Hellenistic+Roman	B	******
TRALLES	Aydın	Roman	-	**
LAODICEIA AD LYCUM .(2 Theathers + Odeion)		.Large Theater Greek	-	-
		.Small Theater Roman	-	-
IASOS	Kıyı Kışlacık	Roman	B	******
HALIKARNASSOS	Bodrum	Greek+Hellenistic (4th century B.C.)	A	******
STRATONIKEA	Eskihisar	-	B	-
KAUNOS	Dalyanköy	Roman	B	******
KNIDOS (2 Theatres)	Reşadiye burnu	-	B (Large Theatre)	-
CEDREAI	Şehir Adası	-	D	***

Table 3.1 (Cont.)

Name	Location	Period	Seating Capacity (2)	Condition (3)
PINARA	Minare			
.Theatre		Greek	B	****
.Odeion		Roman		****
XANTHOS	Kınık	Roman	B	******
ANTIPHELLOS	Kaş	Greek	B	***
TLOS	Düver-Kaleasa	Roman	B	******
BALBURA		Roman	C	***
NISSA	Sütleğen	-	D	-
THEIMIUSSA	Kaleköy	-	D	-
TELMESSOS		Roman	-	*
PATARA		Roman	-	****
LETOON	Bozoluk	Roman	B	**
LIMYRA	Yuvalılar Turunçova	Roman	B	***
TEOS	Sığacık	Greek	-	**
MYRA	Demre	Roman	B	****
PHASELIS	Tekirova	Roman	B	****
KYAENAİ	Yavıköy	Roman	B	***
OENOANDA	İncealiler	Roman	B	****
KADYANDA	Üzümlü	Roman	C	***
RHODIAPOLIS	Hacıveliler	Roman	B	**
APOLLONIA	Kılınçlı	-	D	-
ARYKANDA	Arif	-	B	-
TERMESSOS	Güllükdağı	Greek Type Hellenistic	B (4.200)	****
PERGE	Aksu	Graeko-Roman Type	A (15.000)	*****
SIDE	Side	Roman	A	******
SAGALASSOS	Ağlasun	Roman	A	****
ASPENDOS	Belkıs	Roman	A	******
KREMMA	Girmeği-Çamlık	-	B	-
KIBYRA	Gölhisar	Roman	A	***
SELGE	Zerkköyü	Roman	B	****
ELAIUSSA SEBASTE	Ayaş-Silifke	Roman	B	***
OLBA-DIOCAESAREA	Uzuncaburç	Roman	B	-

1. Some information was provided by Prof. Dr. Cevdet Bayburtluoğlu during the preparation of the table.
2. Seating Capacities: A ..... more than 8000
B ..... 8000 - 3000
C ..... 3000 - 1000
D ..... less than 1000
3. Conditions: ****** Well-preserved
***** Measurements can be performed
**** If it is cleaned measurements can be performed
*** Skene (stage building) is not in a good state or nonexistent
** Buried
* Only location is visible

are given by Bozkurt (1950: 79-119). There are also some contemporary examples of open-air theatres in Turkey. One of them is in the Seymenler Parkı in Ankara and the other one (Açık Hava Tiyatrosu) is in İstanbul. In Turkey, especially in the south and west there are opportunities for the use of open-air theatres for at least 8 months because of suitable climatic conditions. There is a trend to build open- air theatres in holiday villages. The experiences gained through ancient practice should be exploited in the acoustical designing of modern theatres. In the new open-air theatre of the citadel in Antalya, the stage building (skene) is non-existent while there many examples from ancient periods surrounding the town. It should be noted that the stage building is very important factor on the reflection of sound waves.

Ancient theatre building is the origin of all open or closed contemporary theatre buildings. The development of the theatre building according to their shapes is discussed by some scholars. Theatres are classified by Mielziner (1969: 6; 1970) and Silverman (1965) with respect to their forms. Authors agree that there are two main forms which are open stage and proscenium stage.

According to Mielziner (1969: 7) theatres can be classified as follows:

1. Open Stage
   Elizabethan Stage
   Three-sided Arena
2. Proscenium Stage
   Picture-frame Stage
3. Center Stage
   Two-Sided Arena
4. Theatre-in-the-Round
   Arena Stage
5. Hybrid Stage
6. Thrust Stage
7. Multiform Theatre
   Adaptable Theatre
   Flexible Theatre
8. Multipurpose Theatre

Open-air theatres are the typical examples of open stage.

3.2 Architectural Development of the Odeion / Concert Hall

In Roman times many small covered theatres were built for musical performances and recitations; they were called odeion or odeum. The name odeion (Greek) ,odeum (Latin), is derived from ode, song (Bieber, 1961: 220). The oldest known odeum was built by Pericles near the theatre of Dionysus at Athens. Odea were often built in the vicinity of larger theatres. They are distinguished by the rectangular form of the outer walls which carry a roof, and they are always smaller than the open-air theatres. There are examples of combinations of theatre and odeum as in Aspendos in Pamphylia, at Termessos in Pisidia (Figure 3.5) and Sagalasssos.

Another well-known concert hall is the odeum of Agrippa. It was built in the market-place of Athens. The odeum must have been erected around 15 B.C. for Agrippa visited Athens in 16 and 14 B.C. It has been excavated by American archaeologists and a model of it was prepared by Homer Thompson (Bieber, 1961: 221). (Figure 3.6, Bieber, 617-619)

The council-house (bouleuterion) could occasionally be used for musical recitals. There are examples of such uses in Asia Minor. For instance, the bouleuteria of Miletos and Priene were used as odea (Bieber, 1961: 221).

In both the ancient written sources, as well as in the interpretation of the archaeological remains, there is a dilemma concerning the designation of some buildings as odea and bouleuteria. For example, the odeum of Termessos is considered to be a bouleuterion in some sources.

The odeum of Termessos is the city's second but indoor theatre. It is a rectangular hall with walls climbing to a height of 10 meters. The width of the inner hall is 22.4 m., and the wall thicknesses are 1 m. the wall is split into two halves by a belt. The lower half is plain, but the upper part has gained vitality through the use of vertical reliefs. There are windows in the southern and eastern walls. Even though none of the walls survive in their full height, these walls are nevertheless an example of a very advanced technique of wall construction, back in the first century B.C. The odeum seats 600. The entrance was to the west. It was a terrace 6 m. above the foundations of the building. There is an opening from this terrace to the upper levels of the building. The odeum has two doors facing east. Their thresholds are 7 m. lower than those on the west. The seats indicate that the structure had a roof. However, no one has yet figured out how a roof could have been put on a building having a width in excess of 20 m. The odeum's walls were covered with colorful mosaics; this can be deduced from the colored pieces among the debris.

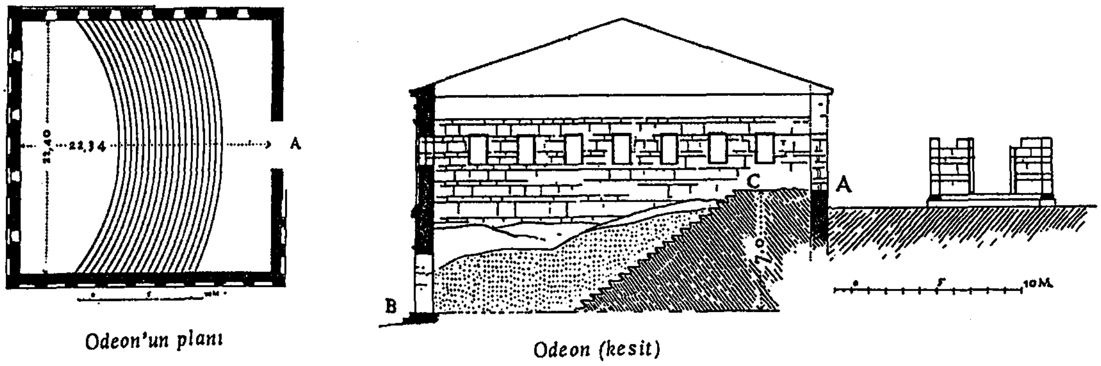


Figure 3.5 Odeum of Termessos (Source: Termessos Milli Parkı, Uzun Devreli Gelişme Planı, 1970, p. 26)

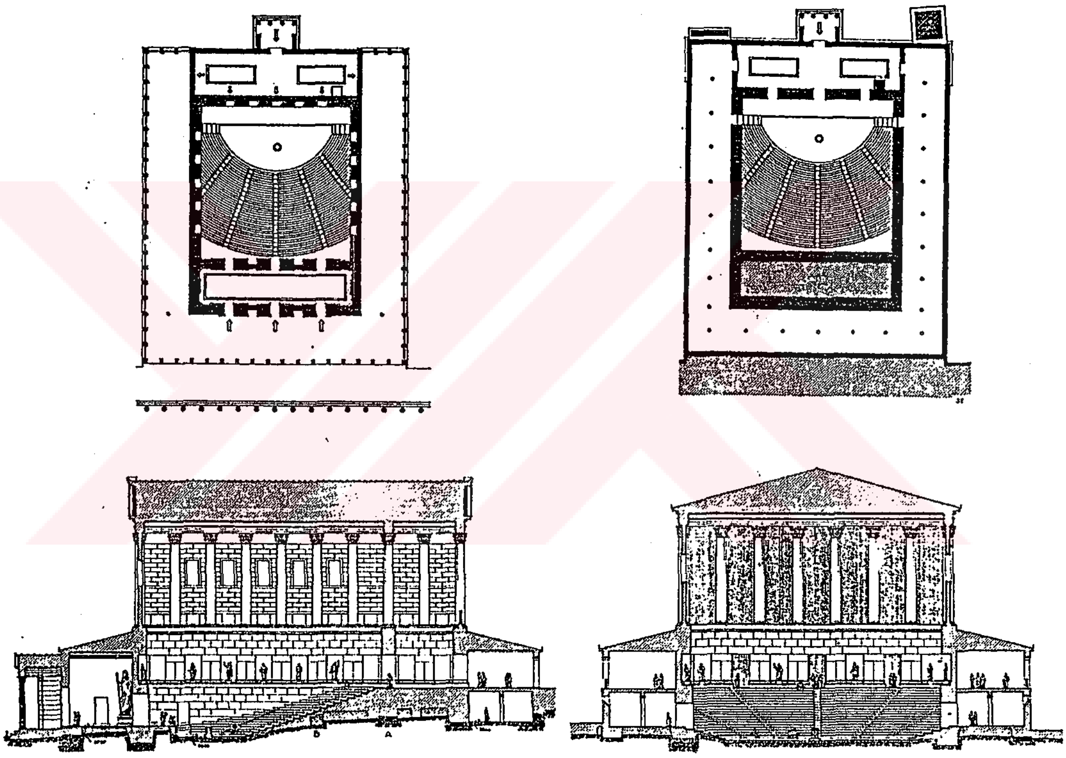


Figure 3.6 Odeum of Agrippa in the Agora of Athens (Source: Bieber, 1961: 176)

The odeum of Ephesus is located to the north of the agora. It resembles a small theatre. Therefore, it is also known as the small theatre. According to the inscription unearthed, it was built as a bouleuterion around 150 by Publius Vedius Antonius and his wife Flavia Papiana (Erdemgil, 1992: 41-44).

Built on the skirts of Panayır Dağı, the structure consists of three main components which are found in all other theatres as well; the cavea, the orchestra and the skene. The semi-circular cavea is divided into two parts by a diazoma in the centre. The marble seats exhibit good quality craftsmanship and most probably, the skene was two storeyed. There is a narrow marble podium just in front of the skene where five doors open on to the podium. The door in the middle is taller and wider than the others. The orchestra is semi-circular. The fact that there are no gutters for rain- water in the centre of the orchestra indicates that the odeum was roofed.

The odeum seated 1400. Spectators entered either through the paradoi (side entrances between the stage and auditorium) or through the galleries which were reached by the vaulted roofed staircases at the entrance of the paradoi. The building was used as an odeum during concerts and as the bouleuterion during the meetings of the boule, or town- council.

The bouleuterion of Aspendos is on the north side of the agora, with a square plan at the front, and semicircular at the back. Conglomerate blocks were used for the whole structure, while repairs were carried out in rubble and cement. The walls were strengthened by columns on the inside. Beyond the front entrance, there was a platform for speakers, then an altar, and then the auditorium. The holes in the walls indicate that the roof was made with wooden beams. In some sources this building is described as an odeum. Since there is no other building of such a type at Aspendos, this one might have been used for both purposes. This is true for several ancient cities at that time. This implies a building of second or third century construction.

The other odea in Asia Minor are in Anemurium, Aphrodisias, Laodiceia ad Lycum, Pınara, Teos and Cretopolis in Pisidia. The odeum in Anemurium is well-preserved. Another very well-preserved odeum was discovered in 1962 in Aphrodisias. Its sunken orchestra and stage were elaborately decorated with mosaics and statuary (Akurgal, 1978: 174). The odeum had more rows of seats than are now visible. The upper tiers collapsed in antiquity and a backstage corridor opened on to a porticoed area, decorated with handsome portrait- statues of prominent Aphrodisians and was connected with the agora. The odeum of Pınara was built in Roman times. It is also well-preserved. The odeum of Teos (a roofed theatre), lying south-east of the Greek theatre and north-east of the sanctuary of Dionysus, is a well-preserved structure of the Roman period.

The odea were concert halls in the modern sense. However, the design of concert halls is very complicated today. The contribution of both architects and acousticians is necessary for a good design of a concert hall.

CHAPTER 4
ACOUSTICAL DESIGN PARAMETERS

4.1 General

The word 'acoustic' (Greek 'akoustikos') is defined as relating to the sense or organs of hearing, to sound, or to the science of sounds. Webster's dictionary explains the word 'acoustics' as a science that treats production, control, transmission, reception and effects of sound and the phenomenon of hearing.

Architectural acoustics can be defined as the study of the generation, propagation and transmission of sound in rooms and buildings. The subject was considered to be a pure art form before the turn of the twentieth century. In the beginning of the century, an American scientist Wallace C. Sabine (1922) laid out the basic groundwork that led to a substantial research activity still ongoing through modern times.

There are two main branches of architectural acoustics. Room acoustics deals with generation and propagation of sound in enclosed spaces. Selection of room geometry, placement of absorptive and reflective surfaces, and arrangement of acoustical parameters to achieve certain results are typical applications of this field. The other main branch of architectural acoustics known as building acoustics is concerned about transmission of sound, especially in the form of noise, through physical boundaries of enclosed spaces.

Several methods have been developed to analyze sound fields inside enclosed spaces. Among these methods, geometrical room acoustics, modal analysis and statistical energy analysis are well-known methods.

4.2 Geometrical Room Acoustics

Geometrical room acoustics approach has been selected here for analyzing the acoustics of ancient theatres. Simulation methods using this approach are explained in the next chapter. Methods of image sources and ray-tracing have been employed for simulation purposes to obtain impulse response and speech intelligibility characteristics.

The impulse response shows the echoes present in the enclosed space. Also, it can be used to determine the reverberation time. Information on location with echoes is very important to characterize the acoustical properties of spaces in architecture.

Noticeable echoes, dead spots and flutter are important design parameters of the spaces for musical performance. There should not be such obvious faults in open-air theatres. If the reflected sound comes to the listener's ear delayed long enough (50 milliseconds or more for open-air theatres), the ear will register this reflected (or indirect) sound as an echo. Dead-spots are the areas that receive very little sound energy because of the audience absorption and absorption by building components. Flutter is the phenomenon caused by trapping of sound between two parallel, hard reflecting surfaces. Sound will be reflected back and forth between such surfaces and decay very slowly.

4.2.1 Acoustical Response

Acoustical response of enclosed spaces can be represented in terms of transient and steady-state response characteristics. Transient response of an acoustic medium has been described by the reverberation time. Recently, impulse response obtained from reflection patterns of sound waves has been used to characterize the transient behavior. The steady-state part of the response can be obtained by summing up the sound energy of direct and reflected sound at a selected receiver position.

4.2.1.1 Reverberation Time

The principal acoustical design parameter of a room or auditorium is the reverberation time. At the beginning of this century W.C. Sabine carried out a considerable amount of research on the acoustics of auditoria and arrived at an empirical relationship between the volume of the auditorium, the amount of absorptive material with in the auditorium and a quantity that he called the reverberation time. This relationship is known as the Sabine formula:

$$RT = \frac{0.161\,V}{A} \quad s$$

where RT is the reverberation time defined as the time taken for a sound to decay by 60 dB after the sound source is abruptly switched off; V is the volume of enclosed space in m^3, and A is the total absorption of the enclosed spaces in m^2 Sabins.

In the open-air spaces such as ancient theatres, reverberation time is not a very important design parameter because of the absence of reflecting surfaces like ceiling structure and side walls. These openings can be considered to be covered by the material that has the highest value of absorptivity in simulation studies.

4.2.1.2 Speech Intelligibility

Speech intelligibility is an important design criterion of spaces for speech. The intelligibility of speech in an enclosure depends mainly on the reverberation time of enclosure, the background noise present, and distance between source and receiver. When the reverberation time, background noise and the distance, increase speech intelligibility decreases. Speech intelligibility can be calculated directly from the room characteristics and geometrical room acoustics methods.

In the theatres for speech the audience desires to understand all words spoken by the actors. The understanding of speech depends on the sound power of the source and its clarity. The listening ability of the audience is an important factor as well as the clearness of the actor.

Directional relationship between speaker and listener should be considered because human voice is directional. Knudsen (1978: 64) prepared 'equal intelligibility contour' in accordance with the directional relationship of speaker to listener. At any point on the contour the speech intelligibility is equal (Figure 4.1).

If the contour is given in dimensional scale, the value of SA is 30 meters as the limit of the acceptable intelligibility without electronic amplification. Clarity of voice and correct enunciation were more important than a strong voice, as splendid acoustics in the Greek and Roman theatres let spoken words and songs reach the uppermost row.

It is known that actors were trained to use their voice as the most important part of their professional equipment. In the Greek theatre, the actor could always rely upon being heard. It is sometimes held that the actor's mask contained a built-in megaphone to protect the voice. This is merely hypothetical. Later authors report other devices (Arnott, 1971: 29-40). Actors became adept at bouncing their voices off the wooden panels of the skene.

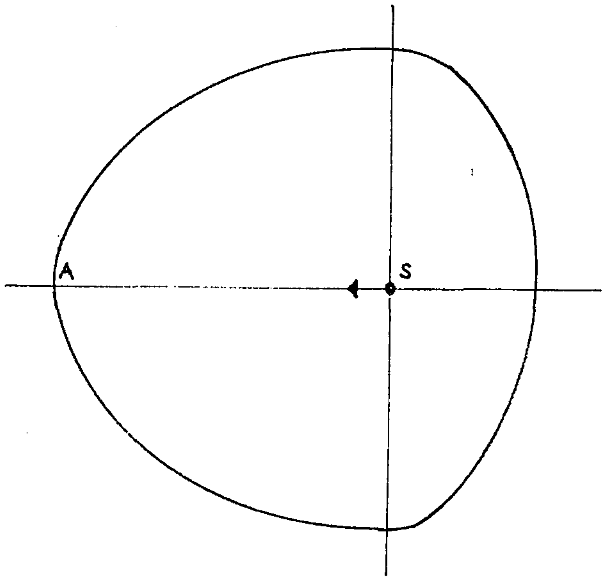


Figure 4.1 Equal Intelligibility Contour. The Speaker is Facing in the Direction of the Arrow. (Source: Moore, 1978: 144)

There are basically four factors which affect the clarity of speech. Firstly, there is the background noise that can mask the desired sound. This level should be kept below 30 dBA. Secondly, there is the sound pressure level produced at the listener's ear by the speaker. This depends on the distance between the listener and the speaker, the volume of the enclosure, and the nature of the speaker's surroundings. Thirdly, there is the reverberation time. In normal speech the syllables follow each other with rapidity. Unless each syllable decays fairly quickly it will tend to mask those following. Therefore the reverberation time must not be too long. On the other hand, if the reverberation time tends to zero then the absence of reflecting components severely restricts the size of an enclosure in which the speech will be heard at a sufficiently high intensity for good intelligibility. On the average, the duration of a syllable in speech is 1/5 s and the gaps between words about 1/3 s. If a speaker calls about 1000 meaningless speech sounds and the listener hears 850 of them correctly, the percentage syllable articulation is 85 per cent. 85 per cent represents very good hearing, 75 per cent is satisfactory and 65 per cent is acceptable value (Knudsen, 1978: 63). Lastly, there is the room shape. The golden dimensions with the removal of troublesome areas such as dead-spots and echoes will, most likely, give satisfactory results.

In a series of studies an objective measure for speech intelligibility termed as the Speech Transmission Index (STI) was developed. Both ray-tracing method and method of images can be used to estimate STI. Nowadays intelligibility can be measured by modern equipment as objective values. In this context, RASTI (Rapid Speech Transmission Index) is a newly developed technique to serve this purpose.

4.2.2 Effects of the Theatre Geometry

The shape and the slope are important acoustical criteria while designing open-air theatres. The form of the theatre affects normalized average distance. Sloping the seats upward affords beneficial acoustically.

4.2.2.1 Acoustical Designing for Direct Sound

It is important to set up design principles for direct sound, especially, in open-air theatres. The shape of the open-air theatre affects the normalized average distance (Çalışkan, 1984). This measure is equal to the ratio of the average distance of all listeners from the sound source to the square root of area occupied by the audience. The semi- circle shape of ancient theatres is the most suitable form to reduce normalized average distance (Figure 4.2).

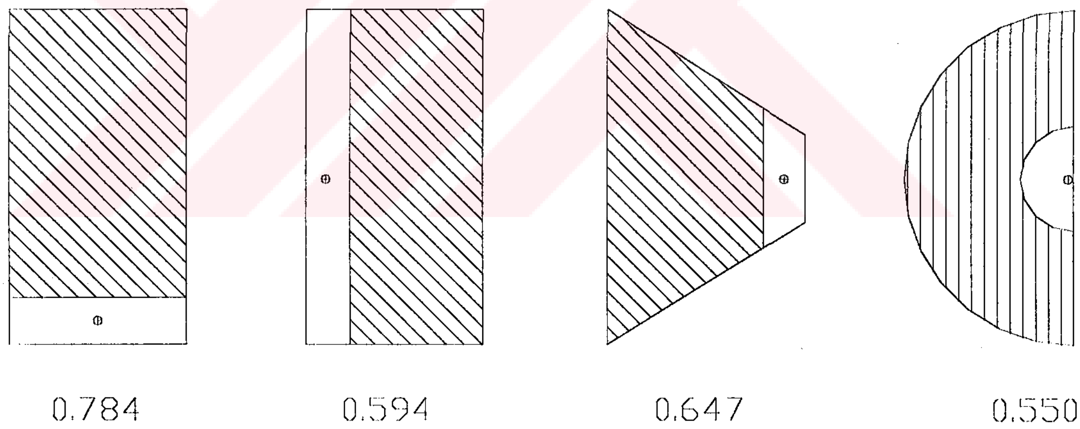


Figure 4.2 Normalized Average Distance Figures for Different Shapes

4.2.2.2 The Slope of Open-air Theatres

Another design parameter for direct sound is related to limit the attenuation of the direct sound due to grazing propagation over the audience. Sloping the seats upward proves beneficial especially if the clearance between a sight line and the head of a listener immediately ahead is kept the same for all seats. A practical value of this clearance is 0.1 meter. In other words, in order to provide a good visibility and sound propagation, the inclination of the theatre should be 12 degrees in the seating area. Figure 4.3 shows the reduction of direct sound attenuation by sloping the seating area.

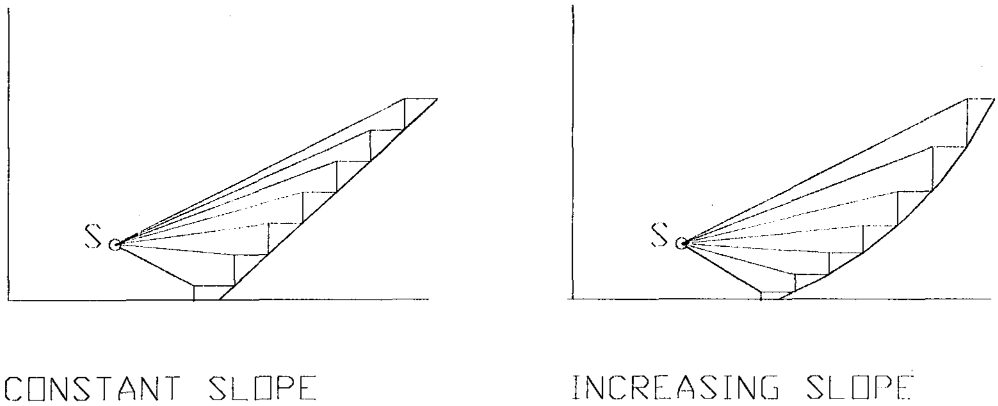


Figure 4.3 Reduction of Direct Sound Attenuation by Sloping the Seating Area.

Ancient Greeks and Romans built their theatres on the hillsides. They knew the effect of the slope on acoustics of open-air theatres. As stated by Vitruvius, the selection of the site was a very important criterion in the design of theatres. The inclination of the some ancient theatres (in degree) are as follows (Canac, 1967: 35):

Table 4.1 The Inclination of some Ancient Theatres

	Before Diazoma	After Diazoma
Aspendos	30	38
Epidaure	23	27
Orange	27.3	31
Vaison	29	29
Herode Atticus	31	31.25
Miletos	30.3	30.3
Pergamon	33.3	-
Perge	32	35
Side	32	35
Dionysos	21	-
Erytrie	17	-
Segeste	30	-
Delphes	27	-
Argos	25	27

The hearing angle developed by Canac (1967) depends on the slope of the theatres. Hearing angle, ε, is defined as the angle between the reflected path of the sound wave (to the receiver, ear level of audience, through image of source) and the inclined surface of auditorium that depends declination angle of cone or its complements, ω ,(Figure 4.4).

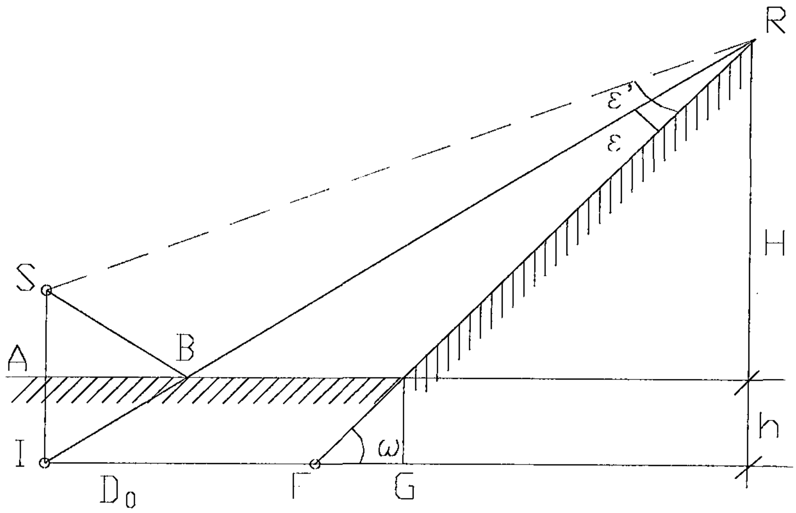


Figure 4.4 The Relation between the Elements of an Ancient Theatre (Source: Canac, 1967: 104).

Sound waves from the source to the receiver should not be obstructed and absorbed by the audiences sitting on lower benches. For this reason hearing angle should be as high as possible (greater than 4 degrees). The canonical equation derived by Canac is given by

$$(D_0 - h \text{ cotg } \omega) / \sin \varepsilon = (D_0 + H \text{ cotg } \omega) / \cos(\omega - \varepsilon) \sin \omega$$

where D_0 (IG) is the length between the source and the first row of the auditorium, H is height of receiver location

$$h = h_0 + 1.60$$

where h_0 is the height of stage, and 1.60 m is the approximate height of the actor's mouth level.

When, ε, hearing angle, increases, h_0 decreases. In Epidauros theatre, ε is calculated to be 5 degrees for h_0 = 3.60 m. This value is reported not to be sufficient for good vision of this particular row. In Aspendos, the hearing angle is 17 degrees in front of the diazoma and 15 degrees immediately after the diazoma. This is a very important characteristics of Aspendos theatre (Canac, 1967: 103-127).

4.3 The Propagation of Sound in Open-air

The propagation of sound in open-air depends on the topography of site, climatic conditions, size of audience and absorption of sound in air. The climatic conditions which affect the propagation of sound are wind, temperature, clouds and fog, and humidity.

The velocity of wind is less near the surface on the earth. Thus if the sound waves travel in the wind direction they will tend to bend towards the earth. If the direction is the opposite, sound waves will tend to bend upwards. If a windy site selected, the theatre should be located in such a way that the wind blows from stage to the audience. It is more preferable to select a wind-free site. If a windy site selected the theatre should be oriented in such a direction that the wind blows from stage to audience and its velocity should not exceed 10 miles per hour (Knudsen, 1978: 66).

If the temperature decreases with rising attitude, which is the usual case, the sound waves bend upwards. In the opposite case, at night, temperature inversion may occur, and sound waves bend downwards.

Clouds and fog effects are not very important factors while analyzing the sound propagation in open-air because sound waves strike the cloud or fog bank at nearly grazing incidence. Then, sound waves may change their directions. Although, this case is not very often, such reflections may become a factor in the acoustics of open-air theatres (Knudsen, 1978: 62).

Sound loses part of its energy as a wave motion when it travels through the air. The attenuation of sound waves is related to the square of the frequency of the sound wave, relative humidity and the temperature. Humidity effect is noticeable at large distances and at higher frequencies. The attenuation increases with temperature.

While calculating the total difference in sound levels between front and back rows of the open-air theatre the losses due to divergence of sound waves, the bending of the waves and absorption by the surfaces nearby should be considered. These total losses are generally very large and they become the main factor as the limitations on the size of open-air theatres with respect to heat absorption and radiation. (Knudsen, 1978: 59-61).

Absorptive surfaces and the size of audience affect the propagation of sound in open-air theatres. The sound reaching the audience is greatly influenced by the surface in between, and the seated audience. Absorptive surfaces cause attenuation of sound and decreasing of the sound intensity. The source should be located so that the audience sitting in the lower row should not obstruct the audience back row.

The topographical, climatic and acoustical characteristics should be considered while selecting the sites of open-air theatres. In this respect, the most important factor is the quietness. The ancient Greeks and Romans had the advantage that interfering external noises (such as traffic noises) were nonexistent in their time. A dense growth of trees around the theatre is beneficial to control background noises. However, the wind direction should be considered according to the noise effect to the wind.

CHAPTER 5

ACOUSTICAL SIMULATION METHODS

5.1 Geometrical Room Acoustics

Several methods have been developed to analyze the sound field inside enclosed spaces. Geometrical room acoustics and modal analysis are two widely popular methods. The modal analysis can be applied to enclosed spaces with simple geometrical shapes. The method involves the solution of three-dimensional wave equation to obtain standing wave patterns and natural frequencies. For complicated shapes the numerical burden posed could prove unfeasibility of the method.

Geometrical room acoustics has become a powerful method for analyzing the sound fields inside enclosed spaces owing to vast technical developments in solid state electronics and computers. Irregularly shaped enclosed spaces approximated with plane reflected surfaces and even open-air spaces can be analyzed by the approach with wavelength and the corresponding frequency limitation.

The geometrical room acoustics approach consists of two basic methods, namely the methods of ray-tracing and image sources. Methods associated with the geometrical room acoustics transform the sound field inside an enclosed space to a sound field in a free field. Effects of reflected surfaces are replaced by sound rays or image sources.

The acoustical properties of ancient and modern open-air theatres can be analyzed and simulated by these two different geometrical room acoustics techniques. In both of these methods, sound waves can be treated as light rays. By this analogy, sound rays are reflected from (hard) plane surfaces in accordance with the laws of reflection. In this case;

1. The incident ray, the reflected ray and the normal to the hard surface at the point of incidence lie in the same plane.

2. The angle between the incident ray and the normal of the plane of reflection is equal to the angle between the reflected ray and the normal (Figure 5.1).

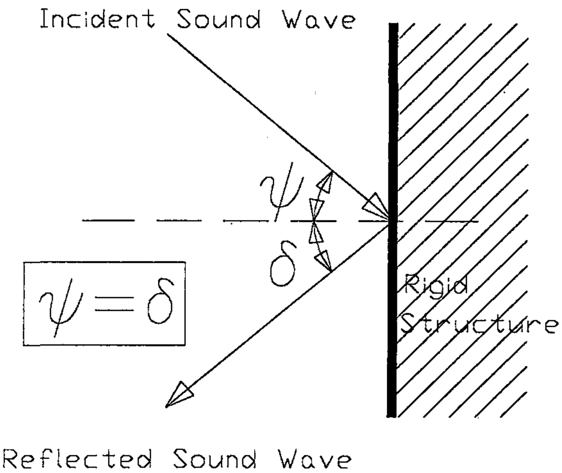


Figure 5.1. Laws of Reflection

Such geometric analogies that form the basis of geometrical room acoustics are the oldest tools of room acoustics. However, they are still in use by architects for analyzing the sound field inside acoustical enclosures and rooms.

5.1.1 Method of Image Sources

The method of image sources considers the sound energy received at a single point due to sources and their corresponding images through different reflected surfaces. With the inclusion of the imaginary source the reflecting surface is removed. The distance between the imaginary source and the reflecting surface is equal to the distance between the real source and the reflecting surface. It is assumed that the image source and the real source operate with the same phase and same frequency (Sorguç, 1990: 12-16).

Sound waves reflected from walls more than once are represented by high order image sources. First order image source represents the first reflection from the boundaries of the space. Order of image sources can be extended as much as to the extent required in the analysis. However, it was revealed that models employing image sources up to the fifth order could yield satisfactory results for totally enclosed spaces (Borish, 1984).

Ancient open-air theatres have very simple geometrical form and construction. They have a conic seating place (auditorium), circular or semi-circular orchestra, and a stage that is attached a perpendicular stage wall. For these reasons their geometry can be easily defined in order to analyze acoustical properties.

It is also possible to use image source techniques for simulating acoustic field in open-air theatres. Sound rays reflected from the orchestra and stage building have been simulated in accordance with the laws of reflection. In this simulation, single source and first order reflection have been used. The primary or first order image of the source associated with the orchestra is I_1, and it lies on the perpendicular line to the orchestra through the source, and at the same distance from the surface as the source point S (Figure 5.2). In the same way, the primary image of the source in accordance with stage building, I_2, lies on the perpendicular line to the stage building through the source (Figure 5.2).

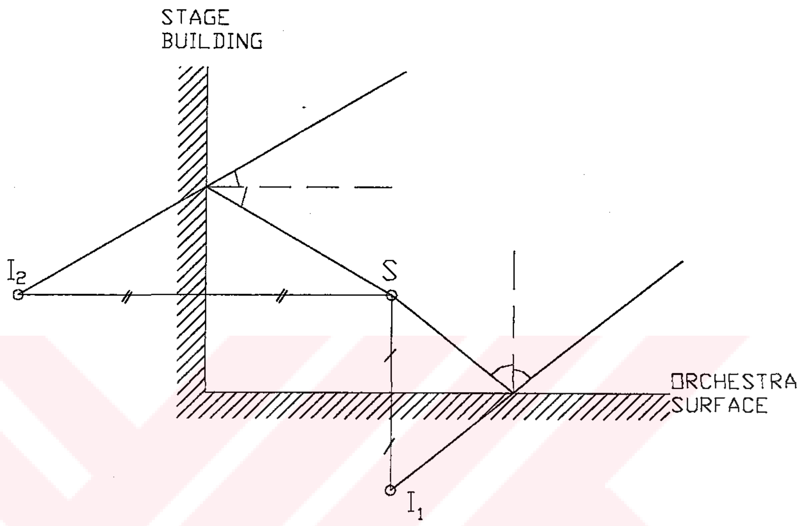


Figure 5.2. Wave Reflection from Orchestra and Stage Building

Canac (1967: 103-127) has derived "Canonical Equation of Ancient Theatres" by using the image method. He has studied the role of the hearing angle, of the orchestra and of the sound source placement on the stage.

5.1.2 Ray-tracing Method

In ray-tracing method sound waves are treated as a collection of rays originating from a point source. In order to have an omni-directional source, rays are generated in all directions. These rays are traced one by one. When a traced ray comes in contact with a reflecting surface, it is reflected back with an equal angle to angle of incidence. The receiver is usually assumed as spherical or cylindrical in shape for acoustical analysis.

The main problem of this method is to select the size of the receiver. If a small size of the receiver is specified, the possibility of a ray passing through the receiver decreases.

Conversely, if a large-sized receiver is specified rays passing through the receiver may be more than necessary.

Order of reflection is one of the termination criteria for traced rays. Usually five reflections are sufficient for many shapes of enclosures. In particular, spaces having complex forms can be analyzed by the ray- tracing method.

Another termination criterion is the distance traveled by a ray. For very long distances, sound intensity may take negligibly small values. Spaces bounded with surfaces having different absorption characteristics can be analyzed. It is certified that the absorption coefficient for most materials depends on the angle of incidence. However, this technique assumes that the absorption coefficient is uniformly distributed for angles of incidence. Perfectly absorbent surfaces will be totally ignored. With a similar assumption, openings can be considered as totally absorbent components of the space. For instance an open-air theatre can be simulated as it is an enclosed space which has a ceiling with pure absorbent characteristics.

5.2 Sound Reflections from Orchestra and Stage Building

In the case of ancient open-air theatres, there are two main reflective surfaces namely the orchestra and the stage building (skene). The analysis of the sound rays reflected from the orchestra and stage building according to geometrical room acoustics approach has been performed (Figure 5.3).

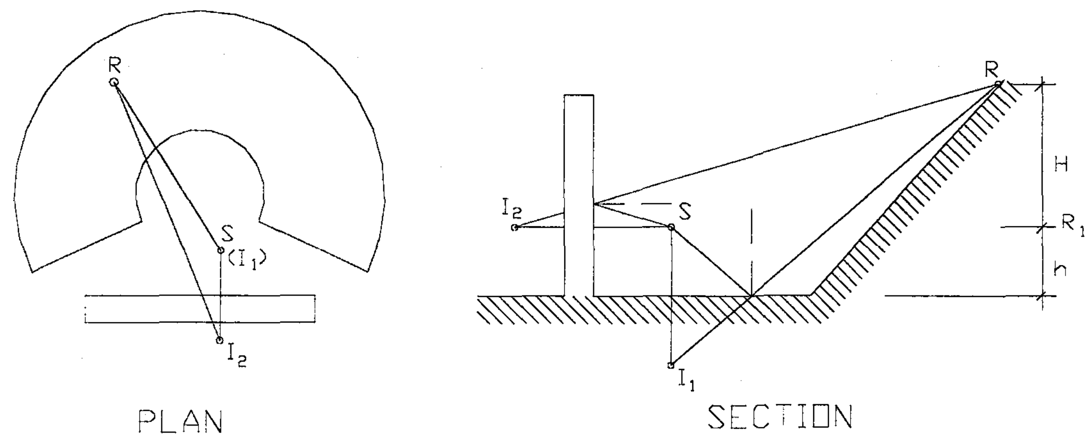


Figure 5.3 Reflections from Orchestra and Stage Building

Length differences between direct and reflected paths from orchestra and stage building are respectively;

$$d_1 = RI_1 - RS$$

and

$$d_2 = RI_2 - RS$$

Time delays between the first order reflections from the orchestra and stage building, and the direct sound are

$$\Delta t_1 = d_1 / c$$

and

$$\Delta t_2 = d_2 / c$$

respectively, where c is the speed of sound.

The difference between the direct and reflected paths from orchestra is shown in Figure 5.4.

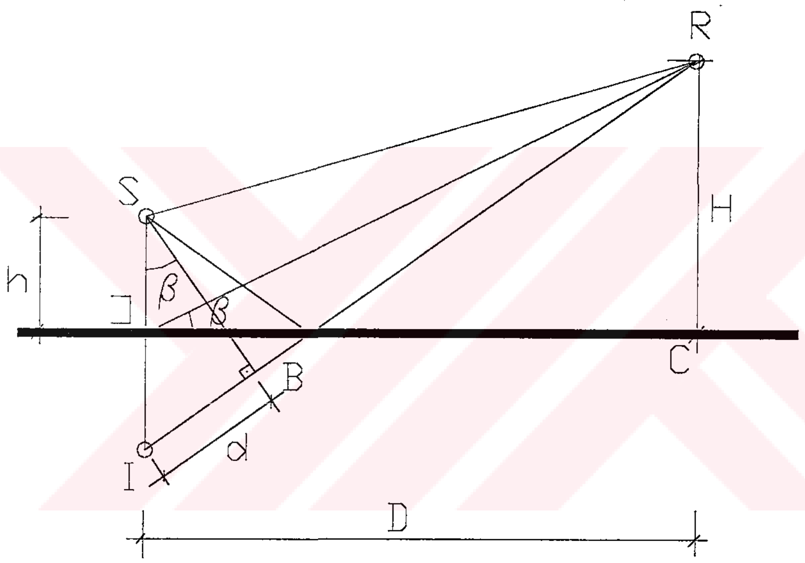


Figure 5.4 Reflection from Orchestra (Source: Canac, 1967:110)

$$d = RI_1 - RS \approx 2h\sin\beta$$

$$d/2h = H/(D^2+H^2)^{1/2} = 1/((D/H)^2 + 1)^{1/2}$$

Then, one gets

$$d = 2h*H/(D^2+H^2)^{1/2}$$

where H is height of the receiver position and D is distance between sound source and receiver.

≈

Difference in paths (d) is also estimated by using right triangles RSA and RI_1B (Figure 5.5).

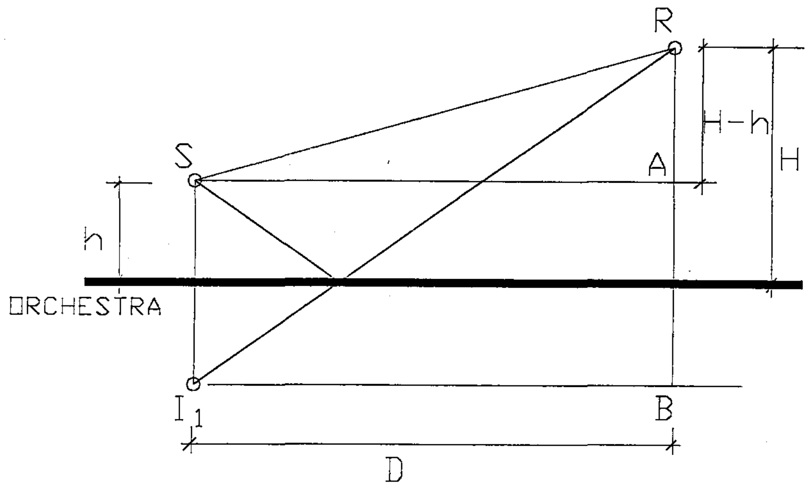


Figure 5.5 Reflection from orchestra

$$RS = ((H - h)^2 + D^2)^{1/2}$$

$$RI_1 = ((H + h)^2 + D^2)^{1/2}$$

$$d = RI_1 - RS$$

RS and RI_1 are in the same perpendicular plane to the orchestra plane.

Length differences between direct and reflected paths from stage building can also be estimated by the same method (Figure 5.6). However, in most general case the reflected path and direct path are not in the same perpendicular plane.

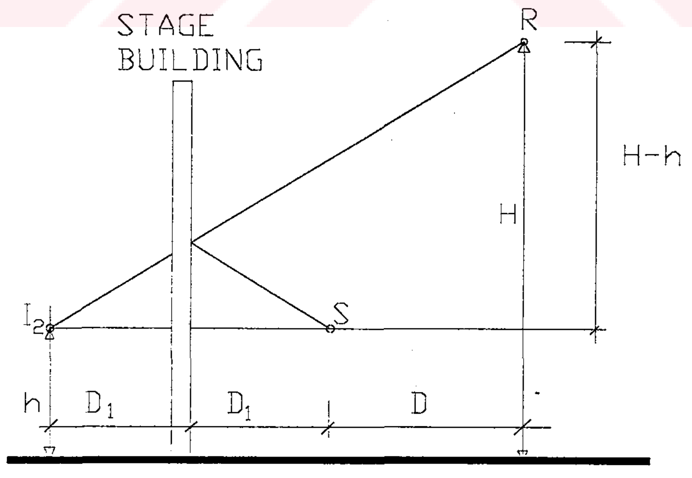


Figure 5.6 Reflection from Stage Building

$$RS = ((H - h)^2 + D^2)^{1/2}$$

$$RI_2 = ((H - h)^2 + (D + 2D_1)^2)^{1/2}$$

$$d_2 = RI_2 - RS$$

Reflected and direct paths of a sound ray form two edges of a tetrahedron for stage building reflections (Figures 5.7 and 5.8).

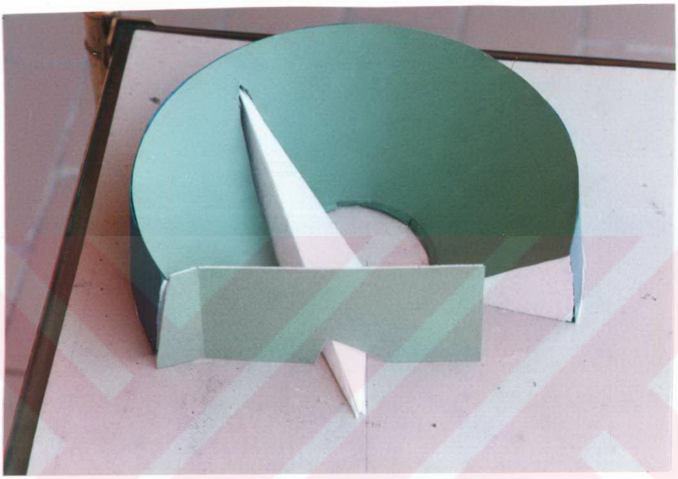


Figure 5.7 Model of the Sound Reflection from Stage Building. (Three-dimensional model of the tetrahedron of which two edges are direct and reflected paths of sound ray. Dimensions of Termessos theatre have been used in the model.)

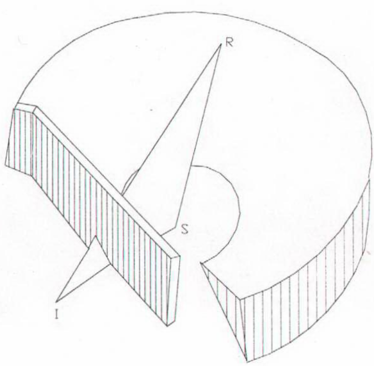


Figure 5.8 Model of the Sound Reflection from Stage Building.

CHAPTER 6

ACOUSTICAL MEASUREMENTS OF SELECTED ANCIENT THEATRES

6.1 Selection of Sample Ancient Theatres for Measurements

A historical survey for ancient open-air theatres in Asia Minor has been included in order to define their locations, capacities and conditions (Table 3.1). Compilation of such data is very important as far as the acoustical measurements are concerned. In particular, the condition of the skene building has an important role on the reflection of sound waves.

The identification and classification of ancient open-air theatres were completed before the selection of theatres for measurements and simulations was performed. The results of this investigation given in Table 3.1 indicate that the number of theatres exceeds that of odea and that they are in better condition. Therefore, it was decided that work would be carried out on theatres for speech. In our time the functions of open-air theatres are both for speech and music. The theatres of Side, Aspendos, Perge and Termessos were originally selected for measurements. The proximity of the theatres to each other and their well-preserved status are the main factors which support this selection. Side, Aspendos and Perge theatres are examples of Roman theatre building in Pamphylia. Termessos theatre is a well- known example of the Hellenistic period in Pisidia. However, acoustical measurements could not be performed in Side theatre because of background noise which propagates from the bus terminal and parking area near the theatre. A short history of theatres of Aspendos, Perge and Termessos is given in Appendix A.

6.2 Measurement Technique

Sound measurements have been conducted in these theatres by a RACAL STORE 4DS instrumentation tape recorder equipped with two FM channels. An explosive sound source located at the orchestra is used to record 8-10 explosions per receiver location. Number of receiver positions are respectively 25, 20 and 20 for the theatres of Aspendos, Perge and Termessos. Figures 6.1, 6.2, 6.3 show these measurement positions on the plans of the theatres.

The height of the receiver position from seating level was chosen 0.65 m as the approximate ear level for the audience. The recording speed is selected as 7.5 ips (inches per second). Two half-inch free field microphones (B&K 4165) with preamplifiers (Gen Rad 1560) are employed in the measurements.

For Aspendos theatre, the height of the sound source from <u>orchestra</u> level is 1.7 m for the positions A1, A2, A3, A4, A5, B2, B4, B5 and 0.1 m for other measurement positions. The location of the sound source for the Aspendos theatre is shown in the Figure 6.1. The height of source has been chosen 1.7 m in the theatre of Perge for the receiver positions at lower cavea and 1.05 at upper cavea. The location of the sound source is shown in the Figure 6.2. The height of the sound source from <u>orchestra</u> level is approximately 0.3 meters in Termessos theatre for all receiver positions. The location of the source in the measurements is shown in the Figure 6.3. Figure 6.4 shows the measurement instrumentation at the site.

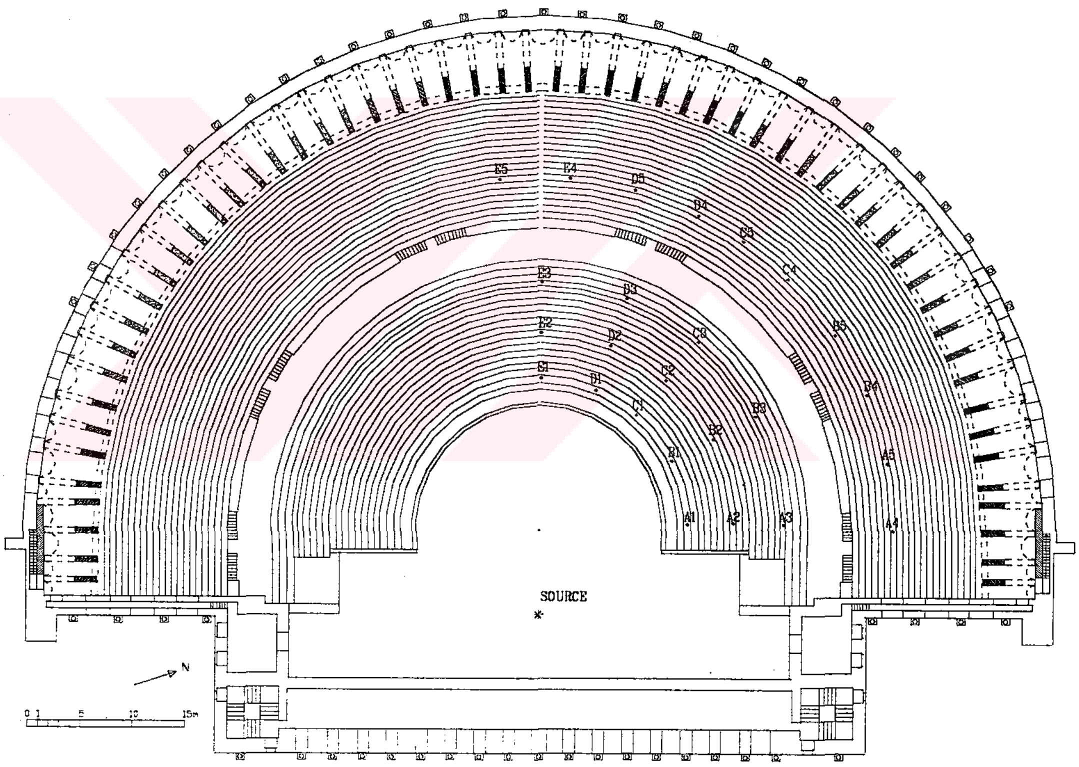


Figure 6.1 Sound Source and Receiver Positions in Aspendos Theatre (Adapted from Bernardi, 1970: Tav.XXXI).

The measurements were conducted twice in 1989 and 1990. Nearly same dates were chosen for measurements in order to establish similar climatic conditions. The dates and times of measurements for selected theatres are shown in Table 6.1.

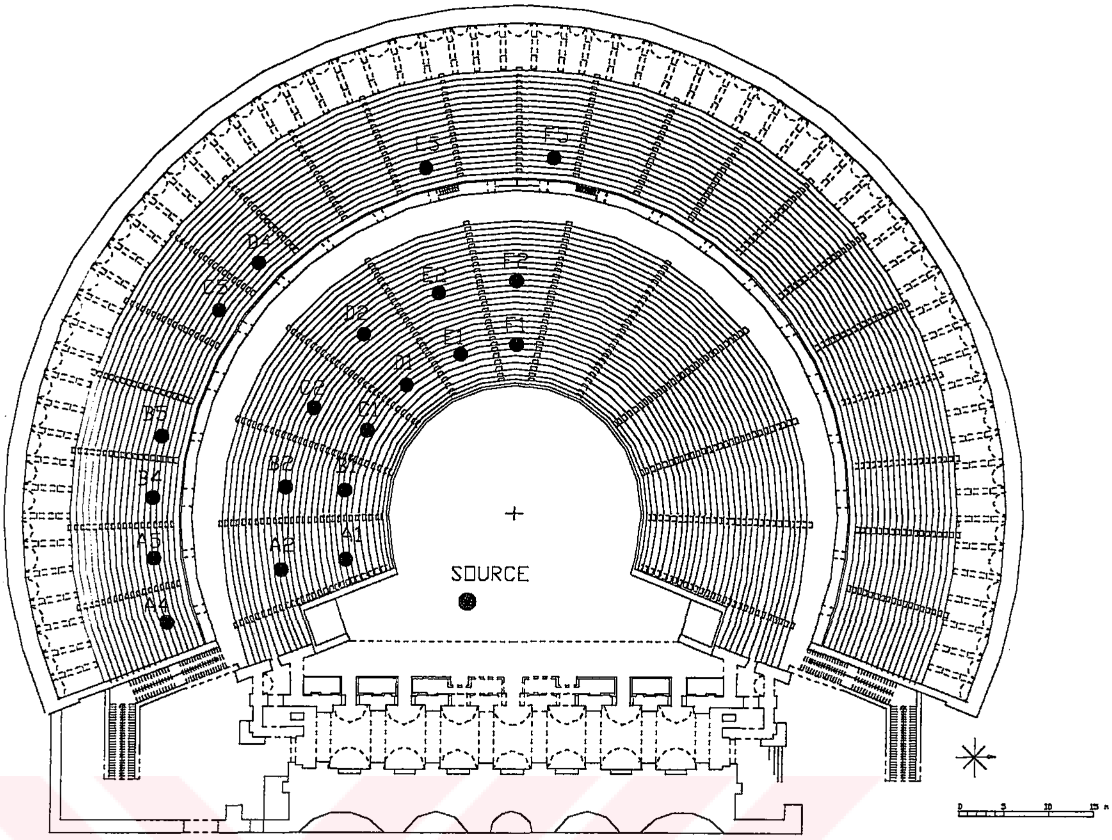


Figure 6.2 Sound Source and Receiver Positions in Perge Theatre (Adapted from Bernardi,1970: Tav.XXVIII).

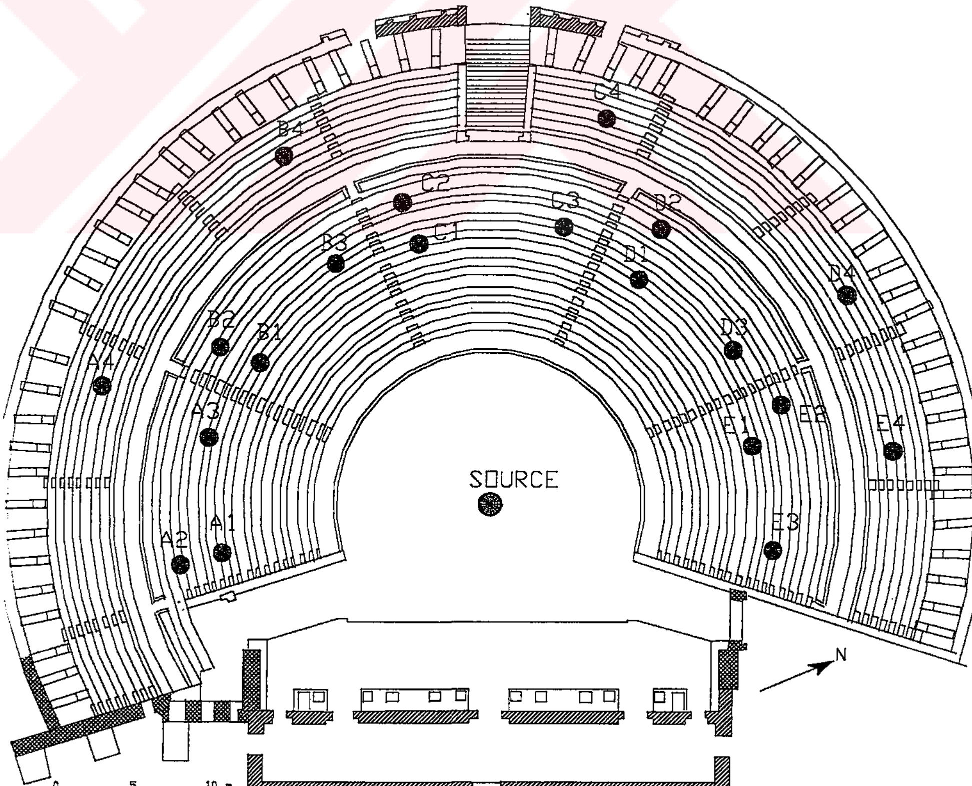
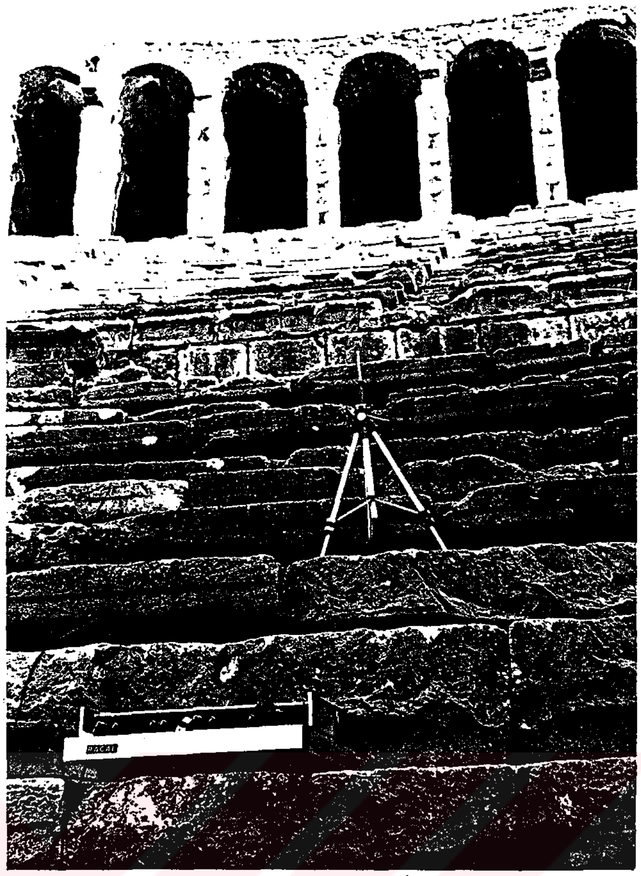
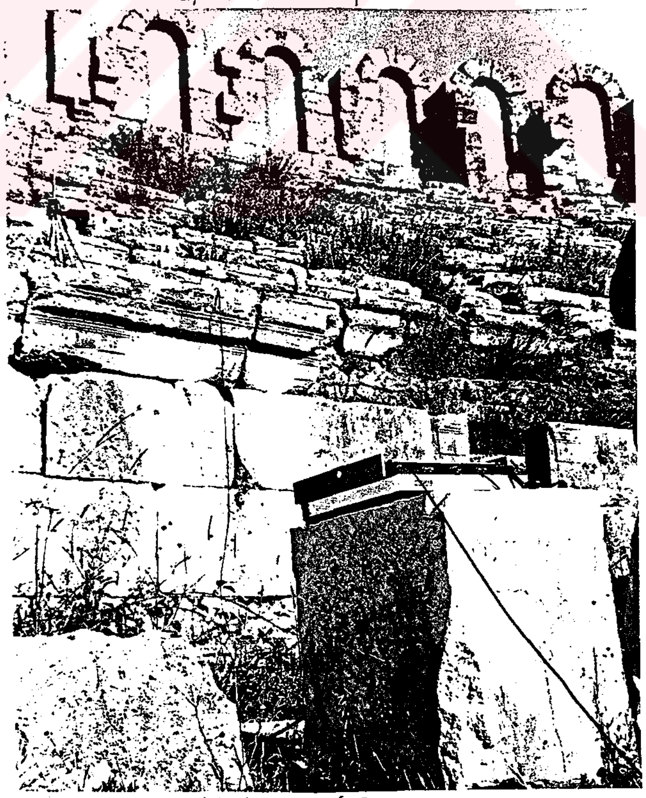


Figure 6.3 Sound Source and Receiver Positions in Termessos Theatre (Adapted from Bernardi, 1970:Tav.I).



a) Theatre of Aspendos



b) Theatre of Perge

Figure 6.4 Measurement Instrumentation at the Site

Table 6.1 Dates and Times of Measurements for Selected Theatres

Theatre	Date	Time
Aspendos	11 May 1989	5.30-8.30 a.m.
Aspendos	14 May 1990	5.30-8.00 a.m.
Perge	12 May 1989	5.30-8.30 a.m.
Perge	13 May 1990	5.00-9.00 a.m.
Termessos	12 May 1989	6.00-7.00 p.m.

The main criterion for the selection of measurement time is the level of background noise. Early morning hours were the most suitable for the Aspendos and Perge theatres. Any time was suitable for Termessos theatre because of its isolated location very far from the highways and the low number of tourists in May.

6.2.1 Climatic Data Measurements

Air temperature and humidity have also been recorded in the theatres during the acoustic measurements. The temperature and relative humidity values during measurement hours have been given in the Tables 6.2, 6.3, 6.4.

Table 6.2 Air Temperature and Humidity Values for Aspendos Theatre

Date	Hour	Temperature (C)	Humidity (%)
11 May 1989	6.20	14.5	88.6
11 May 1989	7.00	15.0	88.8
11 May 1989	7.30	15.2	86.9
11 May 1989	8.00	16.0	84.0
11 May 1989	8.30	17.2	79.0
14 May 1990	5.45	19.0	56.0
14 May 1990	6.00	19.0	56.0
14 May 1990	6.15	19.5	56.0
14 May 1990	6.40	20.0	56.0
14 May 1990	7.00	20.2	56.0
14 May 1990	7.30	21.0	55.0
14 May 1990	7.45	21.5	55.0

Table 6.3 Air Temperature and Humidity Values for Perge Theatre

Date	Hour	Temperature (C)	Humidity (%)
12 May 1989	6.00	12.6	87.0
12 May 1989	6.30	14.3	87.0
12 May 1989	7.00	14.5	86.0
12 May 1989	7.30	17.5	73.5
12 May 1989	8.00	18.6	70.0
12 May 1989	8.30	19.8	66.0
13 May 1990	5.00	17.0	52.0
13 May 1990	5.30	15.5	57.0
13 May 1990	6.00	17.5	54.0
13 May 1990	6.15	18.0	54.0
13 May 1990	6.45	18.5	53.5
13 May 1990	7.00	18.5	53.0
13 May 1990	7.30	18.0	53.0
13 May 1990	7.45	19.0	53.5
13 May 1990	8.00	19.0	53.0
13 May 1990	8.10	20.0	53.0

Table 6.4 Air Temperature and Humidity Values for Termessos Theatre

Date	Hour	Temperature (C)	Humidity (%)
12 May 1989	6.00 p.m.	19.0	47.0
12 May 1989	7.00 p.m.	19.0	48.5

Atmospheric pressure and wind speed measurements have been taken from Antalya Meteorological Center. The average values of the day, 11th May, 12 th May and 13 th May are listed in the Table 6.5.

Table 6.5 Daily Average Atmospheric Pressure and Wind Speed Measurements (Station: Antalya, Station Height 51.051 m, Latitude 36.52, Longitude 30.44)

Day	Atmospheric Pressure (mbar)	Wind Speed (m/s)
11 May	1007.6	2.0
12 May	1009.2	2.4
13 May	1011.8	1.6

6.3 Measurement Data Analysis

The measurement data has been analyzed on a MINC-23 micro computer and IBM PC compatible computers. Acoustical data acquired from theatres has been analyzed by these two different softwares.

6.3.1 Measurement Data Analysis on MINC-23 Micro Computer

The measurement data has been analyzed on a MINC-23 micro computer equipped with an A/D converter at the Data Acquisition Center in the Mechanical Engineering Department of Middle East Technical University. The instrumentation used for data analysis is given Figure 6.5.

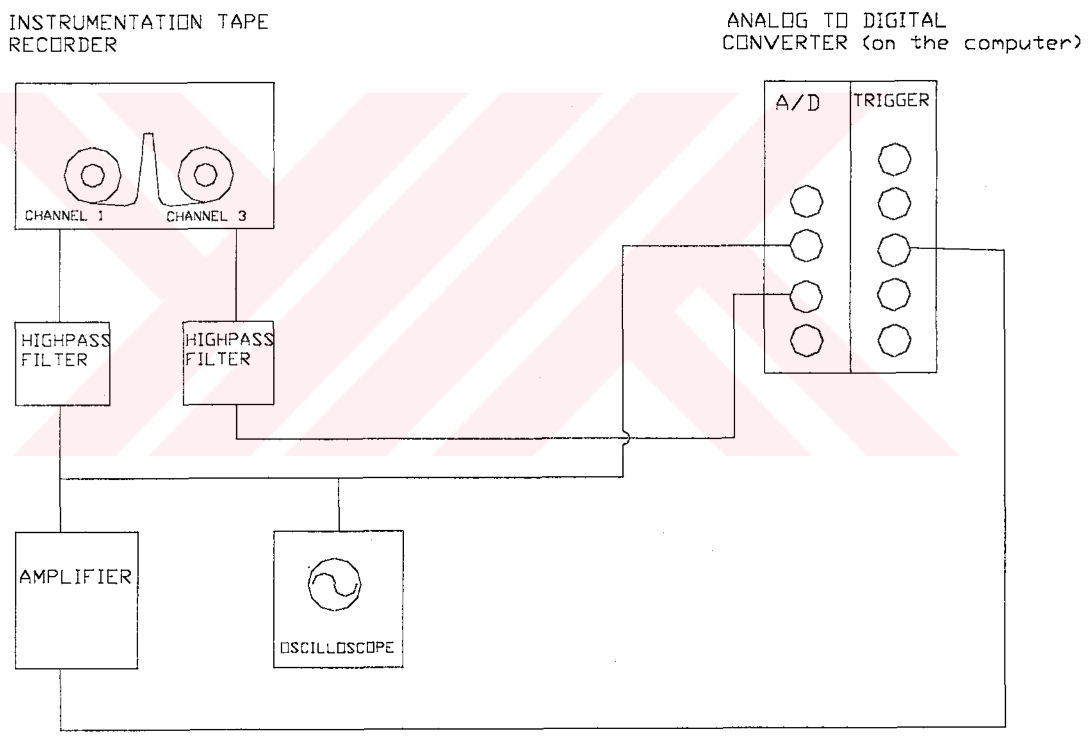
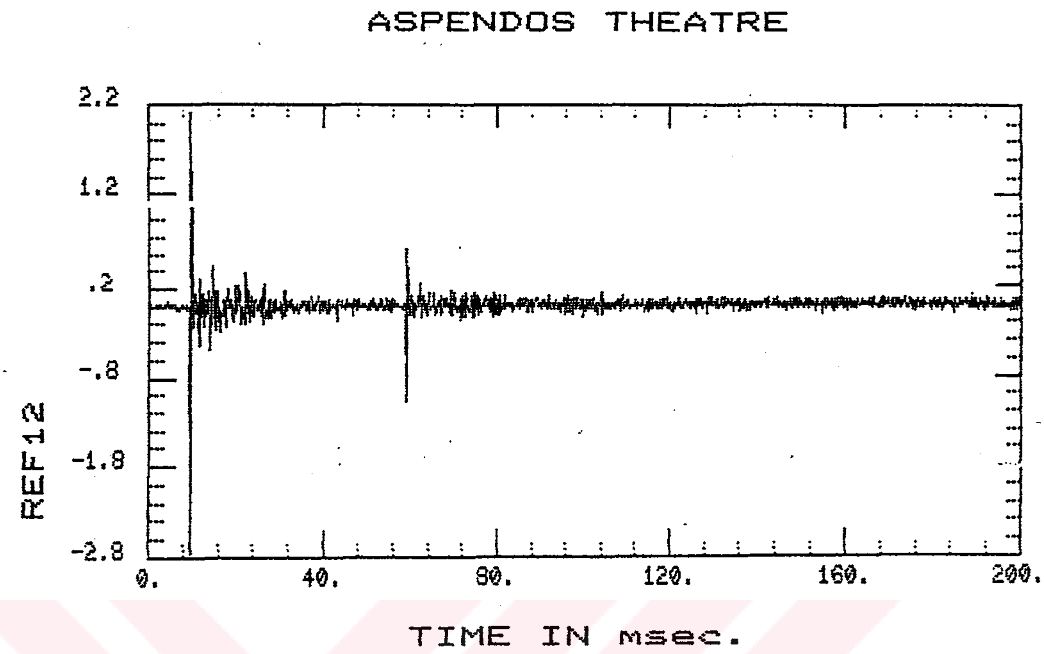


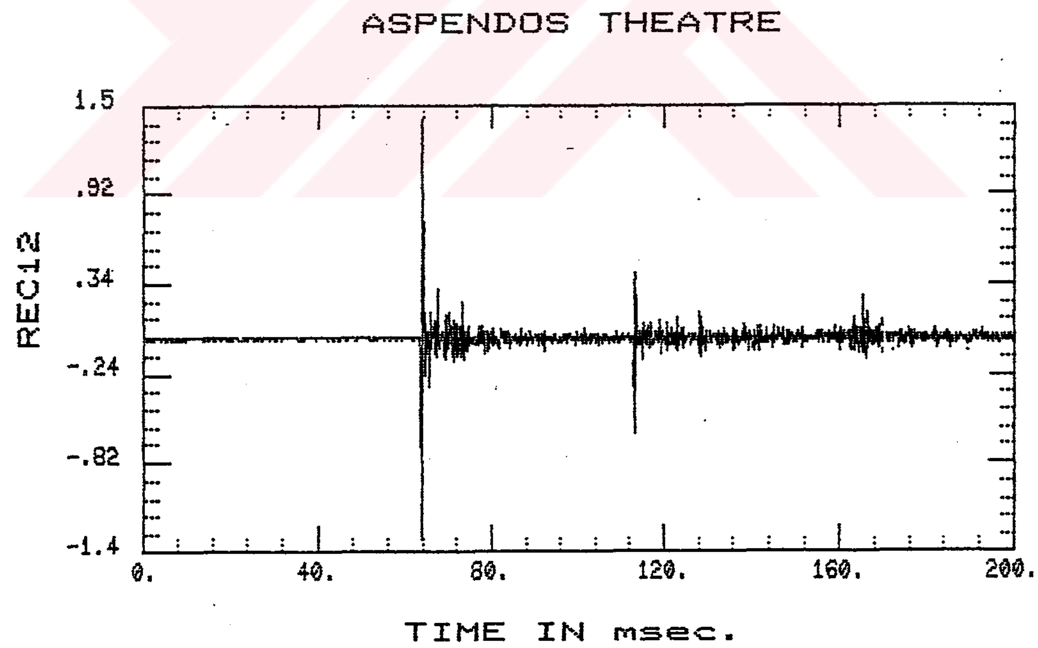
Figure 6.5 The Instrumentation for Measurement Data Analysis

During the data analysis of Aspendos theatre a high pass filter set at 50 Hz has been used. Digitizing frequency and tape speed have been chosen as 1000 Hz and 3.75 ips, respectively to attain a time magnification 2 during playback. During the data analysis of Termessos theatre a high pass filter (10 Hz) has been used. Digitizing frequency and tape speed have been chosen as 1000 Hz and 1.875 ips, respectively, i.e., to attain a time magnification is

4 during playback. The sample echograms of these measurements are shown in Figures 6.6 and 6.7 respectively for Aspendos and Termessos theatres.

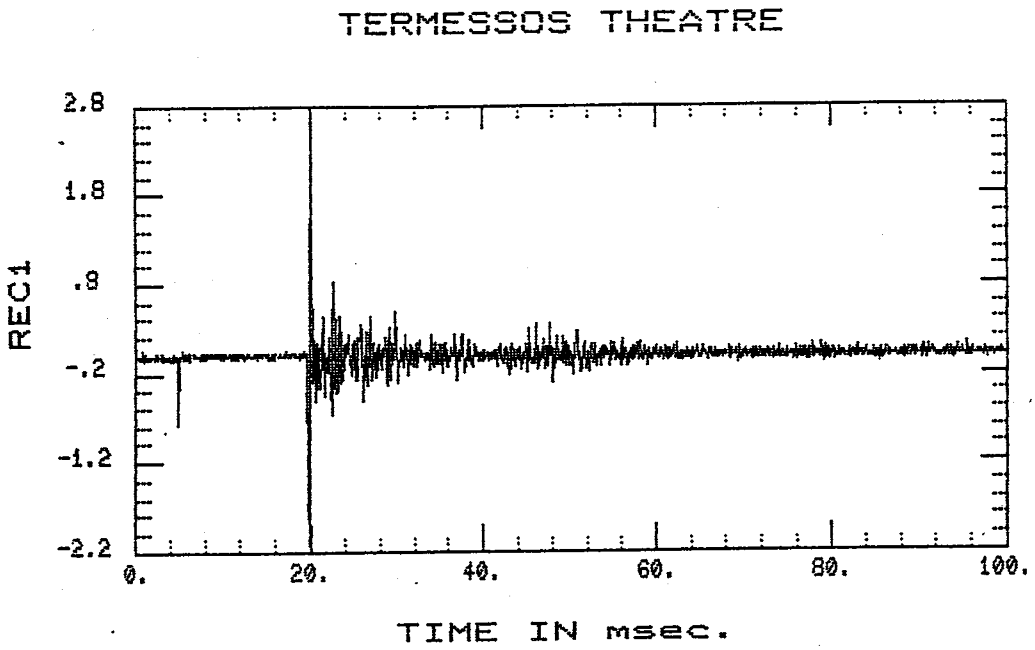


Receiver Position D2

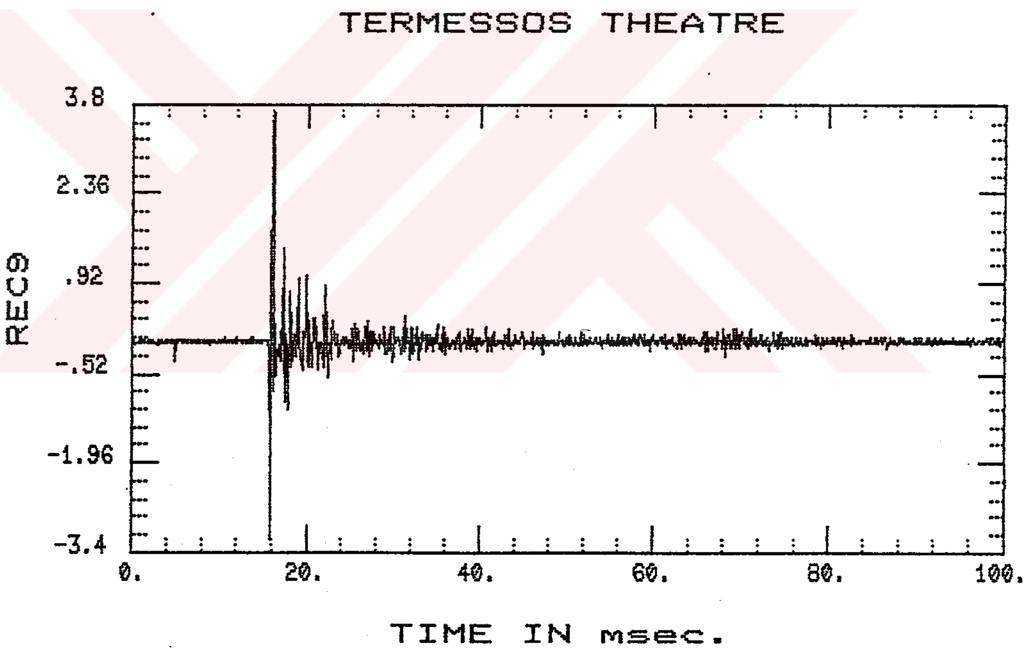


Receiver Position D5

Figure 6.6 Sample Echograms for Aspendos Theatre



Receiver Position A2



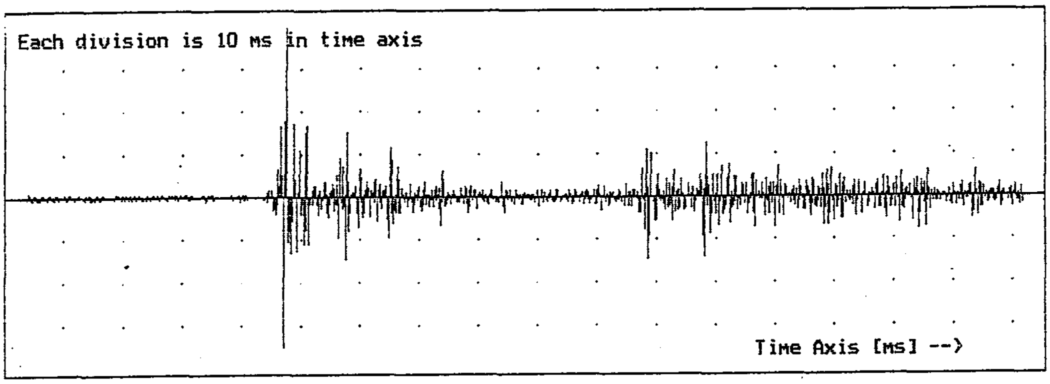
Receiver Position E2

Figure 6.7 Sample Echograms for Termessos Theatre

6.3.2 Measurement Data Analysis on IBM PC or Compatible Computers

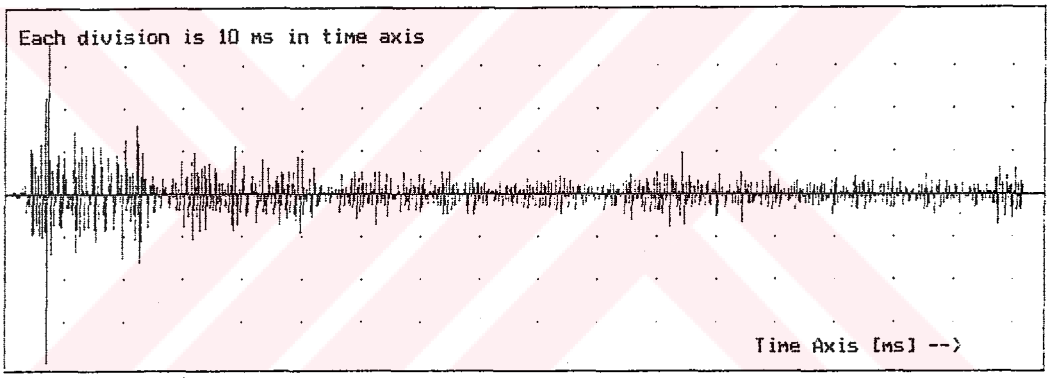
This program is prepared by Sorguç (1990: 130). It is designed to perform impulse response analysis for the impulse response measurements of spaces for a source-receiver pair.

analyzing the measured data, the impulse response is plotted on the screen. Energy decay curve and the associated reverberation time in selected octave bands can be obtained after the impulse response analysis is performed. The measurements of Aspendos, Perge and Termessos theatres have been analyzed by this program. The sample impulse responses are shown in Figures 6.8, 6.9 and 6.10, respectively, for the Aspendos, Perge and Termessos theatres.



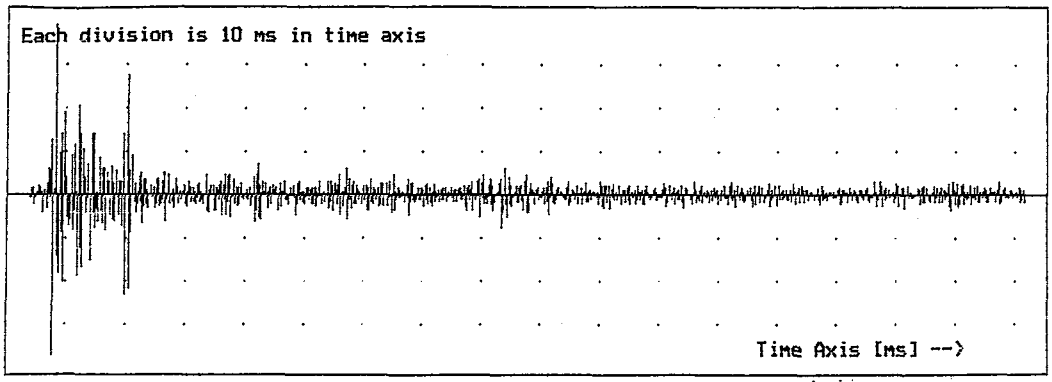
Receiver Position D2

Figure 6.8 Sample Impulse Responses for Aspendos Theatre



Receiver Position A1

Figure 6.9 Sample Impulse Responses for Perge Theatre



Receiver Position C1

Figure 6.10 Sample Impulse Responses for Termessos Theatre

CHAPTER 7

COMPUTER SIMULATION OF SELECTED ANCIENT THEATRES

Aspendos, Perge and Termessos theatres have been simulated acoustically on personnel computers by the methods of image sources and ray-tracing (See Chapter V). Computer softwares used in simulation studies have been prepared at METU.

7.1 Simulation by Method of Image Sources

Method of Image Sources has been implemented on IBM compatible computers by Sorguç (1990) in a graduate thesis as a part of an MS thesis. The software prepared in Pascal programming language is used for acoustical simulation of Aspendos and Termessos theatres by the method. The program consists of a main program and a number of subroutines or units.

The impulse response of the enclosed spaces for a specific source-receiver pair is calculated by using the program named IMAGE. The program is also adapted for open-air spaces by considering openings as covered by a material with almost perfect absorption. The image source data is produced in the program, and the contribution of each image source into the impulse response is calculated depending on the desired frequency ranged. The filtering frequency is specified by the user. Both unfiltered and filtered impulse responses are obtained graphically on the screen. From the filtered impulse response, the energy decay curve is obtained in the frequency band of interest. Reverberation time of the enclosed space can be calculated from this average energy decay curve.

The speech transmission index for a given source- receiver pair is calculated by the program. The image source data is retrieved from the data files and modulation transfer functions are calculated. The speech intelligibility rating for each octave band is then determined.

In order to obtain impulse response characteristics the geometry and dimensions of the space should be introduced. The program is prepared mainly for four room types namely, rectangular, L-shaped, T-shaped, and polygonal rooms. For simulation of ancient open-air theatres the polygonal room type has been used. Data can be entered by specifying the coordinates of the defining points for the space. Reflecting surfaces of spaces need not to be perpendicular to each other. Analysis of distorted rooms with inclined roofs and inclined floors is also possible. It is difficult to define the geometry of the theatre of Perge by the room types above because of its very large capacity and excessive number of corners. Ray tracing method has been preferred for theatre of Perge because of detailed geometry definition property of the program.

Absorption coefficient data for each surface should be entered in six different octave bands. The absorption coefficients of openings in ancient theatres such as the ceiling should be assigned as 1.0 (the biggest value of the absorption coefficient). All contributing image sources for the specified source-receiver pair are generated with in the program. Upon this process, the top, side, and front views of the space with the image sources are displayed on the screen. Figures 7.1 and 7.2 show specified geometry of Aspendos and Termessos theatres, respectively, by IMAGE.

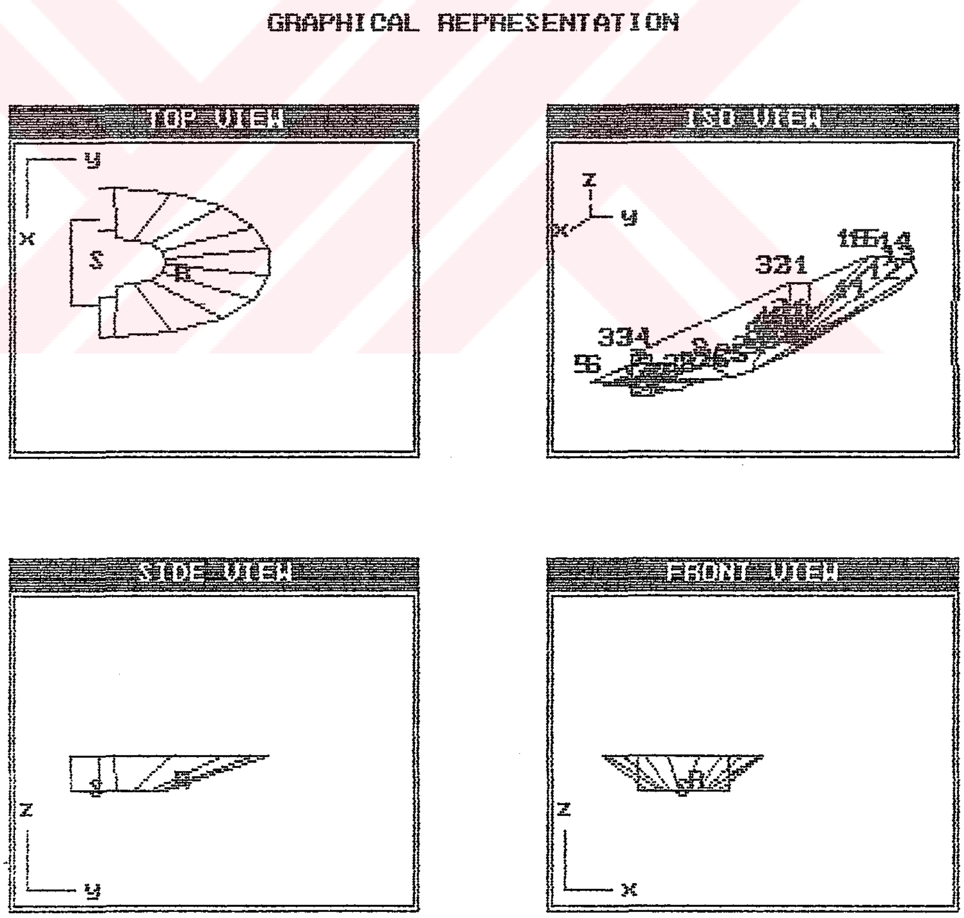


Figure 7.1 Configuration of Theatre of Aspendos.

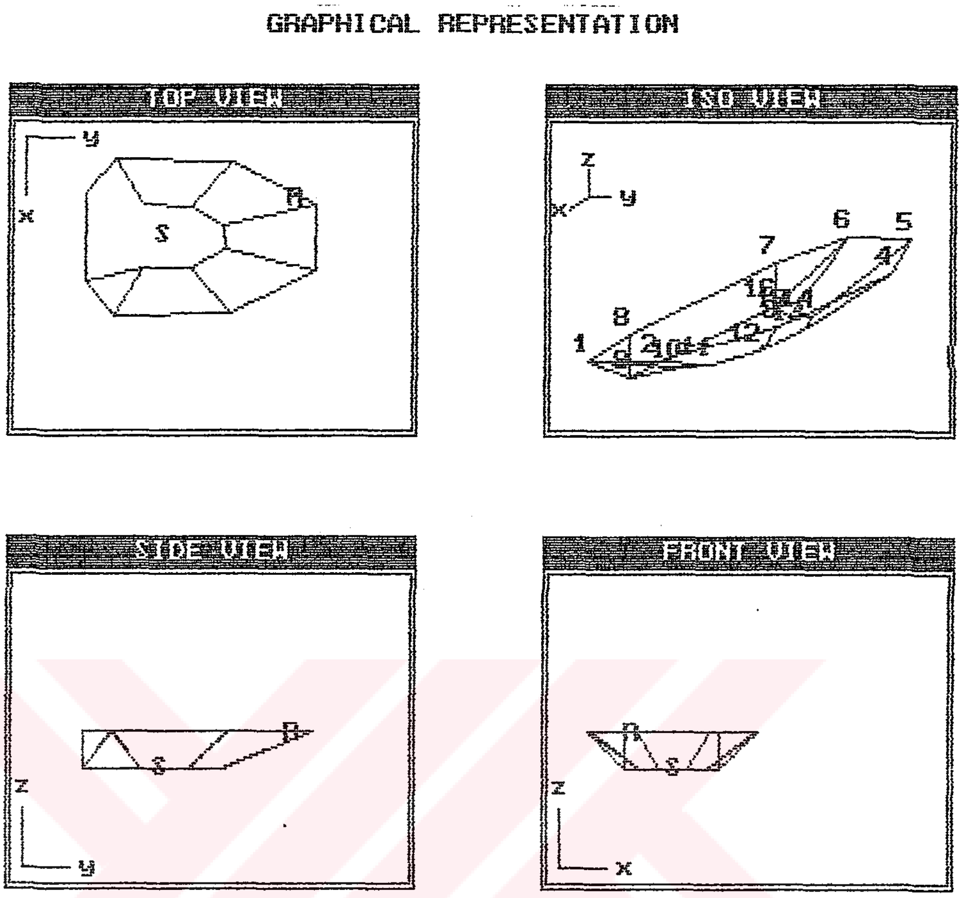
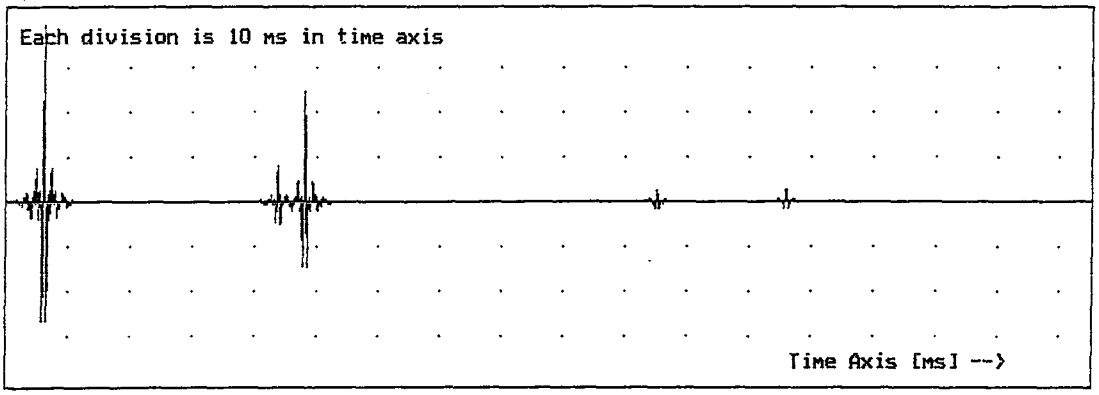


Figure 7.2 Configuration of Theatre of Termessos.

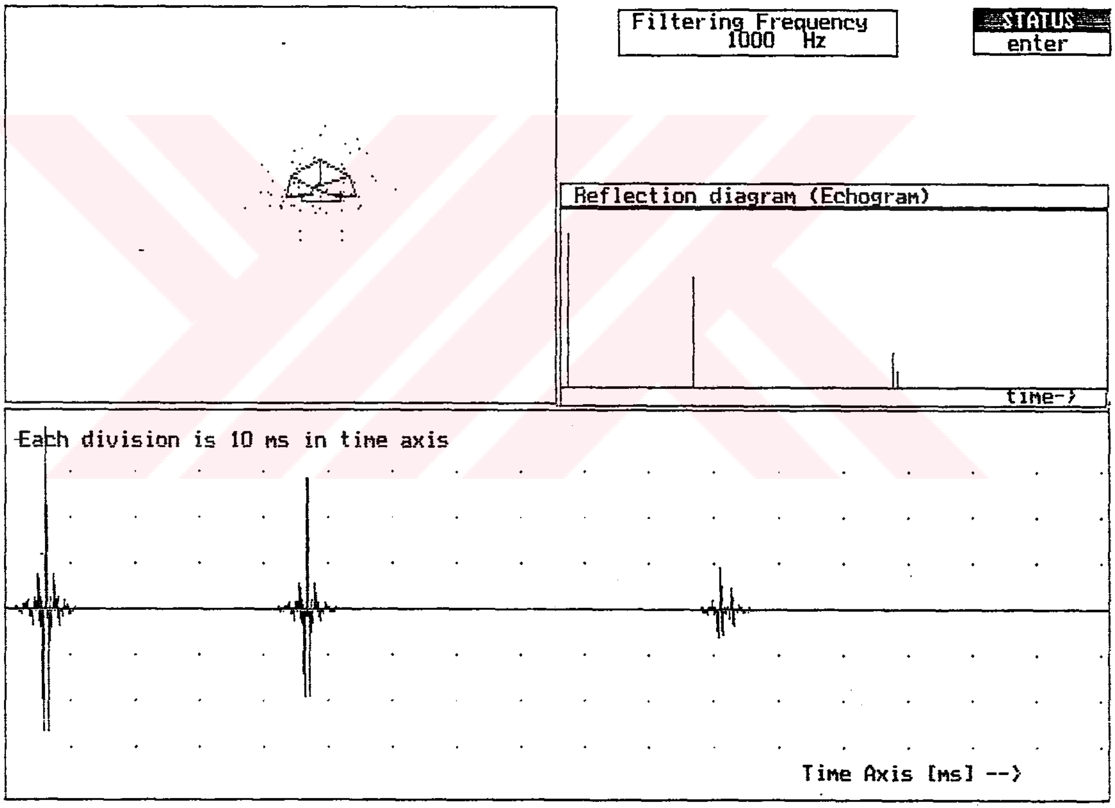
The acoustical simulation is performed on theatres of Aspendos and Termessos for source and receiver positions shown in Figures 6.1 and 6.3.

7.1.1 Theatre of Aspendos

Third order images corresponding to three successive reflections have been used for acoustical simulation of Aspendos theatre. Sampling frequency and sound power level have been specified 1000 Hz. and 100 dB, respectively. Absorption coefficient for the seating area has been taken moderately high (typically 0.5) because the auditorium is considered fully occupied by spectators. The orchestra surface and stage walls are specified as reflected planes with typical absorption coefficient of 0.1. The absorption coefficient of the ceiling open to the atmosphere has been specified as 1.0. The impulse response characteristics for different receiver-source pairs are shown in Figure 7.3.



Receiver Position D2



Receiver Position D5

Figure 7.3. Sample Impulse Responses for Theatre of Aspendos by IMAGE

Speech Transmission Indices (STI) for receiver positions in Figure 6.1 have been calculated to evaluate speech intelligibility. The results vary between 0.75-0.84 in the absence of background noise (Table 7.1).

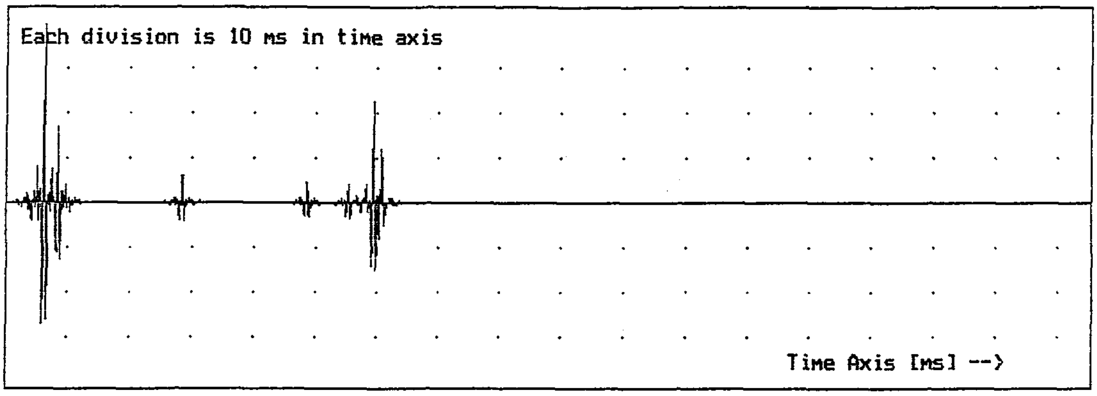
Table 7.1 Speech Transmission Indices for Theatre of Aspendos

Receiver	Speech Intelligibility Index (STI)
A1	0.82
A2	0.80
A3	0.82
A4	0.80
A5	0.78
B1	0.80
B2	0.79
B3	0.78
B4	0.76
B5	0.75
C1	0.79
C2	0.77
C3	0.76
C4	0.80
C5	0.81
D1	0.84
D2	0.82
D3	0.81
D4	0.81
D5	0.80
E1	0.83
E2	0.82
E3	0.81
E4	0.80
E5	0.80

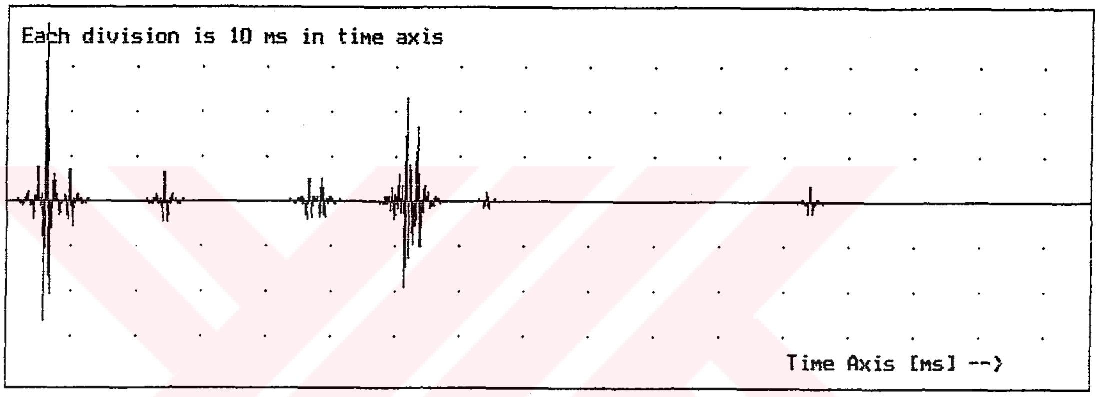
7.1.2 Theatre of Termessos

Fourth order images corresponding to three successive reflections have been used for acoustical simulation of Termessos theatre. Sampling frequency and sound power have been specified 1000 Hz. and 100 dB, respectively. The absorption coefficients of the seating area, the orchestra surface, stage walls and the ceiling open to the atmosphere are specified similarly as in the case of Theatre of Aspendos (see 7.1.1). Impulse response patterns for different receiver-source pairs are shown in Figure 7.4.

Speech Transmission Indices (STI) for receiver positions in Figure 6.3 have been calculated for Theatre of Termessos. Results vary between 0.68-0.85 as tabulated in Table 7.2.



Receiver Position E2



Receiver Position D4

Figure 7.4. Sample Impulse Responses for Theatre of Termessos by IMAGE

Table 7.2 Speech Transmission Indices for Theatre of Termessos.

Receiver	Speech Intelligibility Index (STI)
A1	0.84
A2	0.85
A3	0.84
A4	0.81
B1	0.82
B2	0.81
B3	0.81
B4	0.68
C1	0.84
C2	0.82
C3	0.83
C4	0.78
D1	0.83
D2	0.81
D3	0.83

Table 7.2 (Cont.)

D4	0.81
E1	0.84
E2	0.84
E3	0.84
E4	0.75

7.2 Simulation by Ray-Tracing Method

Ray tracing method has been implemented on IBM compatible computers by Topaktaş (1990) in a graduate thesis as a part of MS dissertation. The software prepared in Pascal programming language is used for acoustical simulation of Aspendos Perge and Termessos theatres by the method. The program consists of a main program and a number of subroutines or units.

Impulse response characteristics of enclosed spaces for a specific source-receiver pair is calculated by using ray-tracing technique. The program is also adapted for open- air spaces by considering the openings as covered by a material with the almost perfect absorption. Impulse response characteristics which contains information for frequencies up to the half of the specified sampling frequency is filtered in time domain by an octave band pass filter. The center frequency of the desired octave band is selected by the user and resulting impulse response is stored. Filtered impulse responses are plotted on the screen. The energy decay curve is then calculated. The speech transmission index for a specified source-receiver pair is also calculated. Modulation transfer functions and speech intelligibility are obtained upon completion of these calculations.

In order to obtain impulse responses the geometry and dimensions of the space should be introduced. The geometry is defined by boundary planes and corners of these planes. Coordinates of the corners (defining points) for the space are specified by the user. The data transfer from AUTOCAD drawing is also possible for these coordinates. Data file structure is compatible with AUTOCAD. Total number of the boundary planes and coordinates of corners must be specified before using the program, RAYTR.

The absorption coefficient of each surface should be specified. Absorption coefficients for openings in ancient theatres such as ceiling should be taken as 1.0. The source and receiver coordinates are other inputs required. Three dimensional drawing of the space and marked source and receiver positions are available on the graphic screen.

Ray directions are generated and stored in a disk file. Tracing of rays is performed by retrieving their directions from the disk file. Valid rays are singled out in 'Find Receiver' option. Rays are stored in another disk file if they reach the receiver during their flight. This file is used for acoustical analysis. Figures 7.5, 7.6 and 7.7 show the specified geometries of Aspendos, Perge and Termessos theatres by RAYTR.

Acoustical simulation for theatres of Aspendos, Perge and Termessos is performed for the similar source and receiver positions shown in Figures 6.1, 6.2 and 6.3. These positions are also shown in the Figures 7.5, 7.6, 7.7.

7.2.1 Theatre of Aspendos

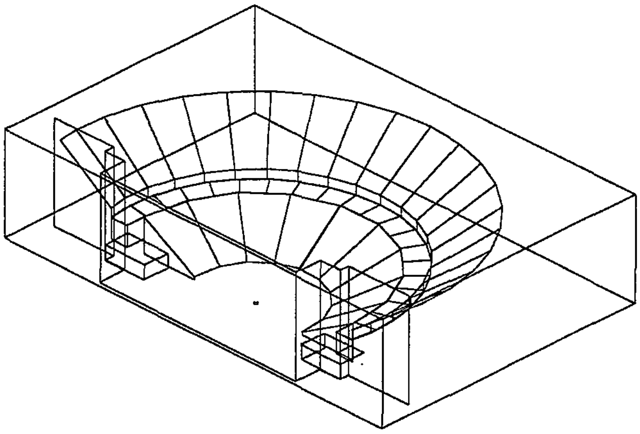
The number of successive reflections has been chosen as five and seven for simulation of Aspendos theatre by ray-tracing. The total number of 16000 emitted rays have been used. The theatre geometry is defined by 95 planes. In order to represent the ceiling and other openings, the theatre is considered in a cubic box covered with a perfectly absorbing material (i.e. 1.0). The stage building and orchestra surface are specified as reflected planes with typical absorption coefficient of 0.2. The seating area is considered as empty (without audience) and absorption coefficient has been taken typically 0.2. Simulations have been performed for 25 receiver positions. The location of the source has been specified as the source location in the measurements as shown in Figure 6.1. The radius of the receiver sphere was specified as 1.05 m. Numbers of the valid rays for reference receivers are shown in the echograms (Figure 7.8.). The pressure echograms are filtered in 1000 Hz. The program has been run both seventh and fifth order reflections. Impulse responses and three dimensional source receiver configurations for the fifth order reflections and impulse responses for the seventh order reflections are presented in Appendix C.The most interesting receiver-source positions with three-dimensional drawings for the seventh order reflections are discussed in Chapter 8 in detail.

7.2.2 Theatre of Perge

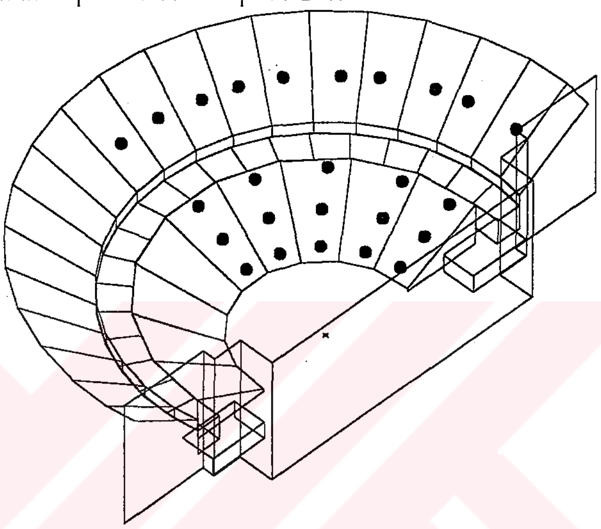
The number of successive reflections has been specified five for simulation of Perge theatre by ray- tracing. The total number of 16000 emitted rays have been used. The theatre geometry is defined by 116 planes. In order to represent ceiling and other openings, the theatre is considered in a cubic box covered with a perfectly absorbing material (i.e. 1.0). The stage building and orchestra surface are specified as reflected planes with typical absorption coefficient of 0.2. The seating area is considered as empty (without spectators) and absorption coefficient has been taken typically as 0.2. Simulations have been performed for 20 receiver positions. The location of the source has been chosen as the same source location in the measurements. The placement of the source is shown in Figure 6.2. The radius of the receiver sphere was taken as 0.7 m. The numbers of the valid rays for reference receivers are shown in the echograms (Figures 7.9.). The pressure echograms are filtered in 1000 Hz. The program has been run for the fifth order reflections.

7.2.3 Theatre of Termessos

The number of successive reflections has been specified as seven for the simulation of Termessos theatre by ray- tracing. The total number of 16000 emitted rays have been used. The theatre geometry is defined by 58 planes. In order to represent the ceiling and other openings, the theatre is considered in a cubic box covered with a perfectly absorbing material (i.e. 1.0). The stage building and orchestra surface are specified as reflected planes with typical absorption coefficient of 0.2. The seating area is considered as empty (without spectators) and the absorption coefficient has been taken typically as 0.2. Simulations have been performed for 20 receiver positions. The location of the source has been specified as the source location in the measurements as shown in Figure 6.3. The radius of the receiver sphere was taken as 0.7 m. The numbers of the valid rays for reference receivers are shown in the echograms (Figure 7.10.). The pressure echograms are filtered in 1000 Hz. The program has been run for seventh order reflections.



a) Theatre Geometry in the Specified Absorptive Box



b) Three-dimensional Receiver-Source Positions

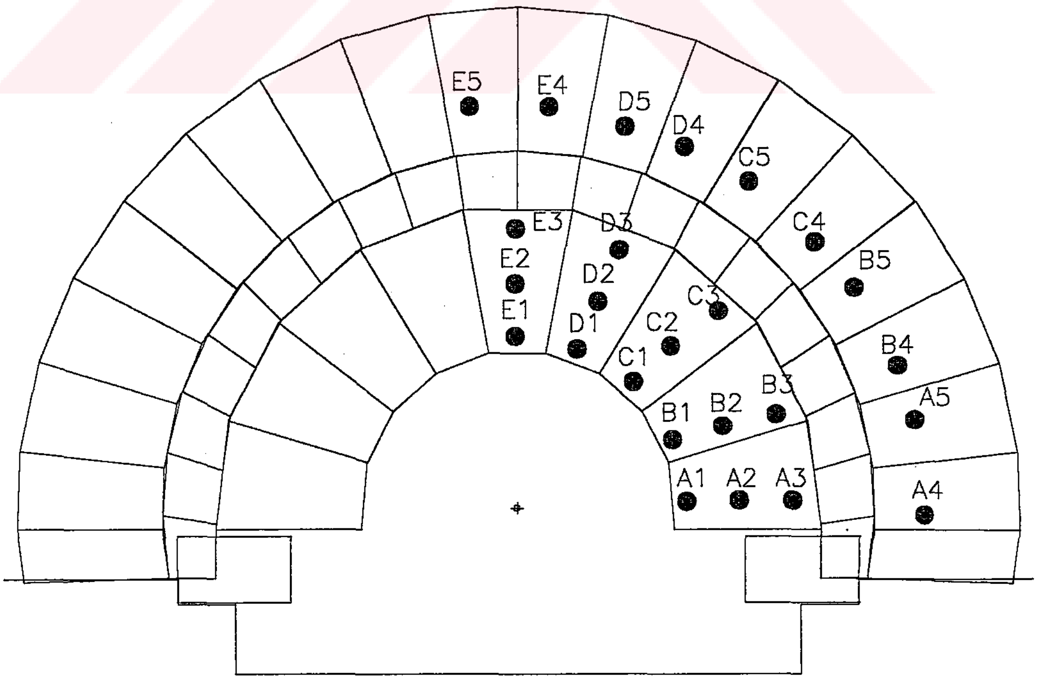
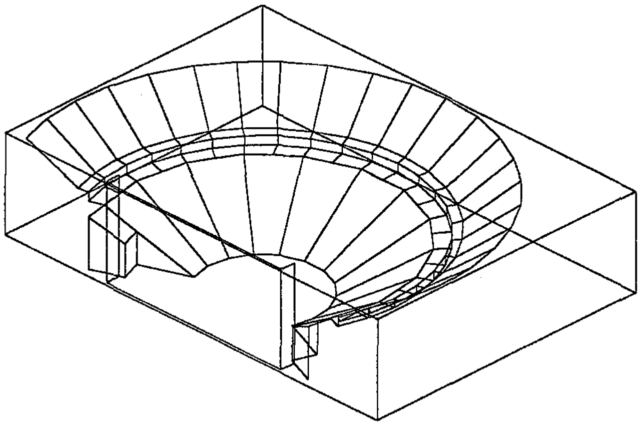
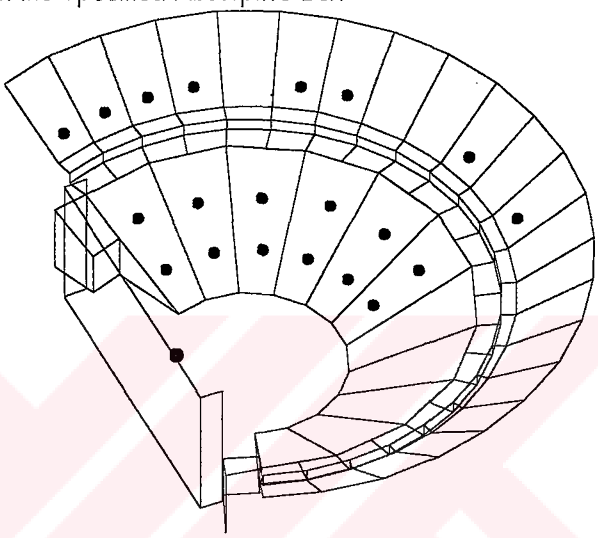


Figure 7.5 Configuration of Theatre of Aspendos by RAYTR.



a) Theatre Geometry in the Specified Absorptive Box



b) Three-dimensional Receiver-Source Positions

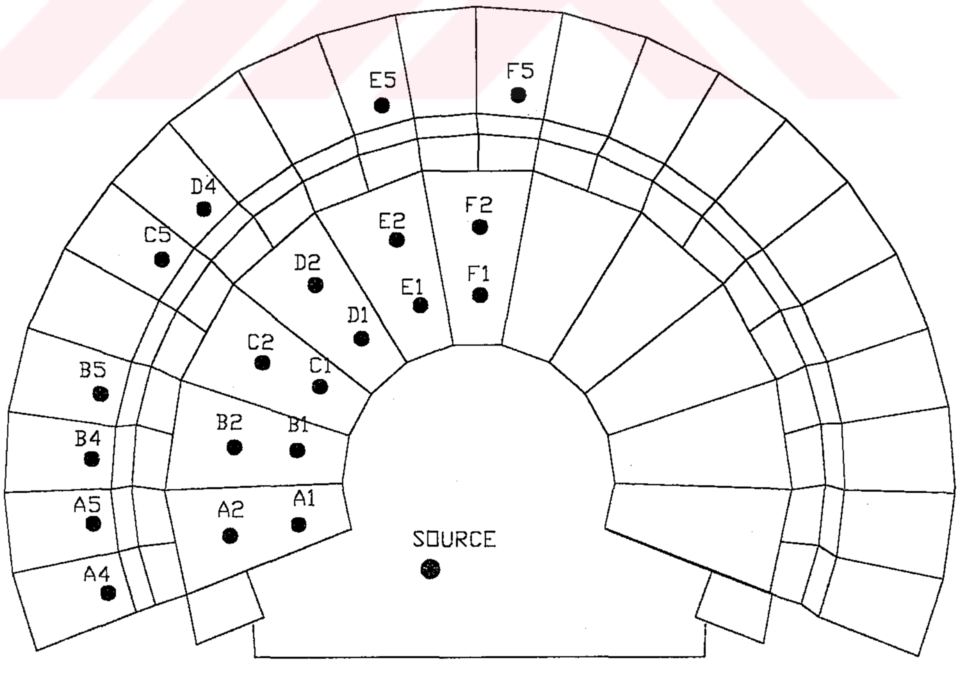
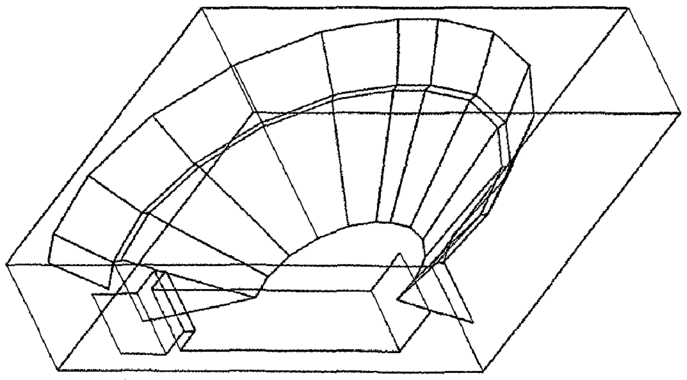
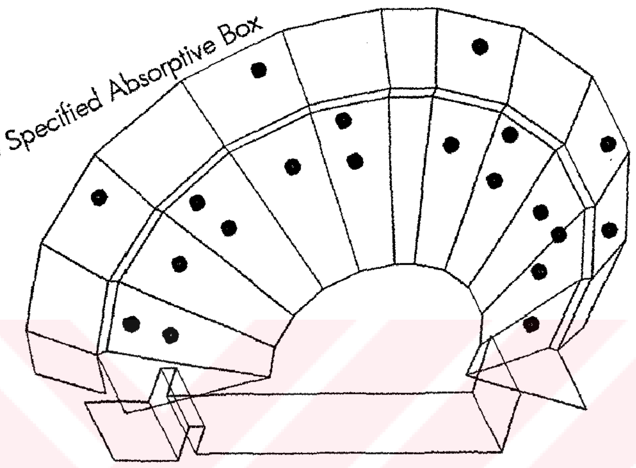


Figure 7.6 Configuration of Theatre of Perge by RAYTR.



a) Theatre Geometry in the Specified Absorptive Box



b) Three-dimensional Receiver Positions

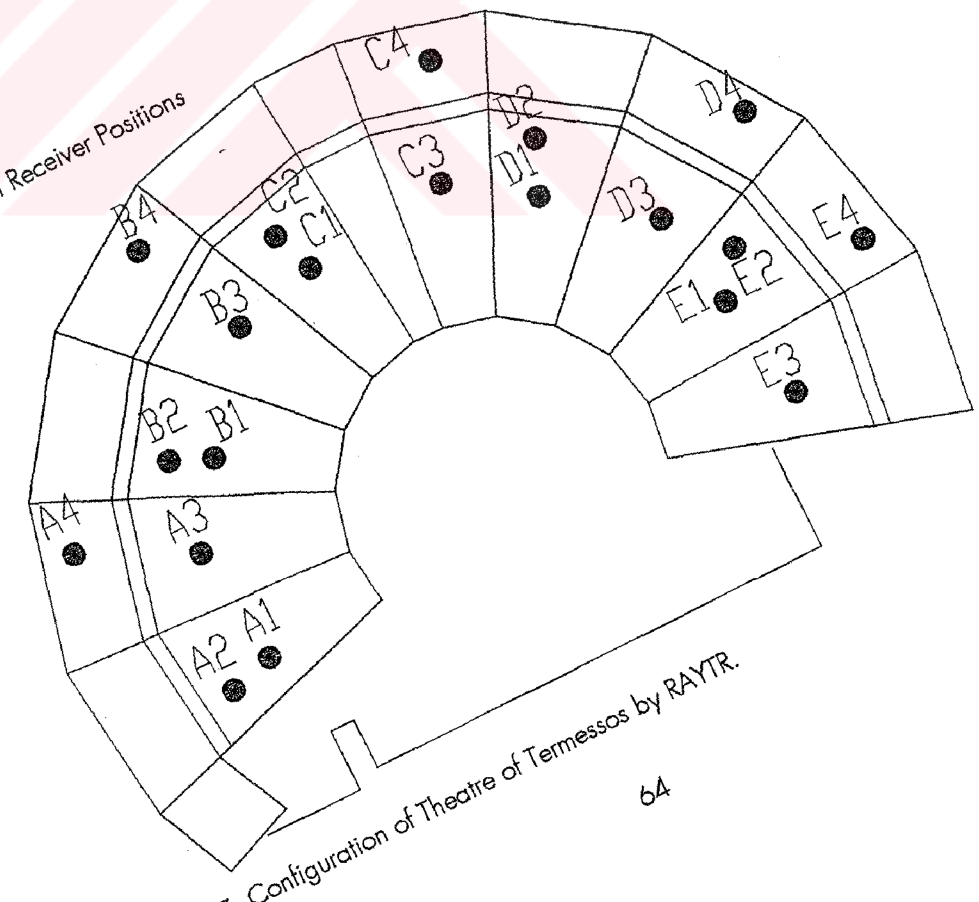
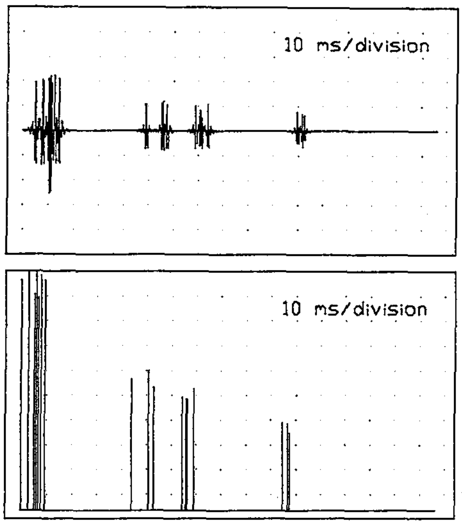


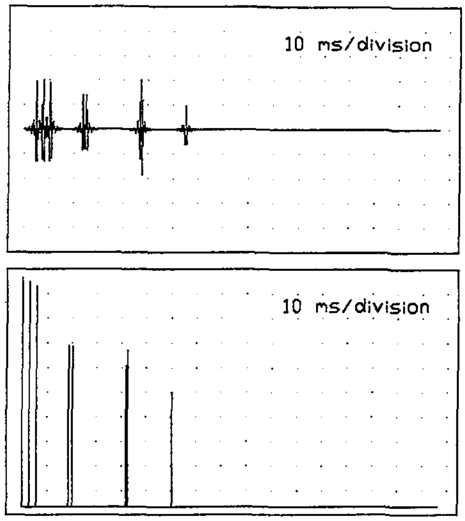
Figure 7.7 Configuration of Theatre of Termessos by RAYTR.



Rays : 16000 Refl. : 7
Valid : 17 Radius : 1.05 m.

Receiver : 56.30 37.00 4.50
Source : 49.20 12.20 0.10
File : r1aspf7.Pth

RECEIVER POSITION D2

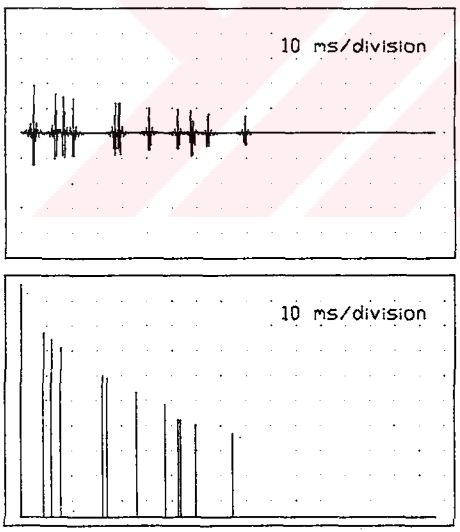


Rays : 16000 Refl. : 7
Valid : 9 Radius : 1.05 m.

Receiver : 58.60 52.00 14.50
Source : 49.20 12.20 0.10
File : r4aspf7.Pth

RECEIVER POSITION D5

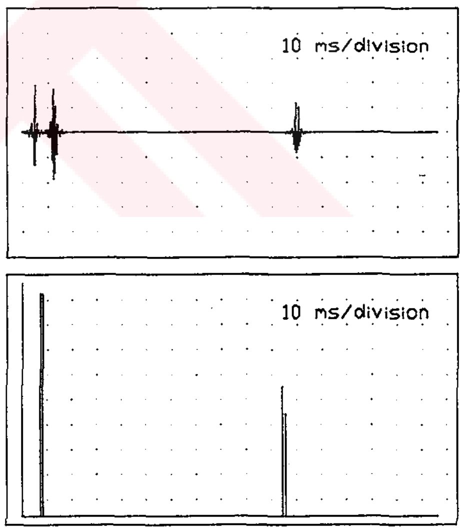
Figure 7.8 Sample Pressure Echograms and Impulse Responses for Theatre of Aspendos in 1000 Hz for Seventh Order Reflections.



Rays : 16000 Refl. : 5
Valid : 14 Radius : 0.70 m.

Receiver : -76.30 28.10 8.44
Source : -55.20 24.60 1.05
File : r2pgf5.Pth

RECEIVER POSITION A2

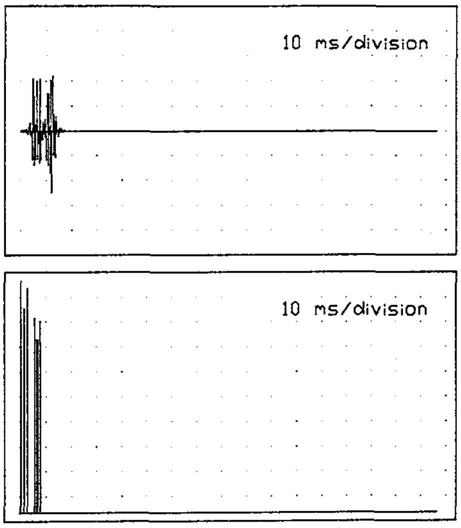


Rays : 16000 Refl. : 5
Valid : 6 Radius : 0.70 m.

Receiver : -46.00 74.50 16.58
Source : -55.20 24.60 1.05
File : r20pgf5.Pth

RECEIVER POSITION F5

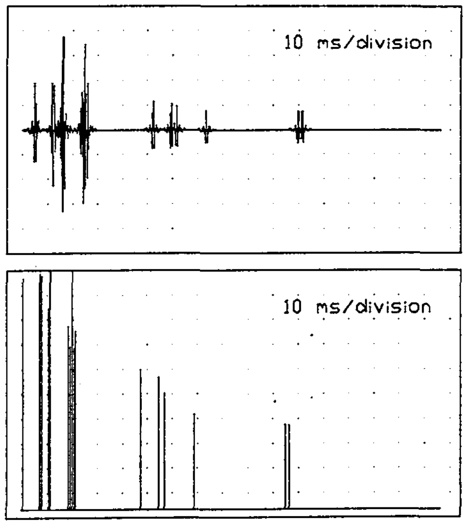
Figure 7.9 Sample Pressure Echograms and Impulse Responses for Theatre of Perge in 1000 Hz for Fifth Order Reflections.



Rays : 16000 Refl. : 7
Valid : 9 Radius : 0.70 m.

Receiver : 54.90 23.20 12.50
Source : 28.50 19.60 0.30
File : r20T95f7.Pth

RECEIVER POSITION D4



Rays : 16000 Refl. : 7
Valid : 18 Radius : 0.70 m.

Receiver : 47.60 26.20 8.20
Source : 28.50 19.60 0.30
File : r18T95f7.Pth

RECEIVER POSITION E2

Figure 7.10 Sample Pressure Echograms and Impulse Responses for Theatre of Aspendos in 1000 Hz for Seventh Order Reflections.

CHAPTER 8

EVALUATION OF THE RESULTS

Results of measurements and simulations for three sample theatres, namely, Aspendos, Perge and Termessos are evaluated according to their acoustical response characteristics. The acoustical criteria used in evaluation studies involve parameters which contribute to the results of measurements and simulations. The acoustical properties of theatres are then evaluated with respect to these parameters.

8.1 Evaluation of Impulse Responses

Impulse responses obtained by acoustical measurements and computer simulations are compared and evaluated for the theatres of Aspendos, Perge, and Termessos. Both the ray tracing method (RAYTR) and the method of image sources (IMAGE) for the theatres of Aspendos and Termessos are used in computer simulations. Theoretical impulse responses for the theatre of Perge are obtained by using RAYTR.

Sound waves with arrival times exceeding 50 ms are perceived by the human hearing system as echoes. Echoes are disturbant to the ear. This phenomenon is not desirable in acoustical design, and must be eliminated and/or controlled. The most critical echoes arise from first reflections which follow the direct sound by time delays exceeding 50 ms. Other reflections are not as problematic owing to increases in traveled distances and subsequent decreases in their amplitudes. Time differences of comparable order between high order reflections are hardly detected by ear due to the attenuation of sound waves by distance. First order reflections with time delays lower than 50 ms, typically around 20 ms reinforce the direct sound to much like of ear. In acoustical design the optimization of this initial time delay is often achieved by properly designed reflecting planes.

8.1.1 Theatre of Aspendos

Impulse responses obtained from simulation methods and measurements for 25 receiver-source pairs are compared for Aspendos theatre. Analysis of experimental data are carried on MINC-23 micro computer and IBM PC. Results of experiments and simulations by IMAGE and RAYTR are compared graphically on the basis of impulse responses. Time differences or delays between the direct sound and reflected paths of sound are tabulated in association with the results of four different simulation and measurement analyses in Table 8.1. It is shown that useful reflections under 20 ms are observed to reinforce the direct sound for increasing the intimacy. These reflections are not included in the tables for this reason. The RAYTR program results which are used in Table 8.1 and following analysis of receiver positions are acquired for seventh order reflections and 16000 rays.

Table 8.1 Reflection Profile for Aspendos Theatre; Comparison of Measurement and Simulation Results (milliseconds).

	MEASUREMENTS		SIMULATIONS	
POSITIONS	IMAGE	MINC	IMAGE	RAYTR
A1	36	36 61	29-31 149	33 50 70 85 145
A2	50 70	32 38 73 121	26 28 141 151	25,79 31,115 38,122 42,125 66
A3	30	31	22	24,79 31,90 35,93 43,97 68,142 71
A4	**	**	41 60 144	33 41 50
A5	**	**	22 131 141 145 147	29 33 37 51 139 162

Table 8.1 (Cont.)

	MEASUREMENTS		SIMULATIONS	
POSITIONS	IMAGE	MINC	IMAGE	RAYTR
B1	50 60	53 57	35 130 143	33 46 74 151 162
B2	-	**	26 33 34 147	26, 85 34,106 50,126 67,147
B3	48 57	47 58 83 89	30 131 146	24,104 32,109 50,114 58,156 66,162
B4	**	**	26 29 128 138 144 145	28 34 131 145 162
B5	-	**	28 31 34 139 140	28, 61 43, 64 47,133 52,146 58,157
C1	-	-	39 116 135	46 115 145
C2	100 105	62	34 38 114	45 66
C3	-	44	32 37 113 130 136	53 58 91 130
C4	10	**	30 34 112 130	24 29 39 48 154
C5	100 105	67 99 107	37	28 36 40 42
D1	42 70	-	40 42 104 124	45 49 72

Table 8.1 (Cont.)

	MEASUREMENTS		SIMULATIONS	
POSITIONS	IMAGE	MINC	IMAGE	RAYTR
D2	60 70	49	38 42 99 120	44 50 65 69 106
D3	68	42 67	36 42 94 116	29 50 58 99
D4	61 71	62 71 75 100 105	39	35 40 44 52
D5	103	49 64 101	40 77 103	43 61
E1	-	-	43 92 114	42 48 70 114
E2	83	-	42 84 107	42 48 65 102 106
E3	-	-	43 76 102	21 54 57 61 94 98
E4	-	61 68 100 105	41 66 94 98	38 57
E5	83 85	34 46 97	41 67 95 98	42

NOTES
- Reflections are not seen
** Measurement data could not be analyzed due to high background noise level

The stone covered surface of the orchestra in the theatre of Aspendos is very smooth and reflective. This is an important property of this theatre. Measurements and simulation results are found to show similarities. This is attributed to the fact that the sound field in the theatre is partly dominated by reflections from the surface of the orchestra.

Receiver positions which measurement and simulation results show similarities are important because of the similar reflection patterns obtained by different methods. These positions with prominent features in their acoustical responses are discussed below:

D2; a first order reflection appears with a time delay of 49- 50 ms which is certified by measurement (MINC) and simulation (RAYTR) results. When the path analysis and three-dimensional figure of this particular position are examined it is shown that reflections took place from the surfaces which are numbered as 3, 84, and 91; those are stage building, kavea (the same part of the kavea in which the receiver position D2 is located) and orchestra surface respectively. Back stage wall is responsible for the first order reflection with a time delay of 50 ms. The time difference between the direct and reflected path from stage wall is in 50 ms for this reason stage wall does not form echoes. Time differences between the direct path and first order reflections from orchestra surface and kavea which is very close to the receiver position are lower than 50 ms. These reinforce the direct sound and do not form echoes. "0" and "1" which are used in the path analysis are reciprocities of source and receiver positions. Three-dimensional model for reflections of sound-rays and path analysis are shown in Figure 8.1 and Table 8.2.

D5; for this receiver position first, second and third order reflections are observed by both RAYTR and MINC. Orchestra surface and kavea which is very close the receiver position are responsible for the first order reflections with a time delay of lower than 50 ms (49 ms in MINC and 43 ms in RAYTR results). The time delay of 43 ms is also observed in the calculation by hand for the first order reflection from back- stage wall (Table 8.14). A third order reflection which strikes firstly, the orchestra surface; secondly, the back stage wall; and than the kavea is observed with a time delay of 64 ms and 61 ms in both measurements by MINC and simulation by RAYTR, respectively. The size of receiver is specified as 1.05 m for theatre of Aspendos. This large size is responsible for non-unique rays that fall into the receiver sphere as oppose to point receiver in IMAGE simulation and nearly point receiver corresponding to the microphone dimension in the measurements. This causes the time differences of 3-6 ms between MINC and RAYTR. A high order reflection appears in 101 ms and 103 ms in MINC and IMAGE results respectively. Three-dimensional model for reflections of sound-rays and path analysis for D5 receiver position are shown in Figure 8.2 and Table 8.3.

A2 and A5; for these receiver positions very complicated high order reflections are observed. It is shown that the low order reflections which reinforce the direct path and high order reflections which cause to form echoes for these cases A2 and A5. The side walls of stage building are

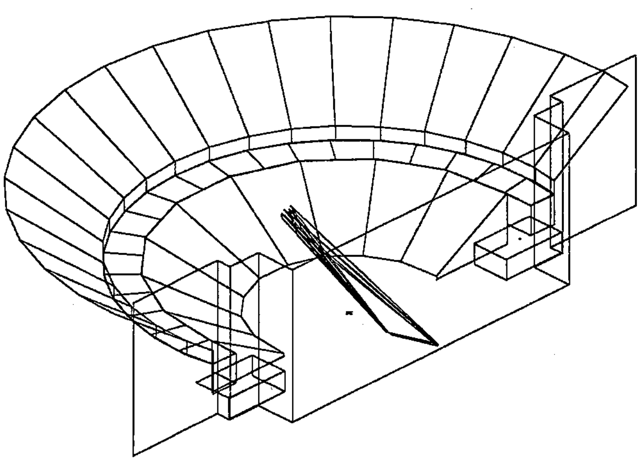


Figure 8.1 Sound Reflections for Receiver Position D2 in the Three-dimensional model of Theatre of Aspendos.

Table 8.2 Path Analysis for Receiver Position D2 in Theatre of Aspendos.

```
16000     7
  56.30  37.00   4.50   1.05
  4
 1.0000
 0   49.20   12.20   0.10
 3   50.69    4.90   0.71
84   57.02   35.96   3.31
-1   57.11   36.89   4.53
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
62.7994
  4
 1.0000
 0   49.20   12.20   0.10
91   49.43   12.98   0.00
84   56.04   35.53   2.89
-1   56.37   36.86   4.59
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
49.0464
  3
 1.0000
 0   49.20   12.20   0.10
 3   50.40    4.90   1.02
-1   55.68   37.03   5.08
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
43.7826
  3
 1.0000
 0   49.20   12.20   0.10
91   49.36   12.73   0.00
-1   56.80   36.84   4.53
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
28.3447
```

Table 8.2 (Cont.)

2
1.0000
0 49.20 12.20 0.10
-1 55.86 37.16 4.24
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
27.5366
3
1.0000
0 49.20 12.20 0.10
91 49.37 12.82 0.00
-1 56.16 37.14 3.90
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
26.5458
4
1.0000
0 49.20 12.20 0.10
91 49.35 11.28 0.00
3 50.39 4.90 0.69
-1 55.63 37.14 4.21
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
41.5435
4
1.0000
0 49.20 12.20 0.10
91 49.33 11.48 0.00
3 50.57 4.90 0.92
-1 56.57 36.83 5.37
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
44.4187
3
1.0000
0 49.20 12.20 0.10
91 49.34 12.73 0.00
-1 56.04 37.05 4.63
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
28.7782
2
1.0000
0 49.20 12.20 0.10
-1 56.92 36.75 4.80
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
29.1216
4
1.0000
0 49.20 12.20 0.10
91 49.46 12.98 0.00
84 56.72 35.16 2.84
-1 57.13 36.55 4.65
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
48.8758
2
1.0000
0 49.20 12.20 0.10
-1 55.44 37.20 4.56

Table 8.2 (Cont.)

```
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
28.5877
  2
 1.0000
 0   49.20   12.20   0.10
-1   56.36   36.89   4.95
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
29.7102
  3
 1.0000
 0   49.20   12.20   0.10
84   55.63   37.18   3.68
-1   55.70   37.56   4.14
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
49.9575
  4
 1.0000
 0   49.20   12.20   0.10
91   49.47   13.12   0.00
84   55.67   34.58   2.33
-1   56.13   36.52   4.89
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
48.3356
  4
 1.0000
 0   49.20   12.20   0.10
 3   50.56   4.90   0.58
84   56.11   34.82   2.54
-1   56.21   36.53   4.85
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
62.1888
  5
 1.0000
 0   49.20   12.20   0.10
91   49.42   11.12   0.00
 3   50.67   4.90   0.58
84   57.01   36.31   3.49
-1   57.08   37.03   4.42
 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001
63.1145
```

responsible for the reflections greater than 50 ms. Inside surfaces of the side walls should be covered by absorptive materials in order to preserve such reflections. Figure 8.3 and Figure 8.4 show these complicated reflections for A2 and A5 receiver positions respectively.

D3; First or low order reflections are observed similar to D2 receiver position. Back-stage wall, orchestra surface and the part of kavea (the same kerkides as in D3 receiver position) are responsible for these reflections. Three-dimensional model for reflections of sound-rays and path analysis are shown in Figure 8.5 and Table 8.4.

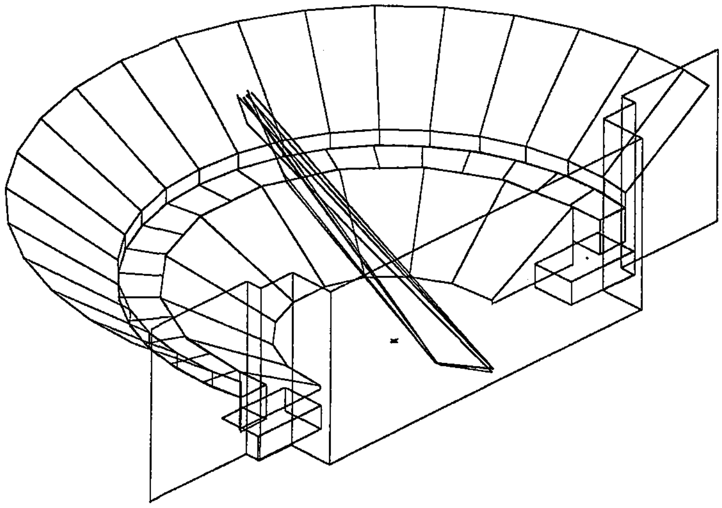


Figure 8.2 Sound Reflections for Receiver Position D5 in the Three-dimensional model of Theatre of Aspendos.

Table 8.3 Path Analysis for Receiver Position D5 in Theatre of Aspendos.

```
16000     7
  58.60  52.00   14.50    1.05
 2
 1.0000
 0   49.20   12.20    0.10
-1   58.58   52.30   13.62
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
47.5823
 5
 1.0000
 0   49.20   12.20    0.10
91    49.28   11.72    0.00
 3   50.41    4.90    1.43
74    58.08   51.08   11.13
-1   58.19   52.83   14.02
 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001
68.0717
 4
 1.0000
 0   49.20   12.20    0.10
91    49.27   11.82    0.00
 3   50.58    4.90    1.82
-1   59.45   51.92   14.19
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
62.1627

 4
 1.0000
 0   49.20   12.20    0.10
91    49.27   11.82    0.00
 3   50.49    4.90    1.80
-1   58.82   52.07   14.07
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
```

Table 8.3 (Cont.)

61.9001
4
1.0000
0 49.20 12.20 0.10
91 49.30 12.63 0.00
84 56.80 43.57 7.24
-1 58.30 51.36 15.18
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
53.9657
3
1.0000
0 49.20 12.20 0.10
3 50.37 4.90 1.97
-1 57.93 52.22 14.06
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
61.9561
4
1.0000
0 49.20 12.20 0.10
91 49.30 12.61 0.00
84 57.14 44.47 7.78
-1 58.56 51.59 14.92
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
54.4342
2
1.0000
0 49.20 12.20 0.10
-1 58.63 52.21 13.86
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
48.4842
2
1.0000
0 49.20 12.20 0.10
-1 59.02 52.03 14.12
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
49.4709

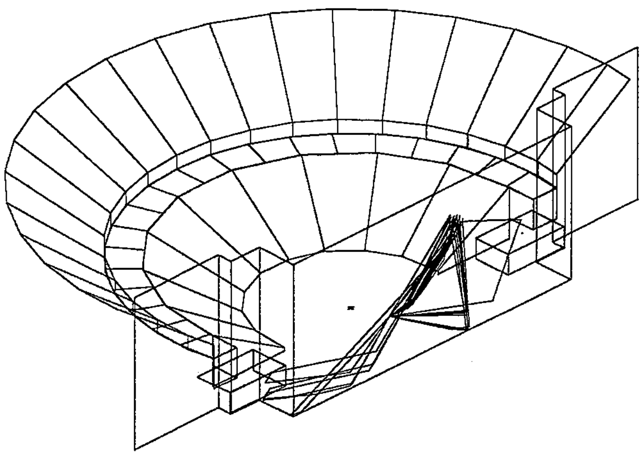


Figure 8.3 Sound Reflections for Receiver Position A2 in the Three-dimensional model of Theatre of Aspendos.

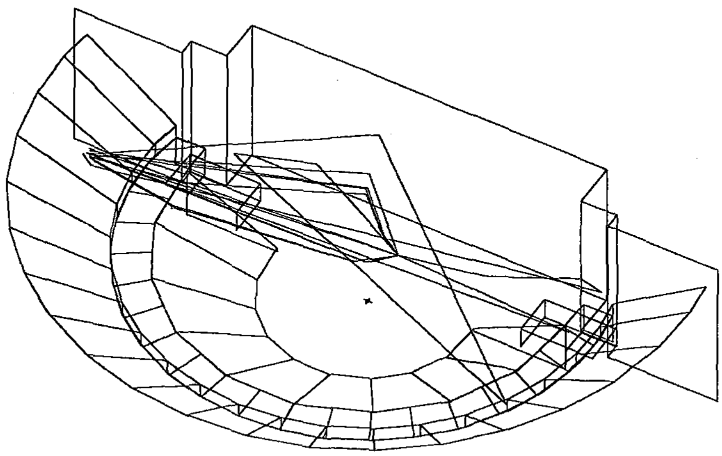


Figure 8.4 Sound Reflections for Receiver Position A5 in the Three-dimensional model of Theatre of Aspendos

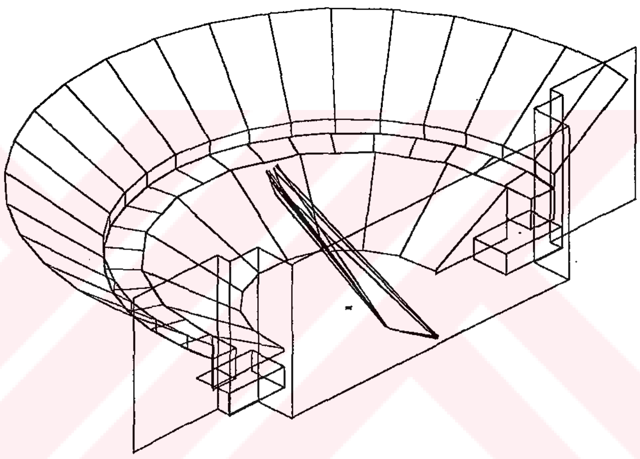


Figure 8.5 Sound Reflections for Receiver Position D3 in the Three-dimensional model of Theatre of Aspendos

Table 8.4 Path Analysis for Receiver Position D3 in Theatre of Aspendos.

```
16000    7
  58.10  41.40   7.40   1.05
  2
 1.0000
 0   49.20   12.20   0.10
-1   57.96   41.61   6.62
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
31.8838
  4
 1.0000
 0   49.20   12.20   0.10
91   49.36   12.73   0.00
84   57.42   38.86   4.91
-1   58.06   41.19   7.59
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
51.3341
  5
```

Table 8.4 (Cont.)

```
 1.0000
 0   49.20   12.20   0.10
 91  49.33   11.48   0.00
 3   50.57   4.90    0.92
 84  57.33   40.85   5.93
 -1  57.42   41.83   7.08
 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001
65.5870
  4
 1.0000
 0   49.20   12.20   0.10
 91  49.34   12.73   0.00
 84  56.71   39.49   5.10
 -1  57.19   41.57   7.44
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
51.6564
  3
 1.0000
 0   49.20   12.20   0.10
 84  57.79   39.53   5.33
 -1  58.30   41.33   7.41
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
51.5918
  3
 1.0000
 0   49.20   12.20   0.10
 84  57.33   40.24   5.61
 -1  57.69   41.69   7.23
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
51.9647
  3
 1.0000
 0   49.20   12.20   0.10
 91  49.32   12.62   0.00
 -1  57.53   41.68   6.91
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
33.0038
  4
 1.0000
 0   49.20   12.20   0.10
 91  49.33   11.57   0.00
 3   50.75   4.90    1.05
 -1  58.49   41.41   6.81
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001

46.2675
  3
 1.0000
 0   49.20   12.20   0.10
 91  49.31   12.60   0.00
 -1  57.20   41.66   7.33
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
34.7469
  2
 1.0000
 0   49.20   12.20   0.10
 -1  58.57   41.12   7.89
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
39.3246
  4
 1.0000
 0   49.20   12.20   0.10
```

Table 8.4 (Cont.)

```
 91   49.32   11.64   0.00
  3   50.75    4.90   1.20
 -1   58.47   41.27   7.68
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
48.8331
```

D4; first and low order reflections appear for this receiver position in the path analysis of RAYTR. Orchestra surface, back-stage wall and parts of upper and lower kavea are responsible for the time delays of 35-52 ms. The reason of disappearance for the reflections greater than 62 ms in MINC results is the random generation of sound rays and errors in specified theatre-geometry. Three-dimensional model for reflections of sound-rays and path analysis are shown in Figure 8.6 and Table 8.5 for D4 receiver position.

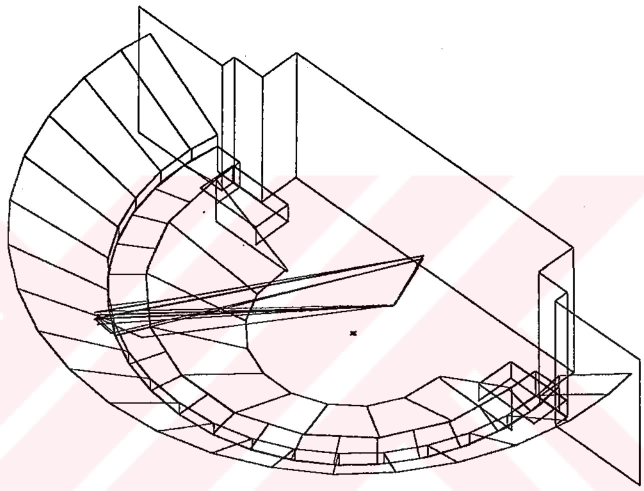


Figure 8.6 Sound Reflections for Receiver Position D4 in the Three-dimensional model of Theatre of Aspendos.

Table 8.5 · Path Analysis for Receiver Position D4 in Theatre of Aspendos.

```
16000     7
  63.70   50.30   14.50   1.05
  2
 1.0000
 0   49.20   12.20   0.10
-1   63.17   50.64   14.11
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
49.2396
  4
 1.0000
 0   49.20   12.20   0.10
 3   51.25    4.90   1.53
72   63.16   47.24   9.84
-1   63.47   50.13   14.62
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
66.7075
  3
```

Table 8.5 (Cont.)

1.0000
0 49.20 12.20 0.10
91 49.30 12.47 0.00
-1 63.90 50.31 14.28
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
49.8718
3
1.0000
0 49.20 12.20 0.10
91 49.30 12.45 0.00
-1 63.84 50.11 14.83
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
52.3401
3
1.0000
0 49.20 12.20 0.10
84 61.37 44.35 8.55
-1 63.57 50.17 14.67
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
54.5740
3
1.0000
0 49.20 12.20 0.10
3 51.21 4.90 2.12
-1 63.68 50.26 14.66
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
62.9505
2
1.0000
0 49.20 12.20 0.10
-1 63.47 50.31 14.69
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
51.5903
5
1.0000
0 49.20 12.20 0.10
91 49.34 11.72 0.00
3 51.28 4.90 1.41
72 63.49 47.73 10.26
-1 63.80 50.32 14.48
5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001
66.9499
2
1.0000
0 49.20 12.20 0.10
-1 63.87 49.87 15.40
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
61.7348
4
1.0000
0 49.20 12.20 0.10
91 49.30 11.86 0.00
3 51.29 4.90 2.02
-1 64.19 49.99 15.09
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
64.2906
4
1.0000
0 49.20 12.20 0.10
91 49.30 11.85 0.00
3 51.30 4.90 2.00
-1 64.24 50.00 14.99

Table 8.5 (Cont.)

```
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
63.9367
   3
  1.0000
 0   49.20   12.20   0.10
 3   51.26    4.90   2.04
-1   64.09   50.29   14.11
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
61.1845
   3
  1.0000
 0   49.20   12.20   0.10
91   49.31   12.46   0.00
-1   64.50   50.00   14.43
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
50.3987
```

E4; a second order reflection with a time delay of 61 ms in measurement by MINC and 57 ms in simulation by RAYTR are observed. Back-stage wall and the part of the kavea which is very close to the receiver position, E4, are the responsible surfaces from this reflection. Three-dimensional model for reflections of sound-rays and path analysis are shown in Figure 8.7 and Table 8.6.

E5; in this particular receiver position a third order reflection with time delay of 42 ms is observed. The ray travels from sound source to receiver position by striking firstly, the orchestra surface; secondly, the back stage wall and lastly the part of the kavea which is very close to the receiver position. This result shows the important role of the skene building and orchestra surface for reflecting the sound to the receivers. Three-dimensional model for reflections of sound-rays and path analysis are shown in Figure 8.8 and Table 8.7.

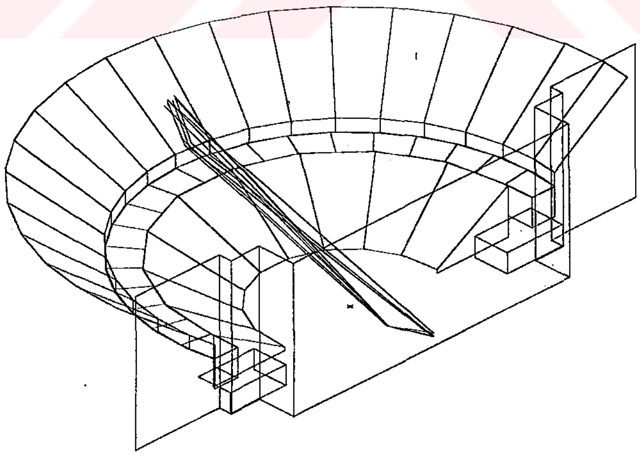


Figure 8.7 Sound Reflections for Receiver Position E4 in the Three-dimensional model of Theatre of Aspendos

Table 8.6 Path Analysis for Receiver Position E4 in Theatre of Aspendos.

```
 16000    7
  52.10  53.70  14.50   1.05
 2
 1.0000
 0   49.20   12.20   0.10
-1   51.52   53.96   13.82
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
47.9283
 4
 1.0000
 0   49.20   12.20   0.10
91   49.22   12.59   0.00
71   51.42   50.20   9.69
-1   51.53   53.47   14.67
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
54.0308
 3
 1.0000
 0   49.20   12.20   0.10
 3   49.64   4.90   1.87
-1   52.58   53.86   13.74
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
60.9475
 4
 1.0000
 0   49.20   12.20   0.10
 3   49.56   4.90   1.40
71   51.80   49.76   9.41
-1   51.82   52.85   14.97
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
67.4484
 4
 1.0000
 0   49.20   12.20   0.10
 3   49.65   4.90   1.43
71   52.44   50.08   9.68
-1   52.52   52.99   14.89
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
67.5627
 3
 1.0000
 0   49.20   12.20   0.10
91   49.22   12.48   0.00
-1   51.72   53.63   14.75
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
51.7978
 3
 1.0000
 0   49.20   12.20   0.10
71   51.66   50.89   10.21
-1   51.78   53.72   14.49
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
54.2052
 3
 1.0000
 0   49.20   12.20   0.10
91   49.23   12.49   0.00
-1   53.13   53.66   14.35
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
50.0350
 3
 1.0000
```

Table 8.6 (Cont.)

0	49.20	12.20	0.10
91	49.22	12.47	0.00
-1	52.65	53.45	15.06

8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
53.1557

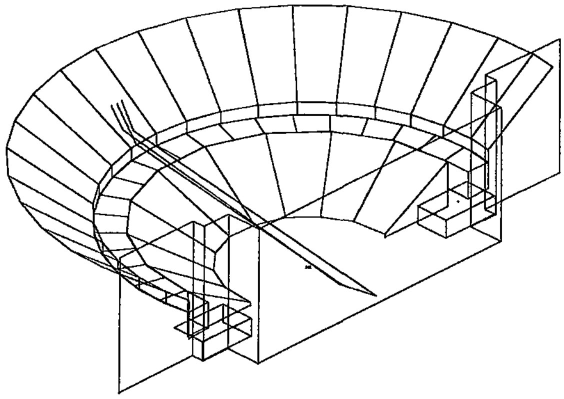


Figure 8.8 Sound Reflections for Receiver Position E5 in the Three-dimensional model of Theatre of Aspendos

RAYTR acoustical simulation program was also run for fifth order reflections and 16000 rays for theatre of Aspendos. Because of the random ray generation there are some minor differences between seventh and fifth order impulse response figures. The fifth order impulse response figures and three- dimensional modeling of each source-receiver pairs are presented in Appendix C.

Table 8.7 Path Analysis for Receiver Position E5 in Theatre of Aspendos.

16000 7
45.20 53.70 14.50 1.05
4
1.0000

0	49.20	12.20	0.10
91	49.16	12.56	0.00
69	44.74	51.84	11.03
-1	44.46	54.01	14.22

6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
54.7139
5
1.0000

0	49.20	12.20	0.10
91	49.17	11.69	0.00
3	48.79	4.90	1.35
69	46.16	51.26	10.53
-1	46.10	53.60	14.57

5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001
68.0416
3
1.0000

0	49.20	12.20	0.10
69	45.07	49.59	9.41
-1	44.63	53.07	14.86

8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
53.7253

8.1.2 Theatre of Termessos

Both simulation methods RAYTR and IMAGE and measurement programs MINC and IMAGE are used for analyzing the theatre of Termessos for 20 source-receiver pairs. Time differences between the direct sound and reflected paths of sound are tabulated in Table 8.8 for these positions. The RAYTR program results which are used in Table 8.8 and the following analysis of receiver positions are acquired for seventh order reflections and 16000 rays. The reflections higher than 80 ms are not compared for the reason that the impulse response figures in MINC program-output are cut approximately at 80 ms for theatre of Termessos.

D4 and E2 receiver positions which are measurements and simulations show similarities are chosen for acoustical response analysis for theatre of Termessos. Other receiver positions are interpreted briefly.

D4; first and second order reflections with a time delay of 48 ms in measurement by MINC and 49 ms in simulation by RAYTR are observed. Back-stage wall, orchestra surface, and the parts of the upper and lower <u>kavea</u> which is very close the receiver position, D4, are the responsible surfaces from this reflection. These reflections lower than 50 ms reinforce the direct sound. The three dimensional model for reflections of sound-rays and path analysis are shown in Figure 8.9 and Table 8.9.

E2; first, second and third order reflections with a time delay of 52 ms in measurement by MINC and 54 ms in simulation by RAYTR are observed. Back-stage wall, orchestra surface, and the part of the lower <u>kavea</u> which is very close the receiver position, E2, are the responsible surfaces for this outcome. These reflections reinforce the direct sound whereas the second order reflections which strike firstly, side walls of stage building; secondly, back-stage wall, and than reach to receiver cause late reflections. Consequently the side walls of the theatre should be covered by absorptive materials to decrease such harmful reflections. The three dimensional model for reflections of sound-rays and path analysis for E2 receiver position are shown in Figure 8.10 and Table 8.10.

A1 and A4; according to MINC and RAYTR results these receiver positions are echo-free.

A2 and A3; late reflections appear in these position, side walls of the stage building are responsible for these reflections.

B1; According to the three dimensional model of RAYTR program, the back stage wall is a position of important reflective surface.

B2; the sound rays which strike the <u>kavea</u> do not produce echoes.

B3 and B4; side and back walls of the stage building form echoes for these receiver-source pairs.

C1, C2 and D1; flutter echoes produced by parallel walls; stage and side walls of <u>kavea</u> are observed in these critical positions. Side walls under the <u>kavea</u> should be covered by an

Table 8.8 Reflection Profile for Termessos Theatre; Comparison of Measurement and Simulation Results milliseconds).

	MEASUREMENTS		SIMULATIONS	
POSITIONS	IMAGE	MINC	IMAGE	RAYTR
A1	-	-	30 34 84	28 31
A2	-	28	28	103 138
A3	-	43 45 77	25 42 56	21 110
A4	-	42 43	46 51 122	-
B1	-	68	38 41 51 62 64	30 50 57 90
B2	-	-	26, 60 32, 72 40, 81 52, 91	23 30 41
B3	-	73	47, 76 48 65 71	24, 89 45,136 66,161 72
B4	-	-	38, 77 60,105 70,120	66 120
C1	34 75	42	49, 79 60, 86 71,101 76	24 26 67 71
C2	75	33	38, 79 52, 85 66,100 76	106 142
C3	-	45	45, 86 58,101 68 77	24 26 67 71
C3	-	45	45, 86 58,101 68 77	24 26 67 71
C4	-	39	37, 82 53, 96 69,123 75	65 74

Table 8.8 (Cont.)

	MEASUREMENTS		SIMULATIONS	
POSITIONS	IMAGE	MINC	IMAGE	RAYTR
D1	-	42	44, 87 51,112 73	26 106 150
D2	-	-	36, 77 41, 86 67,108 71,122 73	26 95
D3	-	26 28	34,120 47 56 62 65	25, 60 28, 83 45,101 49,113 58,134
D4	-	39 48	40, 58 42, 68 56,117	46 49 50 51
E1	-	43	28 42 51	26, 53 32, 81 51, 85
E2	-	43	28 42 51	26, 53 32, 81 51, 85
E3	-	35 43	20 28 33	23
E4	-	35 39	38	-

NOTE
- Reflections are not seen

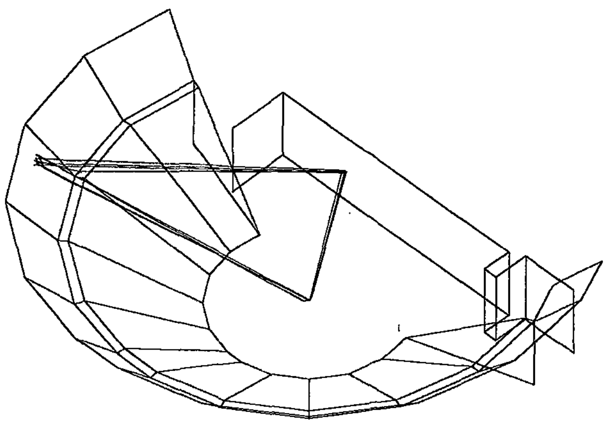


Figure 8.9 Sound Reflections for Receiver Position D4 in the Three Dimensional model of Theatre of Termessos

Table 8.9 Path Analysis for Receiver Position D4 in Theatre of Termessos.

```
16000    7
  51.90   33.40   12.50   0.70
  4
 1.0000
 0   28.50   19.60   0.30
 14   29.06   18.67   0.00
 24   35.80   7.44   3.63
 -1   51.58   33.71   12.13
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
46.5326
  3
 1.0000
 0   28.50   19.60   0.30
 40   51.61   33.09   11.78
 -1   51.87   33.20   12.54
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
32.5527
  4
 1.0000
 0   28.50   19.60   0.30
 14   29.03   18.73   0.00
 24   35.86   7.44   3.88
 -1   51.60   33.47   12.83
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
47.8135
  3
 1.0000
 0   28.50   19.60   0.30
 14   29.02   19.90   0.00
 -1   51.66   33.20   13.12
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
34.2365
  4
 1.0000
 0   28.50   19.60   0.30
 24   36.32   7.44   3.40
 47   50.09   28.84   8.85
 -1   51.84   33.50   12.39
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
48.1639
  4
 1.0000
 0   28.50   19.60   0.30
 14   29.03   18.70   0.00
 24   35.74   7.44   3.77
 -1   51.37   33.69   12.56
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
47.4956
  3
 1.0000
 0   28.50   19.60   0.30
 40   51.23   32.68   11.20
 -1   51.71   32.87   12.64
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
32.4356
  2
 1.0000
 0   28.50   19.60   0.30
 -1   52.08   32.96   12.62
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
30.7066
```

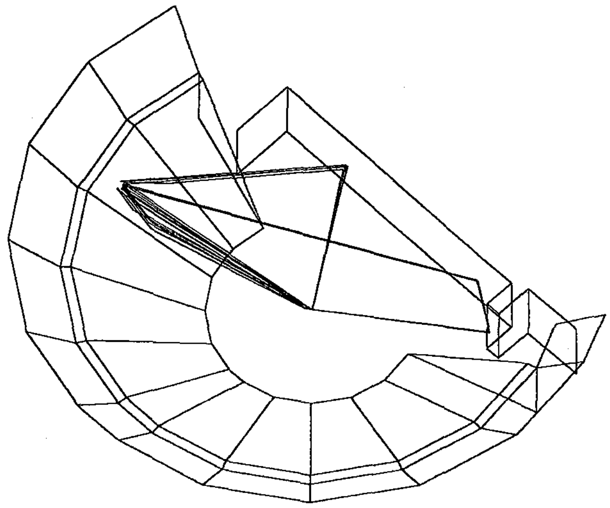


Figure 8.10 Sound Reflections for Receiver Position E2 in the Three Dimensional model of Theatre of Termessos.

Table 8.10 Path Analysis for Receiver Position E2 in Theatre of Termessos.

```
  16000     7
  47.60   26.20   8.20   0.70
  2
 1.0000
 0   28.50   19.60   0.30
-1   47.51   26.42   8.24
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
27.3141
  4
 1.0000
 0   28.50   19.60   0.30
 14   29.13   18.58   0.00
 24   36.11   7.44   3.29
-1   47.70   25.97   8.77
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
44.0171
  3
 1.0000
 0   28.50   19.60   0.30
 14   29.22   19.86   0.00
-1   47.71   26.50   7.67
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
24.7291
  3
 1.0000
 0   28.50   19.60   0.30
 14   29.16   19.82   0.00
-1   47.60   25.93   8.40
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
28.3171
  4
 1.0000
 0   28.50   19.60   0.30
 14   29.53   20.01   0.00
 45   44.01   25.79   4.22
-1   47.27   26.65   8.36
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
31.2039
```

Table 8.10 (Cont.)

4
1.0000
0 28.50 19.60 0.30
23 13.82 10.27 2.71
24 18.29 7.44 3.44
-1 47.66 26.09 8.27
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
60.9355
5
1.0000
0 28.50 19.60 0.30
14 29.51 18.09 0.00
24 36.67 7.44 2.12
47 45.83 21.07 4.83
-1 47.45 25.82 8.73
5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001 5.120E-0001
48.0505
4
1.0000
0 28.50 19.60 0.30
23 13.82 10.38 2.64
24 18.52 7.44 3.39
-1 47.84 25.85 8.08
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
60.3583
2
1.0000
0 28.50 19.60 0.30
-1 47.39 26.25 8.64
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
28.5507
4
1.0000
0 28.50 19.60 0.30
14 29.53 19.97 0.00
45 44.70 25.37 4.44
-1 47.74 26.01 8.12
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
31.6486
4
1.0000
0 28.50 19.60 0.30
14 29.55 19.98 0.00
45 44.35 25.30 4.22
-1 47.61 25.98 8.23
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
31.4502
2
1.0000
0 28.50 19.60 0.30
-1 47.52 25.80 8.67
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
28.5487
3
1.0000
0 28.50 19.60 0.30
24 36.32 7.44 3.40
-1 48.17 25.86 8.09
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
40.8106
3
1.0000

Table 8.10 (Cont.)

```
 0   28.50   19.60   0.30
24   36.04    7.44   3.54
-1   47.61   26.11   8.51
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
43.2826
  3
 1.0000
 0   28.50   19.60   0.30
45   45.18   25.28   4.67
-1   47.88   25.75   8.04
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
31.4578
  3
 1.0000
 0   28.50   19.60   0.30
45   46.14   26.05   5.50
-1   48.03   26.47   7.80
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
31.8969
  2
 1.0000
 0   28.50   19.60   0.30
-1   47.60   26.26   8.15
1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
27.0454
  3
 1.0000
 0   28.50   19.60   0.30
45   44.54   25.64   4.46
-1   47.47   26.27   8.28
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
31.0387
```

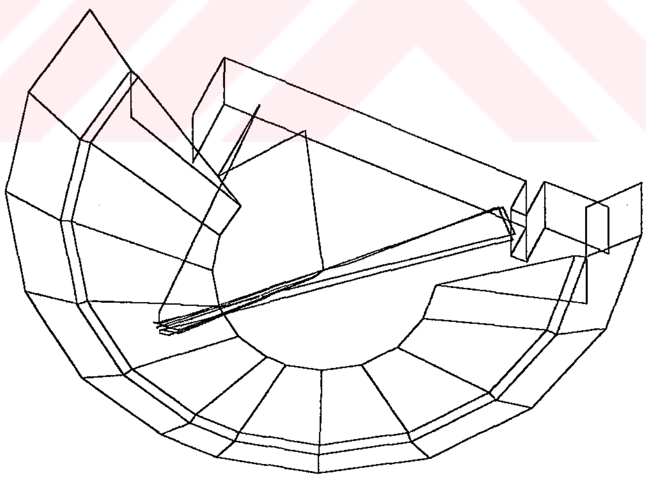


Figure 8.11 Flutter Echo which is Occurred at Receiver Position D1 in Theatre of Termessos.

absorptive material or be angled correctly in order to avoid this kind of late reflections. Figure 8.11 shows the flutter echo formed at the receiver position D1.

C3, and C4; Role of the back-stage wall in order to reinforced direct sound are observed for these receiver positions.

D3; very complicated high order reflections appear with the time delay greater than 100 ms for this position in simulations by IMAGE and RAYTR. Time delays which are observed 56 ms and 62 ms in IMAGE and 58 ms and 60 ms in RAYTR shows similarities. These kinds of results are important to prove the reliability simulation programs. These results indicate that programs support each other. The first order reflection appears with 26 ms and 28 ms in measurements by MINC and 25 ms and 28 ms in simulation by RAYTR. Three Dimensional models of all receiver and source pairs for theatre of Termessos are given in Appendix D.
E4: this position resembles A1 in aspect of echo-free status.

Because of the demolished part of the skene and stone- mass on the orchestra, results of simulation and measurement program cannot support each other for some measurement positions. Measurements which are performed after restoration can yield more reliable results for theatre of Termessos. (Figure 8.12)

Figure 8.12 Stone-mass on the Orchestra at Theatre of Termessos

8.1.3 Theatre of Perge

Measurement results cannot be evaluated because of very large audience capacity of theatre (approximately 15000 persons), demolished skene and very high stone-mass on the orchestra (Figure 8.13). Other important factor which makes the results unreliable is background traffic noise from the nearby highway to the theatre. Despite measurements repeated twice in very early hours of the morning; results are not very reliable due to attenuation of sound energy by larger distances to audience and high traffic noise with mostly low frequency content. Only RAYTR simulation program results can be evaluated for the theatre of Perge in this study.

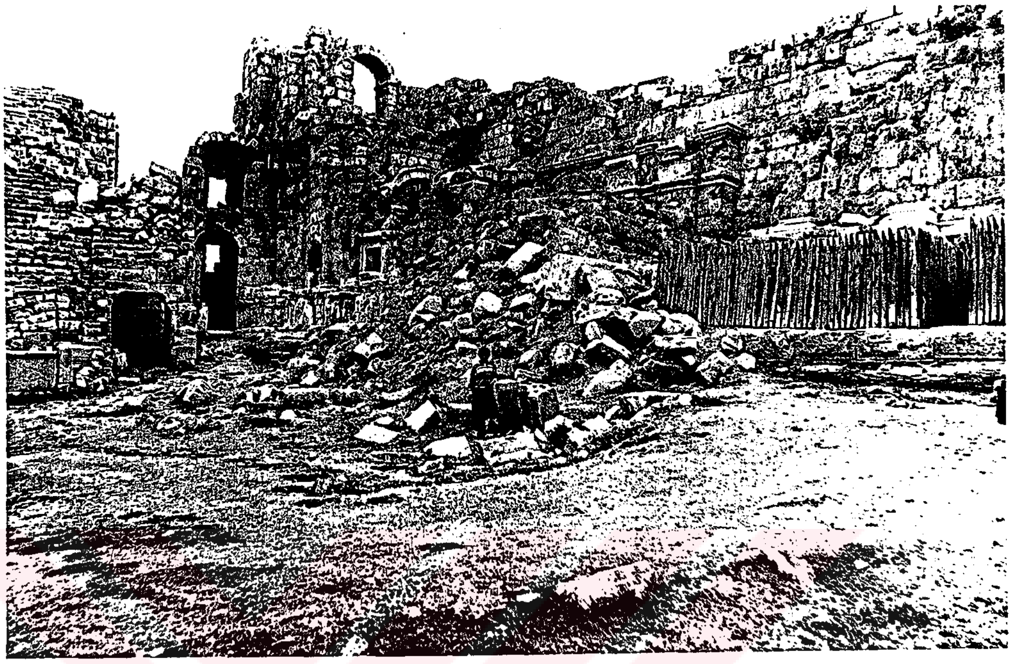


Figure 8.13 Stone-mass on the Orchestra and Demolished Skene at Theatre of Perge

According to the geometrical acoustics simulation, sound rays which reflect from the orchestra surface reach the audience ear level in a very short time. The reason for this small time difference is the proximity of the sound source (1.05 m) to the orchestra surface. Such reflections have an important role on reinforcement and enhancement of sound produced at the orchestra. Reflections under 20 ms are early reflections and these are useful. This characteristic is observed at almost every receiver position of the theatre.

A1; First and second order reflections from orchestra surface and back-stage wall are observed. Higher order reflections from stage side walls cause late reflections.

A2; First order reflection from back stage wall with a 31 ms delay appears for this source configuration. A fourth order reflection which strikes the orchestra surface, stage side walls and kavea respectively reaches the receiver ear with a time delay of 220 ms. This very late reflection caused by stage side wall does not appear in the impulse response figure because of 170 ms time limit of the figure, however it is observed in the path analysis which is the surfaces numbered as 78 and 79. (Figure 8.14 and Table 8.11)

F5; the second and fourth order reflections are observed with time delays of 104 ms and 105 ms respectively. Both side walls are responsible for these late reflections (Figure 8.15 and Table

8.12). The absorptive materials should also be used in theatre of Perge in order to avoid the negative effects of side walls.

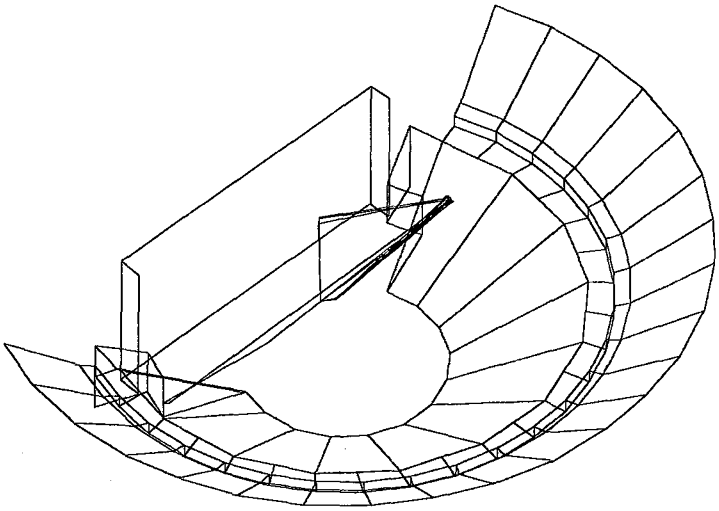


Figure 8.14 Sound Reflections for Receiver Position A2 in the Three Dimensional model of Theatre of Perge.

Table 8.11 Path Analysis for Receiver Position A2 in Theatre of Perge.

```
16000      5
 -76.30   28.10    8.44    0.70
   3
 1.0000
 0  -55.20   24.60    1.05
72  -57.49    24.94    0.00
-1  -76.28    27.72    8.60
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
28.4770
   3
 1.0000
 0  -55.20   24.60    1.05
72  -57.54    24.99    0.00
-1  -76.31    28.09    8.43
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
27.2185
   4
 1.0000
 0  -55.20   24.60    1.05
72  -57.91    24.98    0.00
108  -72.15    26.96    5.51
-1  -76.04    27.81    8.82
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
44.9197
   3
 1.0000
 0  -55.20   24.60    1.05
73  -64.03    15.33    4.21
-1  -76.22    28.13    8.57
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
38.8831
   4
 1.0000
 0  -55.20   24.60    1.05
```

Table 8.11 (Cont.)

72 -57.72 25.05 0.00
108 -75.34 28.15 7.33
-1 -76.42 28.42 8.19
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
46.8947
3
1.0000
0 -55.20 24.60 1.05
73 -64.04 15.33 4.04
-1 -76.30 28.18 8.19
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
34.2173
4
1.0000
0 -55.20 24.60 1.05
72 -57.91 24.96 0.00
108 -72.09 26.82 5.49
-1 -76.04 27.65 8.86
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
44.7990
6
1.0000
0 -55.20 24.60 1.05
72 -45.49 24.47 0.00
78 -25.67 24.19 2.15
79 -26.31 24.73 2.24
108 -75.65 27.67 7.58
-1 -76.27 27.84 8.51
4.096E-0001 4.096E-0001 4.096E-0001 4.096E-0001 4.096E-0001 4.096E-0001
98.4707
3
1.0000
0 -55.20 24.60 1.05
72 -57.59 25.05 0.00
-1 -76.30 28.60 8.23
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
26.1265
3
1.0000
0 -55.20 24.60 1.05
108 -73.65 27.64 6.35
-1 -75.98 28.35 8.68
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
42.7712
3
1.0000
0 -55.20 24.60 1.05
72 -57.47 25.03 0.00
-1 -76.12 28.59 8.62
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
34.7705
4
1.0000
0 -55.20 24.60 1.05
72 -57.97 24.98 0.00
108 -71.49 26.83 5.12
-1 -75.92 27.81 8.95
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
44.5243
4
1.0000
0 -55.20 24.60 1.05

Table 8.11 (Cont.)

72	-57.42	22.24	0.00
73	-63.91	15.33	3.07
-1	-76.01	28.22	8.80

6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
52.0183
2
1.0000

0	-55.20	24.60	1.05
-1	-76.40	28.10	8.13

1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
23.1996

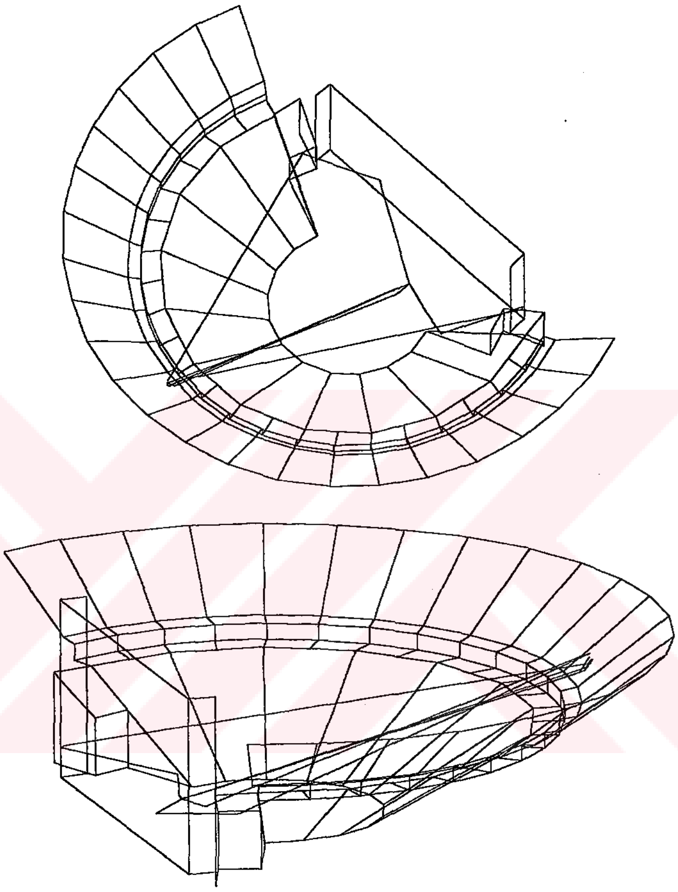


Figure 8.15 Sound Reflections for Receiver Position F5 in the Three Dimensional model of Theatre of Perge

Table 8.12 Path Analysis for Receiver Position F5 in Theatre of Perge.

16000 5
-46.00 74.50 16.58 0.70
3
1.0000

0	-55.20	24.60	1.05
92	-46.55	73.34	14.83
-1	-46.28	74.45	16.65

8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
60.4255

Table 8.12 (Cont.)

```
 4
 1.0000
 0  -55.20   24.60    1.05
73  -38.51   15.33    4.53
78  -26.47   22.02    7.04
-1  -45.95   74.39   17.23
6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
93.4365
 3
 1.0000
 0  -55.20   24.60    1.05
72  -54.69   27.47    0.00
-1  -46.34   74.36   17.14
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
57.9051
 6
 1.0000
 0  -55.20   24.60    1.05
72  -60.57   26.18    0.00
80  -66.12   27.81    1.09
73  -73.47   15.33    3.80
74  -73.78   15.86    3.92
-1  -45.59   74.40   16.11
4.096E-0001 4.096E-0001 4.096E-0001 4.096E-0001 4.096E-0001 4.096E-0001
93.8640
 3
 1.0000
 0  -55.20   24.60    1.05
92  -46.16   74.18   15.49
-1  -46.01   74.76   16.42
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
60.7314
 3
 1.0000
 0  -55.20   24.60    1.05
92  -45.98   73.75   15.18
-1  -45.77   74.56   16.51
8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
60.6230
```

Sound cannot reach the uppermost seating rows of the theatre because of the very large audience capacity and thereby the long distance to be covered by sound waves. For example, any valid ray among the 16000 rays produced for fifth order reflections appears at the receiver position, F2 lies approximately on the centre axis of the theatre. Theatre of Perge can be re-used only by means of electro-acoustical instrumentation in modern times. Sound source can be reinforced electronically by means of loudspeakers placed around the theatre. Loudspeakers should be used to raise the level of sound in the parts of the auditorium where sound waves undergo attenuation by distance and possibly by audience absorption.

8.2 Musicians' Criteria

Musicians' criteria are also important for musical and theatrical performances. A simulation was performed for three different receiver and source positions at orchestra in order to analyze the sound paths from the standpoint of musician' criteria. Figures 8.16, 8.17 and 8.18 show the direct and reflected paths corresponding to these particular positions in three dimensional drawings of theatre of Aspendos. At all of these three musicians' positions late reflections are observed. The stage side walls are shown to be responsible for these late reflections. Possible echoes observed in impulse response pattern in Figures 8.16, 8.17 and 8.18 can be controlled by covering stage side walls with absorptive materials. Path analysis for musician position 1 is shown in Table 8.13.

Musicians themselves have two important criteria to be satisfied. Firstly, the space should respond to their instruments. This implies that some sound energy should be reflected back to the orchestra from the listening area. However, care should be exercised to avoid echoes. Lastly,, musicians should be able to hear each other. Reflecting surfaces around the orchestra will help to accomplish this. (Ginn, 1978: 53). In the case of the open air theatre, these reflecting surfaces are stage walls and orchestra surfaces. These surfaces can be supported by the reflecting planes oriented and angled in suspended ceiling form. In applications where this cannot be realized musicians criteria can be satisfied by employing monitoring loudspeakers on and around the stage or orchestra.

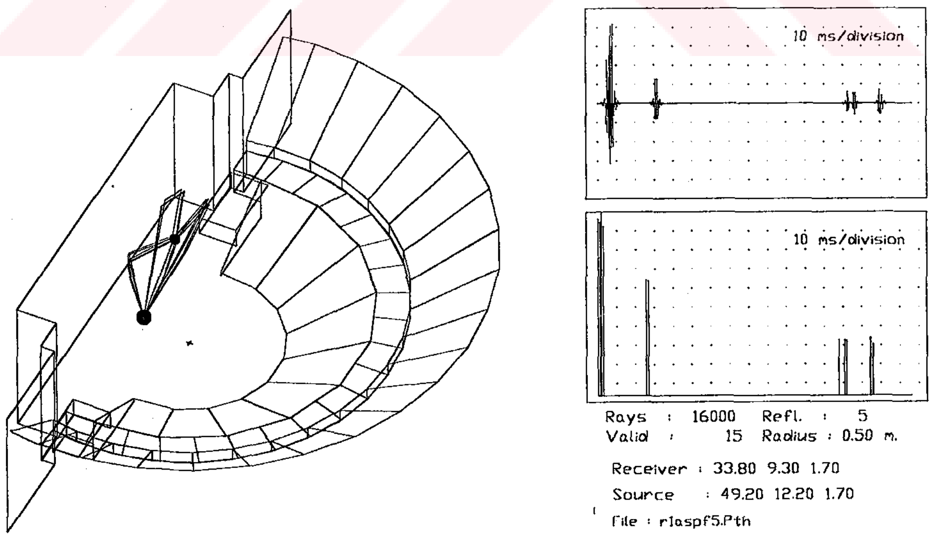


Figure 8.16 Three Dimensional Simulation and Impulse Response Characteristic for Musician Position 1 at Orchestra in Theatre of Aspendos.

Table 8.13 Path Analysis for Musician Position 1 at Orchestra in Theatre of Aspendos.

```
16000      5
  33.80    9.30    1.70    0.50
 3
 1.0000
 0   49.20   12.20    1.70
 3   39.20    4.90    1.85
-1   33.58    9.00    1.93
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
24.0058
 3
 1.0000
 0   49.20   12.20    1.70
91   40.67   10.64    0.00
-1   33.73    9.37    1.39
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
25.0409
 4
 1.0000
 0   49.20   12.20    1.70
91   42.21    6.74    0.00
 3   39.85    4.90    0.57
-1   34.00    9.47    2.00
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
32.7465
 2
 1.0000
 0   49.20   12.20    1.70
-1   33.83    9.15    1.67
 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000 1.000E+0000
24.6401
 4
 1.0000
 0   49.20   12.20    1.70
91   40.87    5.88    0.00
 3   39.57    4.90    0.27
-1   33.76    9.31    1.46
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
24.6525
 3
 1.0000
 0   49.20   12.20    1.70
91   40.90   10.80    0.00
-1   33.70    9.59    1.47
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
25.0051
 4
 1.0000
 0   49.20   12.20    1.70
91   34.22   10.84    0.00
 2   25.03   10.00    1.04
-1   33.75    9.21    2.03
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
73.5962
 4
 1.0000
 0   49.20   12.20    1.70
 3   28.83    4.90    1.63
 2   25.03    6.26    1.62
-1   33.77    9.39    1.59
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
67.3800
```

Table 8.13 (Cont.)

```
  3
 1.0000
 0   49.20   12.20    1.70
 3   39.68    4.90    1.90
-1   33.85    9.36    2.02
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
24.4328
  3
 1.0000
 0   49.20   12.20    1.70
 2   25.03   10.22    1.90
-1   33.81    9.50    1.97
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
73.0776
  4
 1.0000
 0   49.20   12.20    1.70
91   33.65   10.98    0.00
 2   25.03   10.30    0.94
-1   33.80    9.61    1.90
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
73.4867
  3
 1.0000
 0   49.20   12.20    1.70
 2   25.03    9.87    1.70
-1   33.77    9.03    1.70
 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001 8.000E-0001
73.1675
  4
 1.0000
 0   49.20   12.20    1.70
 3   27.99    4.90    1.91
 2   25.03    5.91    1.94
-1   33.91    8.97    2.03
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
68.7985
  4
 1.0000
 0   49.20   12.20    1.70
91   42.46    7.10    0.00
 3   39.54    4.90    0.74
-1   33.85    9.20    2.17
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
33.0752
  4
 1.0000
 0   49.20   12.20    1.70
 3   29.19    4.90    1.80
 2   25.03    6.41    1.82
-1   33.70    9.57    1.87
 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001 6.400E-0001
68.4972
```

8.3 Role of the Skene and Orchestra

Measurement and simulation results support each other for theatre of Aspendos where theatre's reflective surfaces (skene and orchestra) are in well-conserved condition. The most important architectural elements in order to direct and to reinforce sound are shown to be the skene and the orchestra. Figure 8.19 shows the reinforcement of direct sound by the reflector characteristic of skene in an ancient theatre. Selection of proper reflective materials and correct orientation of these surfaces for the skene and orchestra are exploited to have better acoustics.

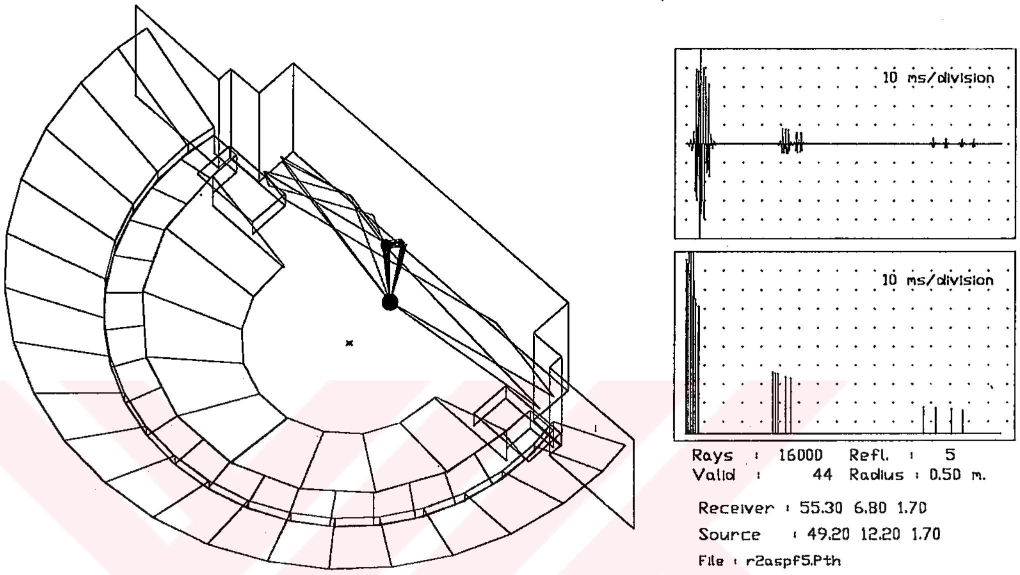


Figure 8.17 Three Dimensional Simulation and Impulse Response Characteristic for Musician Position 2 at Orchestra in Theatre of Aspendos.

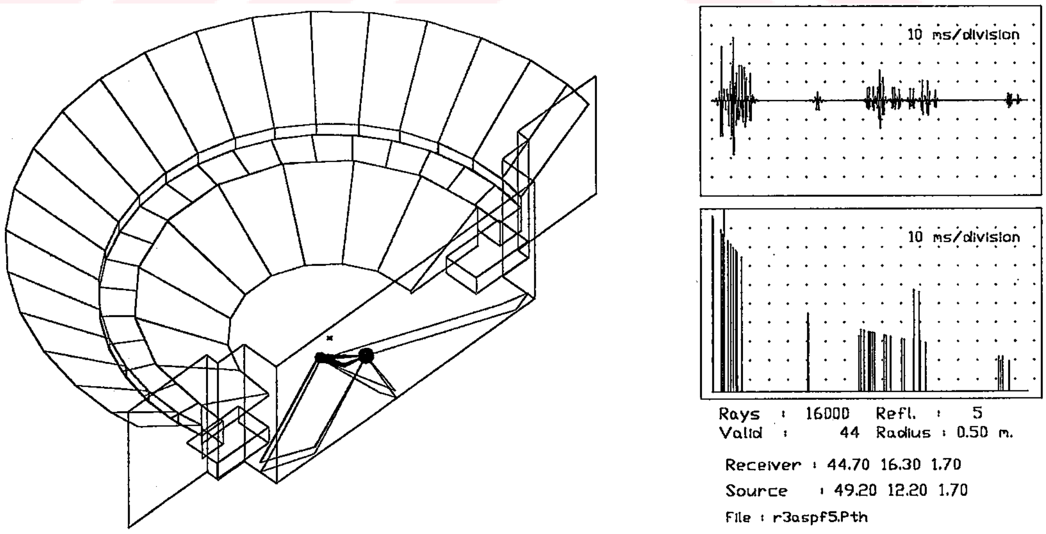


Figure 8.18 Three Dimensional Simulation and Impulse Response Characteristic for Musician Position 3 at Orchestra in Theatre of Aspendos.

Wood as the skene material supposedly used in the ancient Greek theatre is a favorable reflective material if smooth finish on the surface is provided. For orchestra surface and stage building, stone has been used in all of theatres in which acoustical measurements are performed in this study. Stone is known to be a reflective building material if its surface is smooth. High-wooden stage which had been constructed on the orchestra in Greek period is advantageous acoustically in order to direct the sound towards the audience.

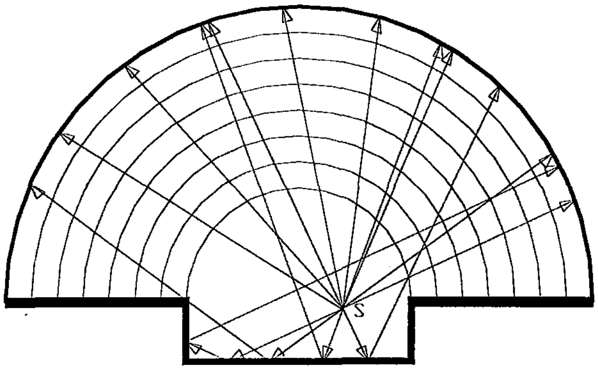


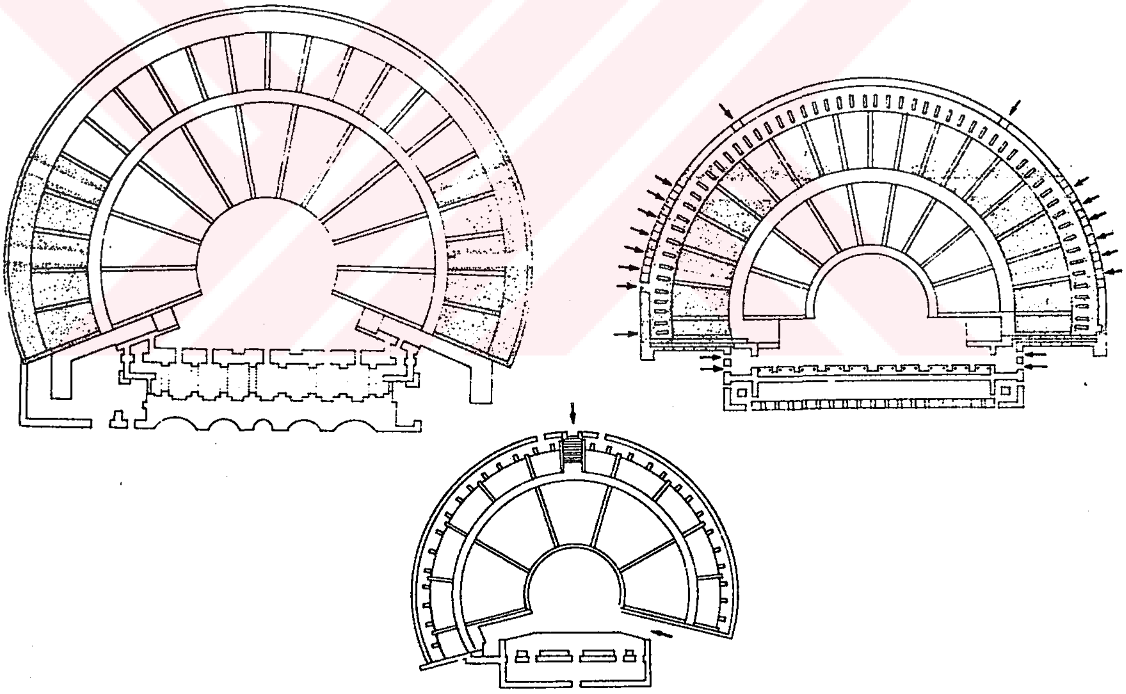
Figure 8.19 Reinforcement of Direct Sound by Reflection from Stage Building

The circular form of the orchestra proves advantageous for spreading the sound homogeneously to the audiences. Height of the stage building is a factor which contributes the reflection of sound. A higher stage building reflects more sound waves than a lower one. The well-known properties of the Roman theatre is its high stage building joined with the auditorium (theatron). Theatre of Aspendos is well-conserved Roman theatre that possesses all these characteristics. However, intersection places of the stage building and auditorium may cause flutter echoes. (Figure 8.11). In order to prevent flutter echo at such places, side walls of the passageway facing the stage back wall should be covered by absorptive materials and/or the position of the sound source should be selected properly. In other words, the sound source should be placed at the orchestra towards to the audience or no audience should be allowed to sit behind the source in front of the stage back wall.

8.4 Effect of the Theatre Form

Forms of ancient open-air theatres influence their acoustical properties. The shape and slope are two main factors associated with the theatre geometry. The shape affects the normalized average distance (Chapter 4.2.2) and the slope influences hearing angle.

Through normalized average distance the design principles for direct sound are evaluated. This measure is defined as the ratio of the average distance of all listeners from the sound source to the square root of area occupied by the audience. Ancient theatres possess minimum normalized average distance characteristics because of their auditoria with conic geometry. This form, with semicircular or exceeding semicircular floor plan, implies the shortest direct sound paths when it is compared with the other conventional forms. (i.e. rectangular, square or fan shape). This measure is calculated to be 0.63 for theatre of Aspendos, while it is 0.54 for theatre of Termessos and 0.52 for theatre of Perge. Hellenistic theatre form with its exceeding semicircular plan has shorter direct sound paths than Roman theatre form. The seating capacities of the theatres which have been used in the calculations of normalized average distances are 9054, 13595 and 4199 for theatres of Aspendos, Perge and Termessos respectively. Seating capacity of theatre of Aspendos is two times larger than that of Termessos theatre while this value for Perge theatre is one and half times larger than that of Aspendos theatre. Figure 8.20 shows the average normalized distances of the theatres of Aspendos, Perge and Termessos with their corresponding forms which are the same scale.



	Perge	Termessos	Aspendos
Normalized Ave. Dist.	0.52	0.54	0.63
Seating Capacity	13595	4199	9054

Figure 8.20 Normalized Average Distances of Theatres of Perge, Termessos and Aspendos. Scale 1/1600 (Adapted from Ferrero, 1988)

Hellenistic theatre form has smaller normalized average distance than Roman form. The reason for this difference is due to the variation in form. Exceeding semicircular auditorium plan is typical in Hellenistic theatre, as in Termessos theatre. This form houses a larger capacity of audiences than the semicircular Roman theatre form. The smaller audience area causes the higher value of the normalized average distance in Aspendos theatre.

Auditorium slope plays a dominant role on the acoustical properties of ancient theatres. The slope affects the hearing angle between the reflected path of the sound wave (to the receiver through the primary image of the source associated with the orchestra) and the inclined surface of the theatre (Canac, 1967: 103-110).

According to Canac, the hearing angle should be maximized (greater than 4 degrees) in order to minimize absorption by the audience at lower or front benches. The hearing angle increases if the height of the stage decreases. In Epidauros theatre this angle is calculated to be 5 degrees for the 3.6 meters stage height and for a sound source located above 5.1 m from the orchestra surface (3.6 m stage height + 1.5 m actor's mouth level), and for a location immediately in front of the <u>diazoma</u>. This value is reported not to be sufficient for good vision of this particular row. In Aspendos, the hearing angle is found to be 17 degrees in front of the <u>diazoma</u> and 15 degrees immediately after <u>diazoma</u> due to a source located above 3.23 m from the orchestra surface. This is a very important characteristics of this theatre. Hearing angles for all measurement positions have been calculated for the sound source location used in the measurements. In these calculations, the height of sound source is 1.6 m equivalent to the mouth level of the actor's. Slopes of the first <u>kavea</u> and second <u>kavea</u> are 30 and 38 degrees respectively. Hearing angles vary between 12.07 -21.20 and they are more than sufficient acoustically as well as for good vision. These values and first order reflections from stage building are given in Table 8.14. First order reflections from stage building vary between 14.5 - 46.9 ms. This measure does not exceed 50 ms limit at any measurement position. This means that the theatre of Aspendos is echo-free for the first order reflections in association with the measurement positions which are selected to be representative for different regions of the theatre. (Figure 6.1). Theatre of Aspendos is superior to the theatre of Perge and Termessos on the basis of these characteristics.

Hearing angles have been calculated for all measurement positions at Termessos theatre. In these calculations, height of sound source is selected 0.3 m as same as the height used in the measurements. Slopes of the first <u>kavea</u> and second <u>kavea</u> are 32 and 35 degrees respectively. Hearing angles vary between 13.16 -16.80 and they are more than sufficient acoustically as well as for good vision. These values and first order reflections from stage building are given in Table 8.15. Time delays associated with the first order reflection of the measurement positions, B3, B4, C1, C2, C3, C4, D1, D2, exceed 50 ms limit. Other positions are echo-free locations for the first order reflections from the stage building. B1 and D3 are intentionally excluded as these two locations possess time delays in the 50 ms limit.

Table 8.14 Hearing Angles and Time Delays for Aspendos Theatre

Position	Hearing Angle (degrees)	Time Delays of First Order Reflections from Stage (ms)
A1	19.52	25.6
A2	15.02	21.9
A3	12.07	19.9
A4	12.37	14.5
A5	12.37	19.4
B1	20.02	39.6
B2	16.69	29.3
B3	12.82	35.3
B4	13.02	25.6
B5	14.12	26.9
C1	20.69	44.9
C2	16.89	42.8
C3	13.72	41.2
C4	14.12	37.3
C5	14.51	40.1
D1	20.97	45.2
D2	17.27	44.6
D3	14.30	44.1
D4	14.80	42.4
D5	15.07	43.9
E1	21.20	46.9
E2	17.53	46.6
E3	14.57	46.2
E4	15.23	43.4
E5	15.23	43.4

Hearing angles have been calculated for the all measurement positions for Perge theatre. In these calculations, the height of sound source is 1.6 m as the mouth level of the actor's. Slopes of the first kavea and second kavea are 32 and 35 degrees respectively. Hearing angles vary between 5.91 - 22.23 and they are sufficient acoustically as well as for good vision. The most critical positions in terms of hearing angle are A4, A5 and B5 which are located on the second kavea and close to the side walls. These values and first order reflections from stage building are given in Table 8.16. Time delays associated with the first order reflection of the measurement positions, C1, D1, D2, E1, E5, F1, F2, F5, exceed 50 ms limit. Other positions are echo-free locations for the first order reflections from the stage building.

Table 8.15 Hearing Angles and Time Delays for Termessos Theatre

Position	Hearing Angle (degrees)	Time Delays of First Order Reflections from Stage (ms)
A1	16.80	28
A2	14.16	24
A3	15.79	41
A4	13.16	36
B1	16.80	51
B2	14.16	48
B3	15.79	57
B4	13.16	57
C1	16.80	61
C2	14.16	61
C3	15.79	61
C4	13.16	73
D1	16.80	58
D2	14.16	58
D3	15.79	50
D4	13.16	45
E1	16.80	43
E2	14.54	44
E3	15.79	28
E4	13.16	22

Table 8.16 Hearing Angles and Time Delays for Perge Theatre

Position	Hearing Angle (degrees)	Time Delays of First Order Reflections from Stage (ms)
A1	12.49	42.0
A2	7.96	30.3
A4	5.91	14.3
A5	5.91	22.3
B1	15.29	49.7
B2	9.59	42.8
B4	5.91	30.0
B5	6.64	37.5
C1	18.58	54.2
C2	12.92	49.7
C5	9.24	47.2
D1	20.49	56.6
D2	15.66	56.0
D4	10.92	51.4
E1	21.60	58.1
E2	17.16	42.7
E5	13.93	56.3
F1	22.23	58.1
F2	18.08	57.3
F5	14.90	56.9

8.5 Speech Transmission Index

Speech transmission index has been calculated with the software IMAGE for theatres of Aspendos and Termessos. The index ranges between zero and unity and it is used as the measure of speech intelligibility. Depending on this index, speech is qualified as given in Table 8.17.

Table 8.17 Speech Intelligibility Rating by STI

STI	QUALIFICATION
0.8 - 1.0	Excellent
0.6 - 0.8	Good
0.4 - 0.6	Fair
0.0 - 0.4	Poor

Speech Transmission Indices (STI) for receiver positions shown in Figure 6.1 in the theatre of Aspendos have been calculated to evaluate speech intelligibility. The results vary between 0.75-0.84 in the absence of background noise (Table 7.1). They show quite similar and satisfactory intelligibility characteristics. This is also a very important property of the theatre of Aspendos.

Speech Transmission Indices (STI) for receiver positions in Figure 6.3 have been calculated for Theatre of Termessos. Results vary between 0.68-0.85 as tabulated in Table 7.2. STI values of theatre of Termessos are also acceptable and satisfactory. Any value below 0.60 which is usually accepted unsatisfactory, has not been determined for the selected receiver positions. Theatre of Perge cannot be modeled by IMAGE because its geometry cannot be specified by restricted numbers of planes. Speech Transmission Indices for theatre of Perge are not tabulated for this reason.

8.6 Conclusions

The ancient theatres, Aspendos, Termessos and Perge, are modeled geometrically by using plans which are prepared by Ferrero (1966,1969,1970). Digitizer has been used in order to reproduce three dimensional models on AUTOCAD from Ferrero's plans for acoustical simulations. On the other hand, these plans are not exactly measured surveys and non-existing parts of theatres are not included in these plans. The real dimensions and conditions of theatres are not corresponding to the plans exactly. Differences between acoustical measurements and simulations for some receiver positions can be explained by all these reasons. However, this study proposes a model in order to analyze acoustical characteristics of open-air theatres. It is necessary to perform more accurate measured surveys if an acoustical design is implemented on an ancient theatre.

RAYTR program has the advantage in order to specify geometries of theatres with desirable numbers of planes. Curved surfaces which constitute theatre seating must be approximated by a series of planes. The geometry of Aspendos theatre is specified with 95 planes in this study. However, this number is inadequate in order to model the real case. Theatres should be specified by a greater number of planes for more accurate results. Some differences are shown between the simulation programs RAYTR and IMAGE because it is possible to input very detailed geometry of theatres with desirable number of surfaces and their properties by RAYTR simulation program.

Random generation of the sound rays is also responsible for some differences between acoustical measurements and simulations. The program should run a few times for same numbers of rays in order to optimize acoustical response results. Another criterion which affects the results is specified size of receiver. The large size responsible for non-unique rays that fall into the receiver sphere in RAYTR is opposed to point receiver in IMAGE simulations and nearly point receiver corresponding to the microphone dimension in the measurements. In contrast, specification of small size for receiver sphere cannot sometimes determine the exact place of receiver which is used in measurements especially for very large theatres just as theatre of Perge. An optimization is necessary for the radius of receiver sphere connected with the capacity of each open- air theatre.

Through this proposed model study, despite the limitation of software, the theatre of Aspendos is shown to possess superior acoustical characteristics on the basis of slope, hearing angle, stage back-wall height, smooth orchestra surface and speech transmission index figures when compared to the theatres of Perge and Termessos. However, it has worst set back on the basis of normalized averaged distance because of its semi-circular Roman shape.

8.6.1 Present Uses of Ancient Theatres

The importance of the skene and orchestra surface for acoustically good design was emphasized previous part of the study. If original stage building of an ancient theatre is damaged, a temporary stage should be set up during the performances. Reflectors should be placed on this temporary stage wall. Correctly placed reflectors provide significant reinforcement of direct sound. Reflectors should be positioned, or angled, so that the uppermost rows of the audience could benefit from the reflected sound. The reflector should preferably be overhead so that reflected sound is not reduced by `audience absorption` as is often the case with wall reflectors. The reflectors can be positioned and angled by means of acoustical simulation software's on computers.

The side walls of the stage building and lower part of the kavea walls which are facing the stage wall are responsible for the flutter echoes. These walls should be covered by absorptive materials in order to prevent possible late reflections. If a new open-air theatre is designed these walls should be angled correctly instead of being located parallel in their original form. RAYTR simulation program can be used in order to determine the difference in energy quantity for different absorption characteristics of surfaces in each frequency band. The side walls which is measured from flutter echoes or stage back walls and orchestra surfaces which are reinforced acoustically can be optimized by changing the absorption characteristics of the planes.

CHAPTER 9

IMPLICATIONS OF ACOUSTICAL DESIGN

9.1 Re-use of Ancient Theatres

Anatolia is a country which houses many old civilizations and their material remains. These civilizations have been interested with the remains of older cultures, and restored and used them. Restoration was carried out using brick in theatre of Aspendos in Seljukid times. This theatre is the best conserved one in Anatolia because of Seljuks' restoration. Turkey has been a focal-point of interest for foreign tourists because of her cultural and historical riches. Since the conservation of the historical environment is a whole, the process in the protection of these values can be examined as a whole also.

Anatolia houses many historical buildings belonging to Greek, Hellenistic and Roman periods besides many other ancient civilizations. Theatres are one of the splendid buildings of these civilizations. Some of the theatre buildings which have survived to our era continue to be used as spaces for various contemporary performances and festivals. In addition to these activities, they are visited by numerous native and foreign visitors in the tourist season. In the Mediterranean region however, the architectural and cultural heritage belonging to various civilizations has been affected negatively because of misuse. Especially ancient theatres have been damaged on account of commercial use. Indeed, only controlled performances should take place in these theatres; the capacities of the theatres should be determined and these capacities should not be exceeded.

Ancient buildings should continue their lives by use, however they ought to be restored in case of need. The balance of conservation versus use should be provided by a master-plan on a country-wide scale.

9.1.1 Conservation and Restoration of Ancient Theatres

The use of ancient buildings requires their restoration and maintenance. For restorations, preferences ought to be determined by a master plan. The determination of these preferences depends on a properly prepared inventory. The heritage of Anatolia which has survived is very rich. This richness has forced the limits of conservation. The researches on this heritage ought to be started and completed in a short time and should be done with great attention to detailed documentation and study. The recording of cultural and natural values, and preparing documents related with their identity are important as an inseparable part of the cultural inventory of the country. The participation of all academic and public institutes to recording studies ought to be arranged. The damages and changes of quality on the natural and cultural heritage have gone into a very rapid process. A much faster and more efficient recording speed is necessary in order to keep up with the pace of this rapid destruction. These documantations will have to be used by later scholars, therefore, the standards should be established for descriptions.

After defining the cultural identity of an ancient building the design stage of restoration can start. The project should be prepared by specialists including restoration experts, architects etc. However, the restoration project of important ancient buildings should be developed by a team of specialists. For instance, architects, restoration experts, specialists of statics, acoustics and building materials etc. should be present in the restoration team of an ancient theatre. All survey and restoration projects ought to be kept in a documentation centre.

The education of technicians and assistant personnel are necessary for healthy restorations. There are some problems in the application such as lack of control and difficulty in obtaining authorized specialists and technicians. Especially, the use of building materials and control of application techniques are important on account of preventing destructive restorations. The effective control and consultant service ought to be provided by the Ministry of Culture. The ministry has got unqualified constructors who have "A" group construction records to do restorations (1). Restorations performed without projects by incompetent constructors can cause severe and sometimes, irreversible damage. In the restoration of the ancient theatre of Side, for example, one seating row has been omitted as a result of carelessness concerning the thickness of building material. This change causes deformations not only on the geometrical and architectural characteristics of the theatre, but also affects acoustical properties which depend on geometry. In order to prevent destructive restoration, consolidation can be sufficient when there is a lack of specialists, building materials and construction technique.

Before starting restoration, the new functions of buildings should be determined in advance. Planning and equipment ought to be planned considering the properties of the new function. In the same way, decisions related to environmental planning and sub-structure (toilets, transportation, parking area etc.) should be taken before restoration proceeds.

Measures ought to be taken to prevent destruction caused by visitors at the archaeological sites. Ancient theatres have a large potential with regard to tourism. They are visited by thousands of tourists in the tourist seasons. In 1988, the theatre of Aspendos took sixth place in order of the most visited archaeological sites. In that year, 241005 foreign and native tourists visited this theatre. During the same year, the theatre of Side was visited by 159829 tourists. Numbers of visitors for theatres of Perge, Side and Aspendos on the basis of data obtained from Directorate of Culture in Antalya are as follows;

	1993	1994
Perge	201330	157928
Side	262866	151586
Aspendos	287934	317042

There are important responsibilities of tourist guides concerning the protection of ancient theatres, as well as other ancient buildings. While theatres in restoration are shown to the tourists attention should be paid for the parts of the theatre which are not strong enough. (e.g. stage building of theatre of Perge). The tours should be organized by a central organization taking into account the equal distribution of the numbers of tourists during the visiting hours of the day.

9.1.2 Use of Ancient Buildings

The participation potential to the environment and flexible possibilities for adaptive contemporary functions of ancient buildings determine their functional values. Variables related with the social, cultural economic and political life of the community are effective on the functional value of these buildings.

The functional value of ancient theatres is quite high. These buildings can be used for tourism and cultural purposes. However, the use should be consciously regulated. While spatial needs increase parallel to the population of towns, the use of existing ancient buildings provides both transfer of history today and creation of spaces which have a contemporary character. It is indeed a pleasure to follow a modern performance in an ancient theatre which has occurred in this way. Existing ancient buildings can be appreciated by continued use through restoration instead of constructing new structures.

It is an incredible fact that the two thousand year old ancient theatres are still in usable condition in Turkey. However, the kinds and frequencies of performances should be determined and their specified capacities should not be exceeded in order to protect them from possible damage. The most suitable function compatible with the original function ought to be given to the ancient buildings by minimum interference for future uses.

Anatolia houses about fifty ancient theatres in different sizes. Besides these existing theatres, there are approximately fifty more theatres which are waiting to be brought into action after the completion of their excavations. While there are so many theatres which need excavations and restorations, it is necessary to take great care of existing theatres in suitable conditions. Most of the ancient theatres appear in the Mediterranean region and they also constitute spaces for touristic activities in the region. However, there are negative aspects in the use of these buildings. In this respect, items for conscious use of the ancient theatres can be examined in three groups:

9.1.2.1 Consolidation

The use of theatres which are not strong enough and which have some damaged parts would cause their further destruction of them if not consolidated and restored before use. Most of the theatres in the Mediterranean region need to be in a better condition. The audience capacity should be determined for the theatres in usable condition and care should be taken never to exceed it. The numbers and frequencies of performances ought to be defined according to an annual plan.

9.1.2.2 Providing Sub-structure and Comfort Conditions

The use of ancient theatres which do not have the necessary sub-structure and comfort conditions can cause harm to these buildings and their environment. Because of insufficiencies in the garbage collection system, the numbers of closets and other comfort conditions, the immediate environment of theatres may turn into a garbage area. The cleaning process can take a long time because of discarded plastic drink-bottles which have long life durations. To protect the immediate environment, all necessary sub- structure and comfort conditions should be provided before theatres are opened-up for use.

9.1.2.3 Kinds of Activities

Theatres can be used for various purposes, whether it be cultural, commercial or touristic. However, the number of cultural activities is usually less than the numbers of touristic and primarily commercial activities. Generally, public concerts should be understood as belonging to commercial use. These kinds of concerts may not be said to include any traditional cultural dimensions.

Theatres of Aspendos and Side have been used for various performances during tourism seasons. Because of the suitable climatic conditions of the region, these buildings can be used approximately eight months. Public concerts took an important place in the theatre of Aspendos in 1990. About ten concerts were performed by Turkish folk, pop and classic music singers or groups. (Information from Directorate of Culture, Antalya).

Besides public concerts, about ten shows which have multi-purpose characteristics took place for touristic purpose in 1990. Five more shows were performed by special groups and can be added to these activities. These performances had either show or folklore characteristics. Occasionally, they were geared towards concerts also. A demonstration of "Sema" ceremony (dervish music/dance) may be presented besides a show which has traditional values such as the presentation of a section from ancient Roman life by these kinds of groups.

In the theatre of Side, six performances appeared for third age groups in 1990 (2). This theatre can be evaluated for the activities of touristic purpose due to the fact that it is located at the central points of accommodation units. However, some walls and parts of the auditorium (theatron) require consolidation and restoration.

It is detrimental to sell an excessive number of tickets in the public concerts in the theatre of Aspendos. The seating capacity of the theatre is around 9000 persons. However,due to the lack control, 15.000 tickets can easily be sold for concert to which may be added the activities of lotteries of newspapers. Moreover, it is possible to enter the theatre without a ticket from the upper galleries. In this respect, entrances should be controlled in order to keep the numbers of the audiences fixed.

The theatre of Aspendos is a magnificent building which exists not only in Turkey but also all over the world. From this point of view, the balance of conservation versus use should be established carefully. For this reason the income which is provided by visitors and from the use of the theatres should be returned for restoration and consolidation of ancient theatres.

Theatres of Aspendos, Side and Ephesus have maximum capacity for use. The theatre of Aspendos has the best physical condition among them all. The traditional Selçuk- Ephesus Festival took place in Selçuk instead of Ephesus ancient town because of the restoration in the ancient theatre of Ephesus in 1994 (Cumhuriyet, 31 Mayıs 1994). Similarly permission was not given to a very famous popular singer for a concert in theatre of Ephesus. This is another example for consciousness in the use of ancient theatres.

While public concerts could be limited in number, cultural activities ought to be encouraged. For public concerts modern open-air theatres could be used instead. However, it would be difficult to find an open-air theatre such as theatre of Aspendos if it were destroyed. An eclectic approach should be followed in making decisions for the kinds of performances. The universal dimensions of activities plays an informative role on the touristic development of the country.

9.1.3 Proposals for Re-Use Coordination of Ancient Theatres

The misuse of magnificent ancient buildings such as theatres can cause damage to their construction and close environments. Income which is provided from visitors and the use of theatres has been collected by private administration which encourages their commercial use, although these kinds of activities destroy them.

The conservation, use and control of these buildings ought to be collected under the same roof. The conservation and use should be realized by a completed plan in all aspects. *By this plan the principles and techniques of conservation, and the principles and conditions of use ought to be clearly determined.* Careful planning should be exercised by optimization of conservation versus use. Components of conservation and use of ancient buildings are not only related to the physical surroundings but also to the social dimension of the problem. An appropriate use can play important roles on the cultural-structure of society and tourism.

Today, there is no healthy coordination and distribution of duties and authority among the Ministry of Tourism and Information, Ministry of Culture, private administrations and local governments. At this point, financial resources, authority, responsibility and control could be collected in only one centre. Special Provincial Government (Il Özel Idaresi) in Antalya has acquired five billion TL. from entrance fees to archaeological sites in 1990, while the Ministry of Culture had difficulties to finance restoration of ancient buildings. Entrance fees have been determined by Ministry of Tourism and Information. These three institutions appear in different duties, moreover there is no integration between them with regard to efficient cooperation.

At this point, the advantages of the local government approach should be discussed instead of the central government system for conservation and use of ancient buildings. For example Universities, related public institutions, municipalities, superior organization of touristic establishments, chambers of trade and industry, etc. can form a consortium. This authorized institute can produce effective work on the form of conservation and use of ancient buildings and archaeological sites, entrance to museums, tourism planning of the region, protection of natural resources, etc. In this way, the existing economic and bureaucratic confusion can be reduced.

There exists an important role for education which starts at the pre-school age for establishing consciousness of conservation and use of cultural heritage. In addition, the public participation in the conservation and use process and support by media are useful to understand the dimensions of the problem and to find measures for the problem.

9.1.4 Acoustical Design Proposals for Ancient Theatres

Acoustical design measures should be taken after completion of the consolidation process in ancient theatres, in accordance with characteristics of theatres and performances. Components which affect acoustical design proposals are scale, form and building materials of theatres.

Theatres which have large capacities like Perge need loudspeakers during musical and theatrical performances. The selection for locations of loudspeakers is an important factor for acoustically good design. Loudspeakers should not disturb actors and musicians. Voices of actors should not interfere with one another. Loudspeakers should be directed toward receivers. Distances between loudspeakers and each receiver should be determined to limit possible echo phenomenon. In cases where echo is unavoidable, electronic means such as time delay units need to be incorporated in sound amplification system. Theatres of Aspendos and Termessos do not need loudspeakers because of their more appropriate space capacities. Ideally, no seat should be more than about 20 m from the stage on the central axis (Moore, 1978: 187).

The importance of stage building (skene) and orchestra was emphasized in previous sections. Reflective materials should be used for these building components. The skene building and orchestra surfaces of ancient theatres used for various performances should be restored according to their original form and materials. If restoration is not possible, temporary stages with their back walls should be set up on the orchestra. Stage walls should be formed in order to reflect the sound to receivers. The materials of the walls and ground of the temporary stage should be selected to be reflective as possible. The form of stage walls in order to achieve acoustically good design is examined in a Russian investigation. (Bledsoe, 1971: 532- 542)

9.2 New Open-air Theatres

New open-air theatres have not been analyzed acoustically in this study. Neither acoustical simulations nor measurements were performed for new open-air theatres, because the main purpose of this study was to examine and compile data on the acoustics of ancient theatres. However, to benefit from the results of simulations and measurements which were performed on ancient theatres, ramifications for new open-air theatre designs were also considered.

Parameters for acoustically good design of open-air theatres by ancient architects were examined in the Discussion section of Ancient Evidence. In this section Vitruvius' Ten Books on Architecture was analyzed in detail with respect to the acoustics of open-air theatres. The main concepts of the book can be enumerated as follows;

. Selection of the site: This has been an important criterion, especially in the modern period since interfering background noises like traffic is very likely in crowded towns. Noise is certainly not a new problem. It has been a source of discontent ever since people have begun living in communities. There are references scattered throughout literature to noise problems caused by early industrial activity and by transportation. For example, in the Greek city of Sybaris in Italy in about 700 B.C., the authorities required that potters and tinsmiths should carry out their business outside the city walls because of the noise they made. This might be regarded as an early form of industrial noise ordinance. A few centuries later, we find several references in Roman literature to noise. Horace, Juvenal and Martial all complained about noise, mostly of "traffic". Apparently the chariot wheels on the cobbled streets were mainly to blame. The Roman authorities responded with a traffic noise ordinance banning delivery vehicles from the Forum because of noise and congestion (Crocker,1981:11).

. Sound Theories; Ancient architects had great experience and knowledge about sound theories and geometrical room acoustics. They had the ability to apply acoustical theories to open-air theatres. However, architects of our era unfortunately are not always aware of the importance of acoustical design even for the buildings like theatres or concert halls. Many open-air theatres which have been built in resorts and in holiday villages do not have stage buildings. In the new open-air theatre of citadel in Antalya, the stage building is non-existent while there are many standing examples from ancient periods surrounding the town. The skene of an ancient theatre is a very important factor on the reflection of sound waves. Experiences gained through ancient times should be exploited in the acoustical design of modern theatres.

. Building materials: Ancient architects proposed reflective material (wooden stage) for all public theatres. Various materials have been produced especially for acoustical purpose in modern times. Contemporary architects should know about the properties of traditional and new materials. The choice of the materials is an important factor which affects the acoustics of open-air theatres.

. Sound vessels: Vitruvius describes sounding vessels which were tuned to resonate to certain pitches of the actor's voice were placed in the auditorium. Modern acoustical devices like resonators and electronic devices can be used when necessary. Loud-speakers should also be used according to the kind of performances or the capacity of theatres.

. Plan of the theatre: Greek and Roman architects developed the theatre form of their time. They had experience about theatre geometry and its influence on acoustical design. They maximized the slope of the auditorium in order to provide good sound propagation.

9.2.1 Requirements of New Open-air Theatres

In Turkey, especially in the south and west there are opportunities for the use of open-air theatres for almost whole year because of the suitable climate of the region. Even in the regions which have the coldest climate, open-air theatres can be used for at least six months. Every town had one open-air theatre or more in the ancient Greek and Roman periods in Asia Minor for their ceremonious and various other performances. However, today's crowded towns do not have open-air theatres which have large audience capacities for either music or theatrical performances.

There are some contemporary examples of open-air theatres in Turkey. Açık Hava Tiyatrosu in Istanbul and Seymenler Parkı Açık Hava Tiyatrosu in Ankara are among these. Obviously, these theatres are insufficient to provide the needs of the town. Hippodromes and stadiums have been used for popular and classical music concerts in recent years. As examples, several musical events attracting audiences numbering in the thousands were performed at Kartal Stadium and Ankara Hippodrome. Open-air theatres are more appropriate than stadiums or hippodromes which have not been built for performances of famous international artists. Ancient theatres have been also used for concerts in recent years. For example, a rock concert was performed at the theatre of Ephesus. World famous opera stars sang at theatre of Aspendos in the summer of 1993. To listen to world-wide famous opera singers in a two thousand year old ancient theatre like in Aspendos is indeed a very exciting event. However, a careful control of use is necessary in order to keep these theatres alive for centuries to come. The first Aspendos Opera and Ballet Festival took place in June 1994. Rumelihisarı Açık Hava Tiyatrosu also provides a considerable space for many performances in recent years.

It is obvious that, modern open-air theatres are inadequate for city needs. Ancient theatres which can be still used provide opportunity as spaces for various performances. Today, ancient theatres have become fatigued because of the density of activities. It is proposed by the Association of Archeology and Archaeologists that ancient theatres should not be assigned to concerts and other activities. New functions which are not compatible to original functions of cultural existence's of country cause their wear and destruction. (Cumhuriyet, 9 May 1994). However if the frequencies and quality of performances and numbers of audiences are controlled, and if these theatres are strong enough, they should be kept intact through use.

NOTES

(1) There are four groups of constructors which are A,B,C and D according to bidding law. "A" group constructors can award the biggest contracts of ordinary buildings. "D" group constructors are specialists of restorations. It is given permission to "A" group constructors for also restorations in recent years. This kind of implementations can cause damages on the ancient buildings.

(2) Third age group is a terminology of tourism sector which is used for people over sixty-five.

CHAPTER 10

CONCLUSIONS

The main purpose of this study is to investigate and explain the excellent acoustics of ancient theatres by conducting acoustical measurements and simulations. A model has been developed by geometrical room acoustics approach for analyzing their acoustical characteristics of these theatres. There exists no previous study including acoustical measurements concerning the acoustics of ancient theatres in Turkey. Computer techniques and acoustical measurements were not used in earlier studies by Canac and Papathanasopoulos which constitute seminal research in the field of ancient theatre acoustics.

The procedure undertaken in this study is as follows; firstly, the ancient theatres suitable for measurements and simulations were chosen; secondly, acoustical measurements were performed in these selected theatres, Aspendos, Termessos and Perge in 1989; then, the measurements were repeated in the following year, 1990, in the theatre of Aspendos. The acoustical measurement records were later analyzed. This study is a prototype to analyze the acoustics of open-air theatres by the geometrical room acoustics approach. However, recent technology makes it possible to get the acoustical impulse results simultaneously as the measurements in the theatre are taken and to record for more detailed and accurate anaysis.

Methods of image sources and ray tracing are used to simulate ancient theatres on the computers. Recent computer technology is also improved to make possible the analysis of larger sound-ray files in shorter time. It is discovered that main frames are more suitable for the investigation of numerous sound source-receiver position configurations. The AUTOCAD software with its three dimensional modeling possibilities can be used with RAYTR as a whole for numerous planes which consist of theatre surfaces and a series of receiver-source pairs. A program has been developed by Topaktaş (1995) which can be put to use comfortably by architects for acoustical analysis of both open and closed spaces as demonstrated by this study.

It is observed that the acoustical characteristics of open-air theatres can be determined by RAYTR. The number of planes in the theatres, number of rays produced for acoustical simulations and the desirable number of receiver- source configurations can be specified by the user. The program presents possibilities for analyzing the acoustical characteristics of both existing buildings and buildings still in the design-process. Future development of the computer program, RAYTR, should be towards optimizing the number of produced rays, the number of planes which define the theatre geometry and the order of reflections. The number of valid rays should be the quantities which can be analyzed easily. The analysis of complicated acoustical response graphics are generally difficult and sometimes inessential. More user-friendly programs would be more appropriate for architects who engage in the acoustical design of a theatre. In this respect, for example, to use the names of the planes instead of their numbers in the path analysis can be more useful to determine their acoustical characteristics such as echo-produce or sound-reinforcement surfaces.

This study proposes a model in order to analyze acoustical characteristics of open-air theatres. Indeed, the results of this study can be used by scientists or technicians who are familiar with the topic. However, the main purpose is to apply the method for acoustical designing in ancient theatres which are generally used in the tourism seasons. This method can be extended to all open-air theatres which are in re-use or contemporary theatre buildings. If the method is applied to an ancient theatre, the exploitation of the measured survey for geometrical specification of theatres is proposed for more accurate results.

Turkey has many ancient theatres still in use. The re-use of these theatres constitutes potential for tourism or general purposes. However, the use of these ancient theatres should be more consciously oriented toward their original function. In this respect, the balance of conservation versus use should be established carefully. Parameters for acoustically good design of open-air theatres by ancient architects should be utilized by also contemporary architects. The experience of the ancients concerning theatre geometry and its influence on acoustical design, and the maximization of the auditorium slope should be taken into consideration and/or re-interpreted by contemporary architects. Design of open-air theaters everywhere is a recent fashion among architects. However, the function of these theatres are generally not specified while the function of the ancient Greek theatres were highly specialized and the requirements of the function in question such as the skene building or correct material use for the orchestra surface were adhered to. There are many recent open-air theaters without stage buildings. The open-air theatre in Antalya Citadel is an example of the type with no stage building (Appendix F, Figure F.5).

The acoustical characteristics of the Aspendos, Termessos and Perge theatres have been determined by acoustical measurement and simulations in this study. The problematic regions of the auditorium with respect to acoustical response are examined for 20-25 receiver-source configuration in these three theatres. The main findings of the study with respect to their acoustical design can be summarized as follows:

. The significance of the skene and orchestra surface emerges; these architectural elements have an important role on the reinforcement of the direct sound by the first order reflections.

. The semi-circular forms of the ancient theatres are very suitable for reducing normalized average distance. This characteristic is important, especially, for open-air theatres from the standpoint of shorter direct sound paths. The sloped auditorium generates an advantage for increasing the hearing angle.

. The side walls of the skene are observed as problematic surfaces with respect to practical sound source locations on the orchestra. These surfaces cause the undesirable late reflections. Hence, to minimize this effect, these components should be covered by absorptive materials in the future use of ancient theatres. The portable surfaces should also be positioned on these side walls in order to change the reflection-angle.

.The lack of ceiling cover in open-air theatres is a disadvantage. However, a temporary or portable orchestra shell can be constructed for the future-use of ancient theatres. According to the characteristics of performances, the reflectors can be formed and angled by using the simulation program RAYTR. However, it may be difficult to optimize a sound reflector for a single sound source at a fixed source position. It is even more evident that the concave reflecting enclosure for multiple sound sources present much greater difficulties. Nevertheless, most orchestra shells have been built with at least concave cylindrical boundary surfaces and sometimes even as a concave quarter-sphere (Cremer, 1978: 103-104). In order to avoid unequal sound distribution from an orchestra enclosure it is better to surround the orchestra by a few, properly directed, plane and stepped surfaces. Such an orchestra shell was developed by G. Izenour for the ancient theatre in Caesarea (Israel). The overall enclosure is basically made of large plane surfaces, but; on a smaller scale, these are folded so that they provide a certain degree of diffusion in the reflected sound, to improve communication among the musicians or performers. The construction of this enclosure, because of the archaeological additional requirement of archaeologists and visitors to the site as well, is such that it can be moved laterally out of the view of the visitors when not needed for a performance (the plan, the section and the photographs of this design are shown in Appendix F).

. It is observed that some sound rays strike the kavea first, and then reach receiver in acoustical simulations. The number of audiences, or empty or full condition of the theatre is a factor on its acoustical characteristics. The reflective characteristics of the orchestra surface and skene are more significant factor while the theatre is full with respect to absorptive properties of audiences. The simulation of the theatres is possible for full or empty conditions by changing the absorption characteristics of kavea.

. Through this proposed model study, despite the limitation of software, the theatre of

Aspendos is shown to possess superior acoustical characteristics on basis of slope, hearing angle, stage back wall height, smooth orchestra surface and speech transmission index figures when compared to theatres of Perge and Termessos. However, it has the worst disadvantage on the basis of normalized averaged distance because of its semi-circular Roman shape.

The findings of this study are also used in the design of modern open-air theatres. The criteria which are used in contemporary theatre-design may be proposed as follows:

. The selection of the site for the open-air theatre is a very significant factor in acoustical performance. The level of background noise should be as low as possible. The trees or plantation around the theatre can be useful to absorb and obstruct background noise. However, the wind direction should be considered according to the noise effect to the wind. In any case, a quiet region of the cities should be chosen for the site of the theatre.

. The audience should be protected from strong wind. The avoidance of the dominant wind direction is an important criterion in locating open-air theatres.Theatres must be oriented in such a way that the dominant wind direction is from the orchestra towards the audience.

. The equal intelligibility contour should be used to determine the optimum shape for the auditorium in relation to stage design. The semicircular form is suitable for the shorter path of direct sound.

. The auditorium should be banked steeply and the stage should be raised. Reflective floor materials should be used on stage for reinforcing of direct sound.

. No seats should be placed more than approximately 20m from the stage. The long distance between the direct and reflected paths of the sound can cause echoes in very large theatres. Distance is also a significant factor for the direct path of sound which affects speech intelligibility. The theatres can be simulated in different forms for acoustically ideal design by RAYTR.

. The design of the orchestra shell is very important for the acoustics of open-air theatres. In this field the study of Alekseer (Bledsoe, 1971: 531-542) has proposed acoustical design principles for outdoor theatres. The number of surfaces which constitute the stage are analyzed on the basis of the level of intensity of direct sound. When the numbers of reflected surfaces increase, the intensity of direct sound also increases. The angles and materials of reflected surfaces are also significant for designing both stage walls and the ceiling in orchestra shells. As an extension of this study the patterns for orchestra shells which are acoustically ideal can be prepared by RAYTR for the use of stage-designers. Shapes, angles, and materials of reflective or absorptive surfaces which are optimized by the computer simulation program are proposed for use in modern open-air theatres. The designed orchestra shells may also be simulated by architects instead of using the proposed patterns with respect to design-freedom. Valuable proposals for the design of orchestra shells are given by Knudsen and Harris(1978: 68-73) with respects to the reflective power of the well-designed shell which increases the average sound level throughout the theatre and enables a more uniform distribution of sound pressure over the seating area.

. The comparatively recent technique for making scale models of open or closed auditoria can be introduced and the results are checked. It is an expensive approach to specify acoustical characteristics. If time and money are not to be wasted, the designer must get as near as possible to a good solution of his problem before the model is built. Although the three-dimensional acoustical model does not permit us to visualize the sound propagation, we can measure and record the sound pressure at locations in the model corresponding to the same locations in the proposed room. From such a test it should be possible to detect faults such as echoes and standing wave phenomena and compare the amount and quality of reverberation in the various parts of the auditorium (Moore, 1978: 197-198). This approach was applied by Canac (1967: 83-102) in the ancient theatre at Orange.

Finally, it should be noted that this study was realized with the interdisciplinary collaboration of architects, mechanical engineers, archaeologists, restoration experts and architectural historians. It is very meaningful and encouraging indeed that the contribution of all these different researchers could be achieved for the analysis of acoustical characteristics in the ancient theatres of Aspendos, Termessos and Perge in this study.

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APPENDIX A

HISTORY OF PAMPHYLIA AND PISIDIA AND SELECTED ANCIENT THEATRES FOR ACOUSTICAL MEASUREMENTS AND SIMULATIONS

A.1 History of Pamphylia and Pisidia

It is still a question how the Pamphylian region passed from the prehistoric age to the historical period. The Hittites who settled mainly in the great loop of the Halys River, extended their borders across Asia Minor. Hittite documents of the end of the 2nd millennium B.C. make mention of 'Ahhiyawa' or 'Arzawa' land, which is supposed to be in the Pamphylian region (Atila and Aydal: 5).

Pamphylia was always under the control of Anatolian states or the power which ruled the whole of Anatolia. The region was invaded by Lydian rule in 547-546 B.C. After Lydian rule Pamphylia came under Persian rule until Alexander the Great invaded Pamphylia in 334 B.C. After his death, the empire was divided among his generals. Antigonus was the first, Pleistarkos' rule followed this period. After Pleistarkos' fall, Pamphylia was governed sometimes by the Ptolemies, who tried to gain over the Mediterranean and sometimes by the Seleucids in Syria. The Roman general Manlius conquered and imposed tribute later on. Quite soon afterwards the western part of Pamphylia was invaded by the Pergamene king Attalus II, at which time the port-city of Attaelia was founded (Atila and Aydal: 5).

In 133 B.C. Pamphylia was bequeathed to the Romans in the will of Attalus III, the last Pergamene king. After a period of freedom it formed part of the province of Cilicia that was annexed by Rome in 103 B.C.

Pisidia is an ancient region of southern Asia Minor, to the north of Pamphylia and to the west of Isauria and Cilicia. To its west the district of Milyas was generally taken as Pisidian but was on occasion included in Lycia, while to its north the populous and strongly hellenized area around Pisidian Antioch was sometimes counted as Phrygian and given the name Phrygia Pisidica or Phrygia Paroreius.

Pisidia included some fertile plateaus and high valleys, such as those of Catarrhactes and Cestrus (Aksu) rivers, which were rich in olives, vines, pastures, timber, resins and iron. But most of the district was composed of the abrupt north-south trending limestone ranges of Mt. Taurus, providing refuge for a lawless population, much given to pillage, which stubbornly resisted its successive conquerors: Alexander the Great, Amyntas of Galatia, and the Roman general Publius Sulpicius Quirinius. At the end of the Republic, the population was organized in small tribes, or in groups of villages known as communes, the chief centres of which were Termessos, Sagalassos, Selge and Cremna.

According to Strabo the Pisidian language was distinct from those of the nearby Solymi and Lydians. The teocratic rule characteristic of ancient Phrygia seems to have prevailed also in Pisidia, where there is evidence of temples with large estates and slave labor, the most famous being that of Men Ascaenus near Antioch.

On the death of King Amyntas in 25 B.C., the greater part of Pisidia was incorporated in the newly constituted Roman province of Galatia, though it was partly regrouped with Lycia and Pamphylia by Vespasian in A.D. 74. Augustus began its Romanization by founding military colonies, first at Antioch and later (c. 6 B.C.) at Cremna, Comama, Olbasa, Parlais and Lystra. In addition, the Via Sebaste was built forward in two directions from Antioch: one branch joining the highway from Laodiceia to Pamphylia at Comama, and the other running to Iconium and Lystra. The advance of Roman civilization was at first slow; and very little coinage was struck in Pisidia in early imperial times, but in the second century A.D. urbanization became more widespread, and baths, markets, gymnasiums, temples and porticoes were built even in the little towns of the Milyades. In the following century, however, the Pisidian cities, like those of many other parts of Asia Minor, suffered a serious decline.

On the reorganization of the empire by Diocletian about A.D. 297, Pisidia was included in the Dioecesis Asiana, and in later Byzantine times it fell partly in the Thracesian and partly in the Anotolic theme (province).

A.2 Theatre of Aspendos

The best preserved Roman theatre in Turkey even in the world is the theatre of Aspendos. The location of the theatre is the southern side of the Acropolis. Figure A.1 shows the location of the theatre on the Aspendos plan. The theatre of Aspendos was partly built with the arch and vault system which was newly developed by the Roman architects at that time. The slope of the ground was also utilized, thus indicating the architect's desire to conform to the age-old Greek custom of erecting a theatre on the slope of a hill.

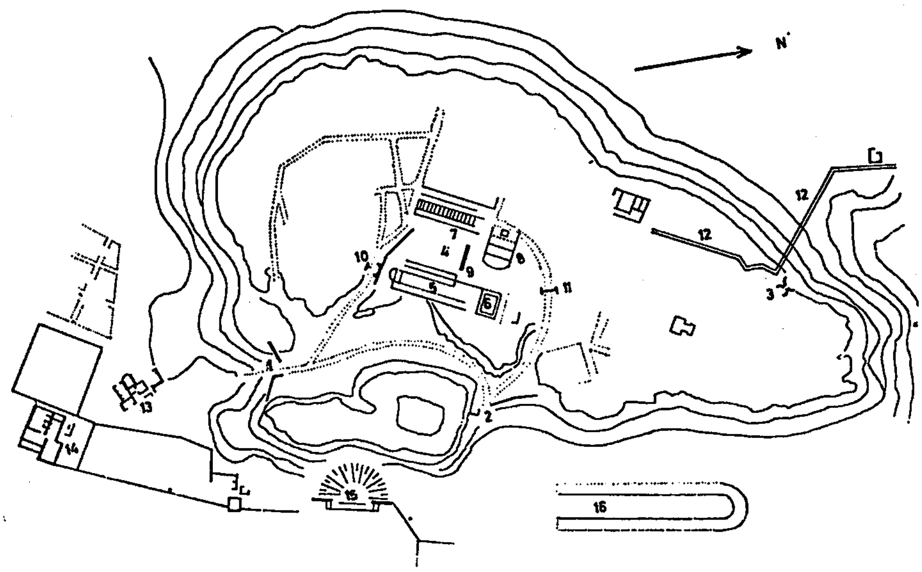


Figure A.1 Location of Theatre in Aspendos (After E. Akurgal, 1978: 334).

The theatre was designed by architect Zeno during the reign of Marcus Aurelius (A.D.161-180). The orchestra is the circular area between the auditorium and stage building. The horseshoe-shaped auditorium was also a Greek feature. In the 3rd century A.D., a stone parapet was built around the orchestra, so that it could be used as arena. In the Greek theatre, the spectators faced a landscape visible from every seat. The Aspendos theatre, on the contrary is cut off from the outside world. The stage building and cavea fitted each other perfectly and the stage building was raised to the level of the cavea finished. The theatre plan and the section are given in the Figure A.2 and Figure A.3.

The building material of the stage building is well-shaped conglomerate blocks. There are five doors at the stage level for performers. The building material of window and door frames are of calcareous stone. Below the artists' entrance, there are two small doors, giving way to the orchestra for wild animals. Four rows of windows were locate on the upper section, one being small and the others larger. The stage building has two storeys, richly decorated with 20 Ionic and Corintian columns. On each storey there are numerous niches supported by small columns.

Plays were performed on a wooden platform (proscenium) in front of the stage building. But in the Roman period gladiatorial spectacles were more important than the plays. While the dramatic masks were used by the actors in Greek comedy and tragedy, humorist accessories were used by the Romans. A general view from the theatre and stage building are shown in Figure A.4 and Figure A.5.

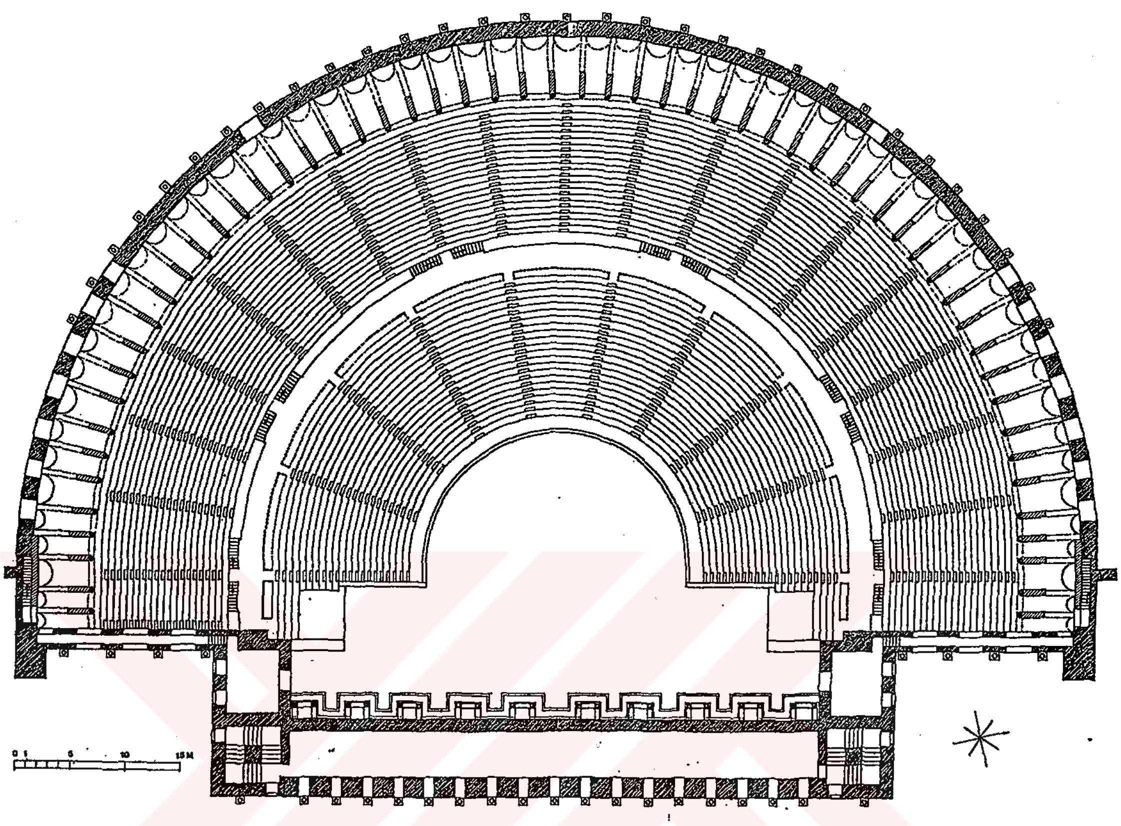


Figure A.2 Theatre of Aspendos, Plan, (After Bernardi, 1970: Tav. XXXI).

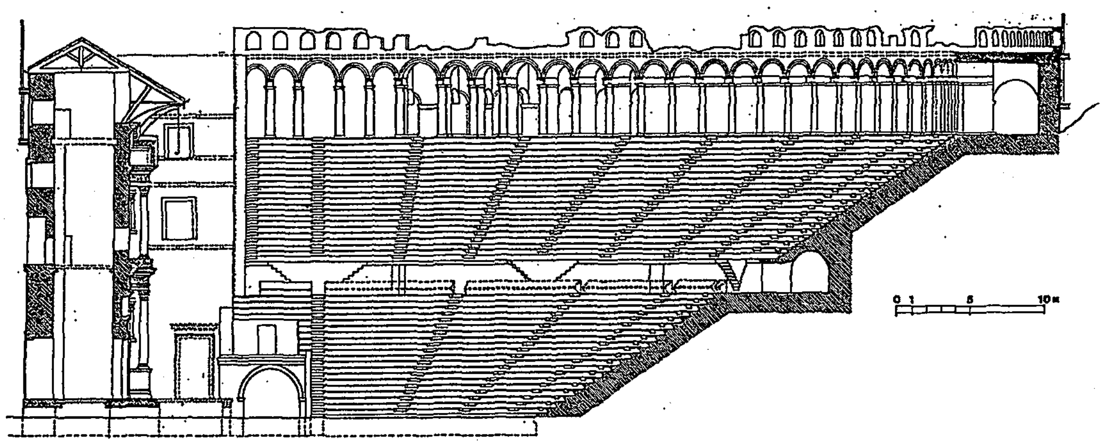


Figure A.3 Theatre of Aspendos, Section (After Bernardi, 1970: Tav. XXXII).

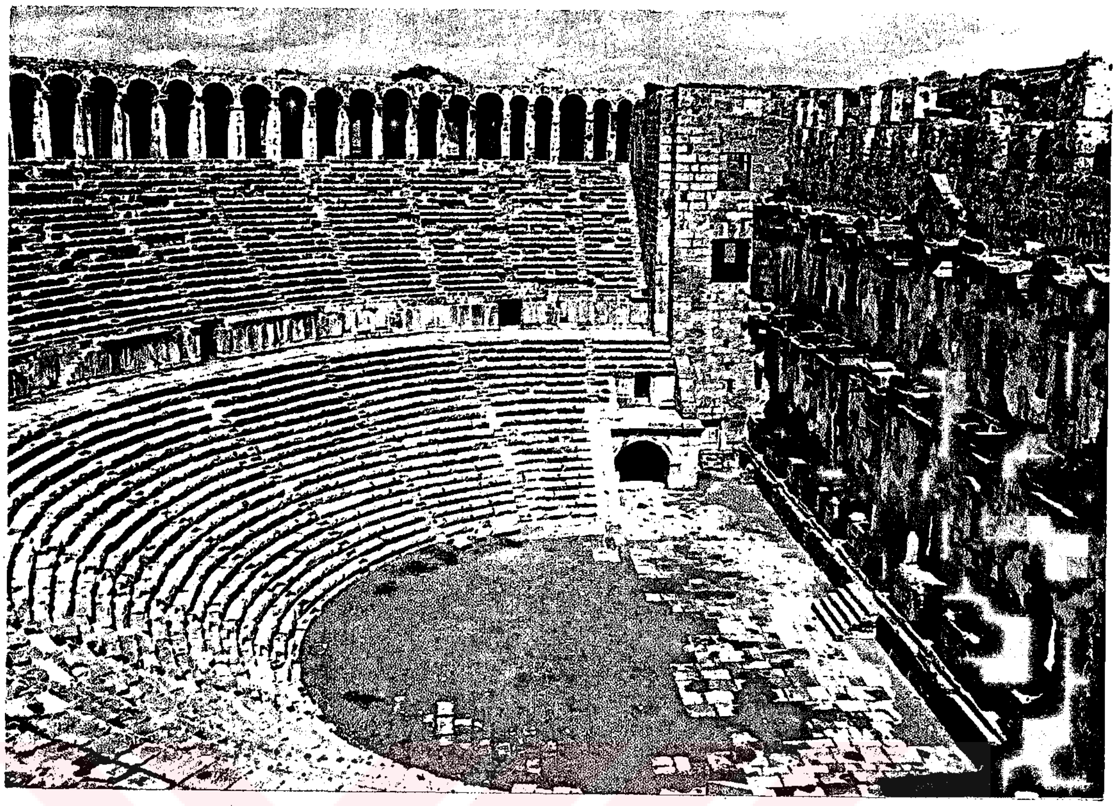


Figure A.4 Theatre of Aspendos, General View.

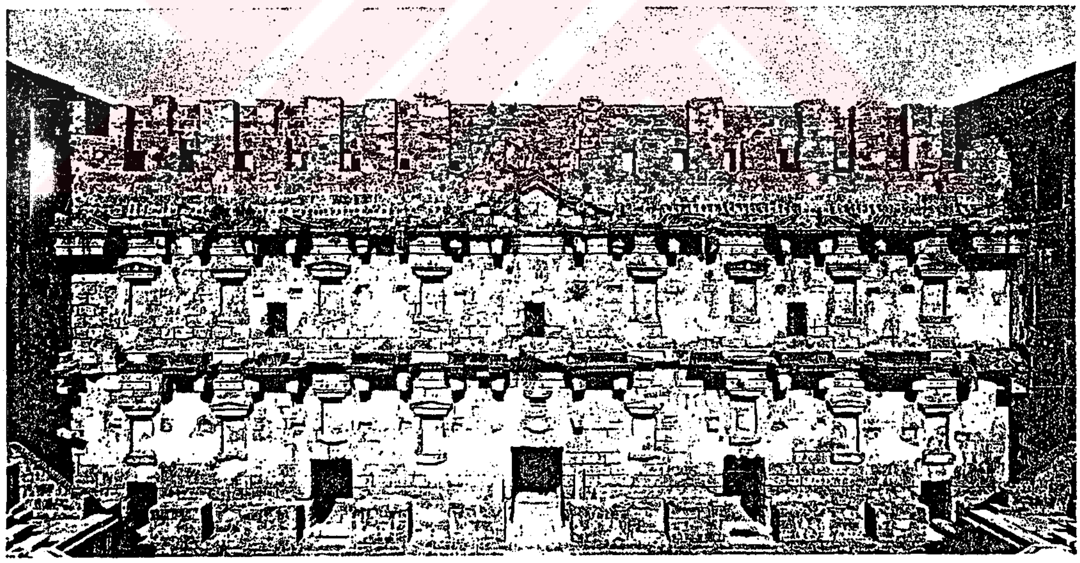


Figure A.5 Theatre of Aspendos, Stage Building.

A.3 Theatre of Perge

This theatre is of the Graeco-Roman type. The auditorium was built against the hillside and it exceeded a semicircle in extent. In addition, the unroofed parodoi (passages) separating the auditorium from the stage building, all perpetuate the Greek tradition, while the diazoma (the horizontal passage around the auditorium) supported by vaulted substructures, the colonnaded gallery running around the top of the auditorium, and the high stage building are architectural features characteristic of the Roman period (Akurgal, 1978: 329-330).

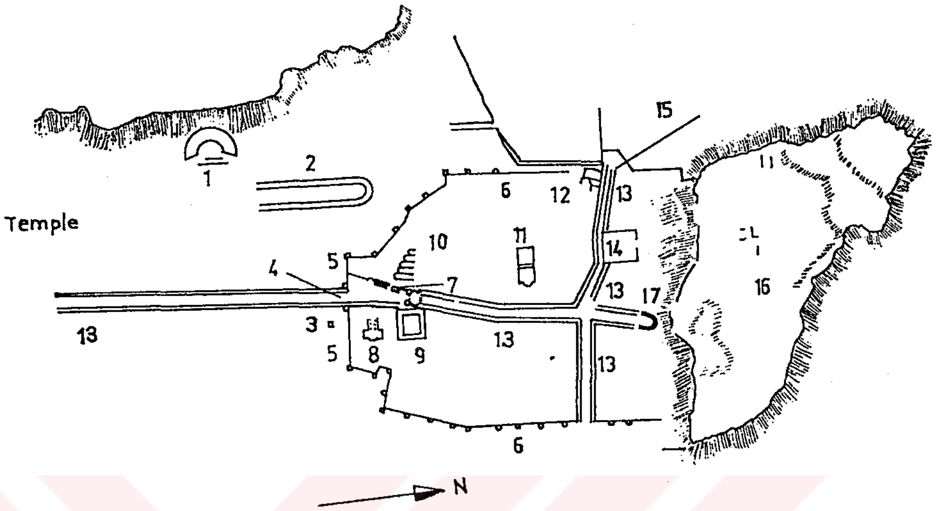


Figure A.6 Location of Theatre in Perge (After E. Akurgal, 1978: 330).

The length of the stage building is 52 m, and it is a tall construction of Roman type. The architectural survey implies that it was a two-storeyed building and richly decorated (Atila and Aydal: 40-44).

There must have been five doors on the facade. The niches on the first facade of the stage were originally decorated with statues. At a later date another wall, 12.2m high, was erected as the outer facade of the theatre, which was converted into a nymphaeum, decorated with five niches. All of the niches contained water basins except the central one. This monumental fountain served as a public water- supply similar to the one at Side.

The theatre could accommodate 15000 spectators, who gained access from the hillside and from the ground level by means of passages on either side of the diazoma and also via the parodoi. The stage building, erected in the second half of the second century A.D., still stands to a considerable height. Judging by the architectural ornaments found, it was two-tiered and richly decorated. It stood on a narrow podium and was decorated with relief's representing mythological scenes. In the late Roman period, when the custom of gladiatorial shows and fights with wild beasts was introduced in Greek cities, a perforated parapet surrounding the orchestra was built on the lower seats of the auditorium, in order to protect the spectators.

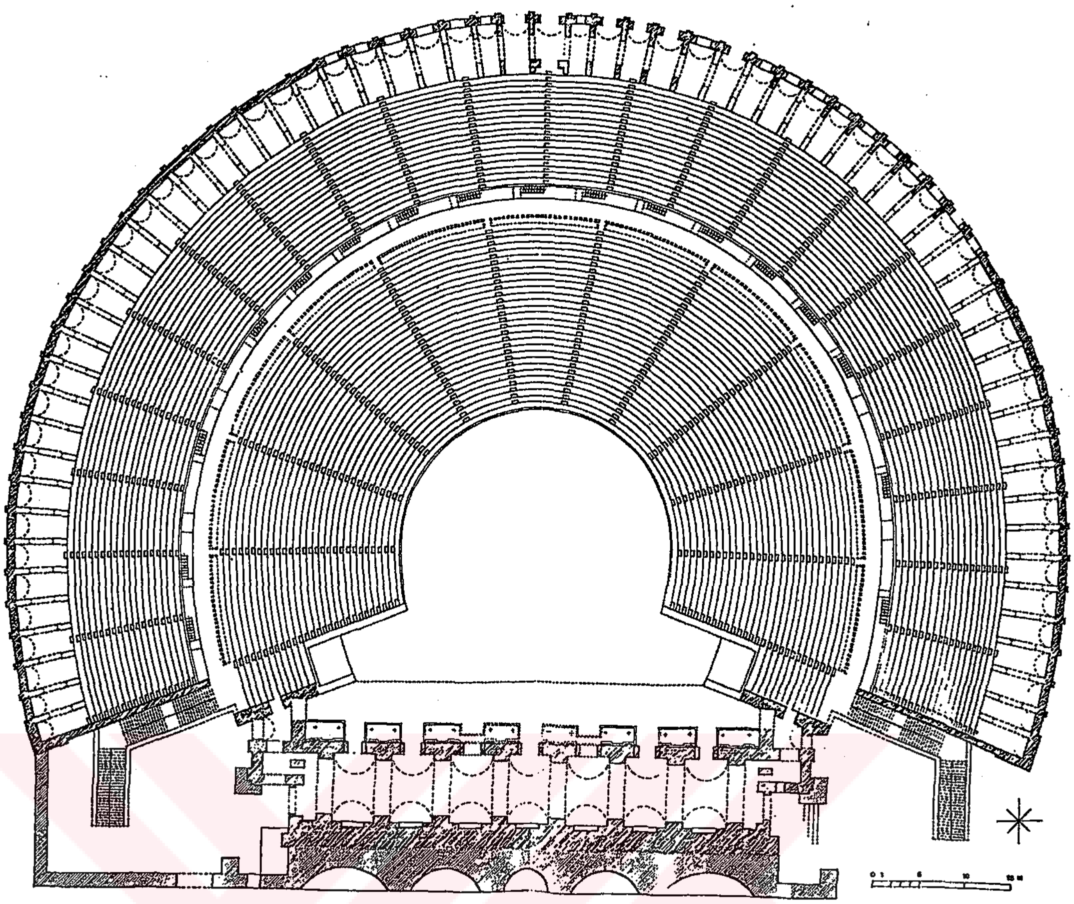


Figure A.7 Theatre of Perge, Plan (After Bernardi, 1970: Tav. XXVIII).

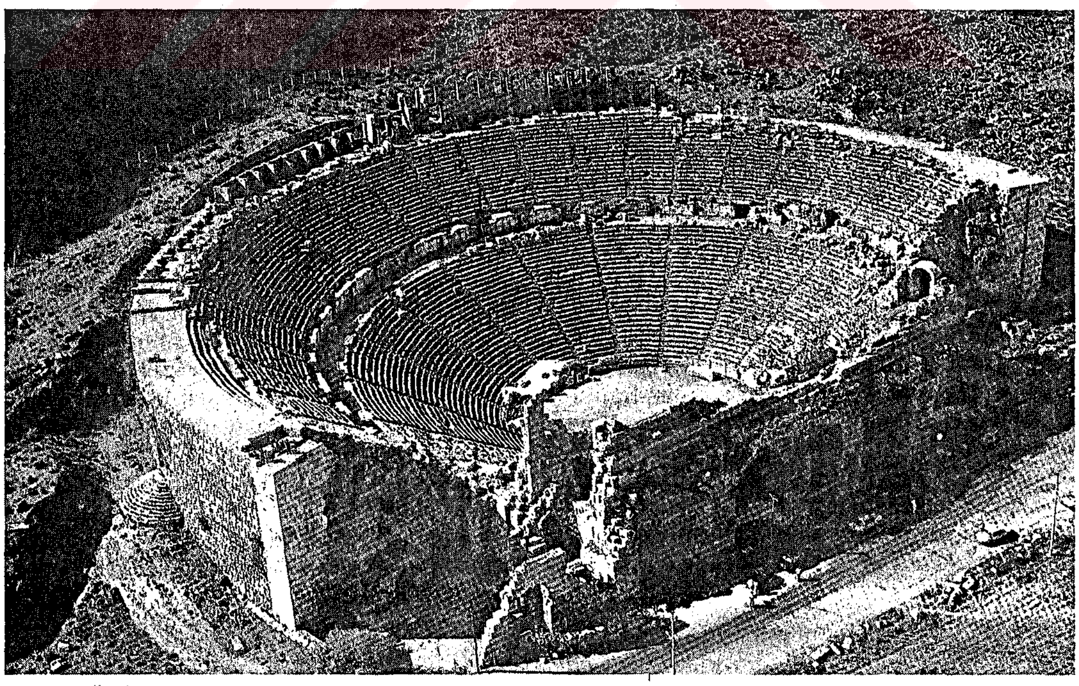


Figure A.8 Theatre of Perge, General View.

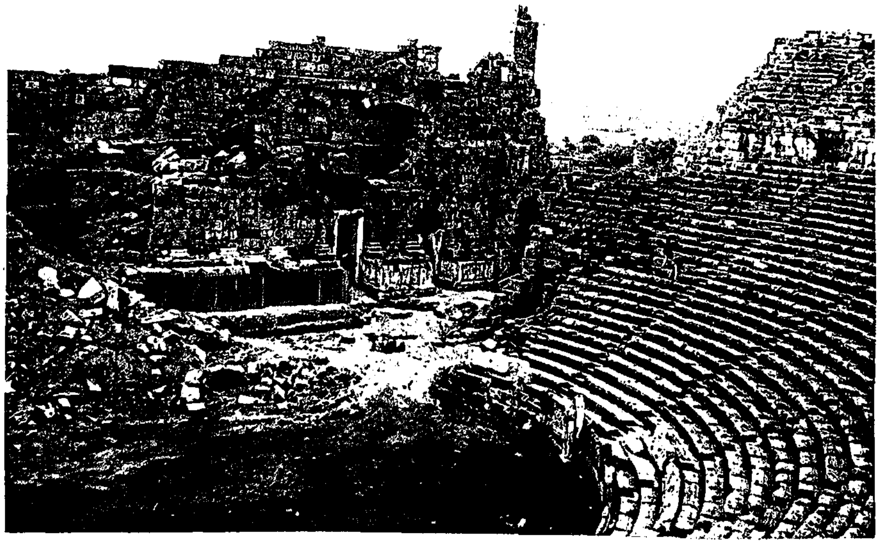


Figure A.9 Theatre of Perge, Stage Building.

A.4 Theatre of Termessos

One of the well-preserved buildings in Termessos is the theatre which has a capacity of about 4200 spectators. It was built in the Hellenistic period, in the classic Greek style. This structure took 13 years to build from 27 to 14 B.C. in the era of the Roman Emperor Augustus. However, it is of the Greek type with its beautiful ashlar masonry, its auditorium exceeding a semicircle, and the absence of the vaulted sub-structures. The stage building is separated from the auditorium and it has five doors with the largest one located in the middle (Figure A6). The *auditorium has 26 seating steps. These are split into two by an arched divider* (diazoma). This passage between the upper and lower cavea has 2.5 m width. The radius of the theatre is 33 m, the height from orchestra base to the top seating level is 12.8 m. The orchestra is an exceeding to semicircle and its radius is 19.8 m. The main entrance to the theatre is through staircases 4 m in width, located in the middle of the auditorium at the rear. Radial steps divide the upper cavea into 10 sections (kerkides) and the lower cavea into 5 sections. Behind the last seating row is a 2.4 m-wide covered gallery which is almost totally ruined today.

The inside of the stage building was an open area 3.6 m wide by 29.4 m long. Underneath the stage was a podium with 5 doors. However, these doors were only 1 m high and probably used for animal fights in the Roman period. ' The stage walls were decorated with columns.

The south parados was later covered by vaults, while the one on the north remained in its original form. In the same period, some 60 extra seats were constructed above this parados. This alteration consisted of the scaenae frons and proscenium. The stage building may have been erected in the late second century. The theatre was also probably used to hold open air meetings, public gathering and fairs.

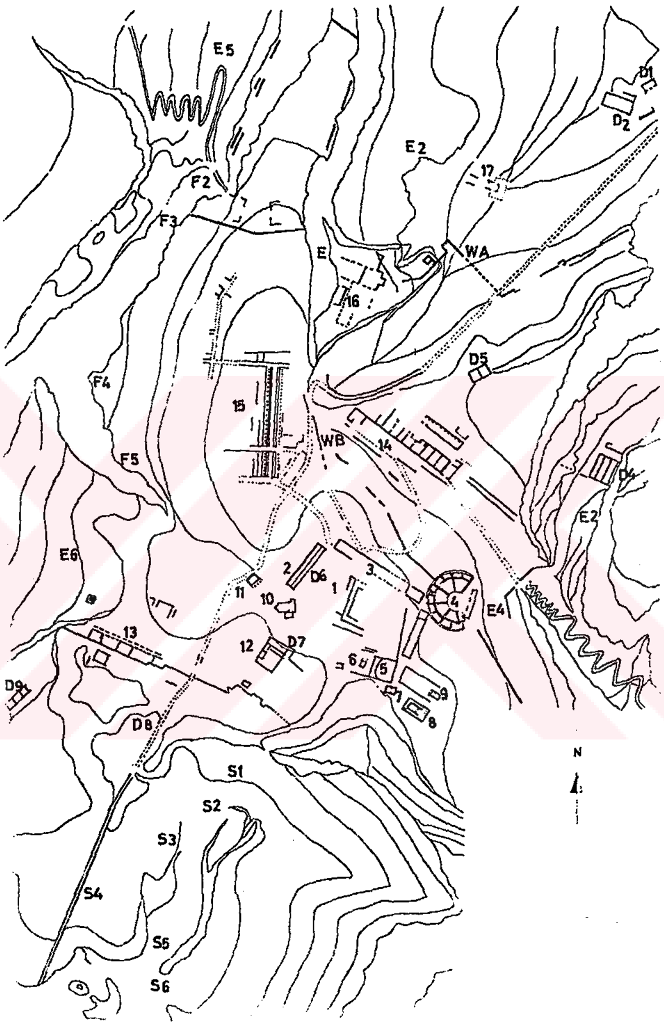


Figure A.10 Location of Theatre in Termessos (After E. Akurgal, 1978: 326).

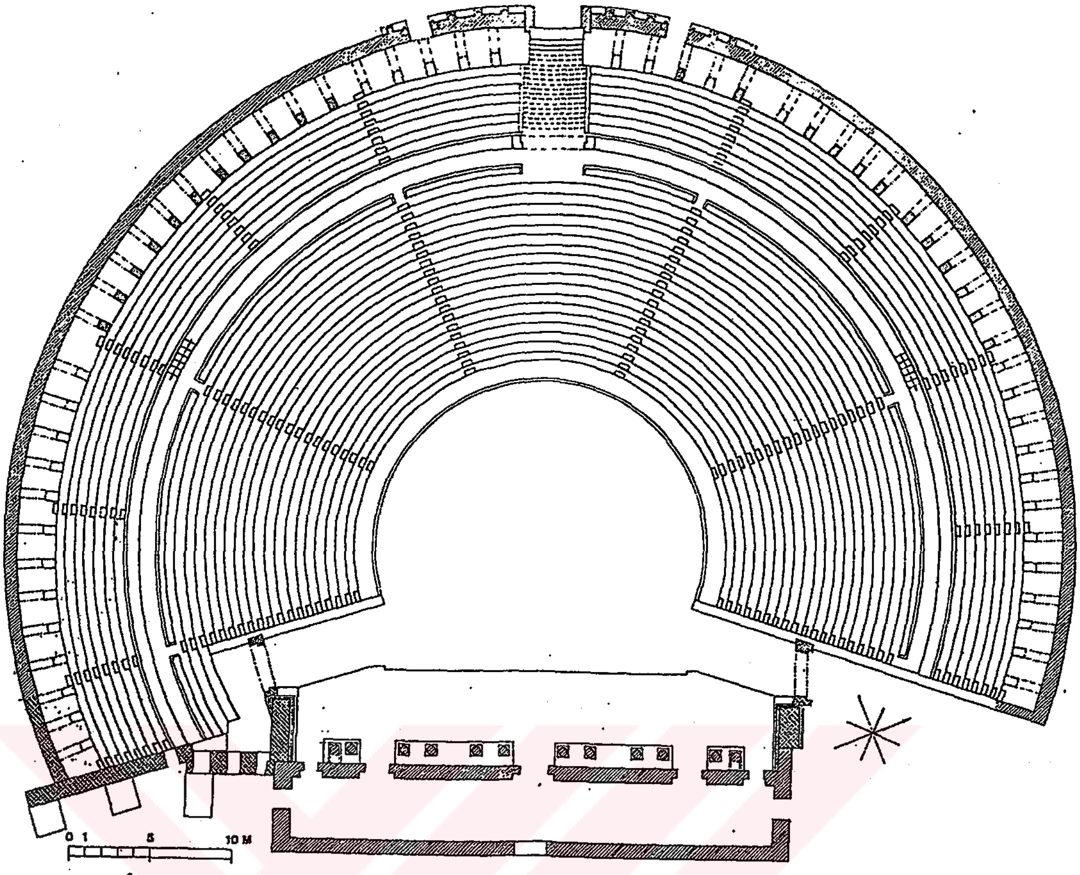
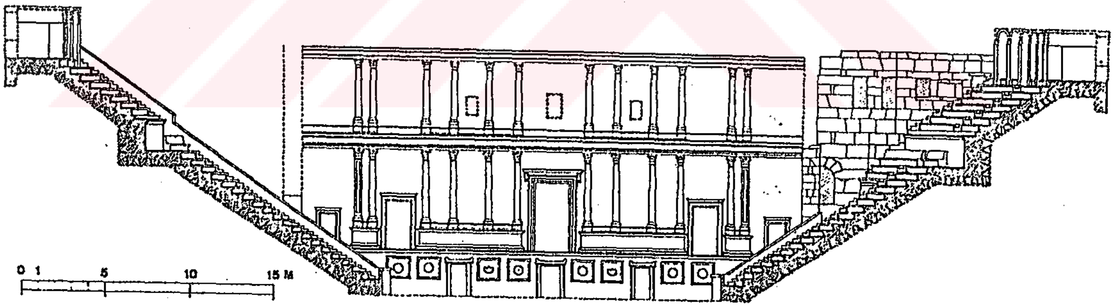


Figure A.11 Theatre of Termessos, Plan, (After Bernardi, 1969: Tav.I).



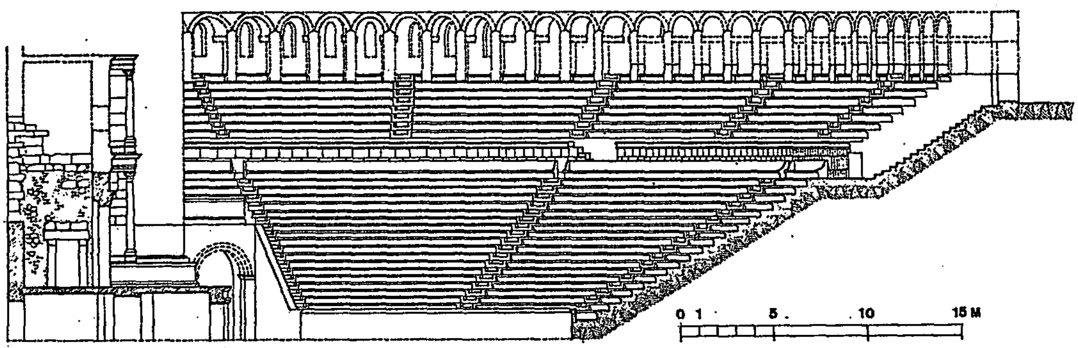


Figure A.12 Theatre of Termessos, Sections (After Bernardi, 1969: Tav.III).

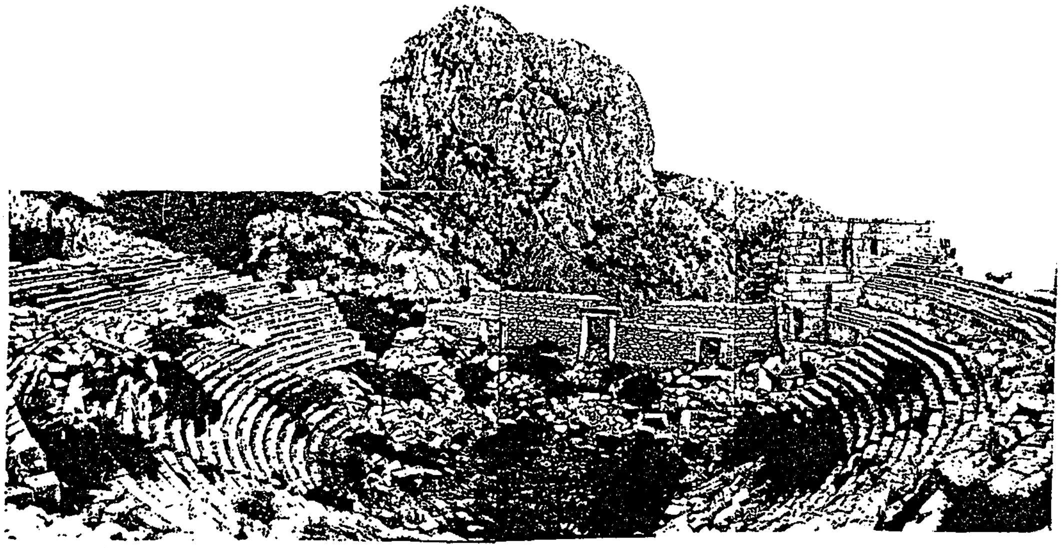


Figure A.13 Theatre of Termessos, General View.

Figure A.14 Theatre of Termessos, Stage Building.

APPENDIX B

EXPLANATION OF ANCIENT TECHNICAL TERMS

AMPHITHEATRE: A building with seats all around the arena, for gladiatorial shows.

ANALEMMA (pl. ANALEMMATA): Retaining wall around the theatron.

BOULEUTERION: The senate or council house where the aristocratic body gathered.

CAVEA: Part of the theatron between two diazomas, so called because originally excavated in a hill-side.

DIAZOMA: A horizontal passage dividing tiers of seats in a theatre or amphitheatre.

EPISKENION: Upper story of the skene building.

HYPOSKENION: The room below the platform of the stage.

KAVEA: See CAVEA.

KERKIS (pl. KERKIDES): Sections of the theatron, in wedge- shape formed by radiating stairs.

NYMPHAEUM: A monumental fountain building.

ODEION (Gr.), ODEUM (Lt.): A roofed music hall.

ORCHESTRA: Original dancing place of the Dionysiac ceremonies and hence the place of actions for the chorus and actors in Greek theatres of Classical and Hellenistic times.

PARASKENION (Gr.), PARASCENIUM (Lat.): Side wings of the skene.

PARADOS (pl. PARADOI): Entrance to the orchestra of the theatre, songs of the chorus sung while entering.

PODIUM: Low wall or continuous pedestal for columns or wall; A raised platform.

POSTSCAENIUM: The rooms behind the skene building.

PROSCAENIUM (Lat.): The Romans used the word for the whole stage as well as for the front of stage and of the stage building.

PROSKENION (Gr.): Building before the skene, the oldest high Hellenistic stage; later the front of the stage.

PULPITUM (Lat.): Roman stage; Podium or platform for the actors.

REGIA: The royal door, the central door of the Roman stage, leading into the palace of the main hero.

SCAENA DUCTILIS: Movable screen serving as background.

SCAENA VERSITIL: Turning prisms, decorated differently on the three sides, serving as a side wing.

SCAENA FRONS: The richly decorated fronts of the skene building.

SKENE (Gr.), SCAENA (Lat.): The booth for the players for changing, etc.

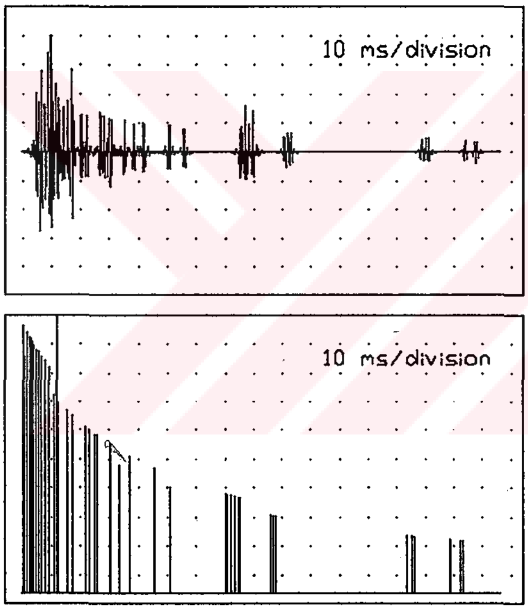
THEATRON (Gr. Seeing place): AUDITORIUM (Lat. Hearing place): of the theatre, later used for the whole building.

APPENDIX C

ACOUSTICAL SIMULATION OF ASPENDOS THEATRE

C.1 Impulse Responses for the Fifth Order Simulation

A1



Rays : 16000 Refl. : 5
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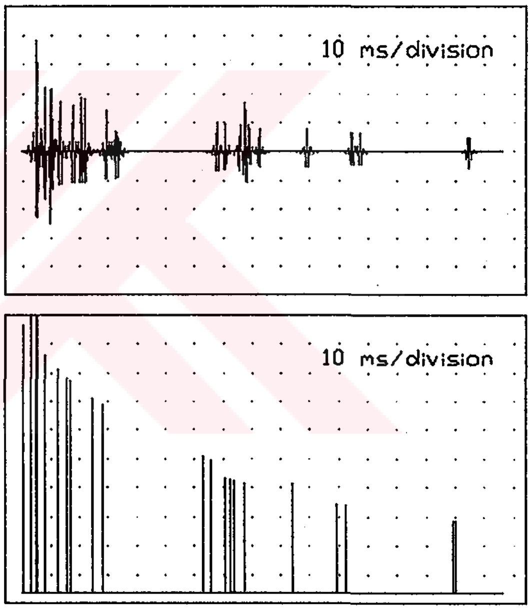
Source : 49.20 12.20 1.70
File : R1ASPF5.Pth

A2



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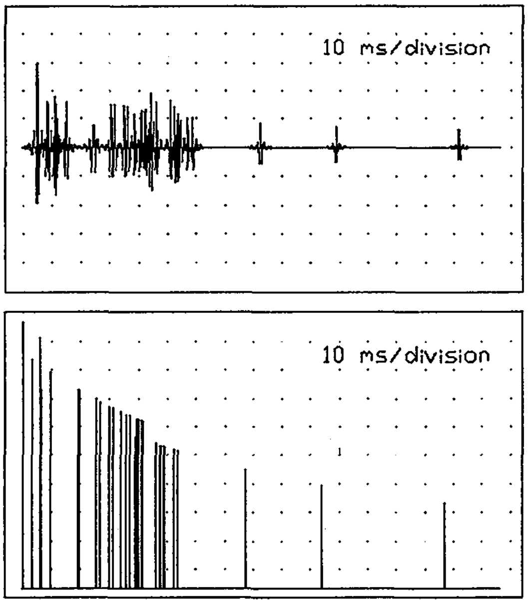
Valid : 25 Radius : 1.05 m.

Receiver : 68.40 19.90 4.50
Source : 49.20 12.20 1.70
File : R2ASPF5.Pth

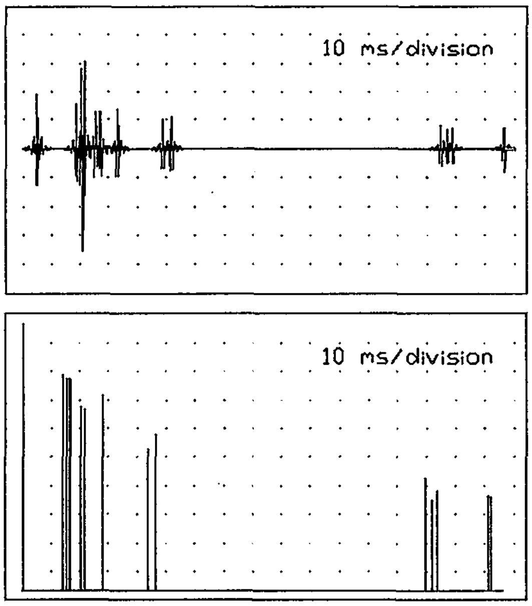
A3



Rays : 16000 Refl. : 5
Valid : 32 Radius : 1.05 m.

Receiver : 73.00 19.90 7.40
Source : 49.20 12.20 1.70
File : R3ASPF5.Pth

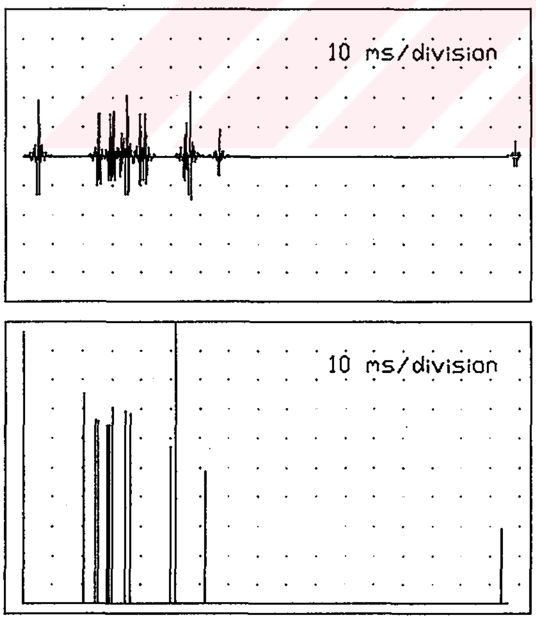
A4



Rays : 16000 Refl. : 5
Valid : 18 Radius : 1.05 m.

Receiver : 84.20 18.60 14.50
Source : 49.20 12.20 1.70
File : R4ASPF5.Pth

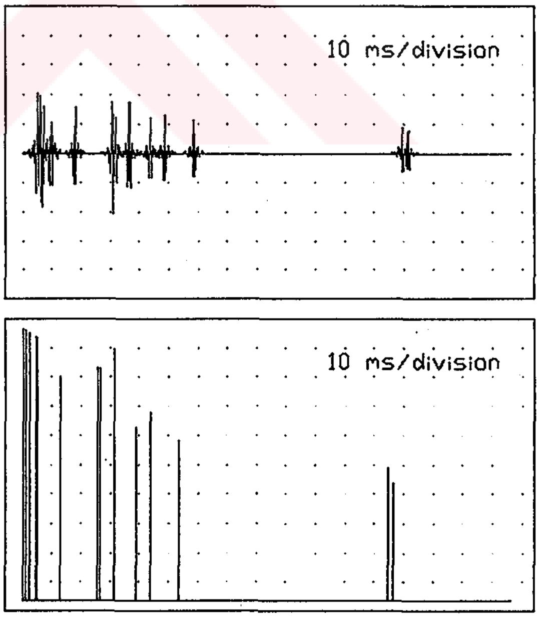
B4



Rays : 16000 Refl. : 5
Valid : 17 Radius : 1.05 m.

Receiver : 81.90 31.50 14.50
Source : 49.20 12.20 1.70
File : R7ASPF5.Pth

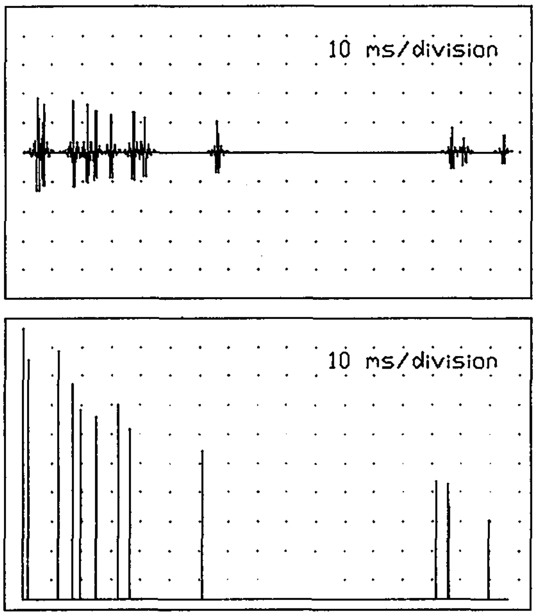
B5



Rays : 16000 Refl. : 5
Valid : 15 Radius : 1.05 m.

Receiver : 78.20 38.20 14.50
Source : 49.20 12.20 1.70
File : R8ASPF5.Pth

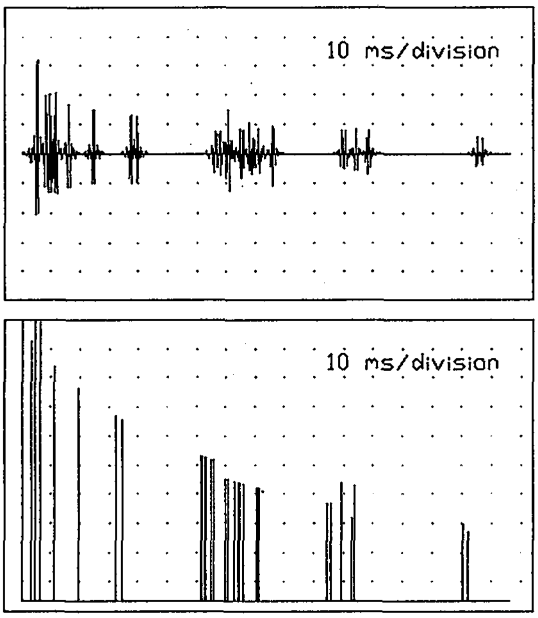
A5



Rays : 16000 Refl. : 5
Valid : 13 Radius : 1.05 m.

Receiver : 83.40 26.80 14.50
Source : 49.20 12.20 1.70
File : R5ASPF5.Pth

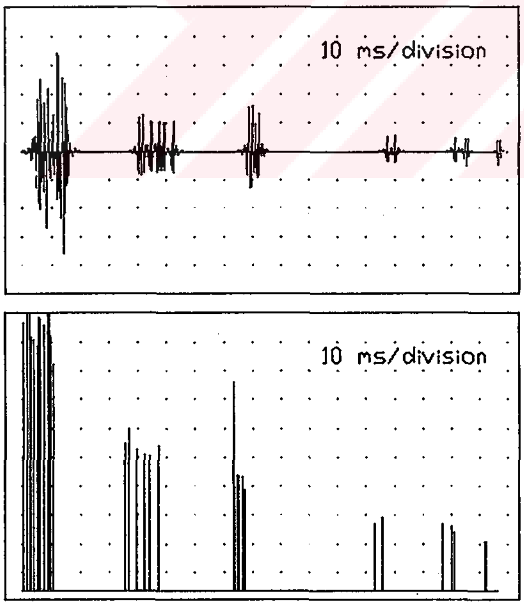
B2



Rays : 16000 Refl. : 5
Valid : 34 Radius : 1.05 m.

Receiver : 67.00 26.30 4.50
Source : 49.20 12.20 1.70
File : R6ASPF5.Pth

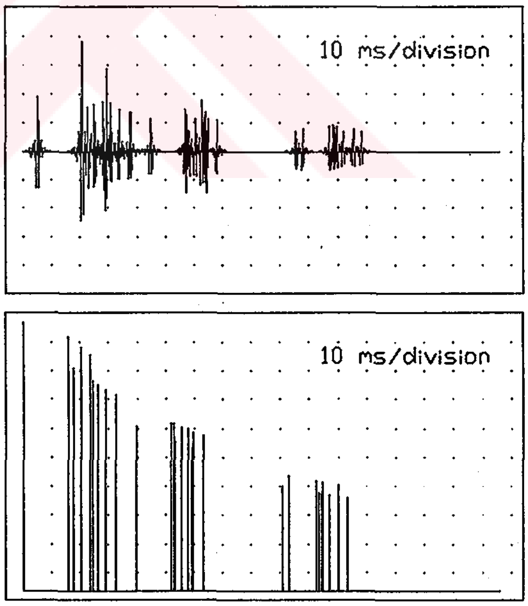
B1



Rays : 16000 Refl. : 5
Valid : 41 Radius : 1.05 m.

Receiver : 62.70 25.10 2.00
Source : 49.20 12.20 0.10
File : r1aspf5.Pth

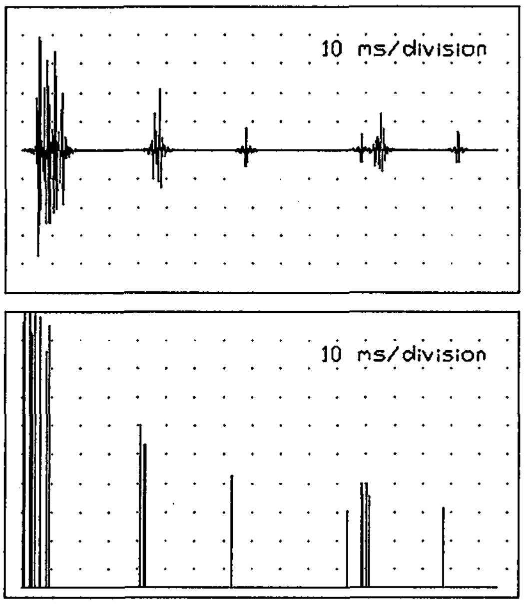
B3



Rays : 16000 Refl. : 5
Valid : 32 Radius : 1.05 m.

Receiver : 71.60 27.30 7.40
Source : 49.20 12.20 0.10
File : r2aspf5.Pth

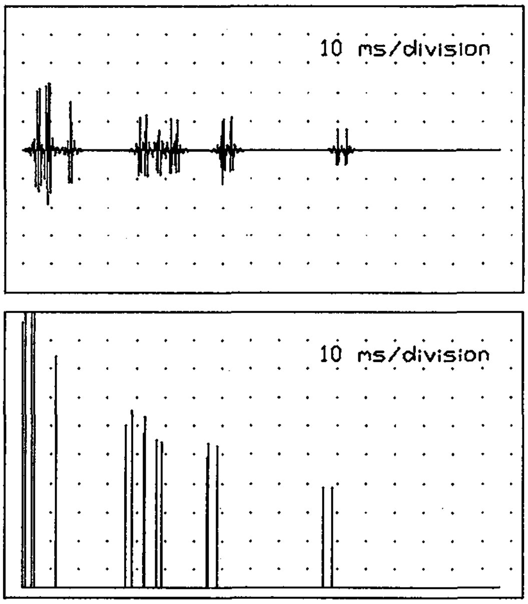
C1



Rays : 16000 Refl. : 5
Valid : 24 Radius : 1.05 m.

Receiver : 59.30 30.10 2.00
Source : 49.20 12.20 0.10
File : r3aspf5.Pth

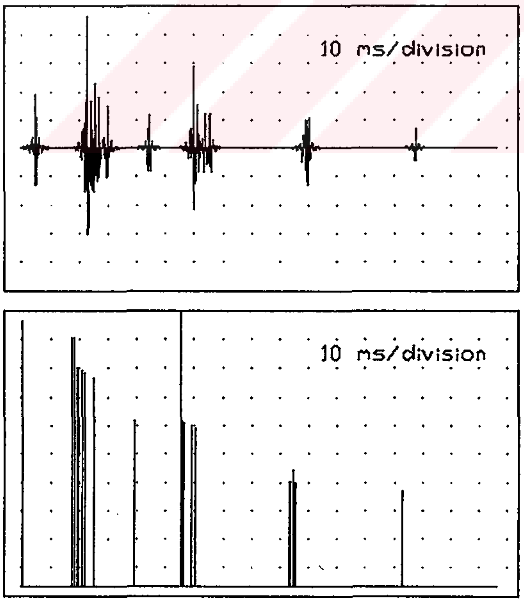
C2



Rays : 16000 Refl. : 5
Valid : 18 Radius : 1.05 m.

Receiver : 62.50 33.20 4.50
Source : 49.20 12.20 0.10
File : r4aspf5.Pth

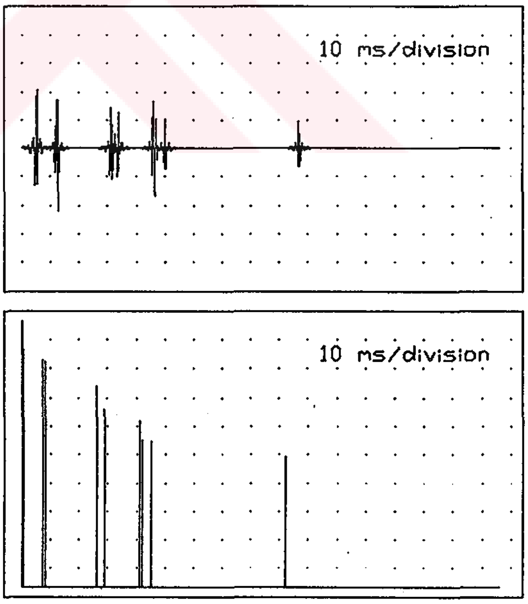
C3



Rays : 16000 Refl. : 5
Valid : 25 Radius : 1.05 m.

Receiver : 66.60 36.20 7.40
Source : 49.20 12.20 0.10
File : r5aspf5.Pth

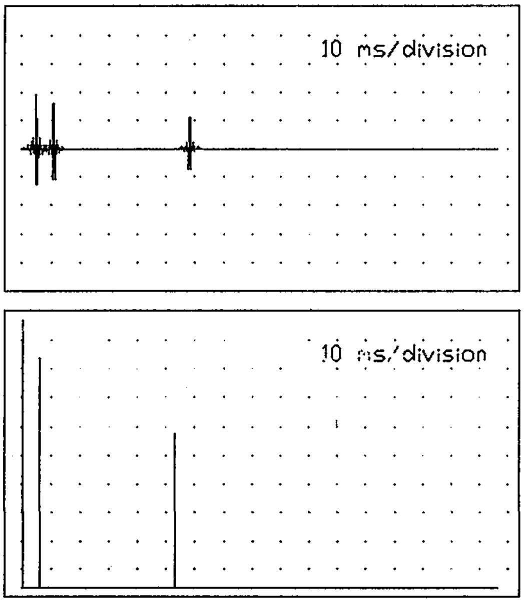
C4



Rays : 16000 Refl. : 5
Valid : 12 Radius : 1.05 m.

Receiver : 74.80 42.10 14.50
Source : 49.20 12.20 0.10
File : r6aspf5.Pth

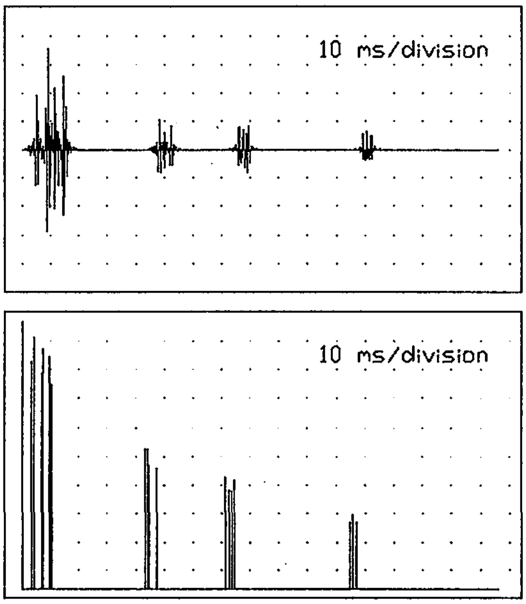
C5



Rays : 16000 Refl. : 5
Valid : 3 Radius : 1.05 m.

Receiver : 69.20 47.30 14.50
Source : 49.20 12.20 0.10
File : r7aspf5.Pth

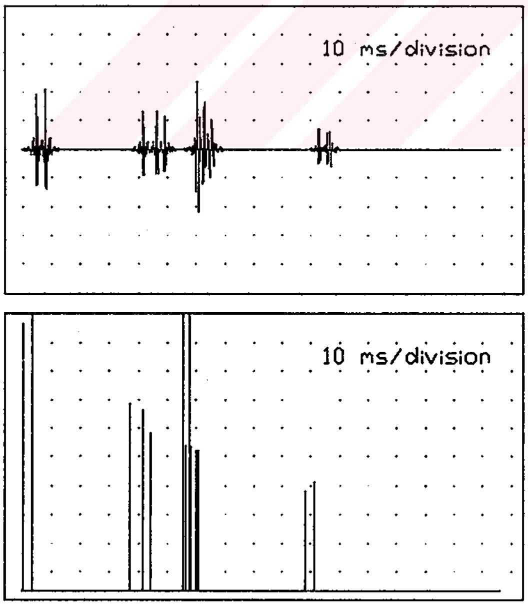
D1



Rays : 16000 Refl. : 5
Valid : 24 Radius : 1.05 m.

Receiver : 54.50 32.90 2.00
Source : 49.20 12.20 0.10
File : r8aspf5.Pth

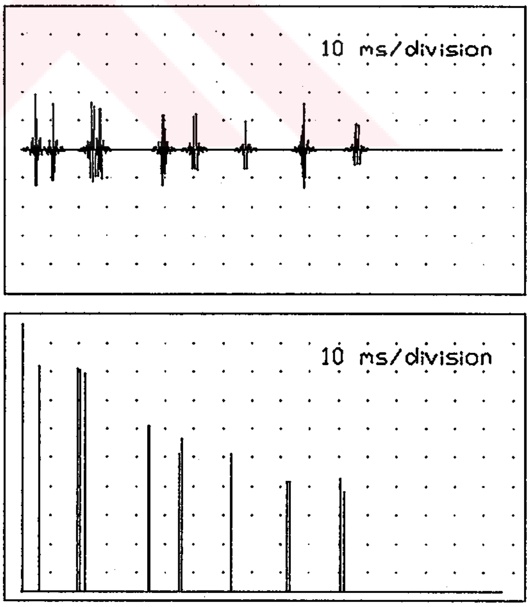
D2



Rays : 16000 Refl. : 5
Valid : 17 Radius : 1.05 m.

Receiver : 56.30 37.00 4.50
Source : 49.20 12.20 0.10
File : R1ASPF5.Pth

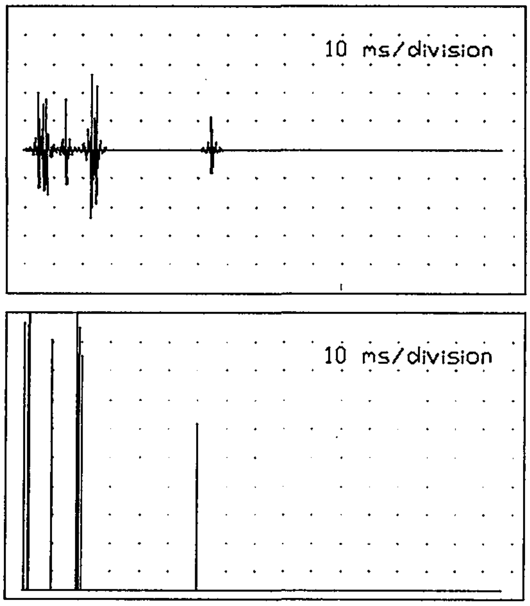
D3



Rays : 16000 Refl. : 5
Valid : 15 Radius : 1.05 m.

Receiver : 58.10 41.40 7.40
Source : 49.20 12.20 0.10
File : R2ASPF5.Pth

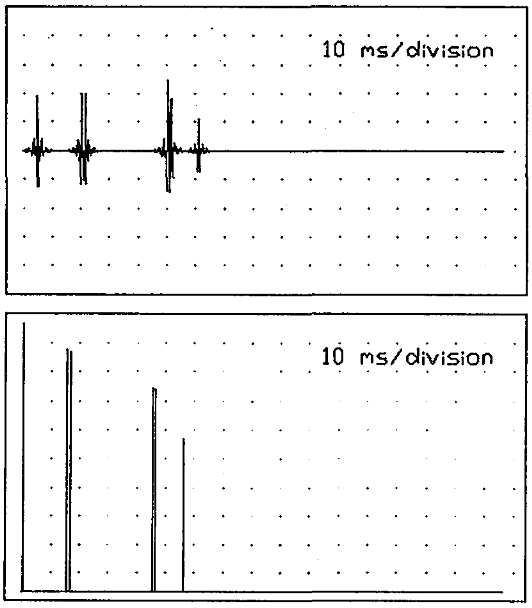
D4



Rays : 16000 Refl. : 5
Valid : 11 Radius : 1.05 m.

Receiver : 63.70 50.30 14.50
Source : 49.20 12.20 0.10
File : R3ASPF5.Pth

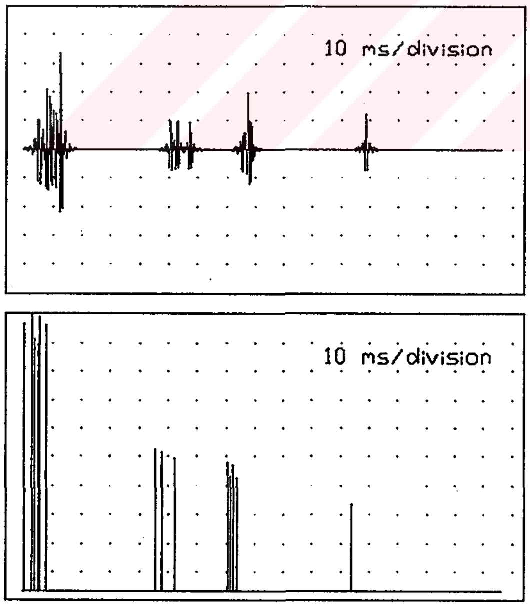
D5



Rays : 16000 Refl. : 5
Valid : 7 Radius : 1.05 m.

Receiver : 58.60 52.00 14.50
Source : 49.20 12.20 0.10
File : R4ASPF5.Pth

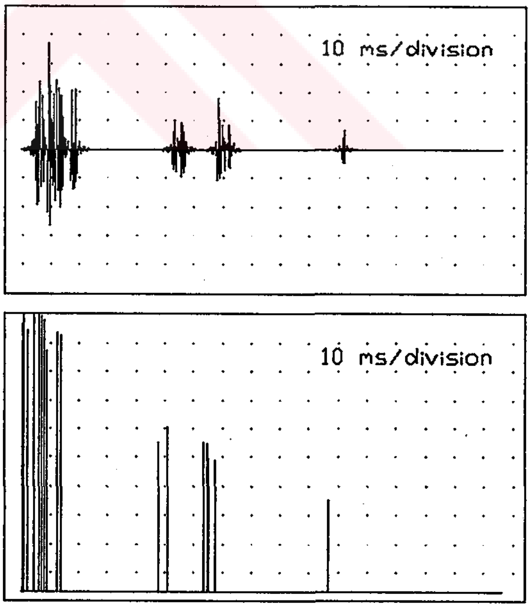
E1



Rays : 16000 Refl. : 5
Valid : 19 Radius : 1.05 m.

Receiver : 49.20 34.00 2.00
Source : 49.20 12.20 0.10
File : R5ASPF5.Pth

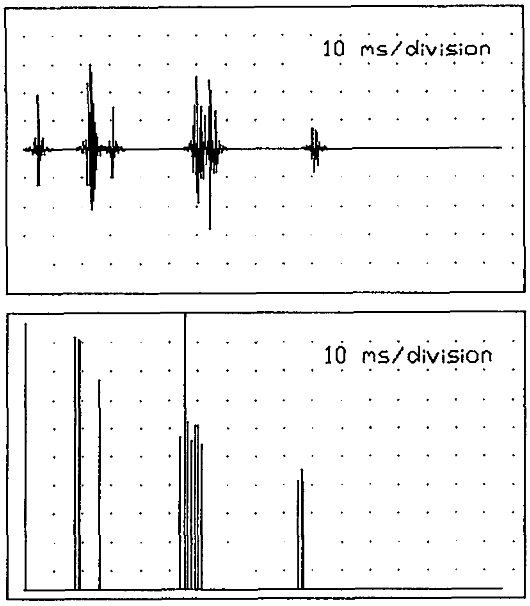
E2



Rays : 16000 Refl. : 5
Valid : 20 Radius : 1.05 m.

Receiver : 49.20 38.50 4.50
Source : 49.20 12.20 0.10
File : R6ASPF5.Pth

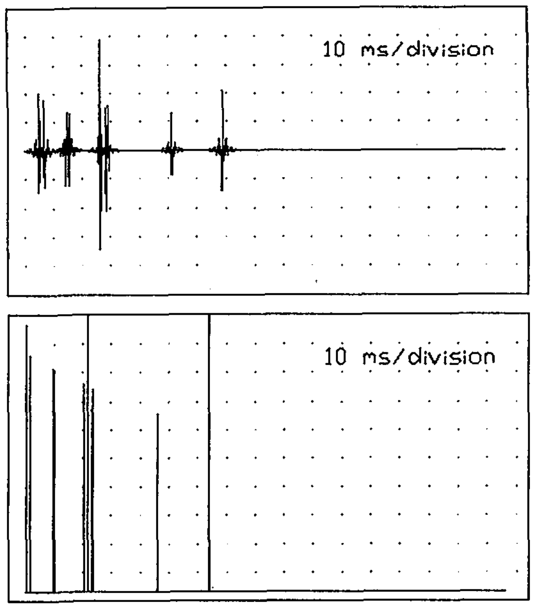
E3



Rays : 16000 Refl. : 5
Valid : 21 Radius : 1.05 m.

Receiver : 49.20 43.20 7.40
Source : 49.20 12.20 0.10
File : R7ASPF5.Pth

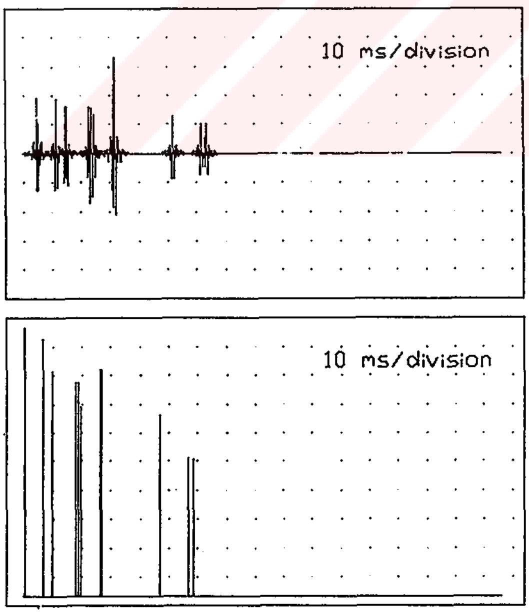
E4



Rays : 16000 Refl. : 5
Valid : 13 Radius : 1.05 m.

Receiver : 52.10 53.70 14.50
Source : 49.20 12.20 0.10
File : R8ASPF5.Pth

E5

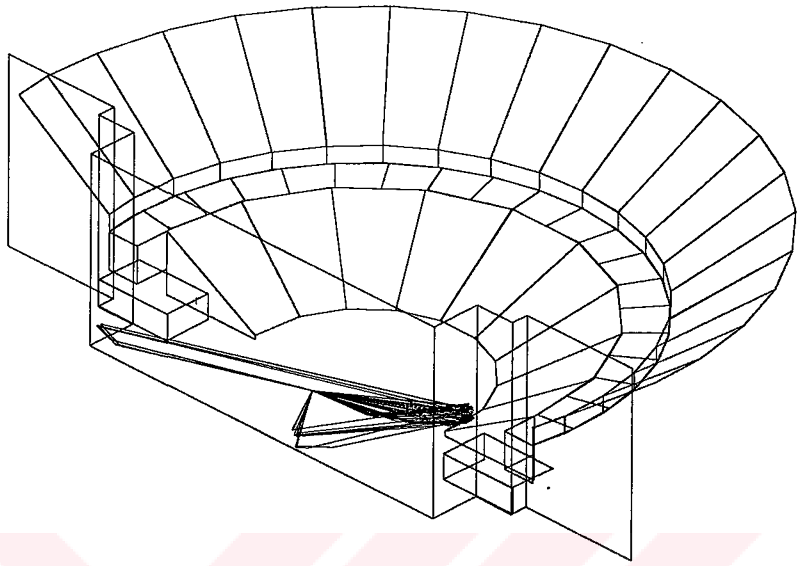


Rays : 16000 Refl. : 5
Valid : 13 Radius : 1.05 m.

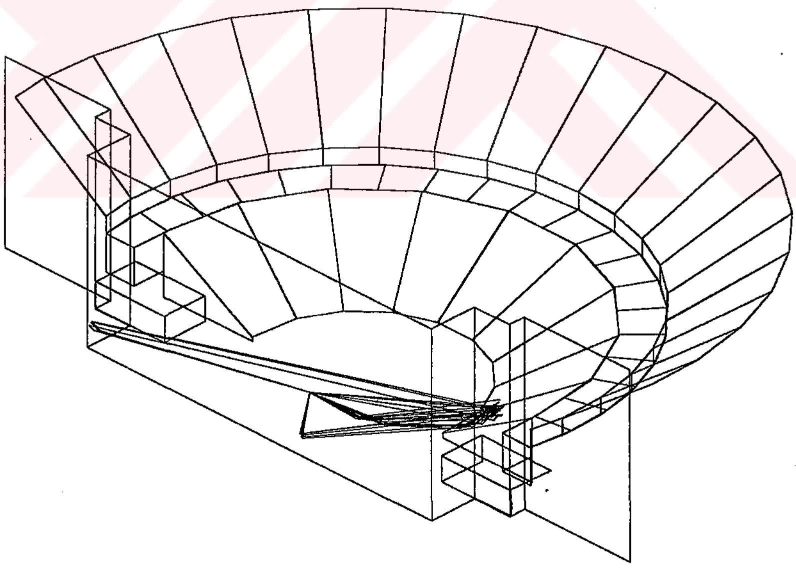
Receiver : 45.20 53.70 14.50
Source : 49.20 12.20 0.10
File : R9ASPF5.Pth

C.2 Three-dimensional Models of the Fifth Order Reflections

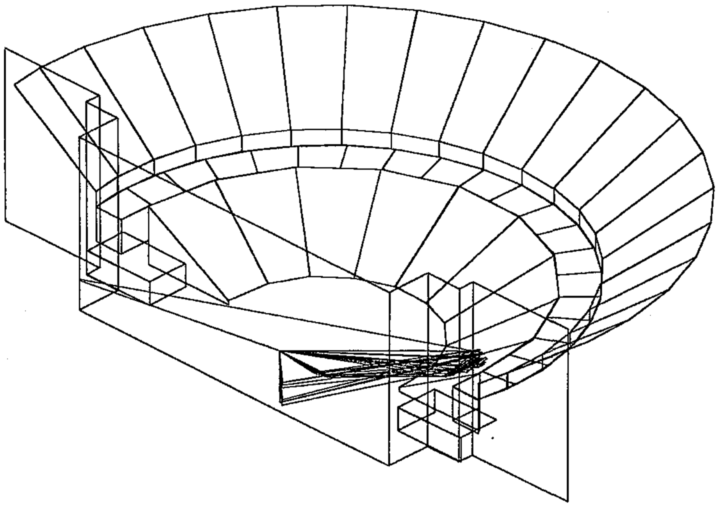
RECEIVER POSITION A1



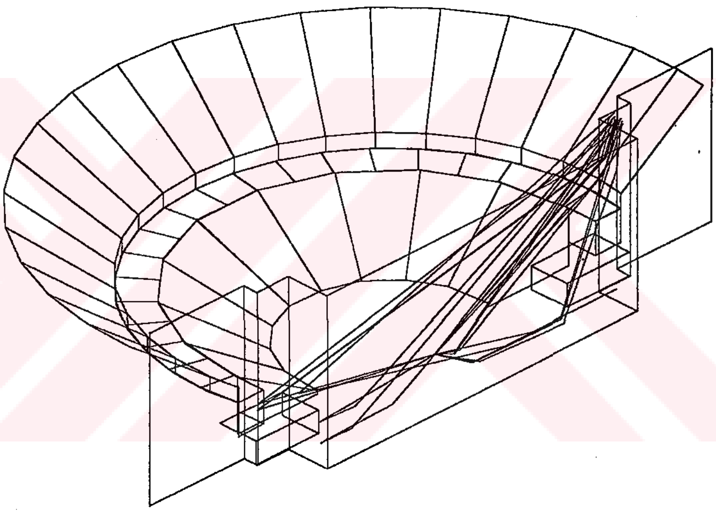
RECEIVER POSITION A2



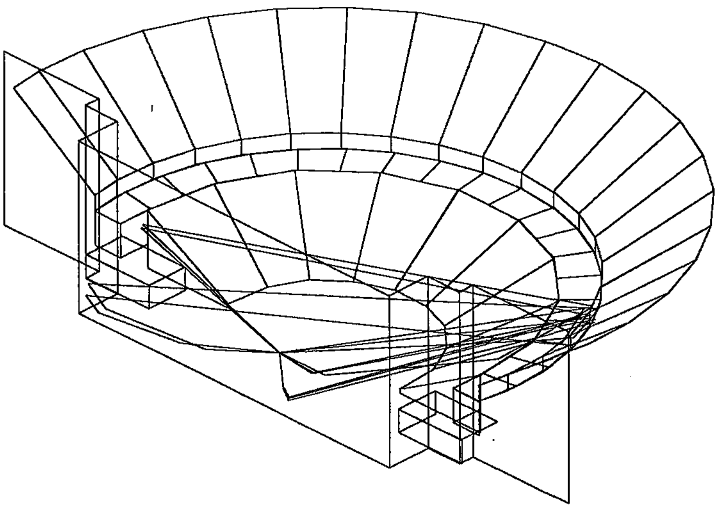
RECEIVER POSITION A3



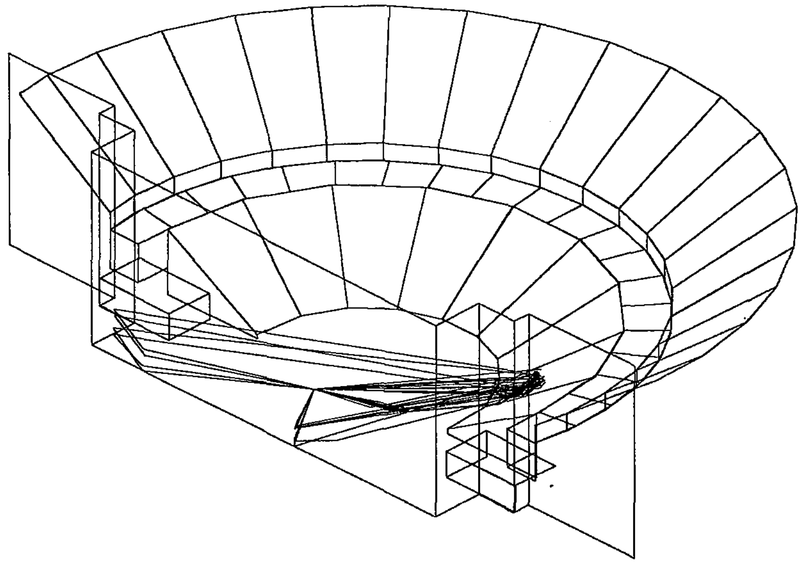
RECEIVER POSITION A4



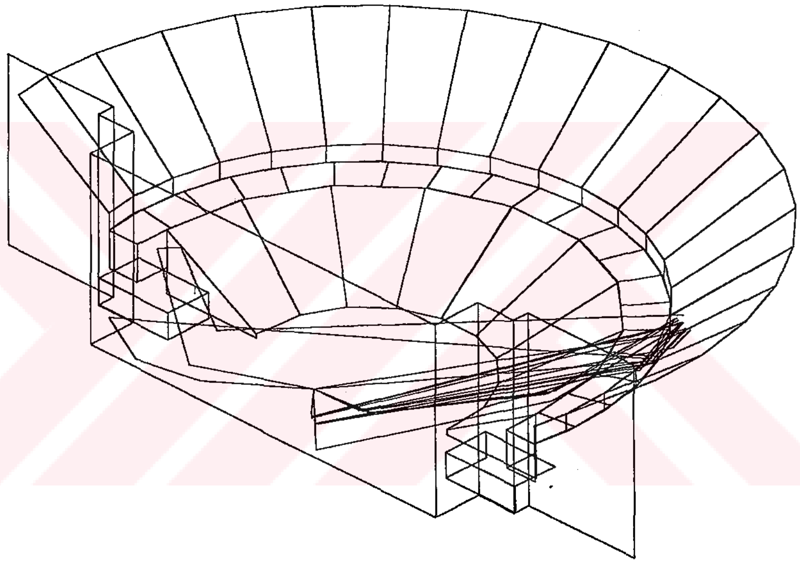
RECEIVER POSITION A5



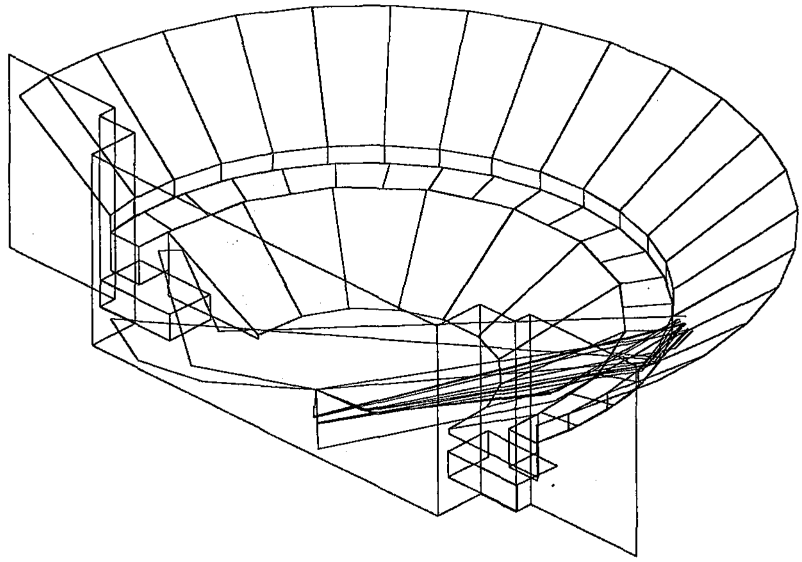
RECEIVER POSITION B2



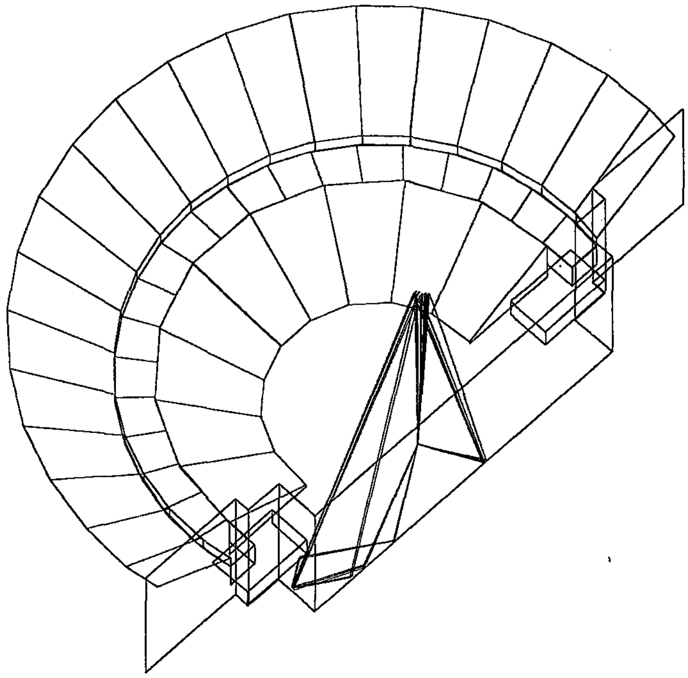
RECEIVER POSITION B4



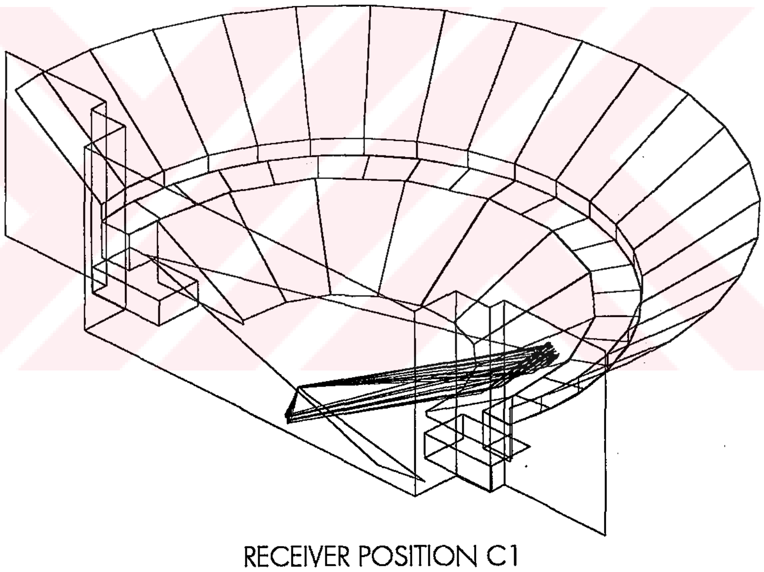
RECEIVER POSITION B5



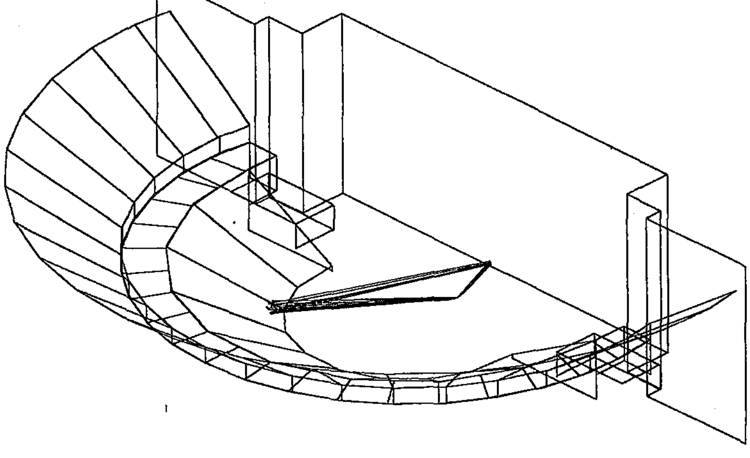
RECEIVER POSITION B1



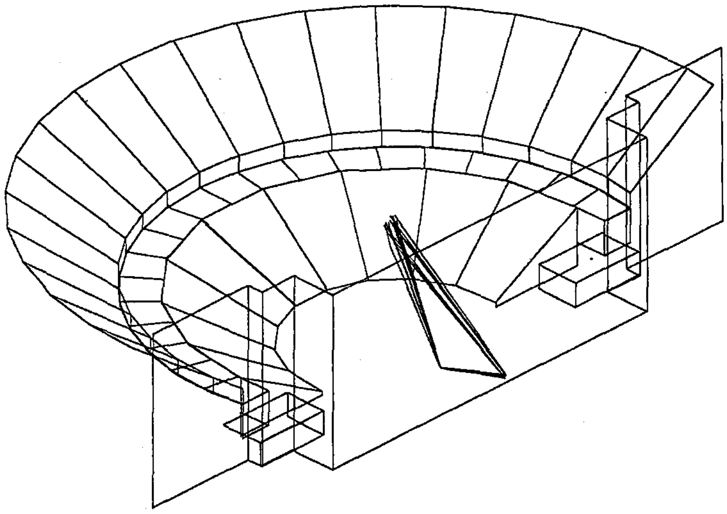
RECEIVER POSITION B3



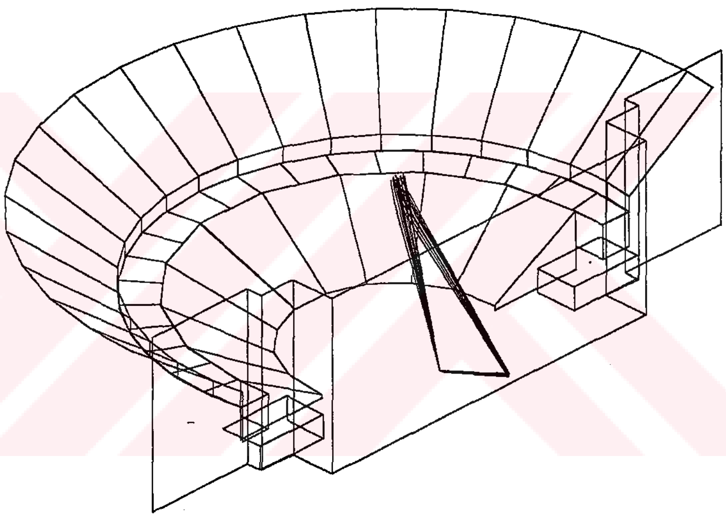
RECEIVER POSITION C1



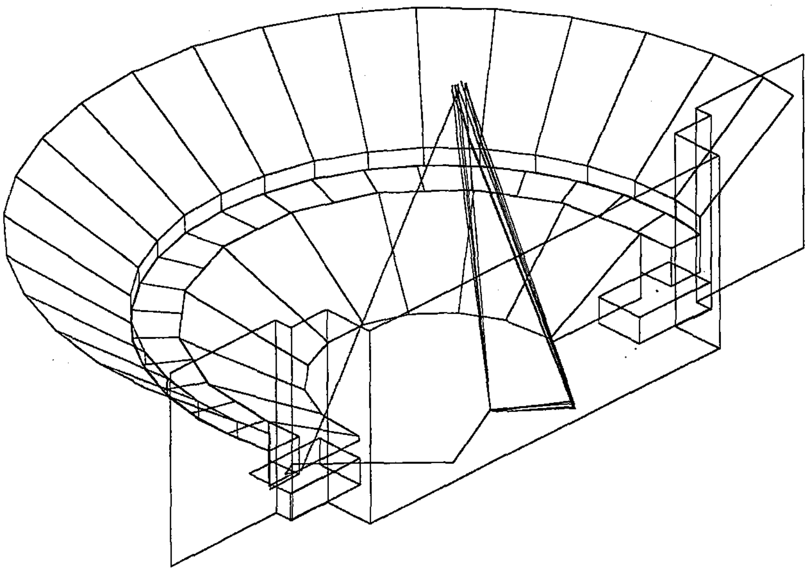
RECEIVER POSITION C2



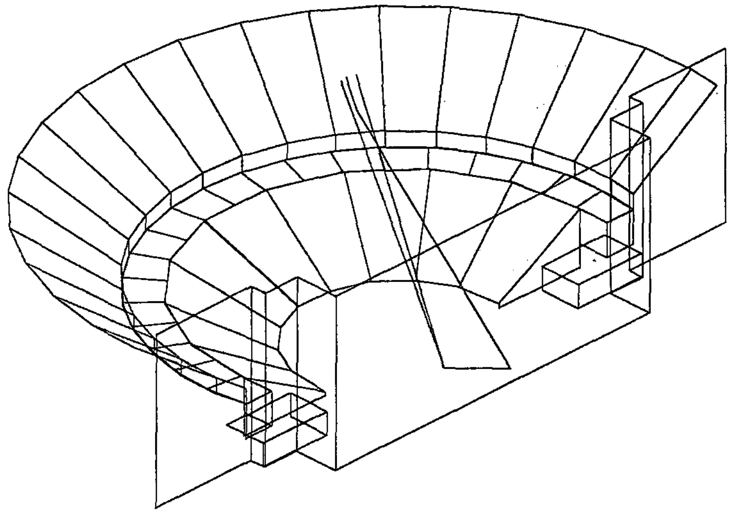
RECEIVER POSITION C3



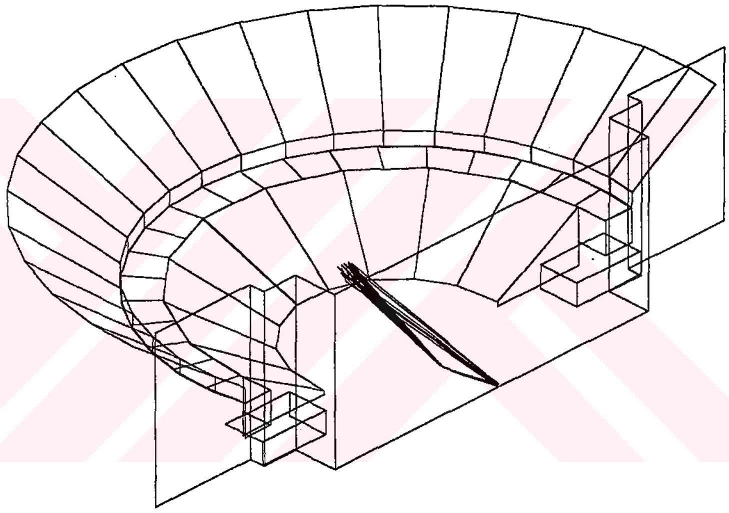
RECEIVER POSITION C4



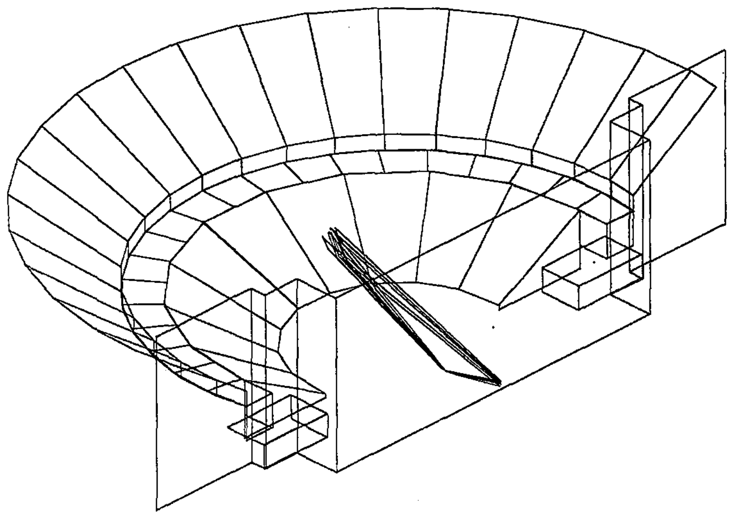
RECEIVER POSITION C5



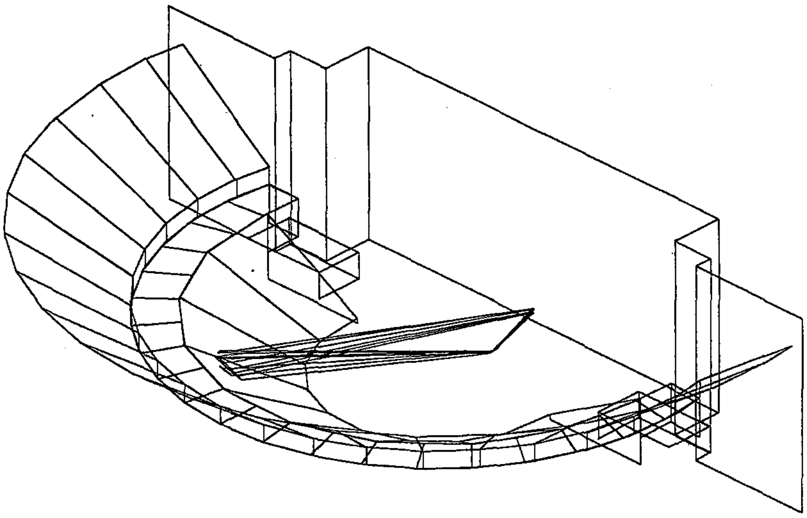
RECEIVER POSITION D1



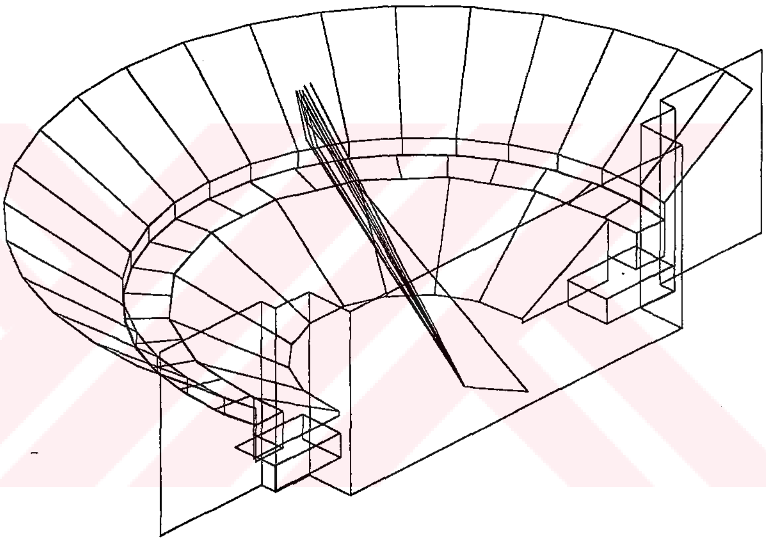
RECEIVER POSITION D2



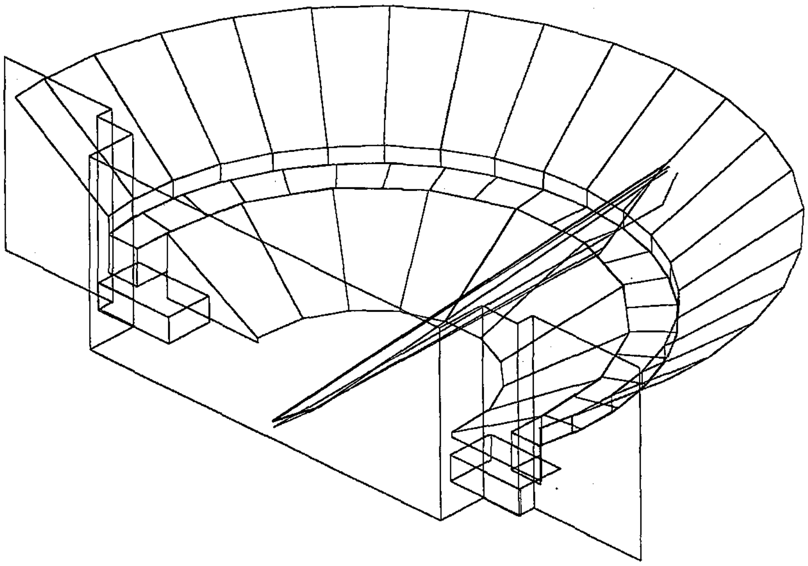
RECEIVER POSITION D3



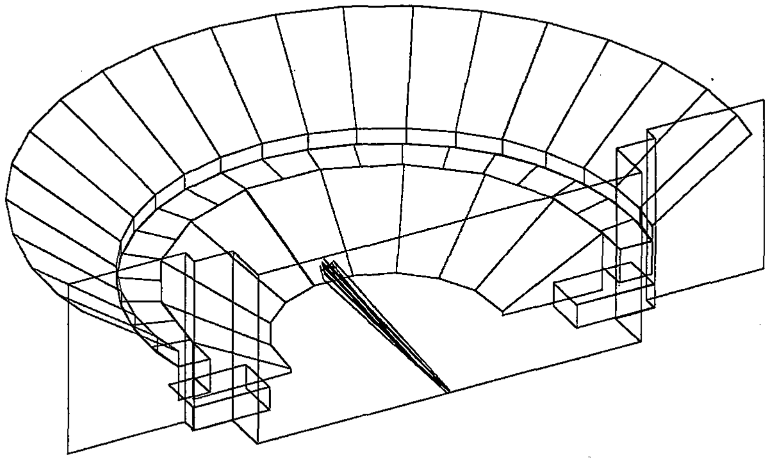
RECEIVER POSITION D4



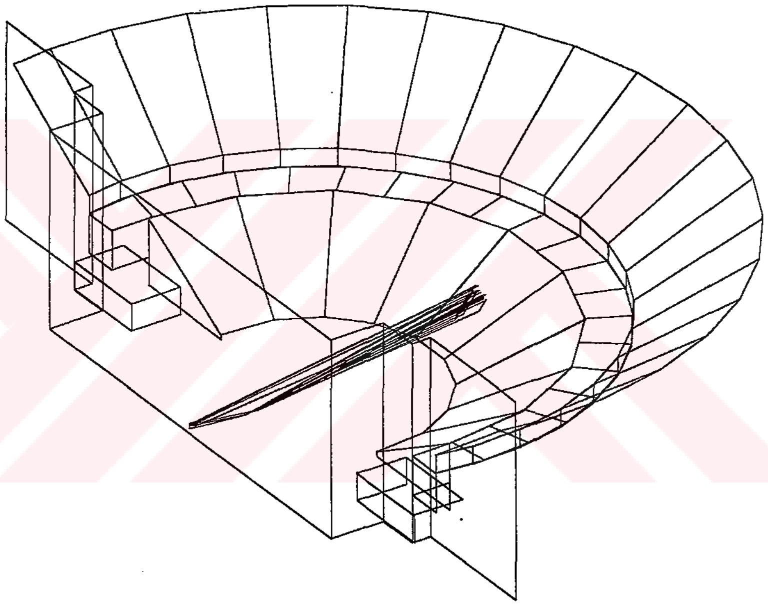
RECEIVER POSITION D5



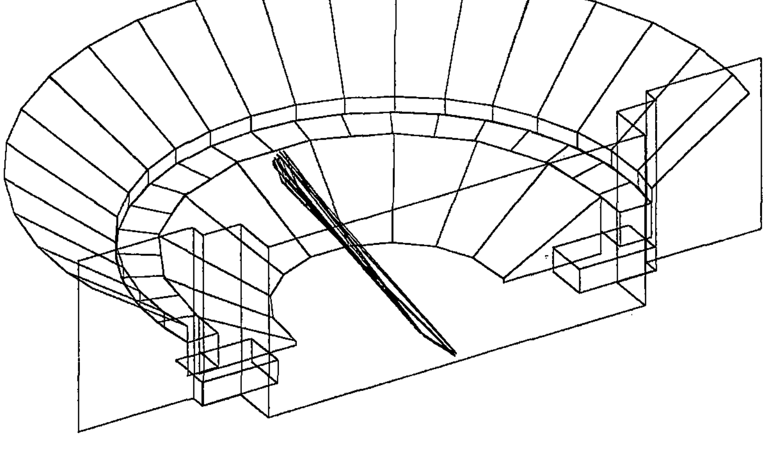
RECEIVER POSITION E1



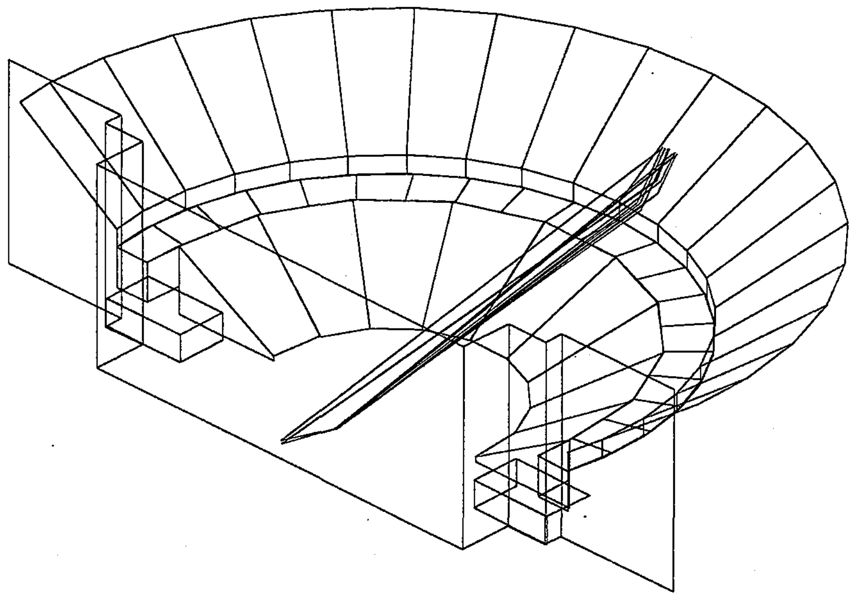
RECEIVER POSITION E2



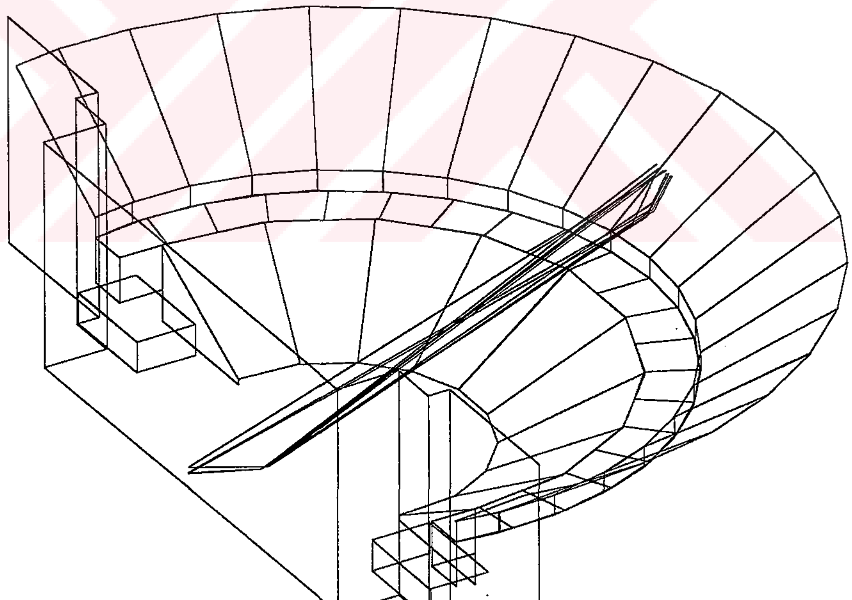
RECEIVER POSITION E3



RECEIVER POSITION E4

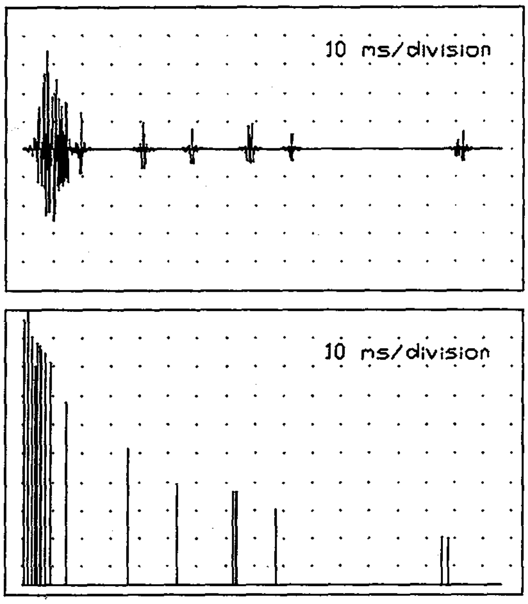


RECEIVER POSITION E5



C.3 Impulse Responses for the Seventh Order Simulation

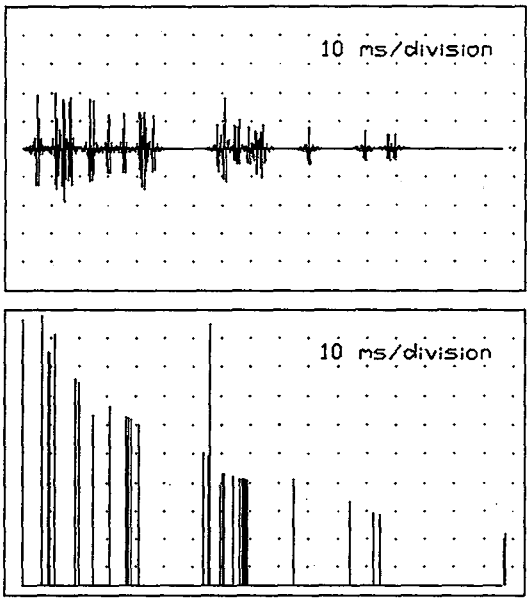
A1



Rays : 16000 Refl. : 7
Valid : 27 Radius : 1.05 m.

Receiver : 63.90 19.80 2.00
Source : 49.20 12.20 1.70
File : r1aspf7.Pth

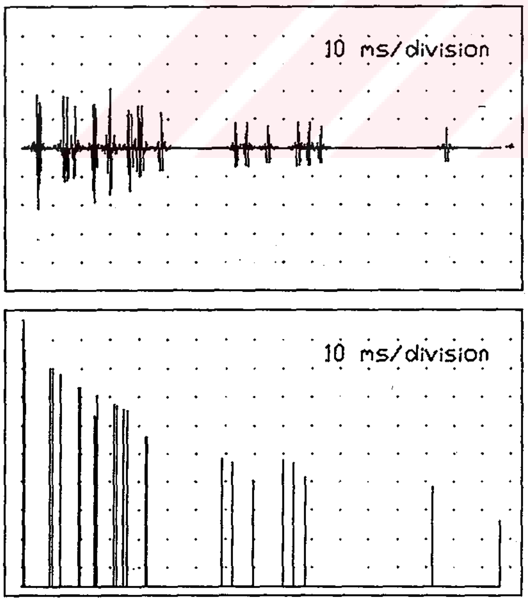
A2



Rays : 16000 Refl. : 7
Valid : 36 Radius : 1.05 m.

Receiver : 68.40 19.90 4.50
Source : 49.20 12.20 1.70
File : r2aspf7.Pth

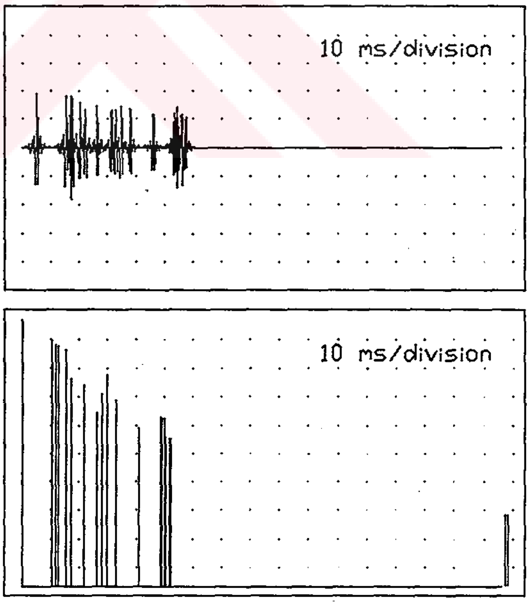
A3



Rays : 16000 Refl. : 7
Valid : 26 Radius : 1.05 m.

Receiver : 73.00 19.90 7.40
Source : 49.20 12.20 1.70
File : r3aspf7.Pth

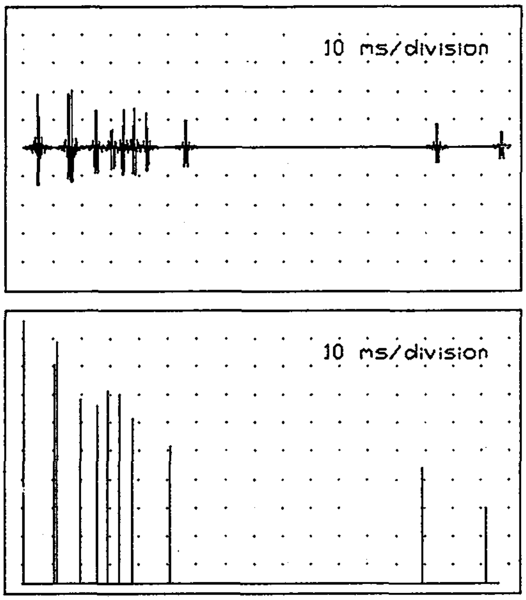
A4



Rays : 16000 Refl. : 7
Valid : 23 Radius : 1.05 m.

Receiver : 84.20 18.60 14.50
Source : 49.20 12.20 1.70
File : r4aspf7.Pth

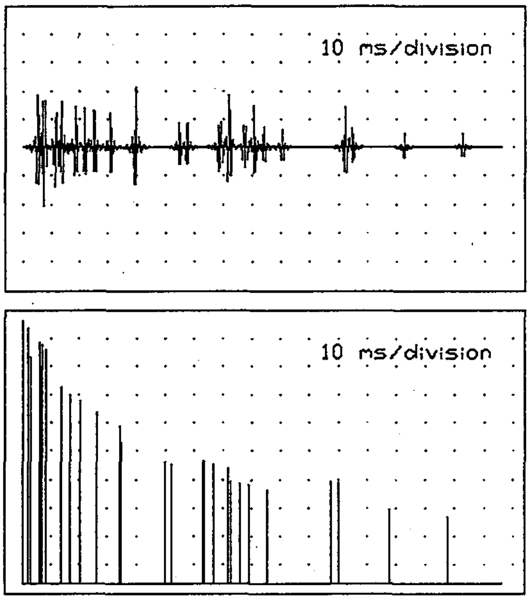
A5



Rays : 16000 Refl. : 7
Valid : 13 Radius : 1.05 m.

Receiver : 83.40 26.80 14.50
Source : 49.20 12.20 1.70
File : r5aspf7.Pth

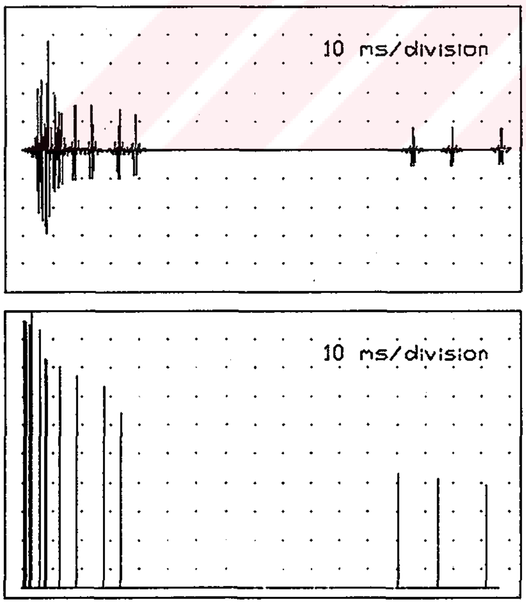
B2



Rays : 16000 Refl. : 7
Valid : 34 Radius : 1.05 m.

Receiver : 67.00 26.30 4.50
Source : 49.20 12.20 1.70
File : r6aspf7.Pth

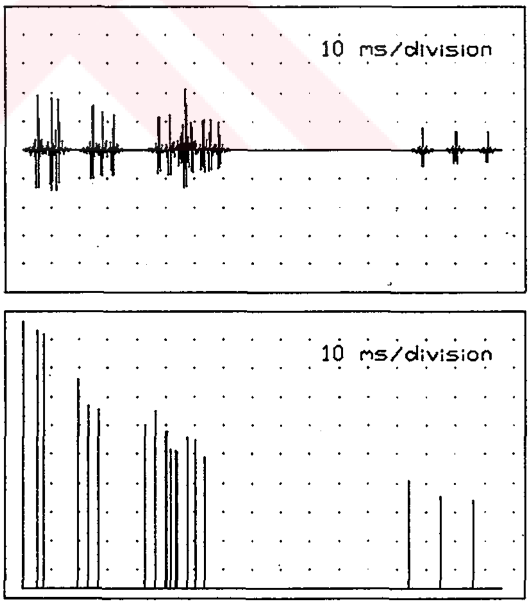
B4



Rays : 16000 Refl. : 7
Valid : 19 Radius : 1.05 m.

Receiver : 81.90 31.50 14.50
Source : 49.20 12.20 1.70
File : r7aspf7.Pth

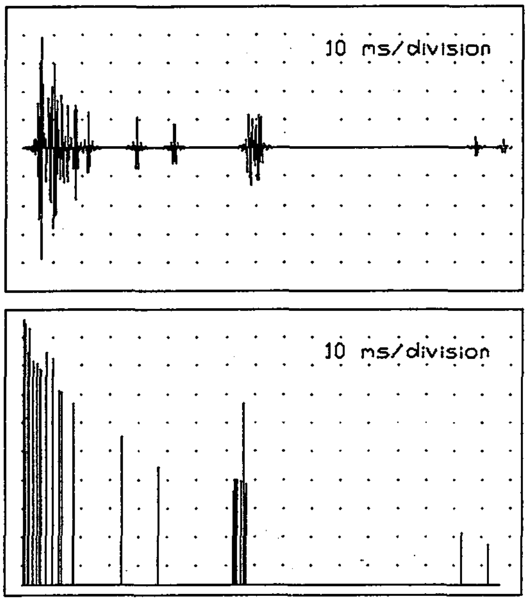
B5



Rays : 16000 Refl. : 7
Valid : 23 Radius : 1.05 m.

Receiver : 78.20 38.20 14.50
Source : 49.20 12.20 1.70
File : r8aspf7.Pth

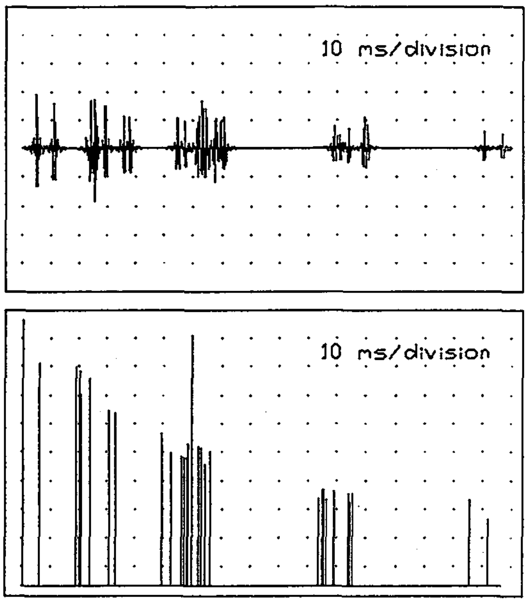
B1



Rays : 16000 Refl. : 7
Valid : 34 Radius : 1.05 m.

Receiver : 62.70 25.10 2.00
Source : 49.20 12.20 0.10
File : r1aspf7.Pth

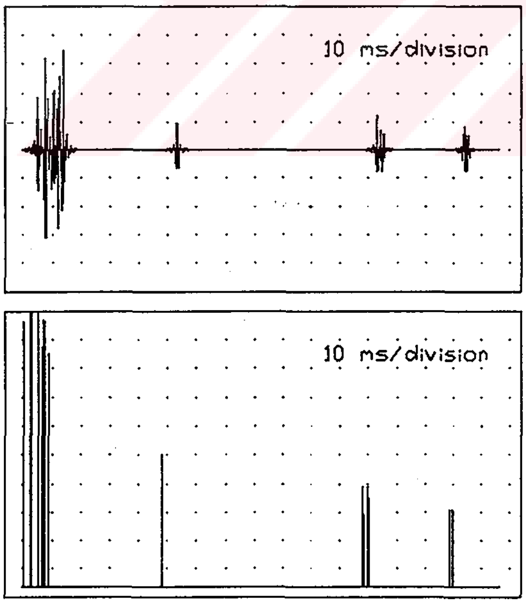
B3



Rays : 16000 Refl. : 7
Valid : 34 Radius : 1.05 m.

Receiver : 71.60 27.30 7.40
Source : 49.20 12.20 0.10
File : r2aspf7.Pth

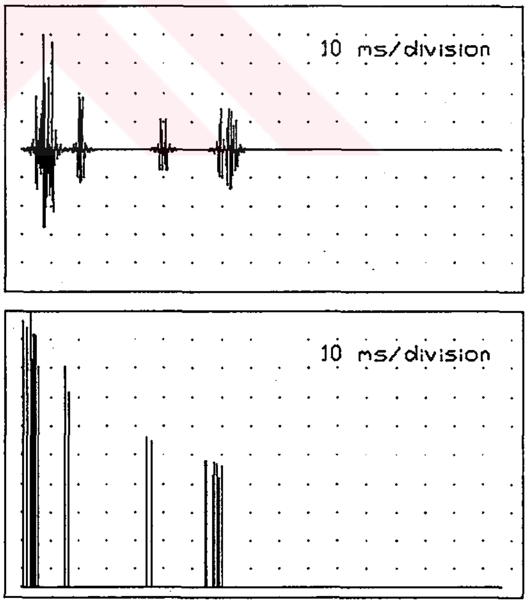
C1



Rays : 16000 Refl. : 7
Valid : 20 Radius : 1.05 m.

Receiver : 59.30 30.10 2.00
Source : 49.20 12.20 0.10
File : r3aspf7.Pth

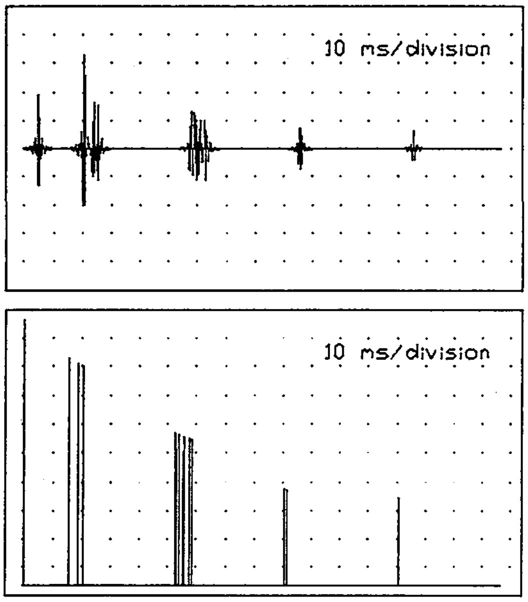
C2



Rays : 16000 Refl. : 7
Valid : 27 Radius : 1.05 m.

Receiver : 62.50 33.20 4.50
Source : 49.20 12.20 0.10
File : r4aspf7.Pth

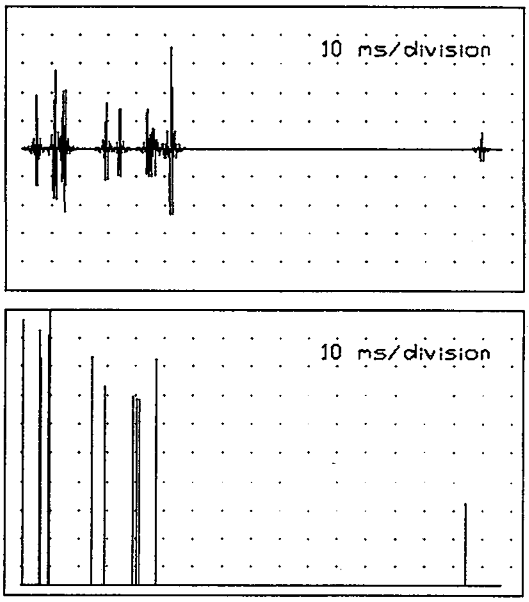
C3



Rays : 16000 Refl. : 7
Valid : 17 Radius : 1.05 m.

Receiver : 66.60 36.20 7.40
Source : 49.20 12.20 0.10
File : r5aspf7.Pth

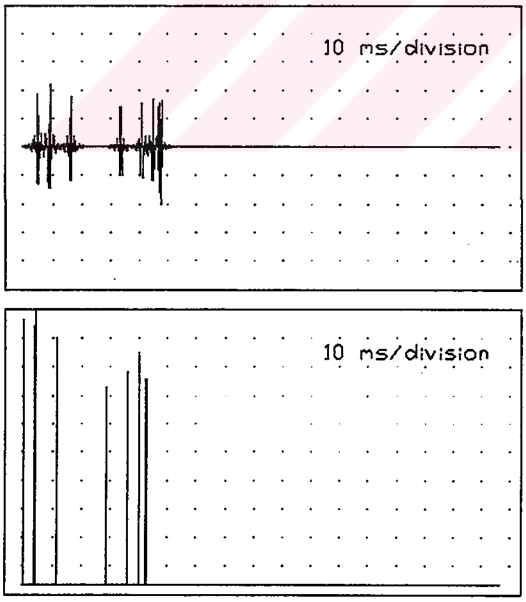
C4



Rays : 16000 Refl. : 7
Valid : 14 Radius : 1.05 m.

Receiver : 74.80 42.10 14.50
Source : 49.20 12.20 0.10
File : r6aspf7.Pth

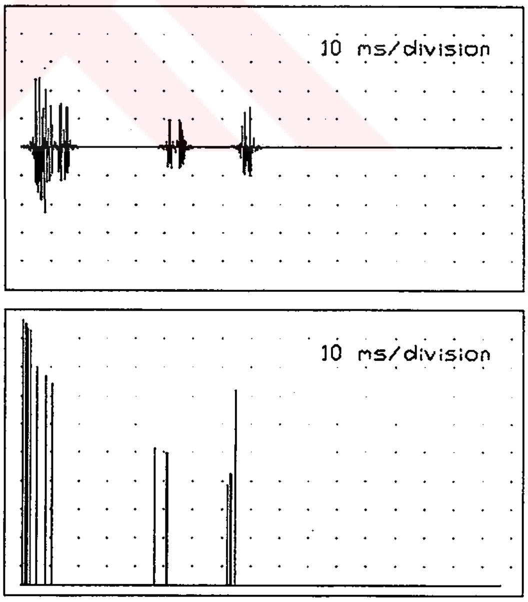
C5



Rays : 16000 Refl. : 7
Valid : 10 Radius : 1.05 m.

Receiver : 69.20 47.30 14.50
Source : 49.20 12.20 0.10
File : r7aspf7.Pth

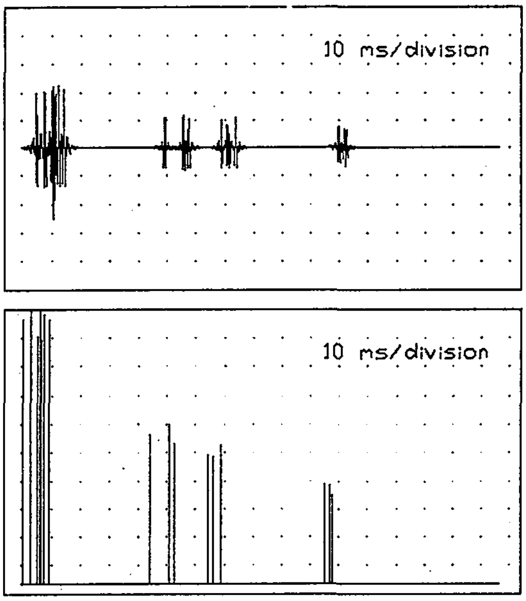
D1



Rays : 16000 Refl. : 7
Valid : 18 Radius : 1.05 m.

Receiver : 54.50 32.90 2.00
Source : 49.20 12.20 0.10
File : r8aspf7.Pth

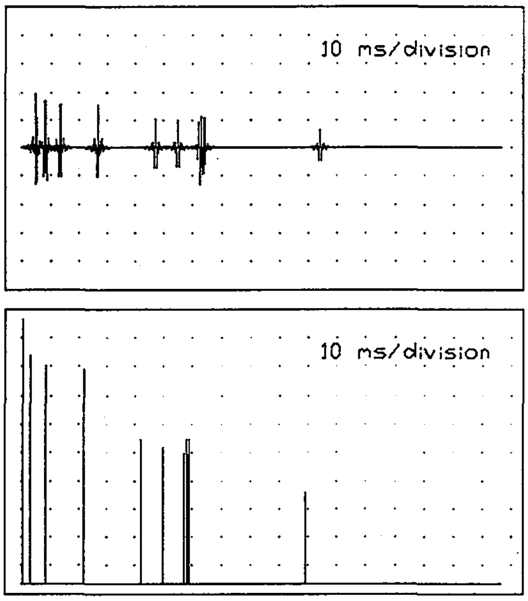
D2



Rays : 16000 Refl. : 7
Valid : 17 Radius : 1.05 m.

Receiver : 56.30 37.00 4.50
Source : 49.20 12.20 0.10
File : r1aspf7.Pth

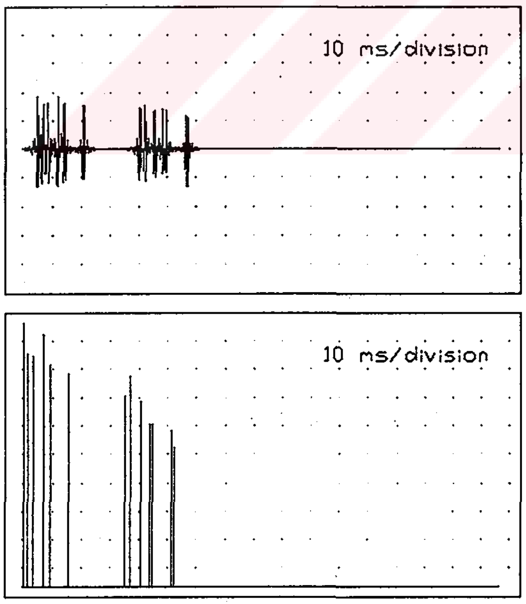
D3



Rays : 16000 Refl. : 7
Valid : 11 Radius : 1.05 m.

Receiver : 58.10 41.40 7.40
Source : 49.20 12.20 0.10
File : r2aspf7.Pth

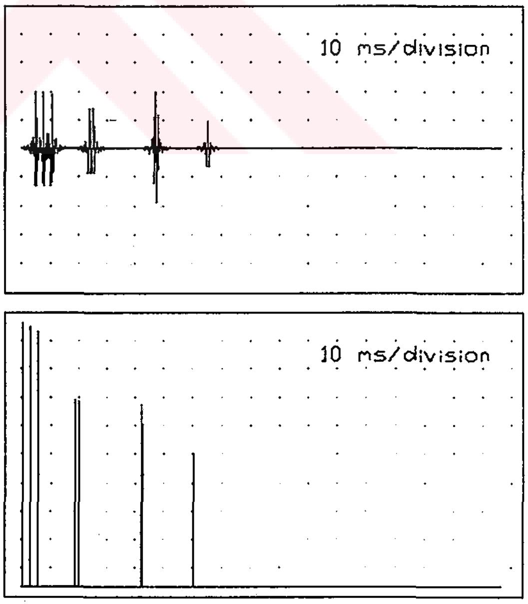
D4



Rays : 16000 Refl. : 7
Valid : 13 Radius : 1.05 m.

Receiver : 63.70 50.30 14.50
Source : 49.20 12.20 0.10
File : r3aspf7.Pth

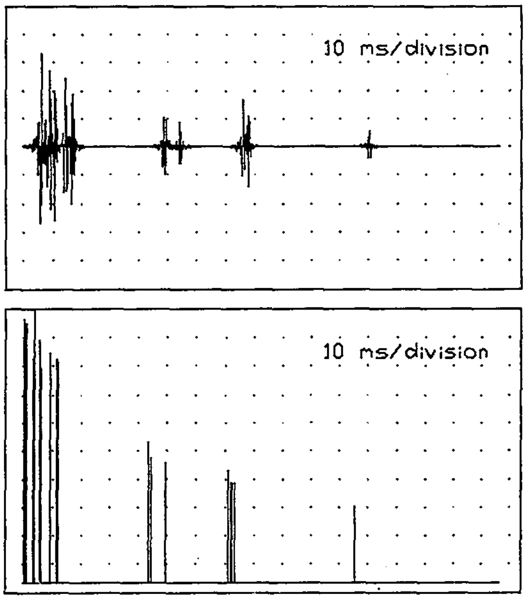
D5



Rays : 16000 Refl. : 7
Valid : 9 Radius : 1.05 m.

Receiver : 58.60 52.00 14.50
Source : 49.20 12.20 0.10
File : r4aspf7.Pth

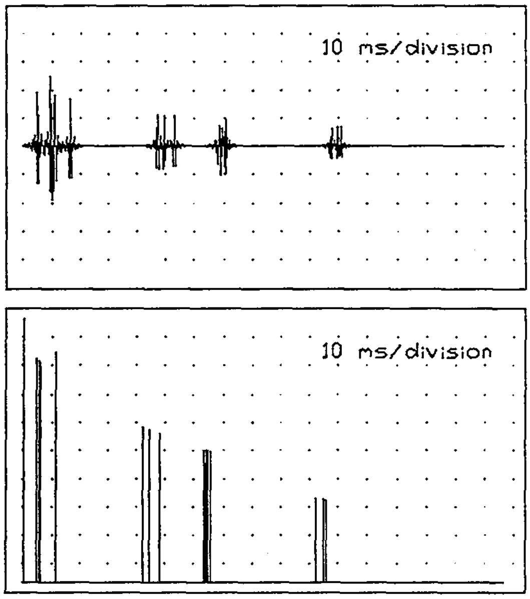
E1



Rays : 16000 Refl. : 7
Valid : 24 Radius : 1.05 m.

Receiver : 49.20 34.00 2.00
Source : 49.20 12.20 0.10
File : r5aspf7.Pth

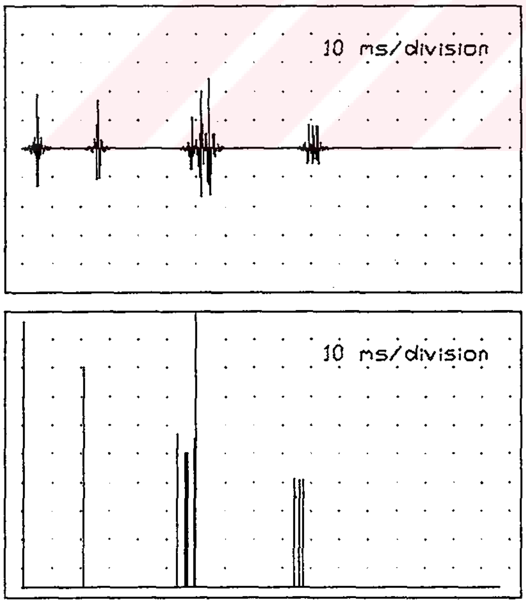
E2



Rays : 16000 Refl. : 7
Valid : 17 Radius : 1.05 m.

Receiver : 49.20 38.50 4.50
Source : 49.20 12.20 0.10
File : r6aspf7.Pth

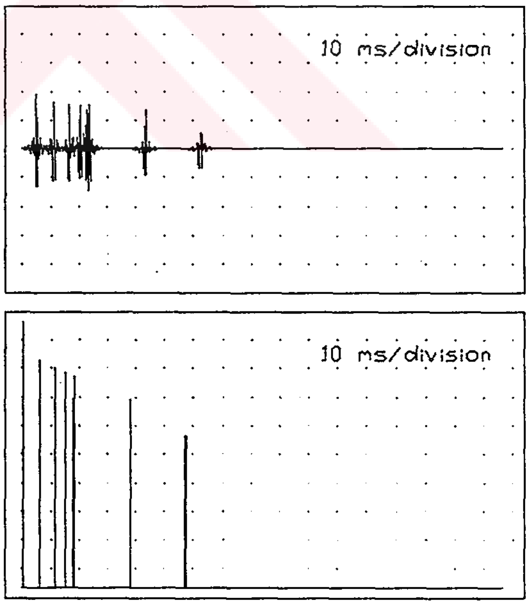
E3



Rays : 16000 Refl. : 7
Valid : 15 Radius : 1.05 m.

Receiver : 49.20 43.20 7.40
Source : 49.20 12.20 0.10
File : r7aspf7.Pth

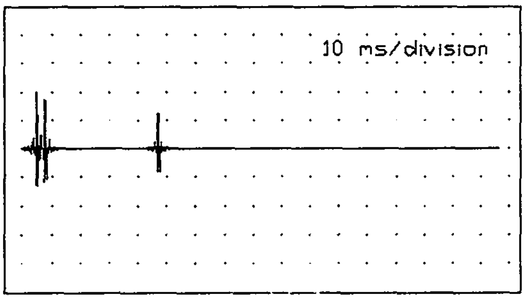
E4

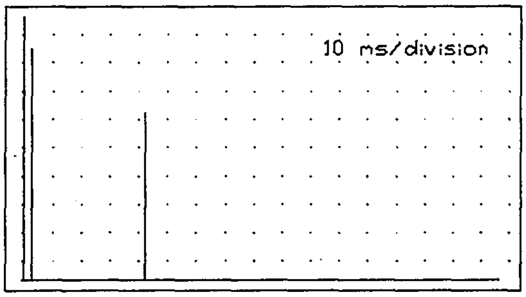


Rays : 16000 Refl. : 7
Valid : 9 Radius : 1.05 m.

Receiver : 52.10 53.70 14.50
Source : 49.20 12.20 0.10
File : r8aspf7.Pth

E5





Rays : 16000 Refl. : 7
Valid : 3 Radius : 1.05 m.

Receiver : 45.20 53.70 14.50

Source : 49.20 12.20 0.10

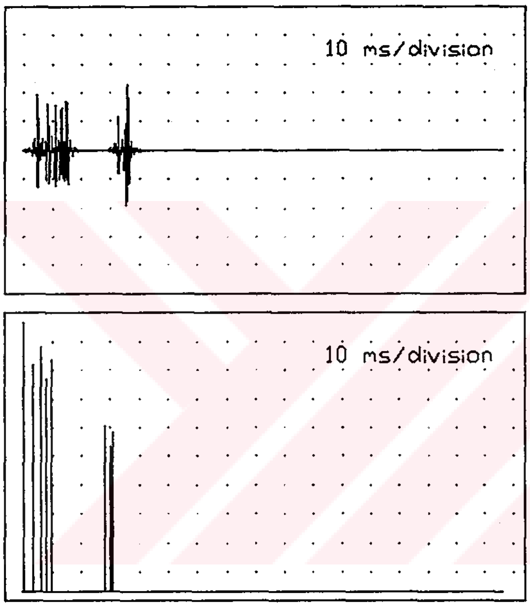
File : r9aspf7.Pth

APPENDIX D

ACOUSTICAL SIMULATION OF TERMESSOS THEATRE

D.1 Impulse Responses for the Seventh Order Simulation

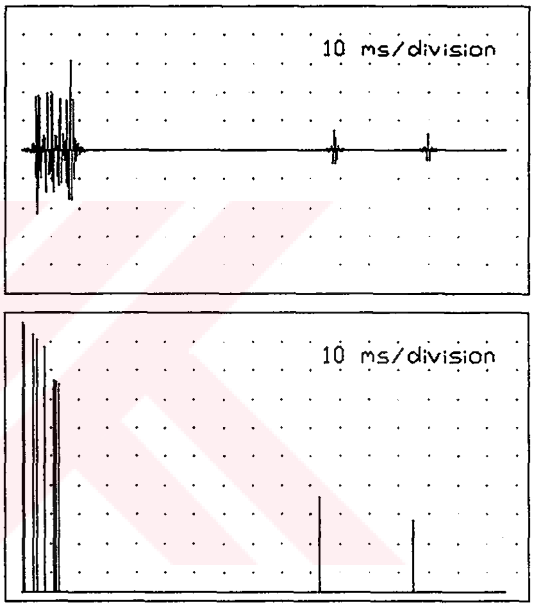
A1



Rays : 16000 Refl. : 7
Valid : 10 Radius : 0.70 m.

Receiver : 10.90 16.40 6.20
Source : 28.50 19.60 0.30
File : r1T95f7.Pth

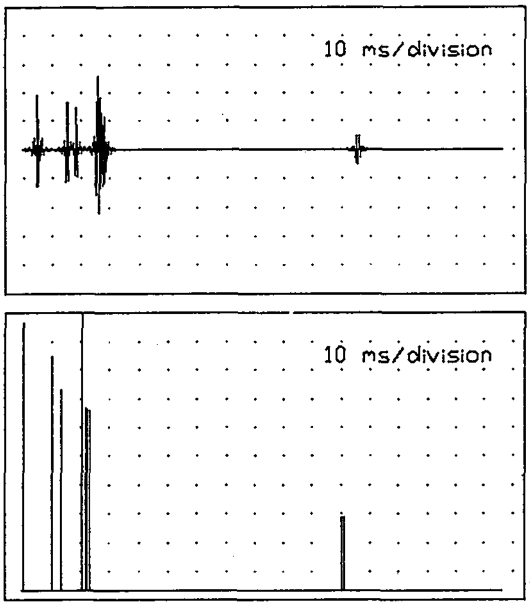
A2



Rays : 16000 Refl. : 7
Valid : 11 Radius : 0.70 m.

Receiver : 8.10 15.60 8.70
Source : 28.50 19.60 0.30
File : r2T95f7.Pth

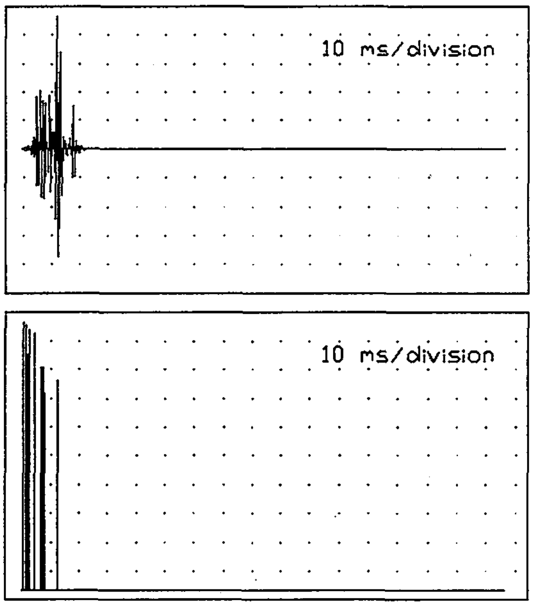
A3



Rays : 16000 Refl. : 7
Valid : 11 Radius : 0.70 m.

Receiver : 10.00 24.00 7.10
Source : 28.50 19.60 0.30
File : r3T95f7.Pth

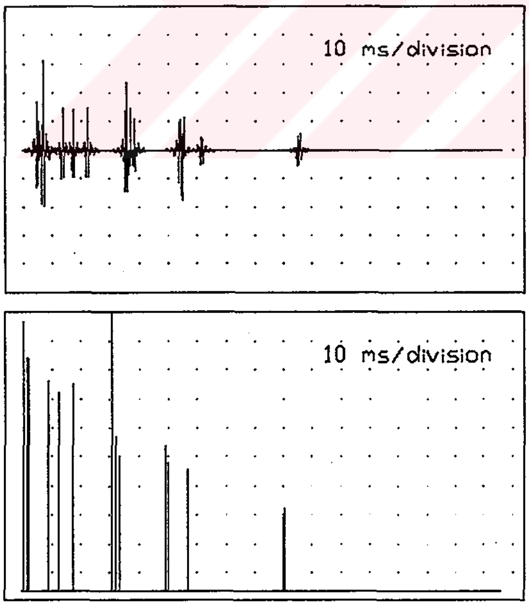
A4



Rays : 16000 Refl. : 7
Valid : 13 Radius : 0.70 m.

Receiver : 3.00 27.40 12.50
Source : 28.50 19.60 0.30
File : R4T95F7.PTH

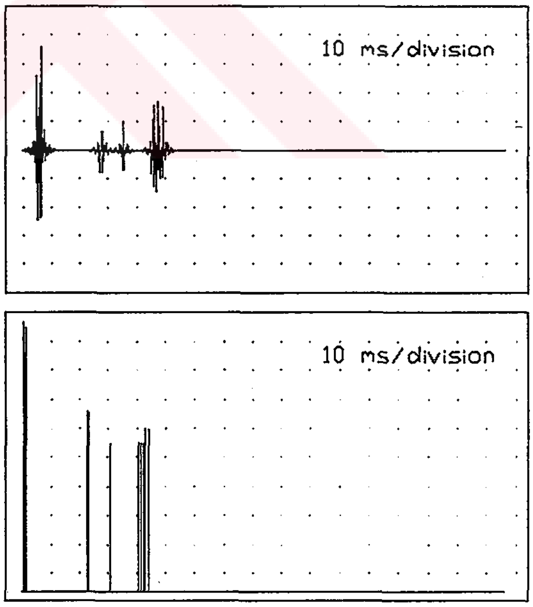
B1



Rays : 16000 Refl. : 7
Valid : 19 Radius : 0.70 m.

Receiver : 13.30 28.90 6.20
Source : 28.50 19.60 0.30
File : r5T95f7.Pth

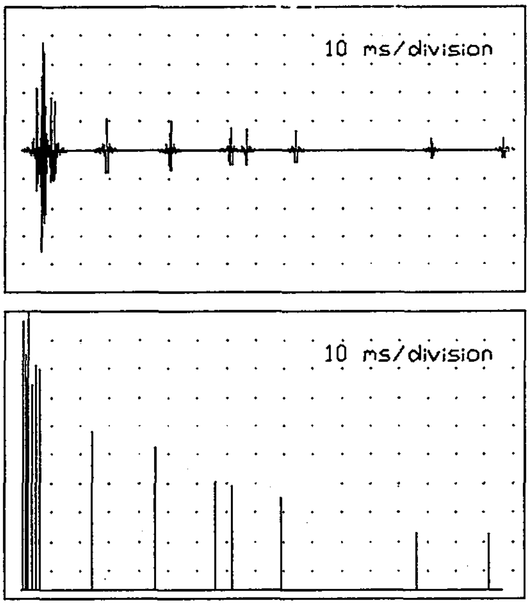
B2



Rays : 16000 Refl. : 7
Valid : 13 Radius : 0.70 m.

Receiver : 10.70 29.90 8.70
Source : 28.50 19.60 0.30
File : r6T95f7.Pth

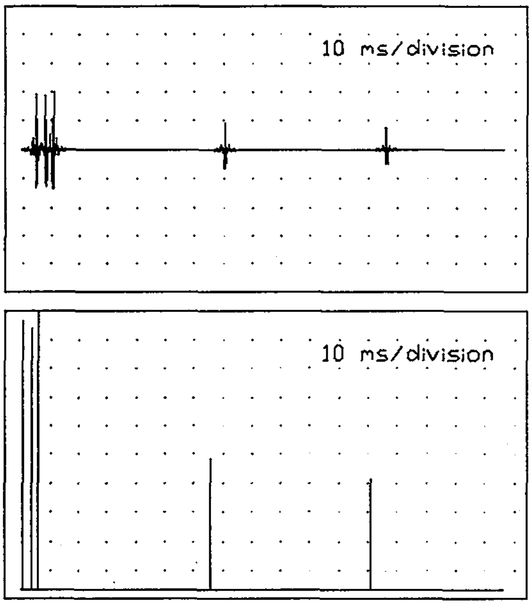
B3



Rays : 16000 Refl. : 7
Valid : 17 Radius : 0.70 m.

Receiver : 18.30 35.40 7.10
Source : 28.50 19.60 0.30
File : r7T95f7.Pth

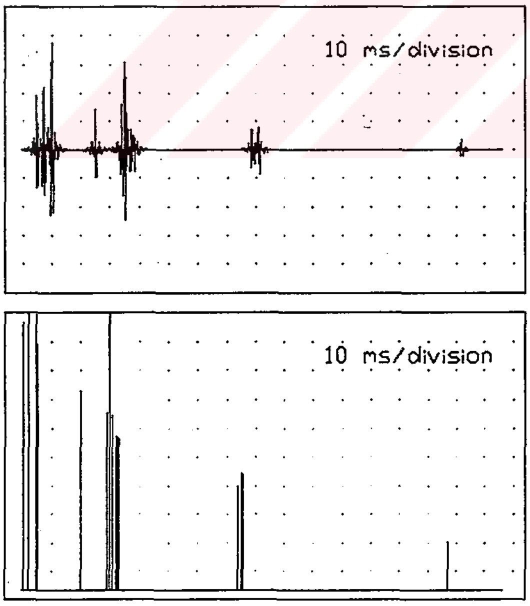
B4



Rays : 16000 Refl. : 7
Valid : 5 Radius : 0.70 m.

Receiver : 14.80 42.40 12.50
Source : 28.50 19.60 0.30
File : r8T95f7.Pth

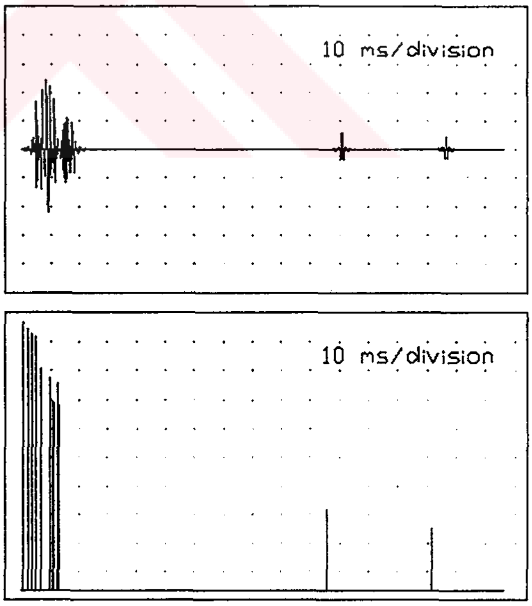
C1



Rays : 16000 Refl. : 7
Valid : 21 Radius : 0.70 m.

Receiver : 23.80 36.70 6.20
Source : 28.50 19.60 0.30
File : r9T95f7.Pth

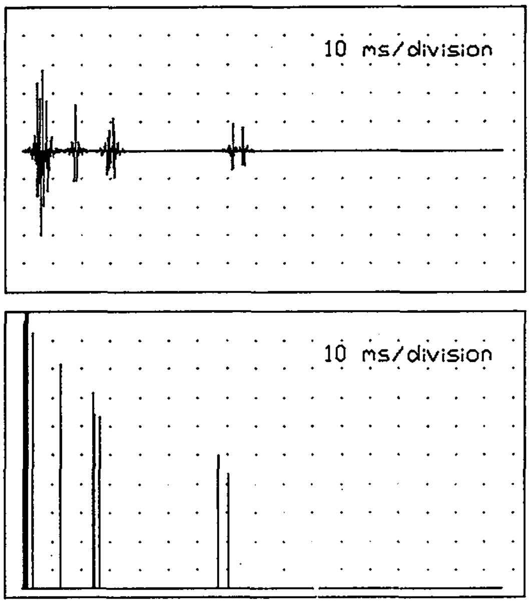
C2



Rays : 16000 Refl. : 7
Valid : 16 Radius : 0.70 m.

Receiver : 22.70 39.40 8.70
Source : 28.50 19.60 0.30
File : r10T95f7.Pth

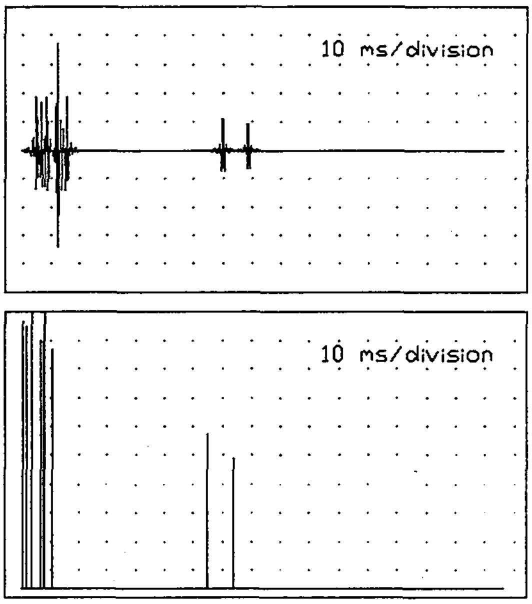
C3



Rays : 16000 Refl. : 7
Valid : 12 Radius : 0.70 m.

Receiver : 33.30 37.80 7.10
Source : 28.50 19.60 0.30
File : r11T95f7.Pth

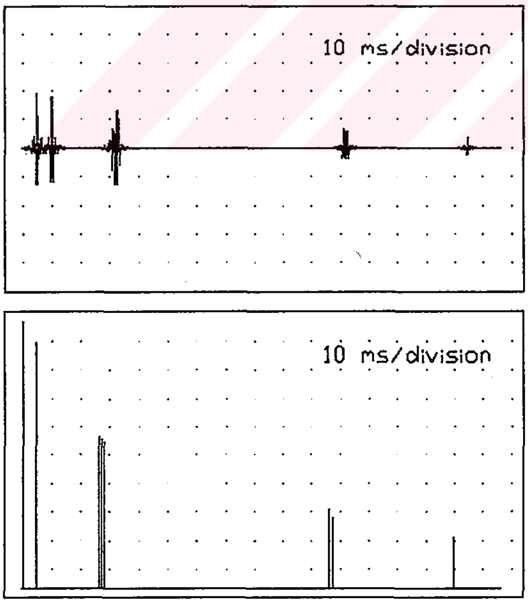
C4



Rays : 16000 Refl. : 7
Valid : 11 Radius : 0.70 m.

Receiver : 36.10 44.90 12.50
Source : 28.50 19.60 0.30
File : r12T95f7.Pth

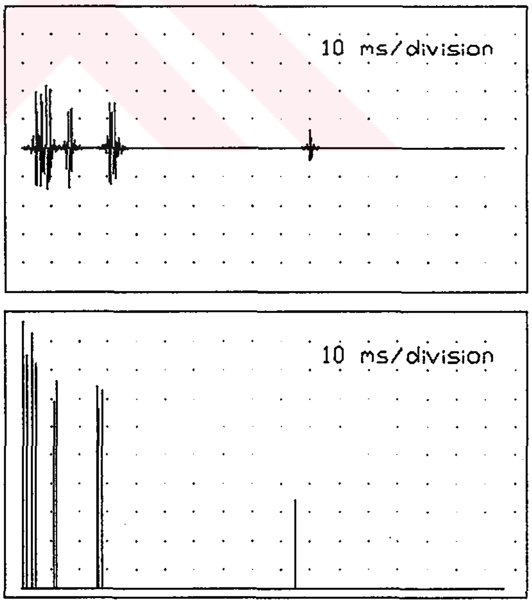
D1



Rays : 16000 Refl. : 7
Valid : 9 Radius : 0.70 m.

Receiver : 38.30 34.40 6.20
Source : 28.50 19.60 0.30
File : r13T95f7.Pth

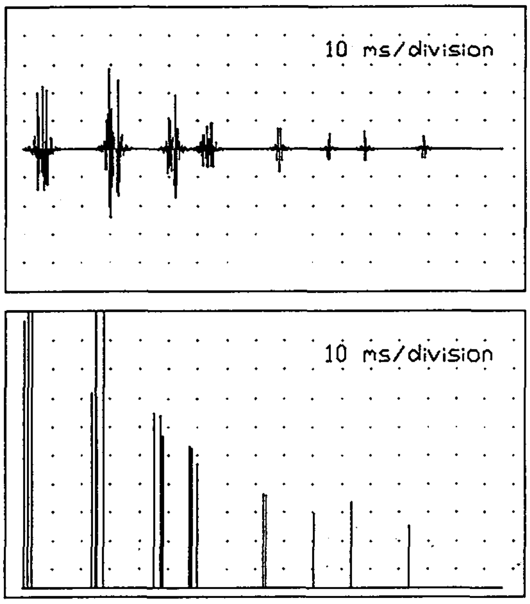
D2



Rays : 16000 Refl. : 7
Valid : 10 Radius : 0.70 m.

Receiver : 39.70 37.70 8.70
Source : 28.50 19.60 0.30
File : r14T95f7.Pth

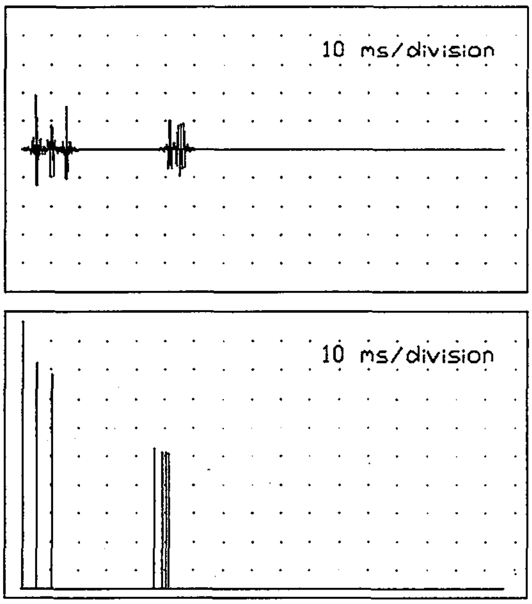
D3



Rays : 16000 Refl. : 7
Valid : 24 Radius : 0.70 m.

Receiver : 44.40 29.80 7.10
Source : 28.50 19.60 0.30
File : r15T95f7.Pth

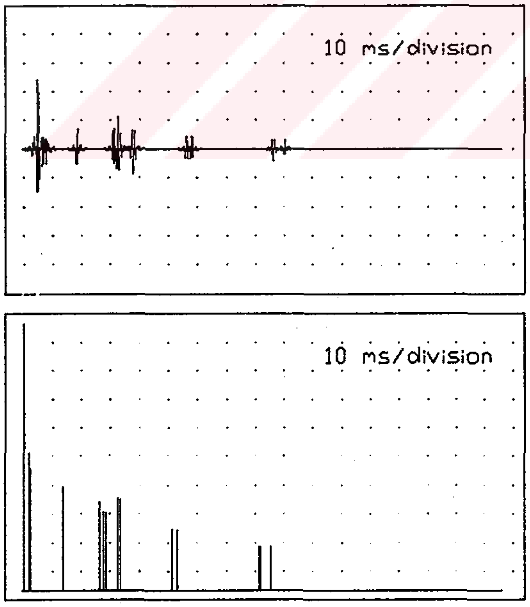
D4



Rays : 16000 Refl. : 7
Valid : 8 Radius : 0.70 m.

Receiver : 51.90 33.40 12.50
Source : 28.50 19.60 0.30
File : r16T95f7.Pth

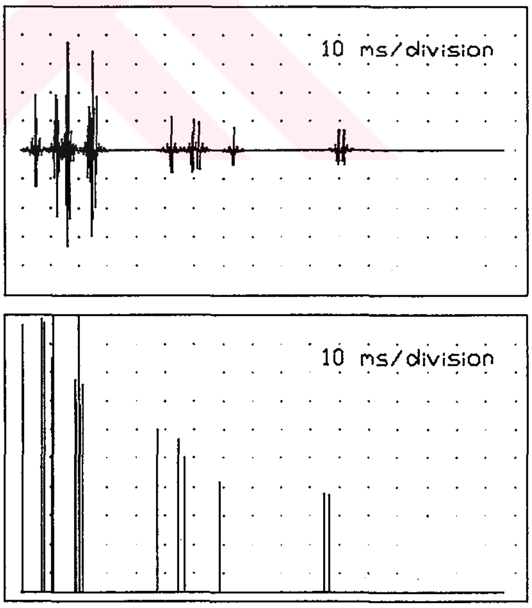
E1



Rays : 16000 Refl. : 7
Valid : 18 Radius : 0.70 m.

Receiver : 45.70 23.50 6.20
Source : 28.50 19.60 0.30
File : r17T95f7.Pth

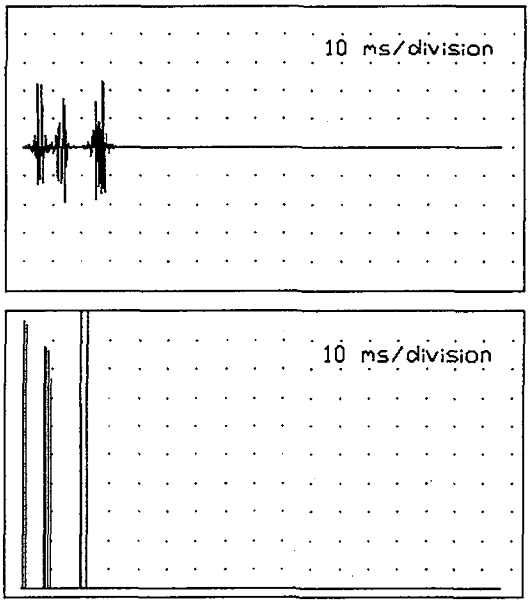
E2



Rays : 16000 Refl. : 7
Valid : 18 Radius : 0.70 m.

Receiver : 47.60 26.20 8.20
Source : 28.50 19.60 0.30
File : r18T95f7.Pth

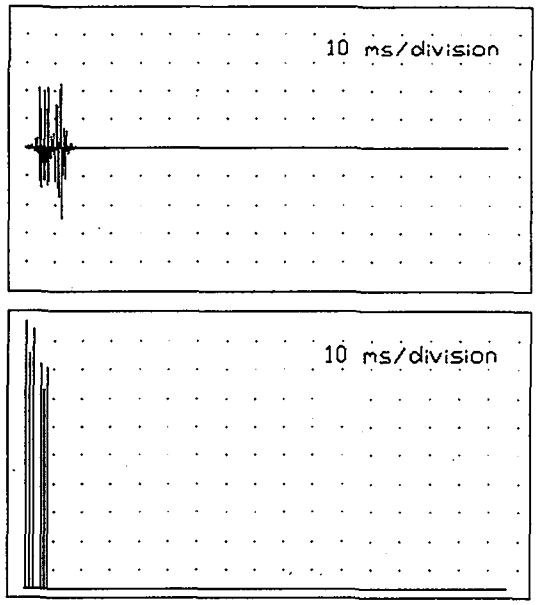
E3



Rays : 16000 Refl. : 7
Valid : 14 Radius : 0.70 m.

Receiver : 47.10 16.60 7.10
Source : 28.50 19.60 0.30
File : r19T95f7.Pth

E4

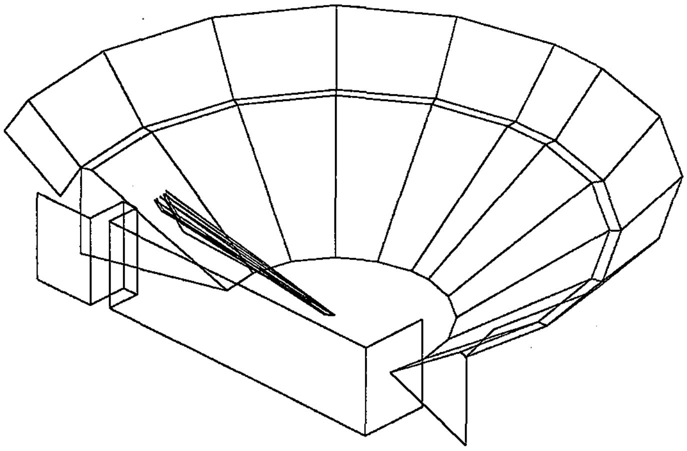


Rays : 16000 Refl. : 7
Valid : 9 Radius : 0.70 m.

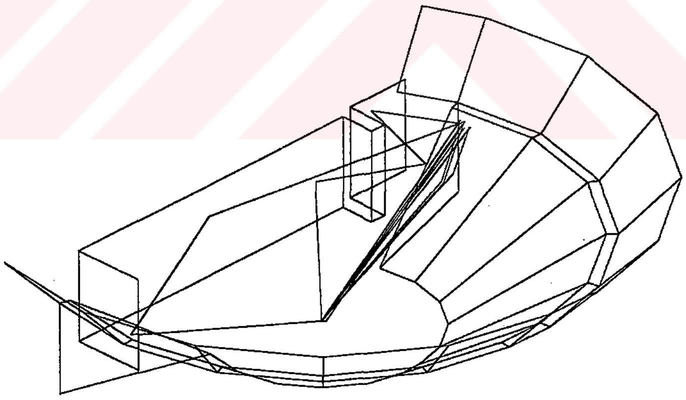
Receiver : 54.90 23.20 12.50
Source : 28.50 19.60 0.30
File : r20T95f7.Pth

D.2 Three-dimensional Models of the Seventh Order Reflections

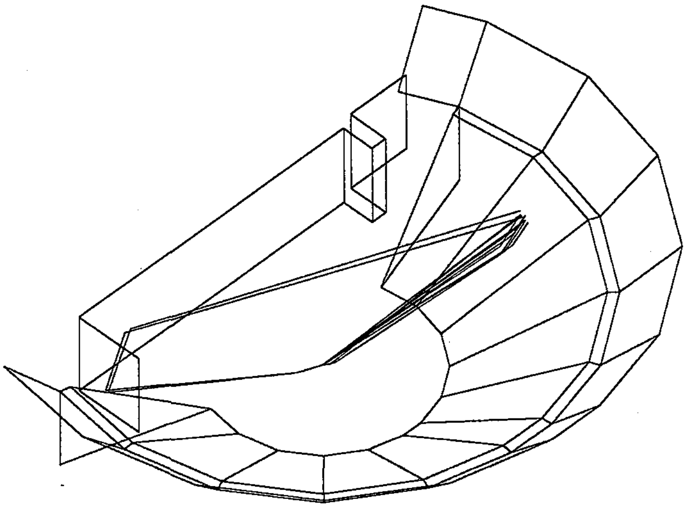
RECEIVER POSITION A1



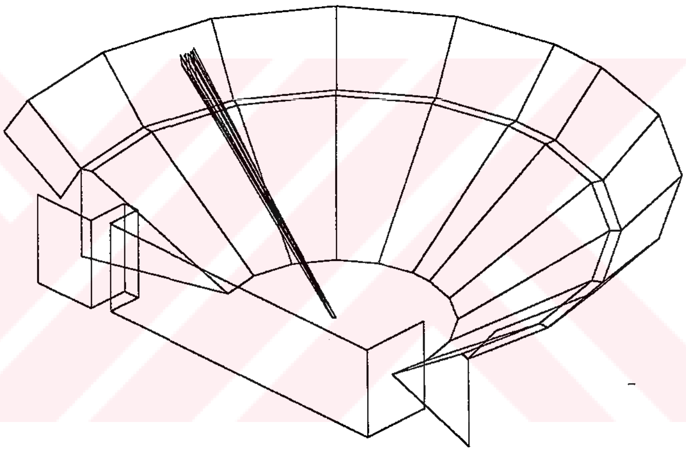
RECEIVER POSITION A2



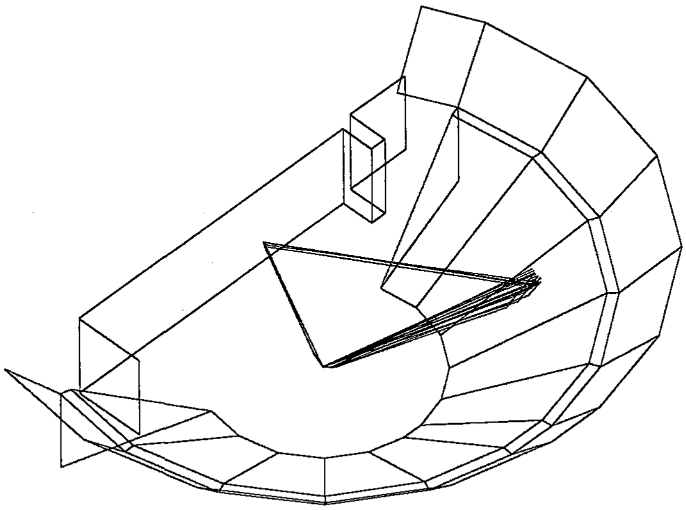
RECEIVER POSITION A3



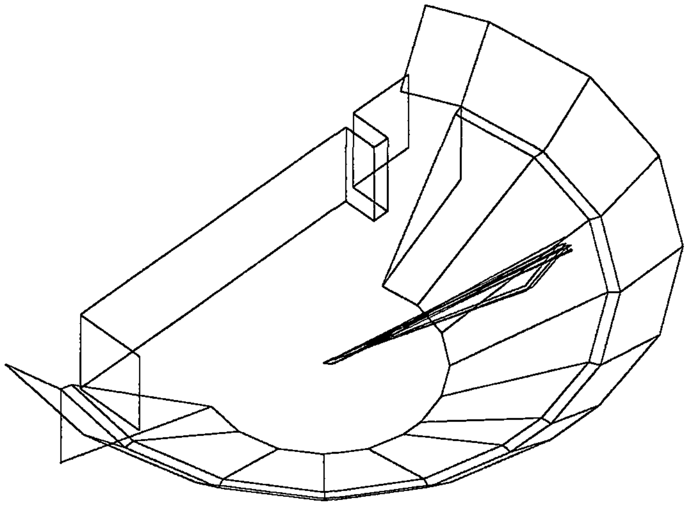
RECEIVER POSITION A4



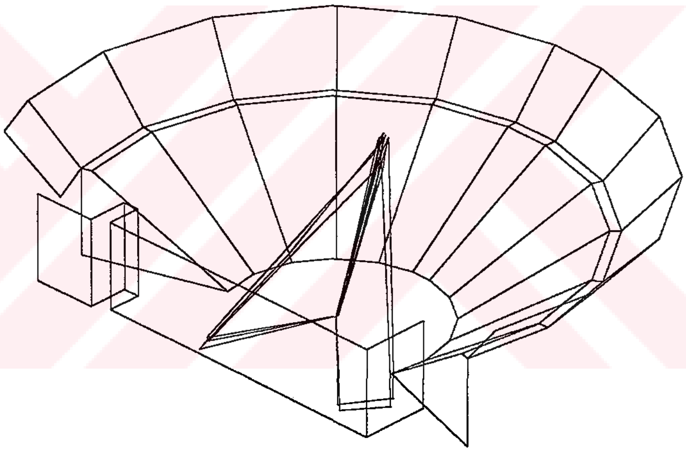
RECEIVER POSITION B1



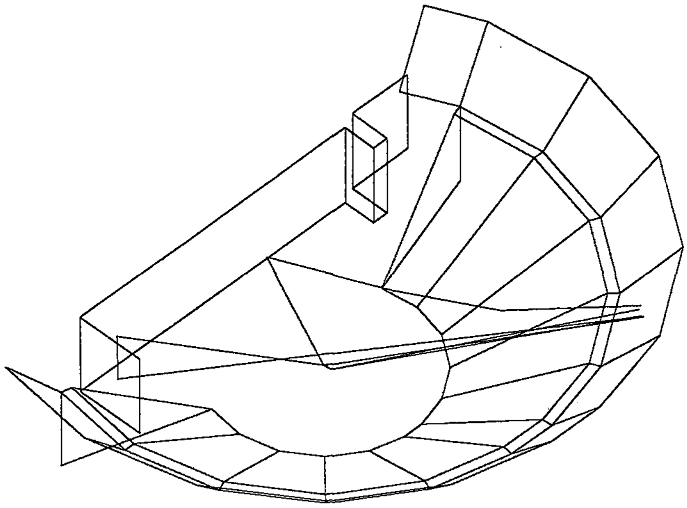
RECEIVER POSITION B2



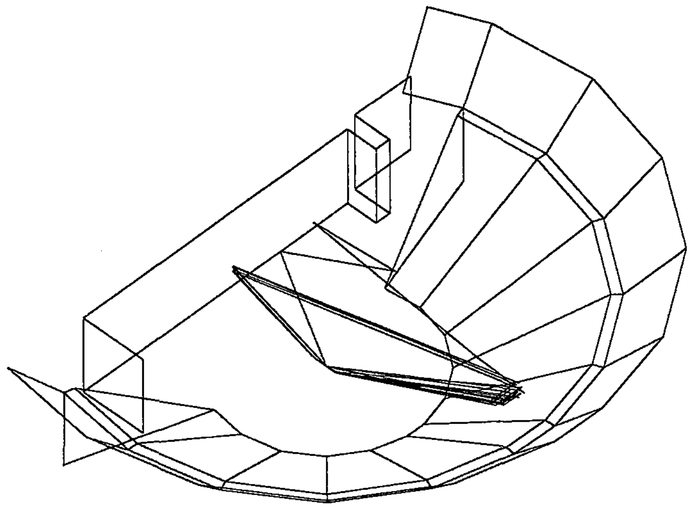
RECEIVER POSITION B3



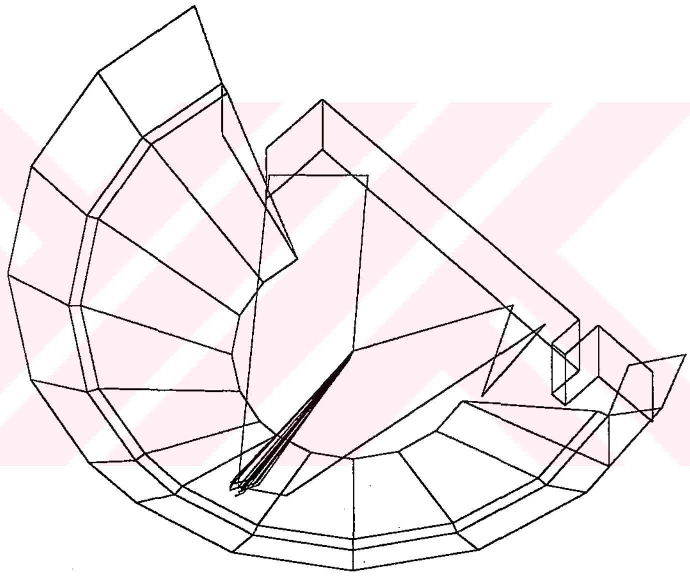
RECEIVER POSITION B4



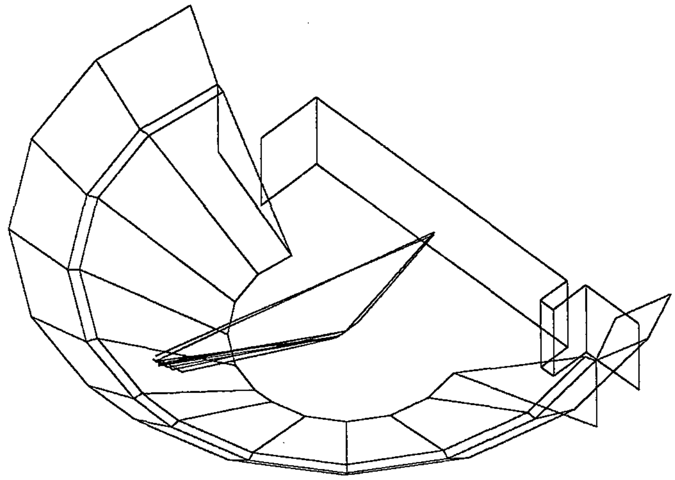
RECEIVER POSITION C1



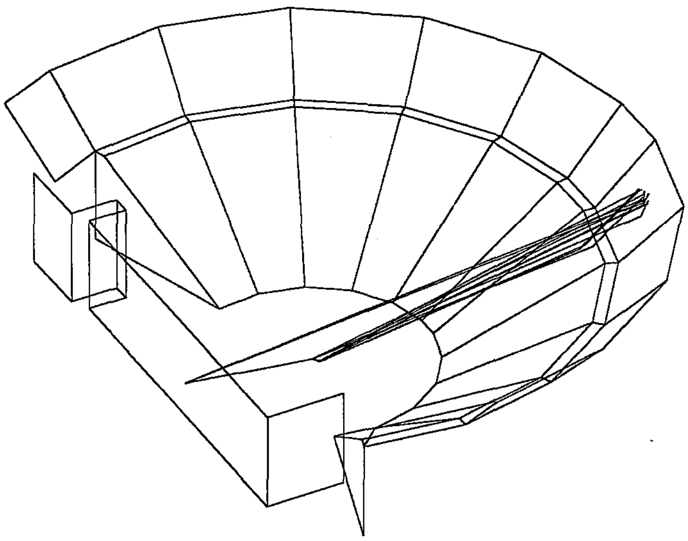
RECEIVER POSITION C2



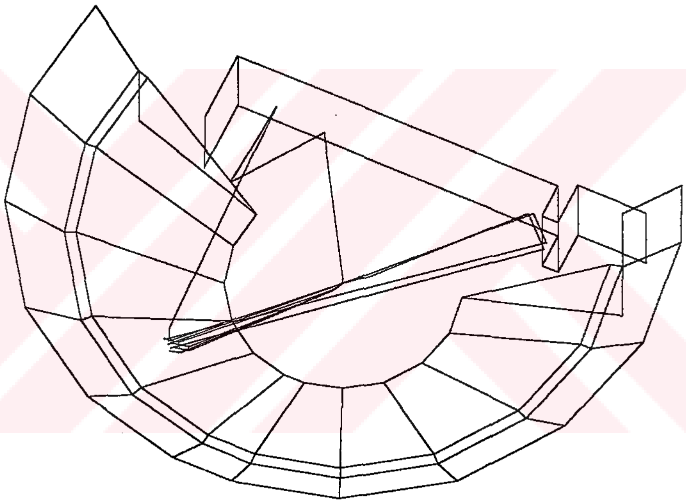
RECEIVER POSITION C3



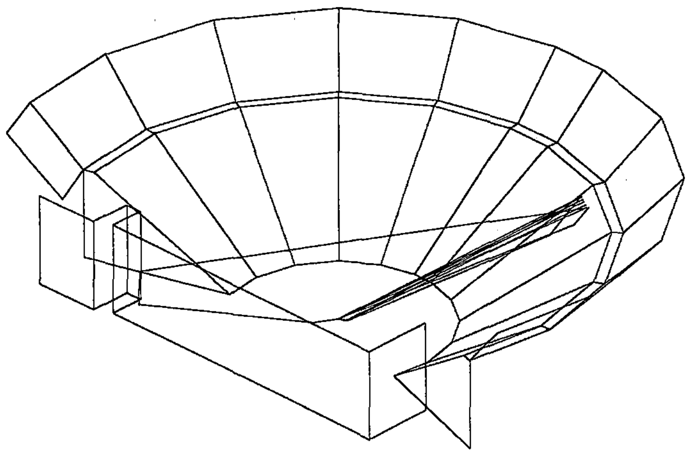
RECEIVER POSITION C4



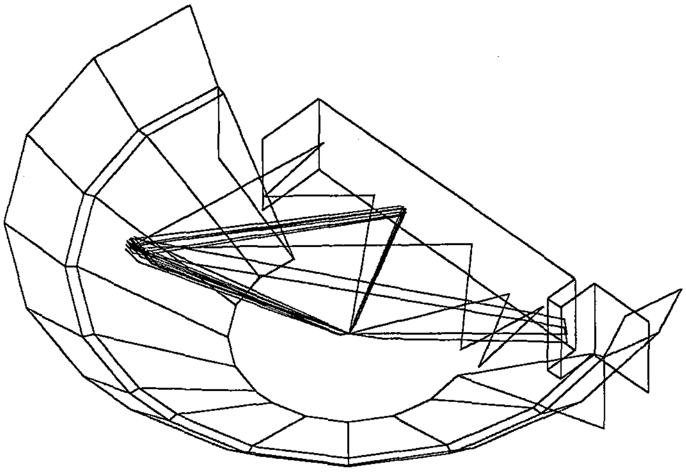
RECEIVER POSITION D1



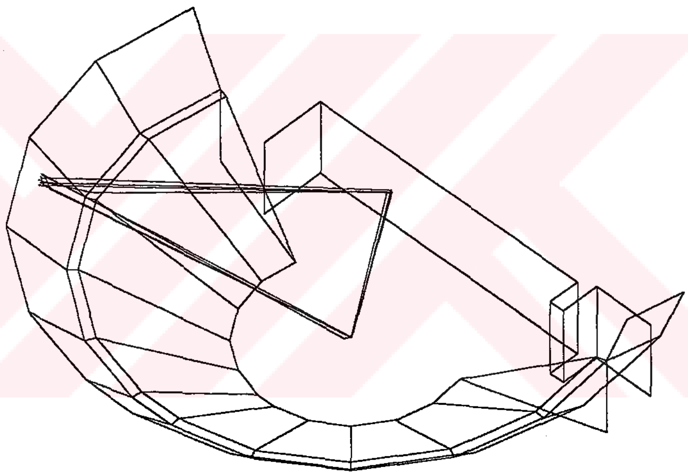
RECEIVER POSITION D2



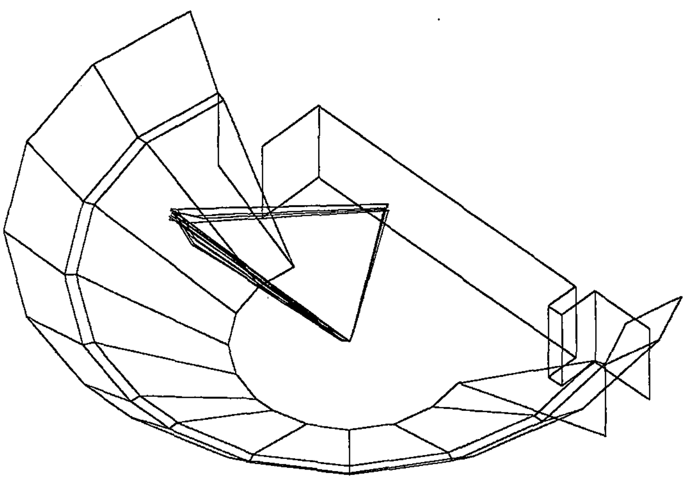
RECEIVER POSITION D3



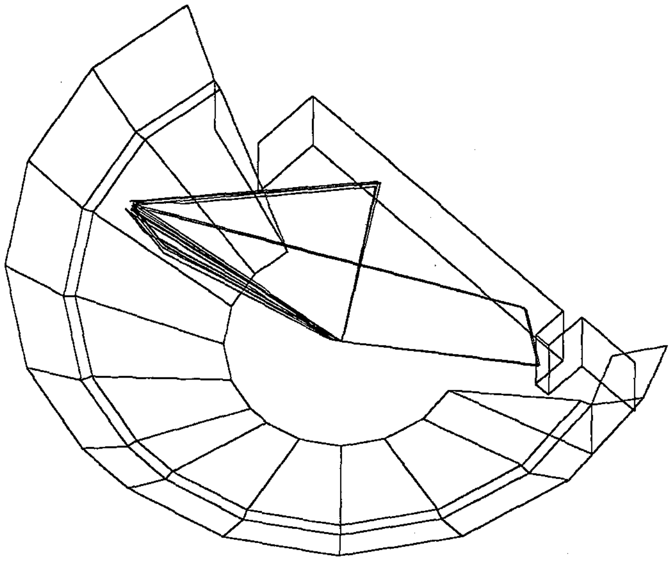
RECEIVER POSITION D4



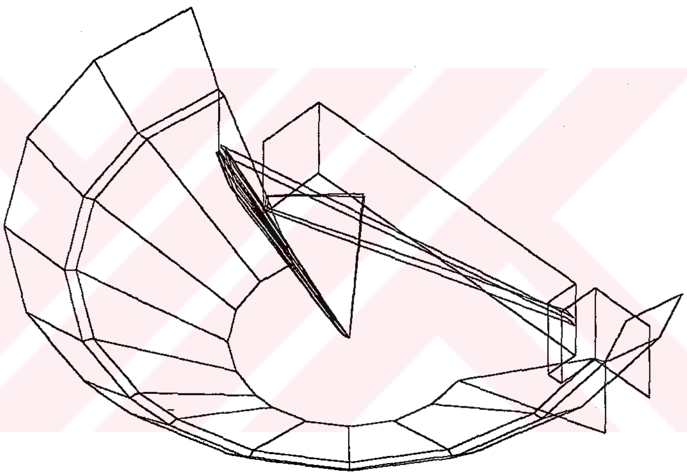
RECEIVER POSITION E1



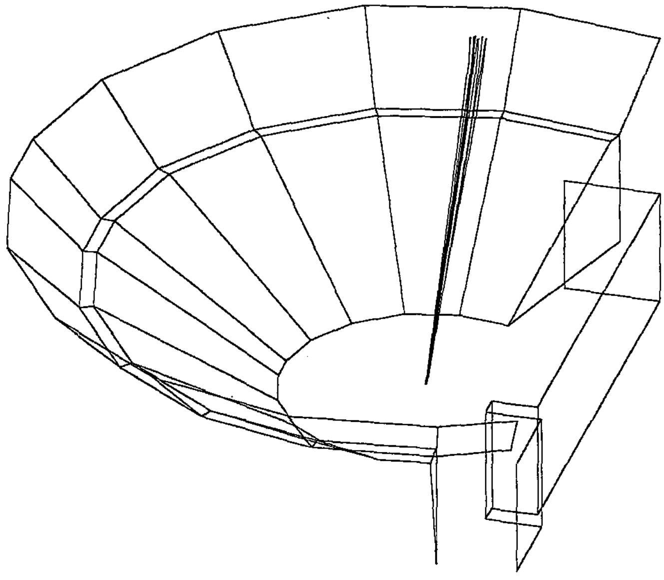
RECEIVER POSITION E2



RECEIVER POSITION E3



RECEIVER POSITION E4

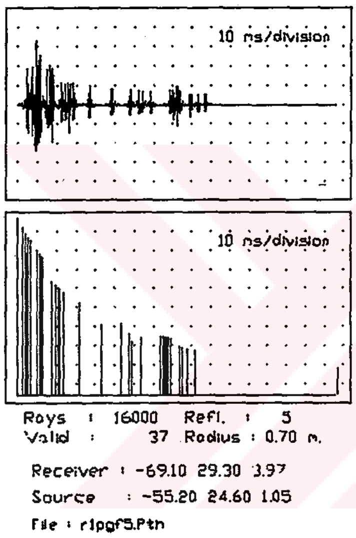


APPENDIX E

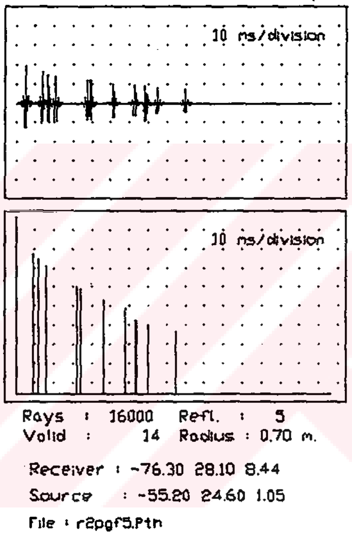
ACOUSTICAL SIMULATION OF PERGE THEATRE

E.1 Impulse Responses for the Fifth Order Simulations

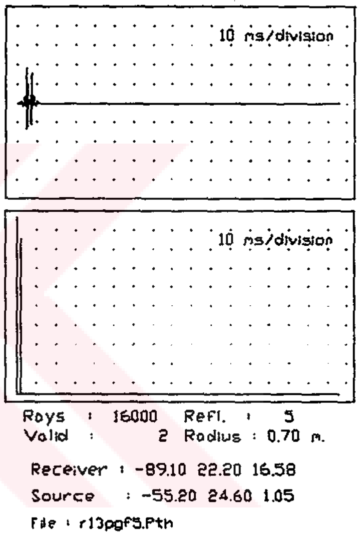
RECEIVER POSITION A1



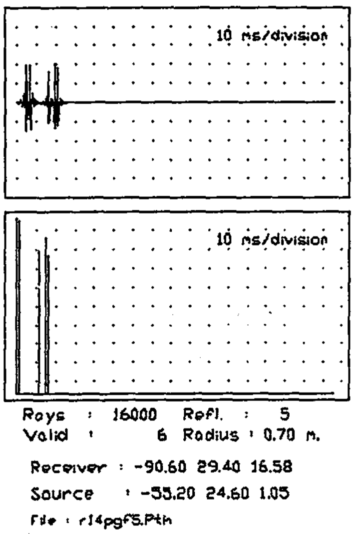
RECEIVER POSITION A2



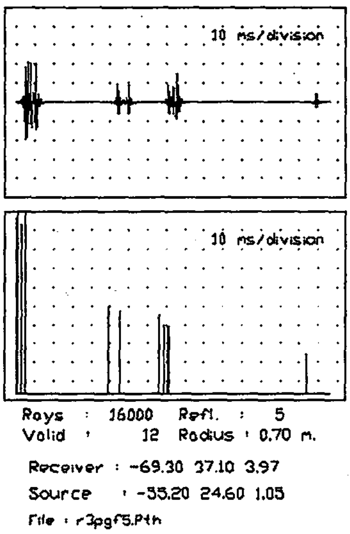
RECEIVER POSITION A4



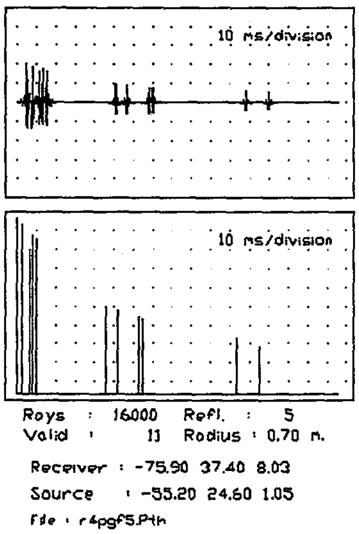
RECEIVER POSITION A5



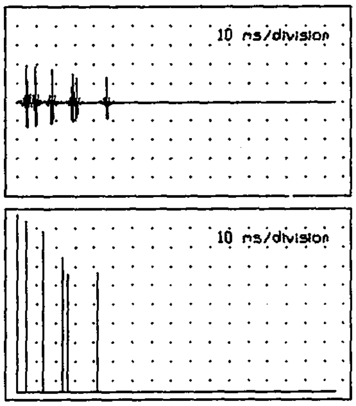
RECEIVER POSITION B1



RECEIVER POSITION B2



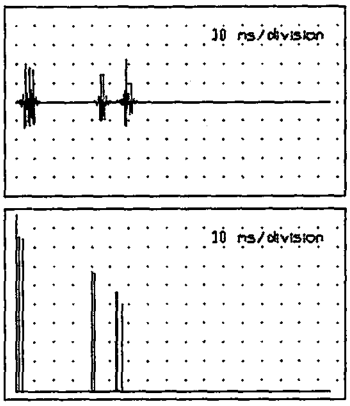
RECEIVER POSITION B4



Rays : 16000 Refl. : 5
Valid : 6 Radius : 0.70 m.

Receiver : -90.80 36.20 16.58
Source : -55.20 24.60 1.05
File : r15pgf5.Ptn

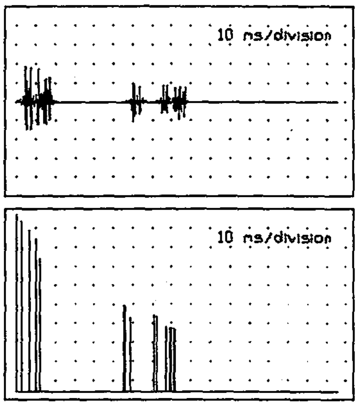
RECEIVER POSITION B5



Rays : 16000 Refl. : 5
Valid : 9 Radius : 0.70 m.

Receiver : -89.90 43.10 16.58
Source : -55.20 24.60 1.05
File : r16pgf5.Ptn

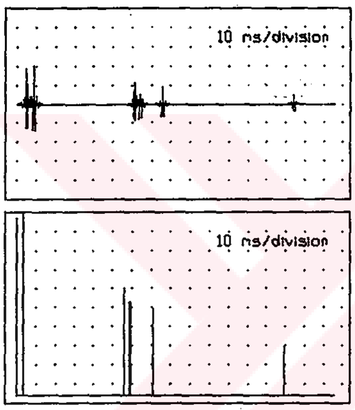
RECEIVER POSITION C1



Rays : 16000 Refl. : 5
Valid : 18 Radius : 0.70 m.

Receiver : -66.90 43.80 3.97
Source : -55.20 24.60 1.05
File : r5pgf5.Ptn

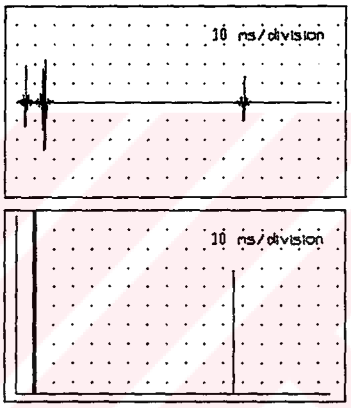
RECEIVER POSITION C2



Rays : 16000 Refl. : 5
Valid : 7 Radius : 0.70 m.

Receiver : -72.90 46.30 8.03
Source : -55.20 24.60 1.05
File : r6pgf5.Ptn

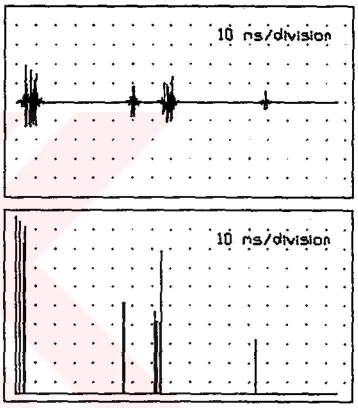
RECEIVER POSITION C5



Rays : 16000 Refl. : 5
Valid : 5 Radius : 0.70 m.

Receiver : -83.50 57.30 16.58
Source : -55.20 24.60 1.05
File : r17pgf5.Ptn

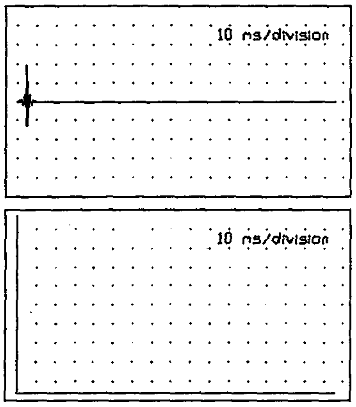
RECEIVER POSITION D1



Rays : 16000 Refl. : 5
Valid : 14 Radius : 0.70 m.

Receiver : -62.50 48.90 3.97
Source : -55.20 24.60 1.05
File : r7pgf5.Ptn

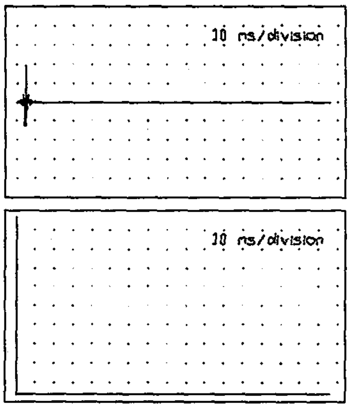
RECEIVER POSITION D2



Rays : 16000 Refl. : 5
Valid : 1 Radius : 0.70 m.

Receiver : -67.40 54.60 8.03
Source : -55.20 24.60 1.05
File : r8pgf5.Ptn

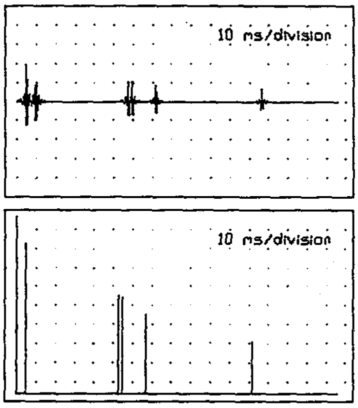
RECEIVER POSITION D4



Rays : 16000 Refl. : 5
Valid : 1 Radius : 0.70 m.

Receiver : -79.10 62.60 16.58
Source : -55.20 24.60 1.05
File : r18pgf5.Ptn

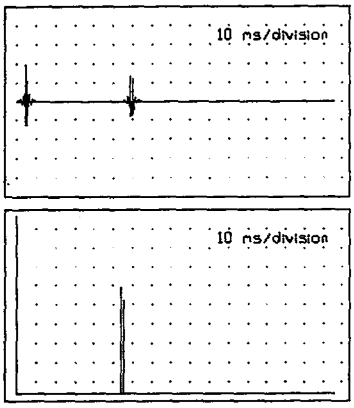
RECEIVER POSITION E1



Rays : 16000 Refl. : 5
Valid : 8 Radius : 0.70 m.

Receiver : -56.30 52.40 3.97
Source : -55.20 24.60 1.05
File : r9pgf5.Ptn

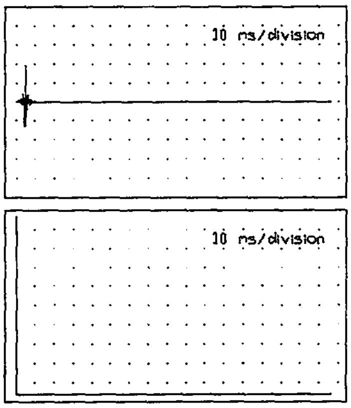
RECEIVER POSITION E2



Rays : 16000 Refl. : 5
Valid : 3 Radius : 0.70 m.

Receiver : -58.80 59.30 8.03
Source : -55.20 24.60 1.05
File : r10pgf5.Ptn

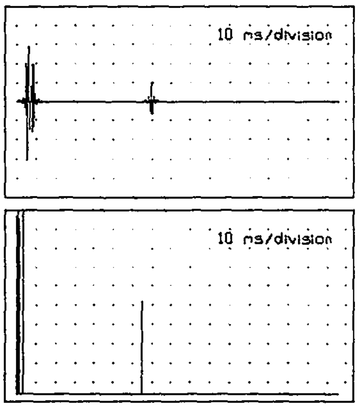
RECEIVER POSITION E5



Rays : 16000 Refl. : 5
Valid : 1 Radius : 0.70 m.

Receiver : -60.40 73.40 16.58
Source : -55.20 24.60 1.05
File : r19pgf5.Ptn

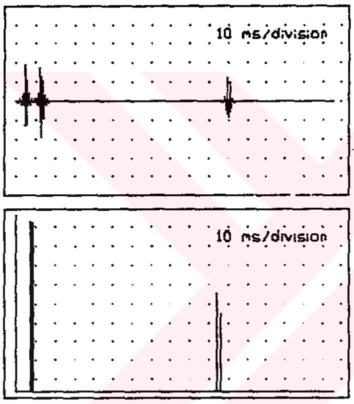
RECEIVER POSITION F1



Rays : 16000 Refl. : 5
Valid : 6 Radius : 0.70 m.

Receiver : -50.00 53.50 3.97
Source : -55.20 24.60 1.05
File : r11pgf5.Ptn

RECEIVER POSITION F5

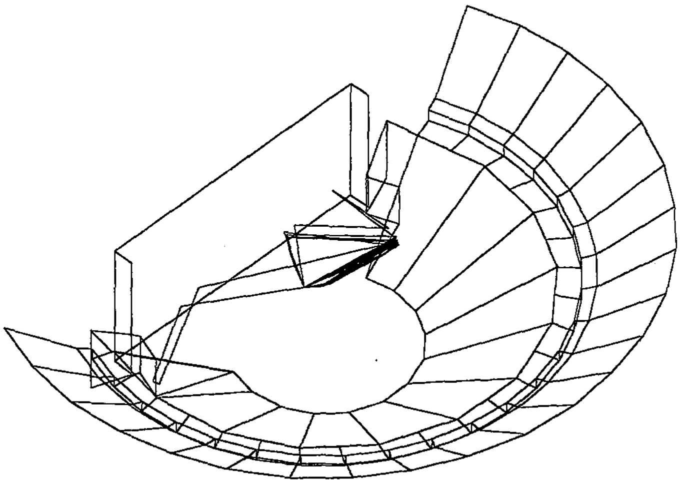


Rays : 16000 Refl. : 5
Valid : 6 Radius : 0.70 m.

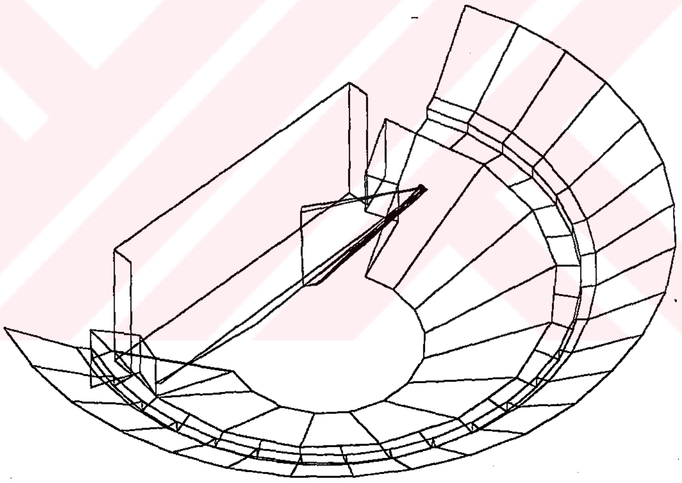
Receiver : -46.00 74.50 16.58
Source : -55.20 24.60 1.05
File : r20pgf5.Ptn

E.2 Three-dimensional Models of the Fifth Order Reflections

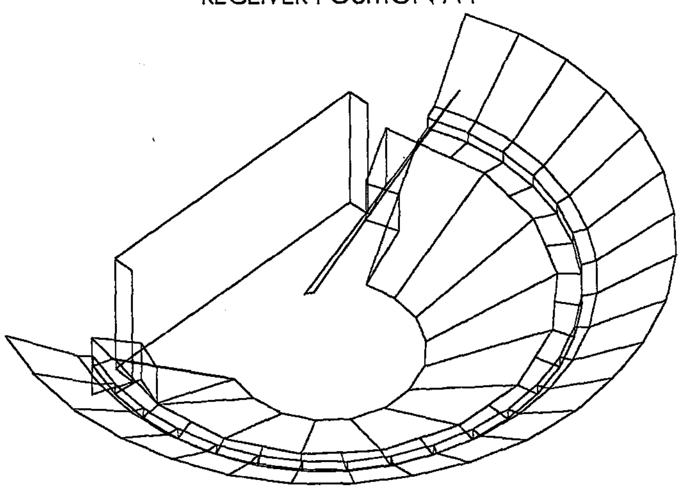
RECEIVER POSITION A1



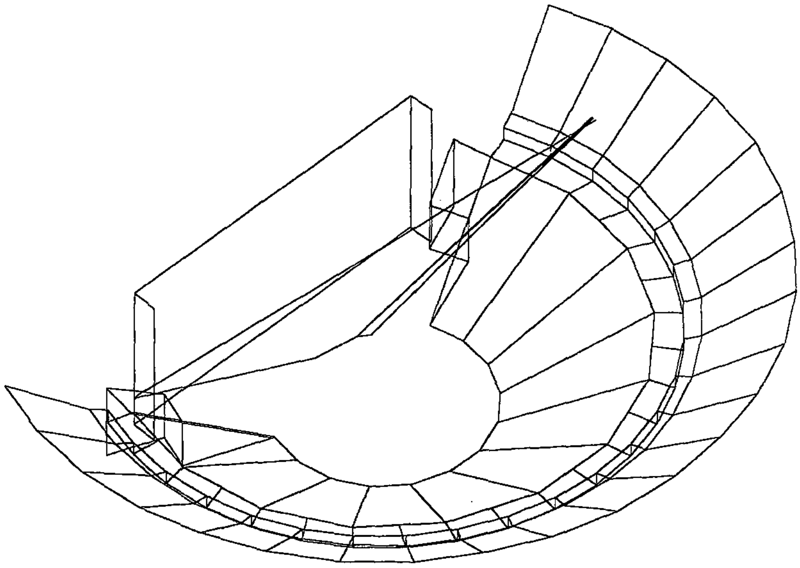
RECEIVER POSITION A2



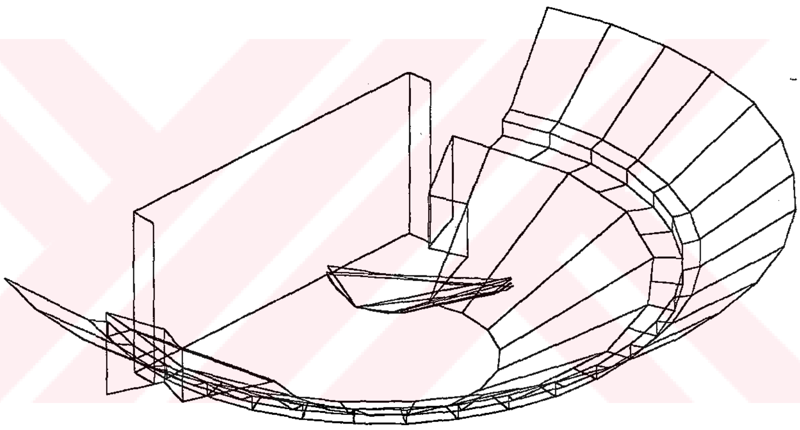
RECEIVER POSITION A4



RECEIVER POSITION A5



RECEIVER POSITION B1



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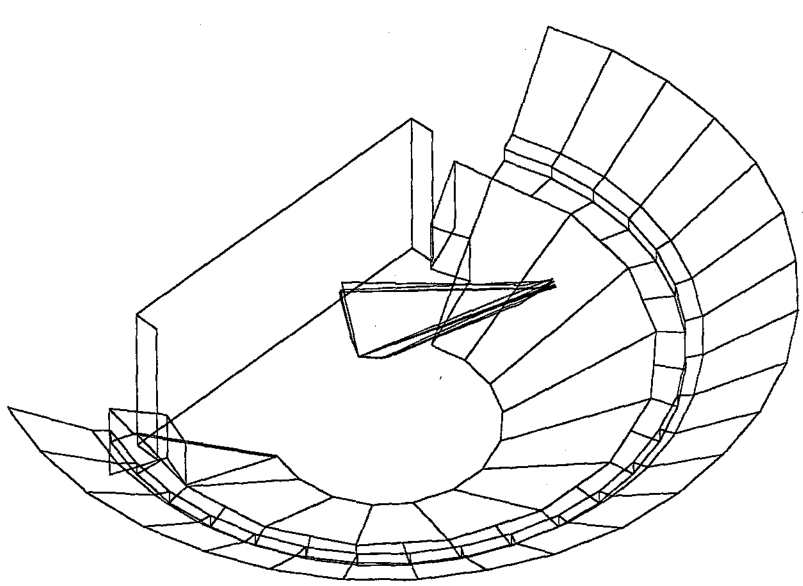
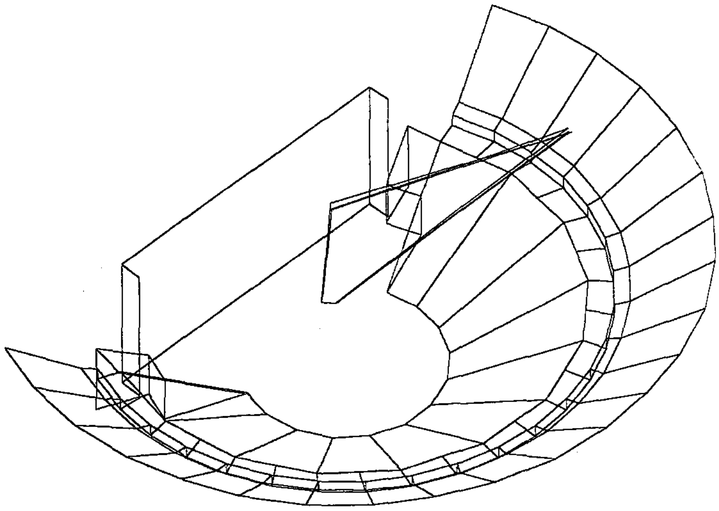


RECEIVER POSITION B4



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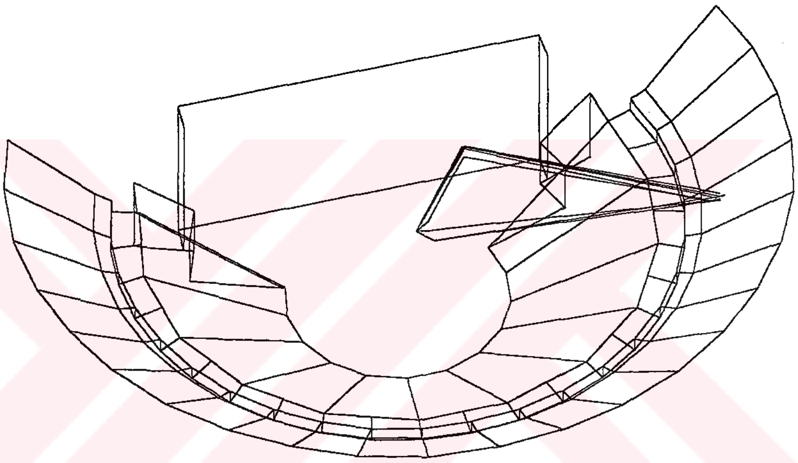
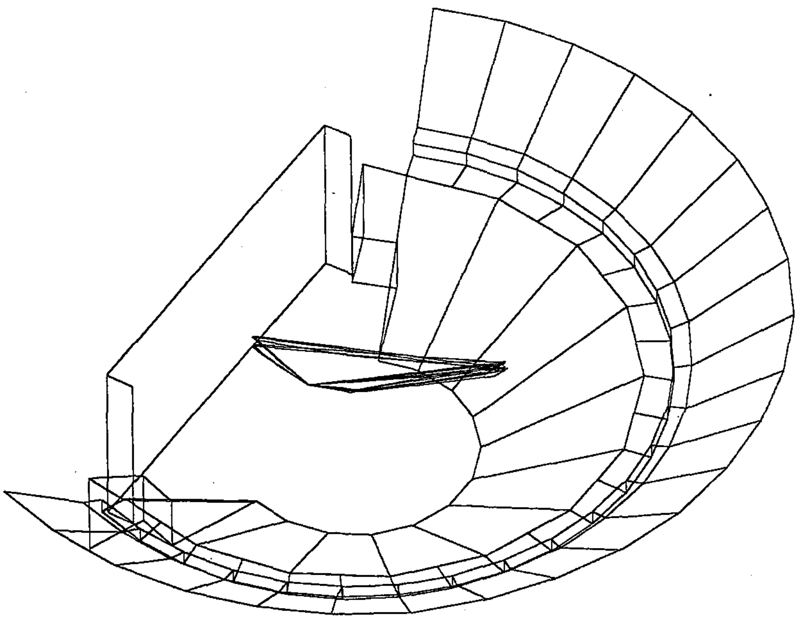
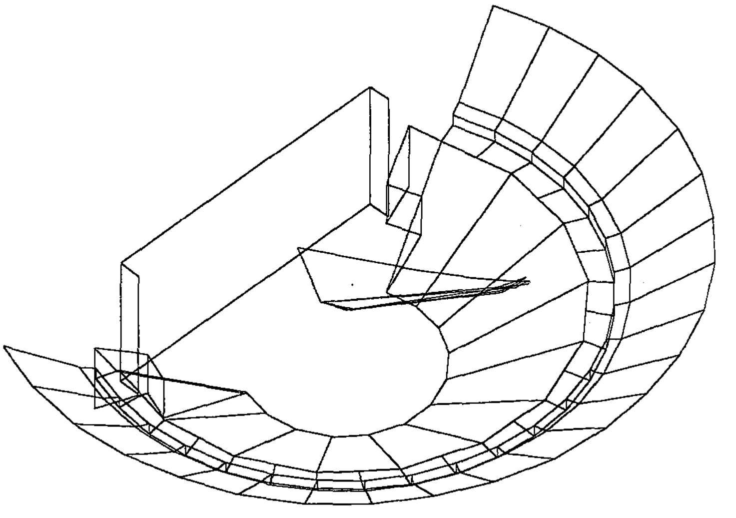


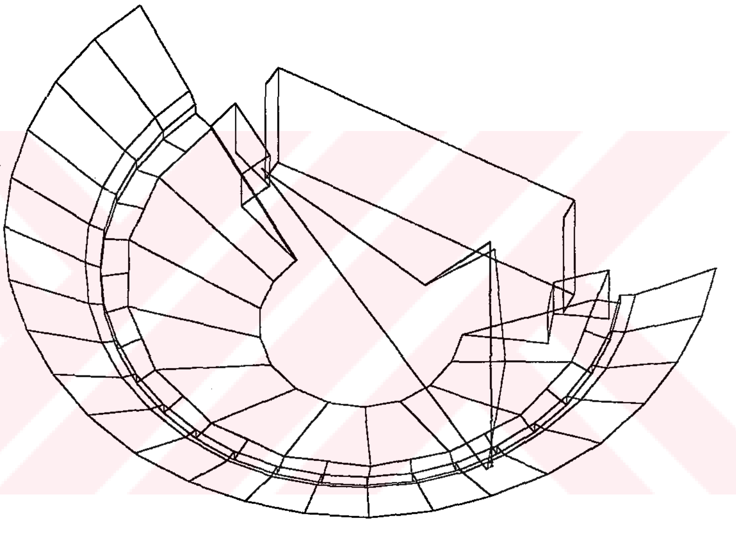
RECEIVER POSITION C1



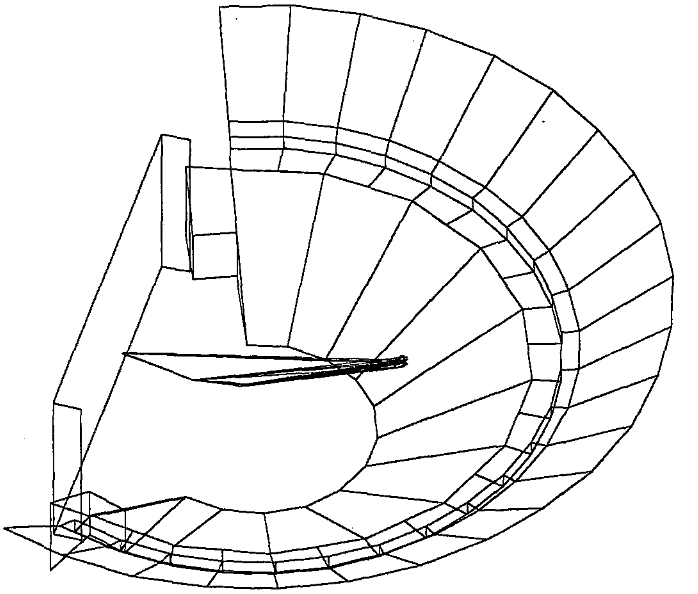
RECEIVER POSITION C2



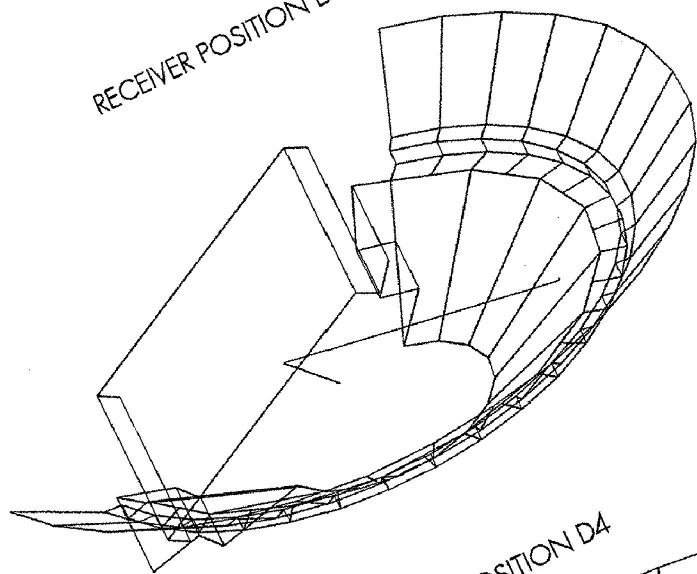
RECEIVER POSITION C5



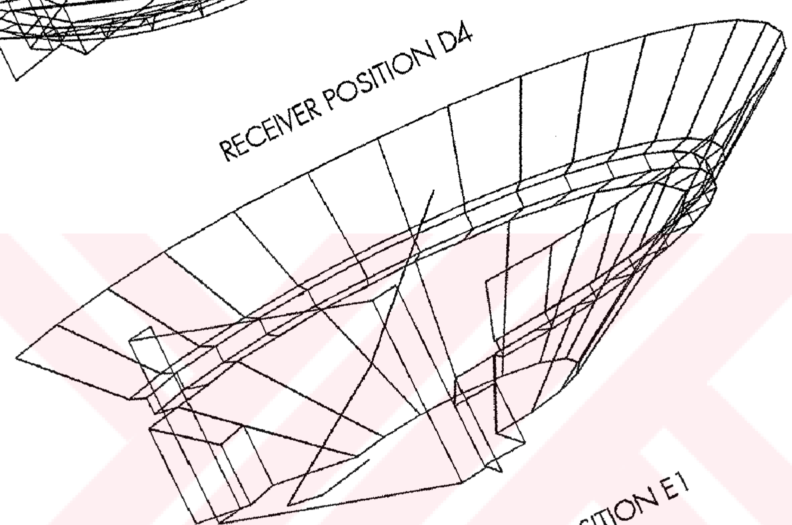
RECEIVER POSITION D1



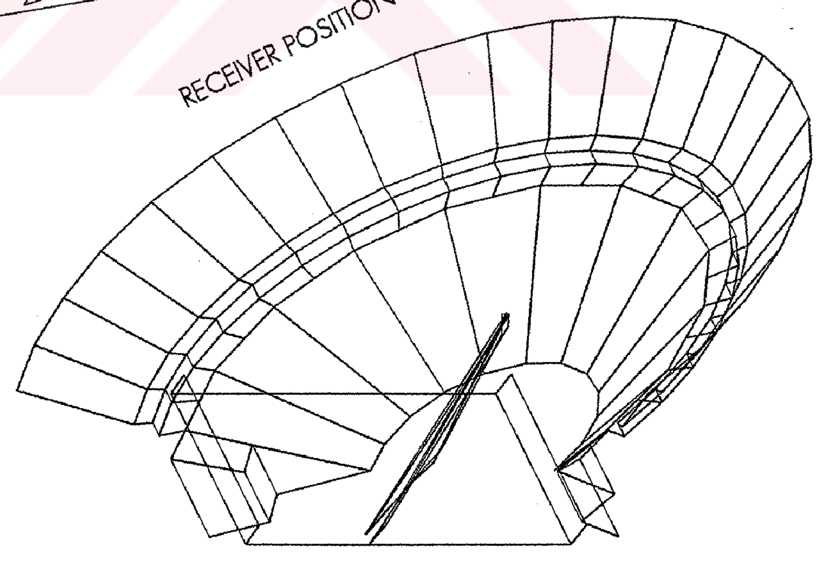
RECEIVER POSITION D2



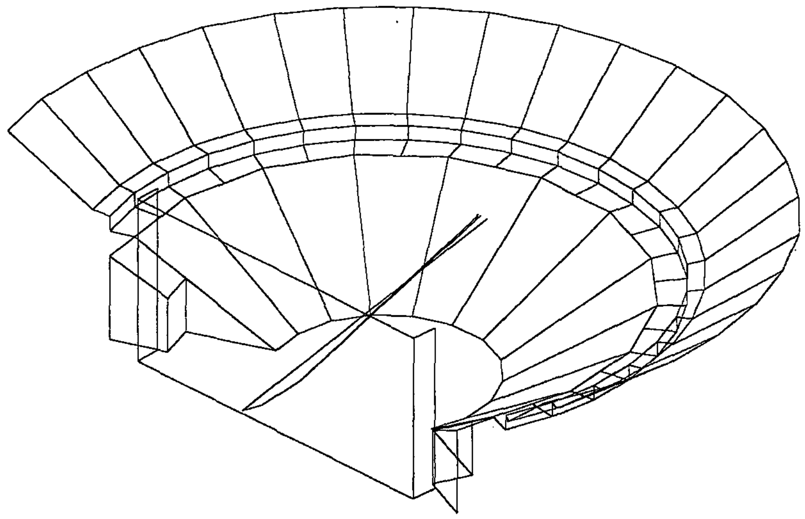
RECEIVER POSITION D4



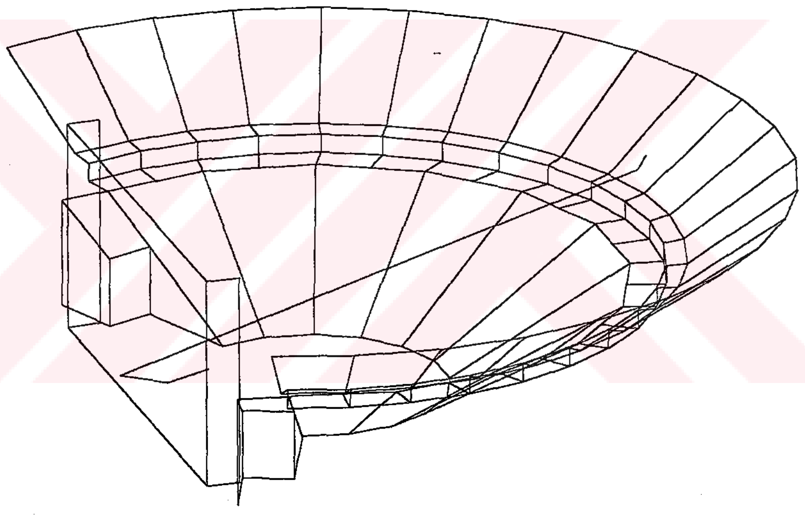
RECEIVER POSITION E1



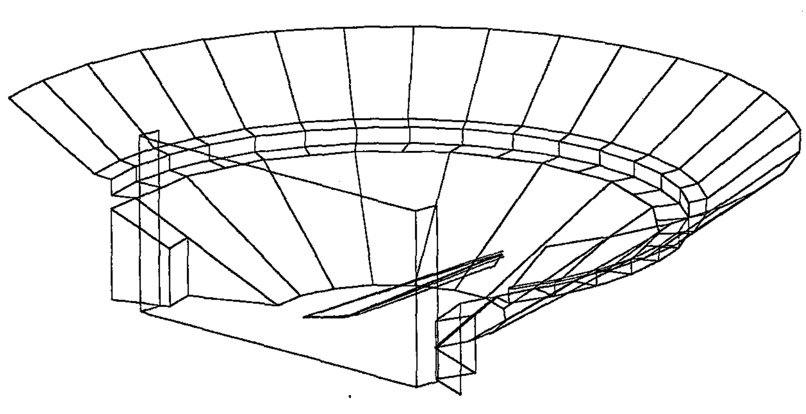
RECEIVER POSITION E2



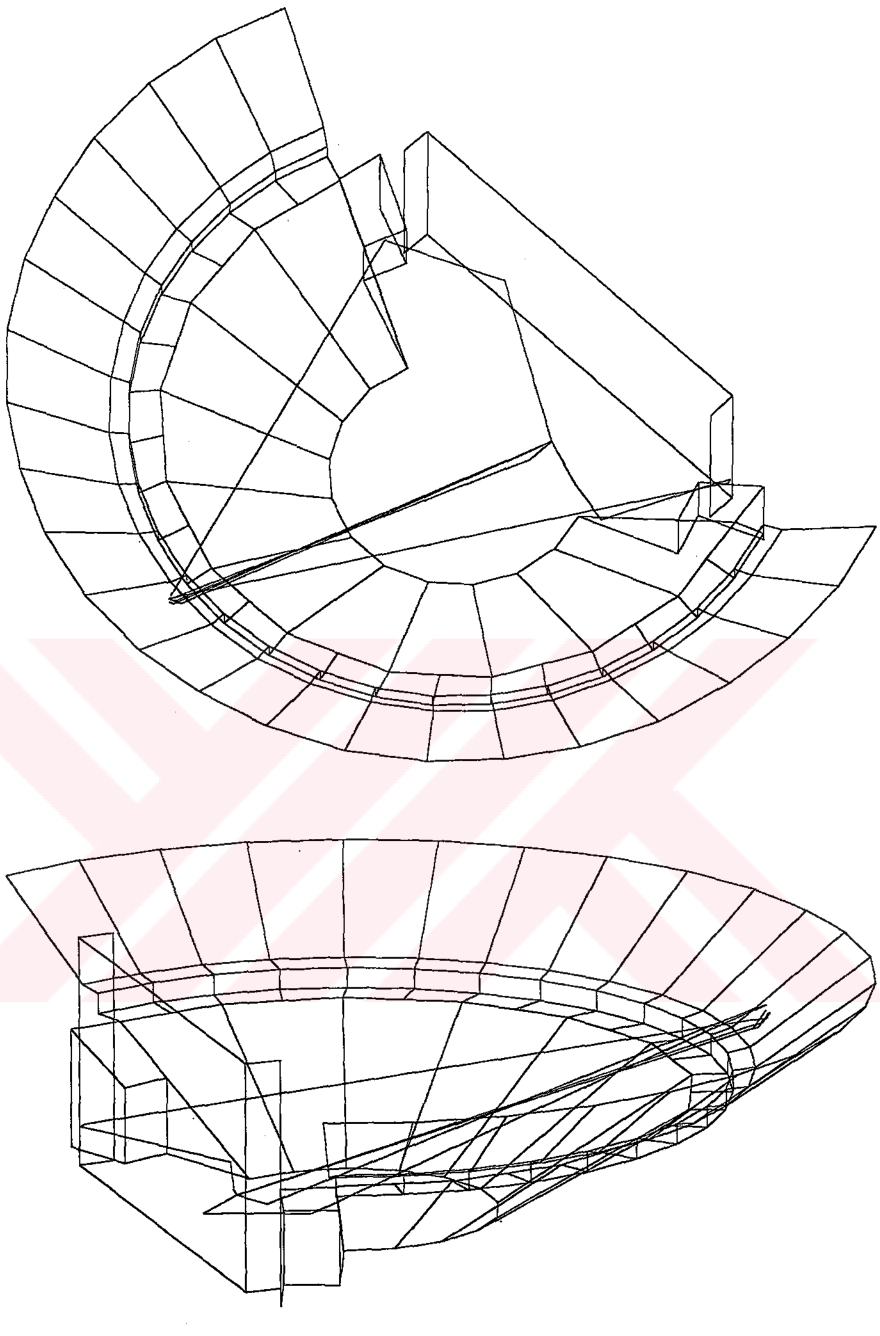
RECEIVER POSITION E5



RECEIVER POSITION F1



RECEIVER POSITION F5



APPENDIX F

FESTIVAL THEATRE, CAESAREA, ISRAEL AND ANTALYA CITADEL THEATRES

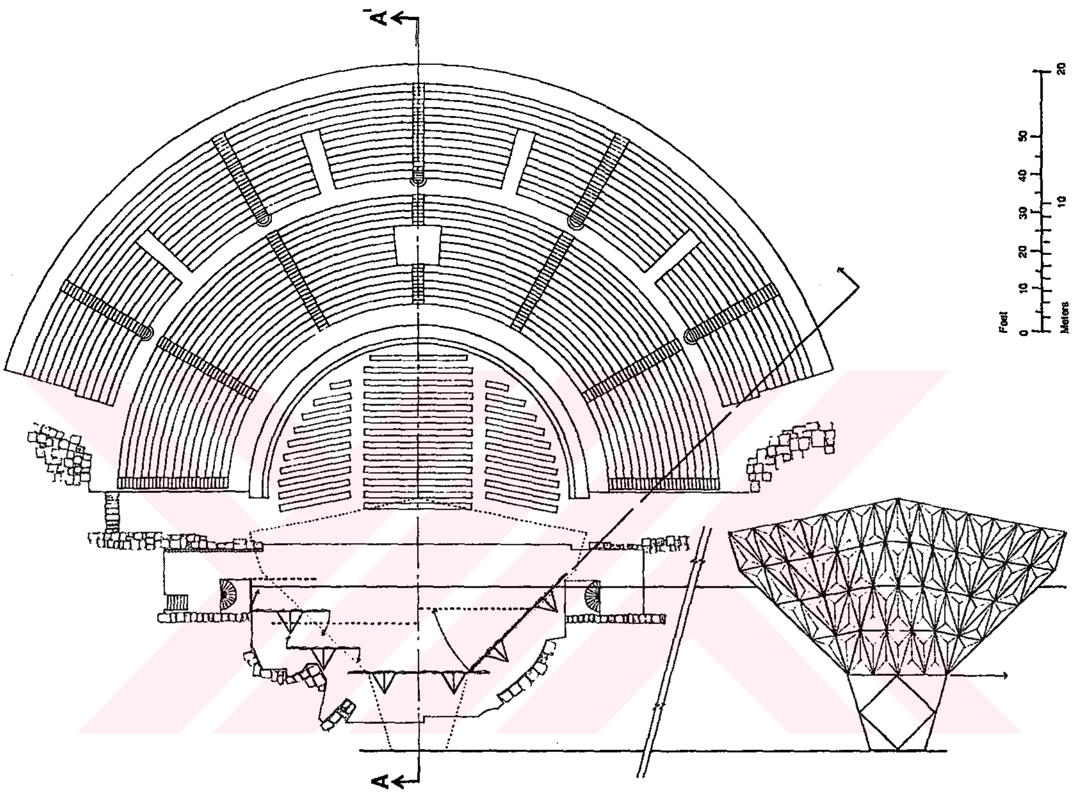


Figure F.1 Festival Theatre, Caesarea, Israel, Plan and Portable Orchestra Shell. (After Izenour, 1977: 327)

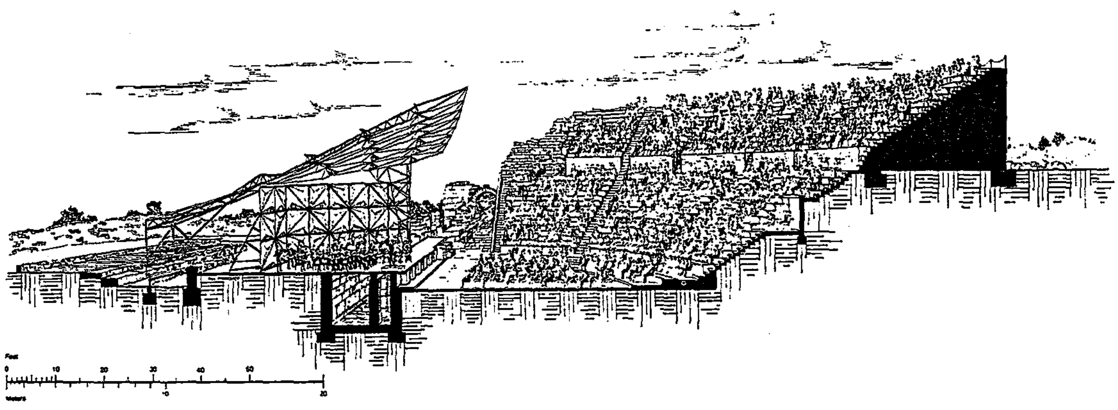


Figure F.2 Festival Theatre, Caesarea, Israel, Longitudinal Perspective Section. (After Izenour, 1977: 327)

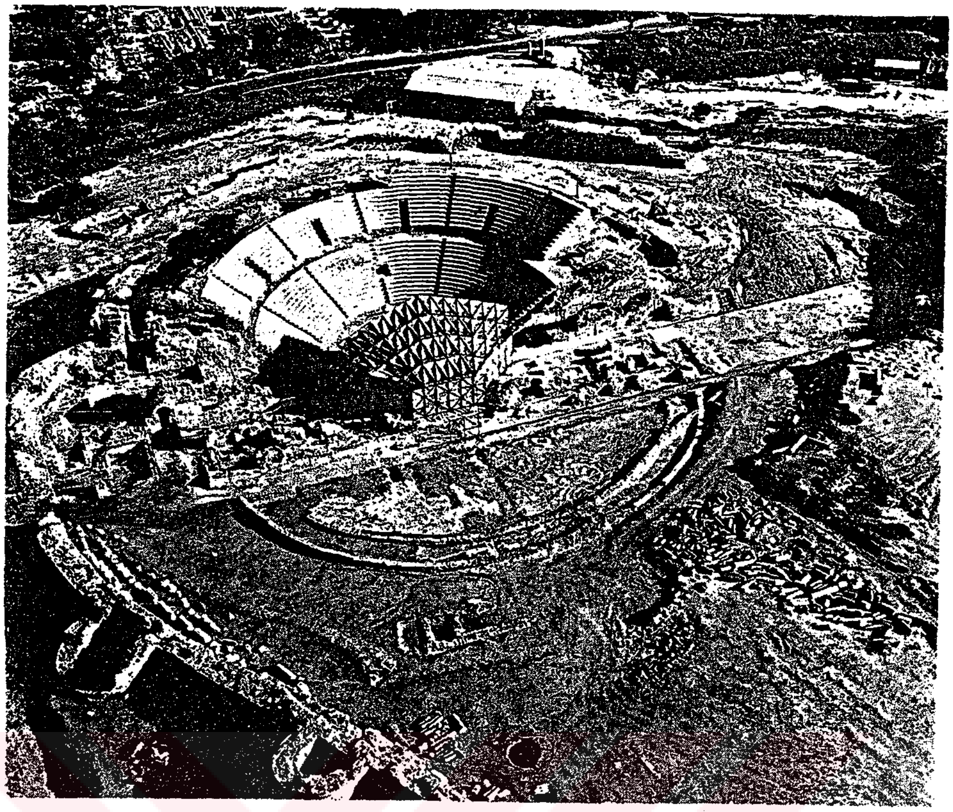


Figure F.3 Festival Theatre, Caesarea, Israel, Aerial Photography. (After Izenour, 1977: 328)

Figure F.4 Festival Theatre, Caesarea, Israel, Aerial Photography of Archeological Site Prior to Restoration. (After Izenour, 1977: 328)

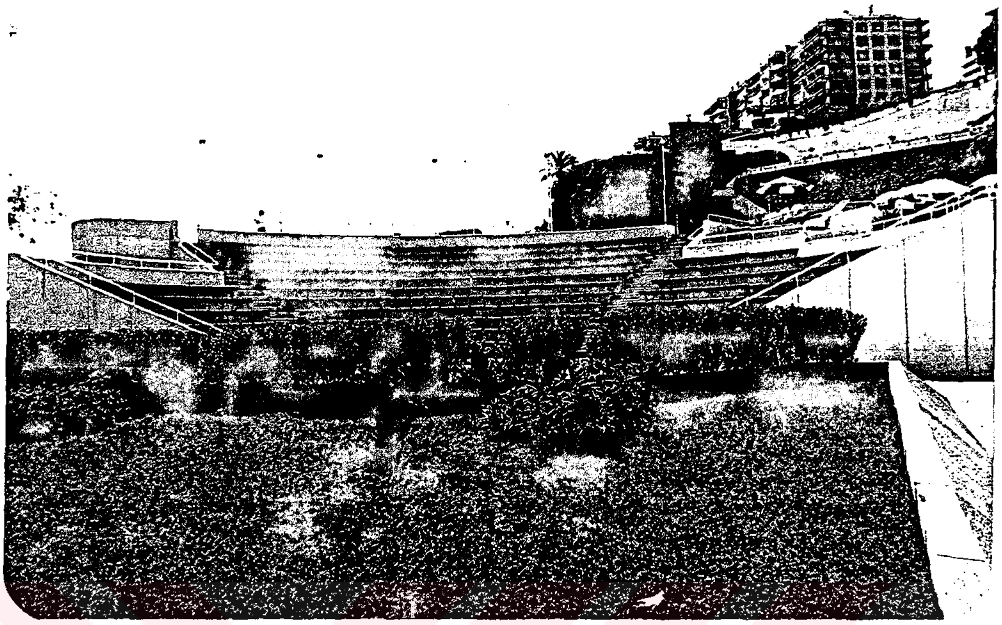


Figure F.5 Open-air Theatre in Antalya Citadel

CURRICULUM VITAE

Demet Irklı was born on September 19, 1956 in Çorum. She is a citizen of the Republic of Turkey. She graduated from Ankara State Academy of Engineering and Architecture in 1979, with a Bachelor of Science in Architecture. She worked as a Research Assistant from 1983 to 1985 in the Department of Architecture at Gazi University. She earned her Master of Science degree in Building Science from the Faculty of Architecture in the Middle East Technical University in 1984. In the same year, she started her Ph. D. study in the Department of Architecture of the same University. She studied at the Institute for Housing Studies in Rotterdam for five months in 1986.

She has been working as Instructor in the Department of Architecture in the Faculty of Engineering and Architecture of Gazi University since 1985. Basic Design, Passive Utilization of Solar Energy in Buildings, Housing Design for Low Income Groups and Architectural Acoustics are among her areas of interest. She is the recipient of several awards in architectural competitions. Among her published works are: Demet Irklı and Nilgün Görer, "An Evolutionary Supply Mode towards Design of the Quality Environments for Low-Income Groups in Turkey; Open House International, Vol. 14, No. 3, 1989, pp. 44-48; Demet Irklı and Mehmet Çalışkan, " Acoustical Properties of Roman Theatre in Aspendos', 11 th I.A.P.S. Conference, Culture, Space and History, Vol. 4, 8-12 July 1990, M.E.T.U., Ankara, pp. 352-361; Demet Irklı and Abdullah Tekin, " The Use of Ancient Buildings for Tourism Purpose: Especially Theatres in the Mediterranean Region". International Symposium on Architecture of Tourism in the Mediterranean. Policies- Planning- Design. Yıldız University, Faculty of Architecture. Vol. 2, Proceedings 1, 13-16 October 1991, İstanbul, pp. 249-255; 'Aspendos Tiyatrosu', Sahne Sanatlarına Hizmet eden Binaların Tarihi ve Mimari Özellikleri (13), LİR, February, 1994, No. 15; 'Termessos ve Perge Tiyatroları', Sahne Sanatlarına Hizmet eden Binaların Tarihi ve Mimari Özellikleri (15), LİR, April 1994, No. 7; Işık Aksulu and Demet Irklı ,' The Problems and Contradictions in Conservation Studies which Occurred between the Planning and Implementation Process-The Example of Ankara Citadel and its Surroundings', 7 th International Congress Building and Life '95, 27-29 April 1995, Bursa, pp. 411-421.