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A Study of Ancient Greek and Roman Theater Acoustics

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Summary
Ancient Greek and Roman open-air theaters had re-known acoustic properties, allowing speech communication for more than 10000 people. Here, acoustic properties for the most famous of these theaters, Epidauros, are analysed and compared to 2 other theaters (Dodoni and Patras' Odeion) via computer-aided prediction and auralisation. Novel, detailed and in-depth conclusions for these theaters acoustics properties are derived and presented, together with audio demonstrations.

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1. Introduction

The good acoustics of ancient Greek open theaters are widely known even to non-specialists and has been in the past the topic of a number of studies [1, 2, 3, 4, 5, 6, 7, 8, 9]. Some ancient theaters exist in a well-preserved state, some others have been partially reconstructed, and there are a number of later-date open Roman theaters (often referred to as Odeia), mainly located around the Mediterranean area. Although in-situ measurements have verified these theaters first class acoustic performance for speech communication, the exact nature of this acoustic quality perceived in such spaces has until now remained an elusive topic based on conjectures and alternative opinions [4, 5, 6, 7, 8, 9]. Most acousticians, archaeologists or even non-specialists will agree that the ancient Greek theater of Epidauros, in southern Greece, examplifies these acoustical and aesthetic qualities and together with its well-preserved state, has achieved a tourist attraction status.

For all the above, it is important to examine in detail these ancient theaters and to establish the reasons for which such open structures allowed perfect speech communication for up to 17000 listeners, a task which for most of contemporary spaces cannot be realised without electroacoustic assistance. It has been also often stated that other, indirect factors may positively influence speech communication in such theaters, namely, the pressure gradients generated by temperature differences across the theater's height, the use of special sound projecting face masks by the actors and the use of resonating vases along the seating tiers [2]. However, past studies make clear that the geometric properties alone were sufficient to ensure good acoustics, this being mainly due to their shape, which allowed good sight lines from all positions, together with optimal sound propagation and reduced audience absorption.

A well-documented account of Epidauros acoustics in relationship to other theaters is given by Shankland [4], where he states the significance of early reflections and scattered sound on the theaters' acoustic performance. To study in detail such theories, an alternative approach has been introduced here, based on a computerised prediction/auralisation method, which introduces a novel methodology for such a study, helping to clarify many of the above factors, having also the following advantages:

(a) The acoustic features of more than one theater can be studied for exactly identical source / receiver parameters, so that comparative assessment of their acoustic performance can easily be established

(b) The acoustic features of these theaters can be assessed for construction stages not necessarily similar to their current states, which are well-established through historic records to better represent their typical form during ancient times. For example, the stage house could be included and for the case of Dodoni, the non-preserved upper gallery of seats could be added.

(c) Exact auralisations can be generated, again for identical source / receiver parameters in these different theaters, hence allowing instant aural comparison of each theater's acoustics.

(d) Detailed tracing of the reflection paths can be established, along with the contribution of the individual reflective surfaces and the angle of arrival of the reflections, tasks not easily accomplished from in-situ measured responses

As is known, such computer-aided simulation of building acoustics provide well-established tool for the study of the acoustic behaviour, especially when are accompanied by auralisation for the virtual representation of these spaces under typical scenario of their response to speech

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Table I. Koilon and orchestra features.

Theater	Radius (m)	Slope angle (°)	Seat rows	Audience capacity	Radius (m)	Material
Epidauros	59	26.2 (lower) 26.5 (upper)	55	14.000	9.775	earth
Dodoni	64.5	23.5	56	17.000	9.35	earth
Patras' Odeion	23.75	30.8	28	2.300	4.45	mosaic

Table II. Stage house features.

Theater	Proskenion dimensions L×W (m)	Skene dimension L×W (m)	Paraskenion dimensions L×W (m)	Stage preserved today
Epidauros	22×3.17	19.75×7.25	3.7×3.7(×2)	No
Dodoni	31.2×3.15	31.2×9.1	6.34×5.5(×2)	No
Patras' Odeion	8.7×0.75	26.3×5.55	15.3×6.6	Yes (partially)

or music signals [10]. Hence, the current work describes an application of these techniques to open theaters of antiquity of historic significance. The results of these auralisation experiments are made available through electronic means (see accompanying CD and the electronic address [11]), so that the present work may be considered as a companion to an earlier paper by the authors [12], concerning the acoustics of closed buildings of Greek antiquity.

The paper is organised as follows: a brief description of the features of the theaters is given in section 2. The methodology for the computer-aided acoustic simulations and auralisations, as well as a description of the acoustic parameters studied is given in section 3. Section 4 contains the results for the acoustic performance of the theaters for various conditions of listener placement, audience presence, etc. The results and some general conclusions are discussed in section 5.

Finally the Appendix contains historic data and a list of Audio demos which are provided on the CD of this issue of Acta Acustica united with Acustica.

2. Description of theaters

2.1. Structure of ancient open-air theaters

The ancient open-air theaters of the classical Greek and Roman period combine the following architectural elements [1]:

(a) Koilon-(Cavea in Latin): the semi-circular symmetrically-shaped steeply-sloped tiered seating section, divided into wedge-shaped sub-sections by radially ascending staircases, as well as horizontal cross-aisles ("diazoma"). Lower and upper sections ("cunei") are created by these aisles. For Greek period theaters, stone was used for all these sections.

(b) Orchestra: the main circular flat stage in front of the koilon, where traditionally the actors and chorus were performing. The classical period Greek theaters had packed earth orchestra floor, whereas the later period Hellenistic and Roman theaters had marble or stone-covered floors.

(c) Proskenion (called Pulpitum for Roman theaters): the flat rectangular stage area in the back of the orchestra and in front of the stage house (Skene).

(d) Skene: the main rectangular stage house structure containing a raised stage, corridors and rooms, which were often used as background stage scenery.

(e) Paraskenion (called Postscaenium for Roman theaters): the side rooms and buildings, often integrated with the Skene, used for the preparation of actors.

2.2. Theater details

2.2.1. Epidauros

The ancient theater of Epidauros is located in the region of Argolid, at the eastern Peloponesse in southern Greece, being one of the most well-known and better preserved ancient theaters [13]. The theater was constructed late in the 4th and early in the 3rd century BC, with a second construction phase during the mid of the 2nd century BC, possibly being the design of architect Polyklitos. Even in the ancient times it was considered by Pausanias (II, 27, 5) to be the most harmonious and beautiful open-air theater, features related to the structure's adaptation to the shape of the hillside and its famous acoustic quality [1, 4]. The theater has a capacity of 13000–14000 people [3] and was initially used for solo singing, chanting, musical contests (mainly for solo instruments) and theatrical performances of ancient drama plays. Similar types of activities are still currently entertained in the site during the summer months.

Special features of the theater are the double slope of the koilon (in the vertical plane) as well as the side sections of the koilon (in the horizontal plane), which extends more than the typical semi-circular shape, hence enclosing the orchestra (Figure 1a). The theaters' architectural parameters are given in Tables I and II.

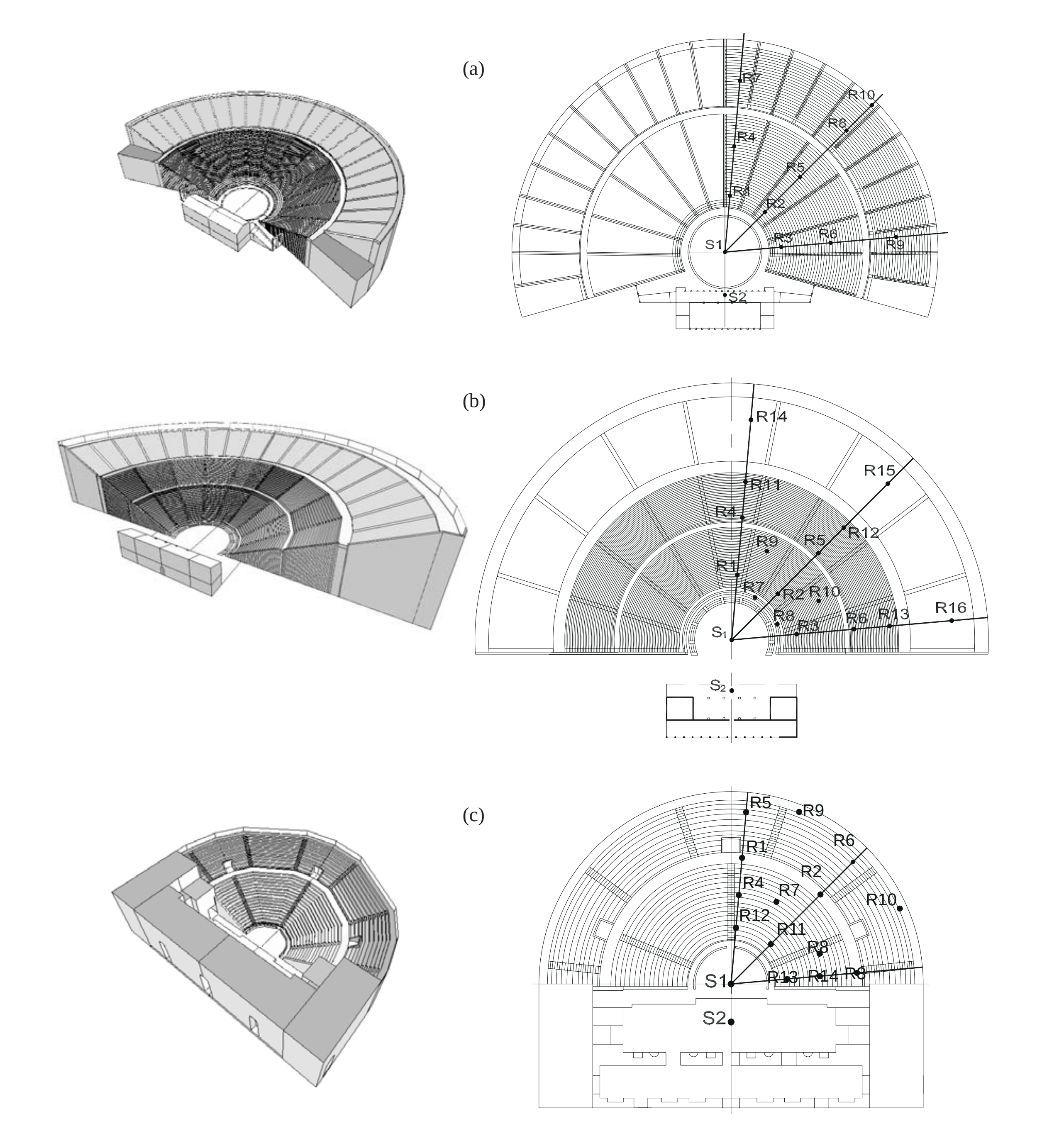

Figure 1. Plan and 3-D views of the ancient theaters studied, with the designated source and receiver positions: (a) Epidauros, (b) Dodoni, (c) Patras' Odeion.

2.2.2. Dodoni

The ancient theater of Dodoni is located at Epirous, in the northwestern part of Greece, being one of the largest open-air theaters of the ancient world [14]. The theater was constructed early in the 3rd century BC, on a natural hillside recession. The construction followed 4 phases, of which the first (297–219 BC) is considered to be the theaters' classical period and will be examined in detail here. The theater had a capacity of 17000 people and was initially used for religious ceremonies, chanting, and theatrical performances of ancient drama. The theater was destroyed by the Romans in 167 BC, but it was later reconstructed as an arena. Today it is partially preserved, mainly through the lower and middle section tiers and some remains of the upper section (Figure 1b). The theaters' architectural parameters are given in Tables I and II.

2.2.3. Patras' Odeion (Odeum in Latin)

It is one of the largest and most prominent Roman theaters (Odeia), located within the modern-day city of Patras, in southern Greece. The theater was constructed early in the 2nd century AD, having a capacity of 2300 spectators, but became disused after the 3rd century AD. The structure was discovered in 1889 covered by earth and was later restored, used until this day for music and theatrical performances. Special features of the theater is that brick was employed for the construction of the koilon and its facade although seating and aisles were covered by marble. The theater features a complex and large brick stage structure ("skene" or "scaenae"), typical of Roman theaters, which is still largely preserved today (Figure 1c). The theaters' architectural parameters are given in Tables I and II.

3. Method

3.1. Procedure

This work has evolved through the following stages:

(a) A selection was made of two representative open theaters of the Greek antiquity with noted historic significance and acoustic features. The first, Epidauros, is famous for its excellent acoustics and its fine state of preservation. The second, Dodoni, is one of the largest open theaters of the ancient world, although it is currently not as well preserved as Epidauros. For comparison and extending the scope of the study, a representative Roman-period theater (Patras Odeion) was also selected. Exact architectural drawings of these buildings were obtained through archaeological and other records [3, 14].

(b) Acoustic simulations were conducted using well-established computer-aided tools, employing typical positions for source (designated by S_N) and receiver (designated by R_N), defined from typical positions used for the performers (Figure 1). For these simulations, and given the theater's symmetric form, typical listener positions were assigned at 3 different horizontal angles θ_N with respect to the axis of symmetry:

(i) central-arc positions, with $\theta_1 = 5°$,
(ii) middle-arc positions, with $\theta_2 = 45°$ and
(iii) side-arc positions, with $\theta_3 = 85°$.

For each one of these 3 angular settings (with respect to a centrally located source), receiver positions were chosen at various distances from the source, of which 3 (R1, R2, R3) being at equal source / receiver distances for all 3 theaters for easy comparison of results (i.e. $d_1 = d_2 = d_3 = 15.63\,\mathrm{m}$), as is shown in Figure 1. It is clear that the vertical angle φ_N may vary for each theater / placement combination.

For each of these simulation sets, 2 source (S) positions were tested, S_1 for source located at the center of the circular stage ("orchestra"), and S_2 for source located at the background scenery stage ("proskenion"), given that these were typical positions for the actors during the ancient or even the contemporary theatrical performances. Furthermore, 2 options for audience presence (L) were considered, where L_1 indicates a theater empty of other audience and L_2 indicates the theater to be full of audience. Finally, two alternative noise conditions were simulated: (i) a typical low-level ambient noise and (ii) a typical audience noise condition, whose octave-band SPL is given in Table III.

Table III. Octave band distribution of noise (in dB) added to simulations.

Noise Type	Center frequency of band (Hz) 125	250	500	1000	2000	4000
Low-level ambient noise	45	38	32	28	25	23
Typical audience noise	40	46	49	42	38	34

(c) Auralisations were generated, based on the estimated building's impulse response(s), using specially-recorder anechoic speech material. In order to evaluate the acoustic contribution of each of the theater's architectural elements (e.g. koilon, stage, etc.), alternative versions of the auralisations were also produced with the appropriate architectural elements removed from the simulations.

3.2. Acoustic simulations

For the acoustic simulation, a commercially available, geometric acoustic-based program was employed [15]. The program uses 3 different algorithms to derive echograms and acoustic parameters:

1. Standard ray-tracing with a spherical receiver which estimates sound pressure level (SPL), lateral energy fraction (LEF), and most known parameters (D-50, C-80, RASTI etc.),
2. Image Source Model (ISM) (e.g. [16]), for detailed early reflection calculations, based on first order images of the main source in all reflecting planes and second order sources created by calculating new images in all reflecting planes (except of the previously calculated). This procedure is repeated until the specified maximum arrival-time is reached.
3. Randomised Tail-corrected Cone-tracing (RTC) for the full response but handling deterministically the direct sound and first order specular and diffuse reflections. With this approach, echograms (impulse responses) for auralisation were generated.

For the particular tests, given the lack of proper reverberation in the open theaters, the ISM method was used for early reflection estimation and images up to 9th order were allowed for the calculations. As is known, the ISM may be inefficient or inaccurate in modeling reflection paths not directly visible by the receiver, but given the shape of the theaters, this method would predict accurately the early reflections. Hence possible drawbacks of this approach could relate to diffuse field modeling (see below) and possible small inaccuracy for modeling early reflections for the case of audience presence. In addition, for the RTC component calculations, a high number of rays was employed in order to increase the accuracy of these calculations.

For all tests, it is likely that some inaccuracies may arise for modeling the diffuse components of the sound field, given that such calculations can be only roughly handled by the existing computer prediction methods [17].

Table IV. Acoustic parameters of Epidauros theater without (L_1) and with audience (L_2), for source at S_1 and low-ambient noise. The first column indicates the receiver position / Distance from Source S_1 im m.

	RASTI (%)		Ts (ms)		D-50 (%)		C-80 (dB)		LEF (%)		G-10 (dB)		SPL (dB)	
	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2
R1/15.63	91.3	94.5	6.0	4.1	97.7	98.4	19.6	21.3	14.7	8.0	4.2	2.6	62.2	60.6
R2/15.63	90.1	95.0	10.6	5.9	94.1	97.1	14.2	18.1	7.8	5.3	2.3	1.1	60.3	59.1
R3/15.63	80.9	89.2	19.6	11.0	88.1	93.7	10.0	13.2	11.7	7.6	1.3	-0.2	59.3	57.8
R4/29.42	84.7	92.9	9.3	5.0	94.2	97.4	17.0	20.8	5.6	3.2	-4.6	-5.0	53.4	53.0
R5/29.42	81.9	89.0	12.5	7.0	92.7	95.9	13.4	16.6	10.7	5.5	-4.0	-5.1	54.0	52.9
R6/29.42	78.9	86.8	24.0	13.1	79.4	89.6	9.2	12.0	6.9	3.8	-5.1	-6.3	52.9	51.7
R7/47.59	89.7	96.4	8.5	4.7	94.0	97.1	14.3	18.5	4.6	2.9	-8.3	-9.0	49.7	49.0
R8/47.59	90.2	96.6	10.5	5.4	93.5	97.2	15.4	19.2	3.8	2.1	-8.9	-9.6	49.0	48.3
R9/47.59	69.8	79.2	34.5	18.1	74.9	86.6	7.1	9.7	12.0	7.2	-8.9	-10.2	49.1	47.8
R10/57.60	92.3	98.0	8.1	4.8	95.2	97.8	15.2	18.8	5.3	1.8	-10.6	-11.3	47.3	46.7

The specific program (as most other programs) employs Lambert's law to convert a frequency and surface-specific portion of the specular reflection energy into diffuse reflections. The parameters for this diffuse contribution can be user-defined and for the specific tests, geometrical considerations were employed, along with heuristic listening tests, in order to specify this parameter in the most realistic way. Specifically, for each reflective surface (e.g. koilon elements, passages, stairs, stage, etc.), a specific diffusion coefficient was assigned following physical considerations, assigning larger diffuse values for higher frequencies and smaller areas of reflective components. After initial estimation, the final value for these parameters was decided via auralisation tests, aiming at the most realistic acoustic representation. Clearly such a diffuse component modeling will suffer since diffusion coefficients can not be exact (being also not easily measurable in practice) and the angle of such scattered components can be only statistically represented. Furthermore audience scattering will mostly suffer by such an approach.

A problem for modeling such open-air theaters where only few early reflections are generated together with a significant amount of early scattered components was found to relate to potential computational / arithmetic sensitivity to the statistical nature of these diffuse reflections. Probably due to the assignment of random variables for such scattered components (following Lambert's law), arithmetic predictions would slightly vary during each simulation, an effect which would be insignificant when modeling reverberant, closed spaces.

For the source, a representative loud male speech signal at a level of 73 dB-SPL was specified, having typical speech directivity, located at positions S_N, at a height of 1.5 m from the floor.

3.3. Acoustic parameters

The acoustic parameters examined were:

1. The SPL level at the receiver position in dB-SPL, as a sum of the 125–4000 Hz band components.
2. The response Center-Time (T_s) in ms [18], from which an estimate of the equivalent Reverberation Time (T_{60}) was derived according to [19].
3. The response Strength factor G-10 parameter in dB, being the sound pressure level relative the free field sound pressure at $d = 10$ m from the source [18].
4. The source Definition (D-50) and Clarity (C-80), early-to-late energy-ratio based parameters calculated according to their respective definitions [20, 19, 18].
5. The Rapid Speech Transmission Index (RASTI), calculated from the estimated echogram according to [21, 22].
6. The Lateral Energy Fraction LEF [18] (often referred to as LEF1) evaluated according to:

$$\mathrm{LEF} = 100 \frac{\int_{5\,\mathrm{ms}}^{80\,\mathrm{ms}} h^2(t) |\cos\psi| \, \mathrm{d}t}{\int_{5\,\mathrm{ms}}^{80\,\mathrm{ms}} h^2(t) \, \mathrm{d}t},$$

where ψ (°) is the reflection angle related to the ear to ear axis of the listener looking towards the main source as defined by the head direction [18]. LEF is well correlated to the spatial impression [23, 24].

Cumulative results for all positions and conditions are given in Tables IV, V and VI.

3.4. Auralisations

For the auralisations, binaural post-processing of the simulated impulse responses was employed [15], which were derived from the estimated octave-band echograms at the designated source and receiver positions. The recreated sound is generated by the convolution of the synthesised impulse response with the anechoically recorded mono material (in 16-bit, 44.1 kHz Wav-format), the resulting file being produced in binaural (2-channel) Wav-format and alternatively for efficient Internet downloading from the electronic address [11], in ISO/MPEG Layer III (.mp3) compressed format. Given the binaural nature of the simulations, these are suitable for audio reproduction via headphones.

Table V. Acoustic parameters of Dodoni without (L_1) and with audience (L_2), for source at S_1 and low-ambient noise. The first column indicates the receiver position / Distance from Source S_1 im m.

	RASTI (%)		Ts (ms)		D-50 (%)		C-80 (dB)		LEF (%)		G-10 (dB)		SPL (dB)	
	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2
R1/15.63	89.4	95.3	8.2	4.9	97.0	98.5	18.3	22.6	14.5	7.5	3.4	2.4	61.4	60.4
R2/15.63	89.0	92.9	10.3	6.6	95.6	97.4	15.5	18.6	18.5	9.4	2.8	1.4	60.8	59.4
R3/15.63	83.6	90.3	16.9	9.8	89.2	94.4	11.1	14.4	15.6	9.0	1.4	0.0	59.4	58.0
R4/29.42	89.1	94.8	9.0	5.8	96.4	98.0	17.3	20.2	7.8	3.8	-3.2	-4.0	54.8	54.0
R5/29.42	87.1	92.9	9.0	6.4	95.9	97.5	15.6	18.4	6.4	4.6	-2.9	-4.2	55.1	53.8
R6/29.42	79.9	86.4	19.9	12.8	84.9	91.2	10.0	12.6	7.9	4.4	-5.2	-6.0	52.8	52.0
R7/11.59	91.9	95.2	7.4	4.8	96.7	98.2	20.3	23.5	10.5	6.9	4.7	3.9	62.7	61.9
R8/11.59	92.7	95.5	9.7	6.1	94.9	97.3	15.9	19.2	11.9	7.4	3.9	2.9	61.9	60.9
R9/22.84	83.7	91.2	14.9	8.2	86.7	93.6	12.4	15.8	9.8	5.0	-1.4	-2.4	56.6	55.6
R10/22.84	89.2	93.5	11.2	7.5	93.2	95.8	13.3	15.5	6.2	3.2	-2.6	-3.3	55.4	54.7
R11/38.02	84.3	94.0	12.2	6.7	91.7	96.5	14.1	17.1	6.5	2.5	-6.6	-7.0	51.4	51.0
R12/38.02	83.5	93.0	10.9	6.8	94.3	97.2	13.8	16.9	4.4	2.5	-6.9	-7.3	51.1	50.7
R13/38.02	77.2	85.7	20.0	11.9	84.5	92.8	10.8	13.5	6.9	3.6	-7.5	-8.1	50.5	49.8
R14/52.95	86.6	92.0	12.6	7.9	90.5	94.7	14.8	17.9	5.7	2.7	-8.6	-9.2	49.4	48.8
R15/52.95	87.0	92.0	14.9	9.0	92.3	95.3	13.8	17.0	6.7	3.8	-8.9	-9.5	49.1	48.4
R16/52.95	79.8	86.6	19.8	12.3	85.5	92.6	9.9	13.0	5.4	3.7	-9.2 -	10.1	48.8	47.9

Table VI. Acoustic parameters of Patras' Odeion without (L_1) and with audience (L_2), for source at S_1 and low-ambient noise. The first column indicates the receiver position / Distance from Source S_1 im m.

	RASTI (%)		Ts (ms)		D-50 (%)		C-80 (dB)		LEF (%)		G-10 (dB)		SPL (dB)	
	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2	L_1	L_2
R1/15.63	89.7	95.6	8.1	4.6	96.6	97.5	17.1	23.0	7.4	2.9	0.8	0.4	58.8	58.4
R2/15.63	90.9	93.7	6.3	5.4	97.5	97.4	21.3	19.9	6.4	4.1	-0.6	-0.9	57.4	57.1
R3/15.63	87.8	91.4	14.0	9.6	90.6	94.2	16.3	14.6	9.9	3.5	-0.2	-1.1	57.8	56.9
R4/11.03	95.2	95.9	7.0	4.7	97.3	99.0	18.3	23.6	14.1	5.1	5.7	4.3	63.7	62.3
R5/21.30	95.8	96.1	6.4	5.0	97.6	99.2	22.0	24.2	6.5	5.1	-0.3	-1.5	57.7	56.5
R6/21.30	85.6	96.5	11.5	3.9	92.1	99.2	16.5	28.5	8.4	4.0	-3.2	-3.7	54.8	54.3
R7/11.59	92.4	94.7	7.5	5.6	95.9	98.4	21.3	20.1	7.7	5.8	3.5	3.4	61.5	61.4
R8/11.56	88.4	95.2	11.8	7.4	94.5	98.0	17.4	20.1	12.6	7.8	4.0	2.6	62.0	60.6
R9/22.84	90.5	99.2	10.7	5.5	90.7	98.8	16.6	30.1	13.2	16.6	-1.0	-0.7	57.0	57.3
R10/22.84	92.7	92.9	9.0	8.0	95.5	98.3	18.4	21.9	10.7	9.1	-2.8	-2.2	55.2	55.8
R11/6.95	95.9	96.1	6.9	4.4	98.3	99.5	21.0	27.2	15.2	8.5	9.7	8.0	67.7	66.0
R12/6.95	96.0	98.3	6.4	4.1	98.9	99.1	24.3	28.7	15.5	8.4	10.8	9.7	68.8	67.7
R13/6.95	92.5	91.1	10.7	7.4	97.0	98.0	22.6	20.8	25.5	11.3	8.6	6.5	66.6	64.5
R14/11.03	85.0	90.3	13.2	9.1	90.0	96.2	17.1	19.9	21.0	11.1	4.3	3.2	62.3	61.2

Audio examples of the auralisations are made available in the electronic address [11], as well as in the CD accompanying this report (see Appendix A2).

4. Results

Given the large possible permutations of each theater's architectural evolution and source / listener / audience / noise combinations, the presentation in this section will be initially focused on the form of the theaters which is as close as possible to their contemporary state so that the stage house structures are not initially considered. For all cases, except otherwise stated, a central orchestra speaker position is chosen (S_1), aiming at the theater's horizontal axis of symmetry also assuming a theater empty of audience (L_1). This can be considered to be the most typical scenario of the ancient and contemporary use, also favoured by the actors as resulting to the best "on scene" sound for their rehearsals [4]. Again, except otherwise stated, a typical low-level ambient noise interference was assumed, with frequency distribution given in Table III.

4.1. Sound field components

All tests have yielded echogram results, typically illustrated by Figure 2a,b,c, dictating that the sound field of these open-air theaters consists of the following acoustic components:

1. The direct signal, properly attenuated and delayed with respect to the receiver position.

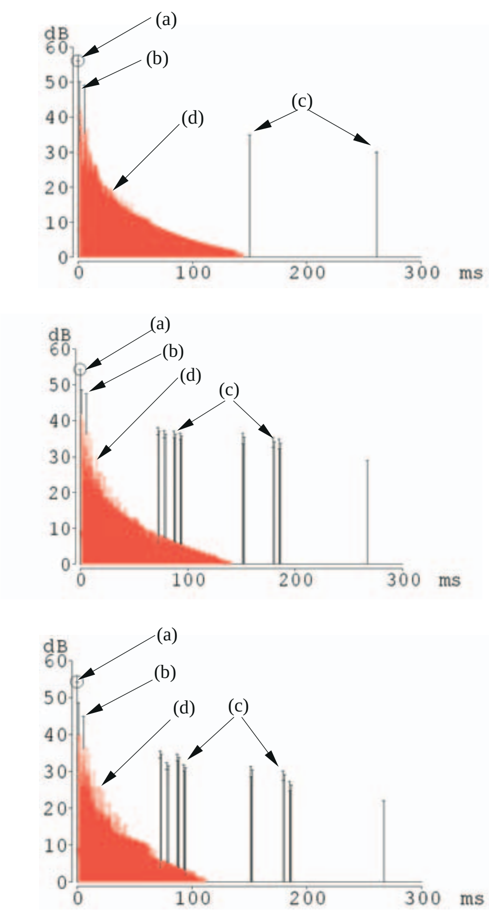

Figure 2. Echogram for the R3 receiver position in Epidauros (without audience): (a) direct signal (b) early specular reflections (c) late reflections, (d) diffuse field.

2. One or two early 1st order specular reflections from the orchestra floor and the koilon seat risers, typically arriving within 10 ms after the direct signal and being attenuated by 10 –15 dB approximately. When the speaker is moved to the S_2 position (on the stage), then additional early reflection components are generated from the stage back walls.

   A first obvious conclusion can be derived here, since such early reflection is known [20, 19, 24] to assist speech intelligibility and perceptually enhance source acoustic properties.

3. Late 2nd or 3rd order reflections, arriving at intervals 40–300 ms after (a), being attenuated by 30 dB approximately, generated from multiple path reflections on the opposite sides of the koilon, or from the orchestra floor / koilon facade path. Typically, these reflections are separated by an interval 20 –100 ms from those of group (b), above, and have wide angles of arrival (with respect to the source / receiver axis). This group is mainly generated for off-axis listener positions away from the central arc area, containing up to ten reflections for the side-arc positions, as opposed to one or two reflections for the middle-arc positions.

Table VII. Estimated, position averaged Reverberation Time values (T_{60}, in s) for the theaters.

	Without Audience	With Audience
Epidauros	0.2	0.11
Dodoni	0.18	0.11
Patras' Odeion	0.13	0.08

   Assuming a typical ambient noise floor given in Table III it is most likely that this group of reflections will not be audible to the theater audience, except for loud speech passages when the reflection level would exceed this noise level. Informal listening tests were also carried-out in order to confirm the audibility of these late reflections. For these tests, audio auralisation files corresponding to adverse settings (e.g. distant receiver and audience present) were modified with the addition of noise having spectral properties as is given by Table III, at appropriate level. After listening to these auralisations for noisy conditions, it was observed that such late reflections were largely masked by the noise, so that they can be assumed to be inaudible.

4. A diffuse exponentially decaying reflection field, extending up to 150 ms after (a) and consisting of dense scattered reflections on the unoccupied stone seats (or audience heads [4, 25]), the orchestra and other koilon elements, generated from the components (a) and (b) above.

Clearly, as expected, a proper reverberant field is absent, given that these theaters are open and indirect estimation for T60 produces values below 0,2 s. (see Table VII). When the theaters were studied having full-capacity audience, it was observed that all reflection groups (b to d above), were attenuated (typically by up to 5 dB) and furthermore, the diffuse components had a different distribution in time and frequency. This results to a further reduction of T_{60} (Table VII). Significantly, the most listener positions in Patras' Odeion, the sound field contains mainly the direct signal (a), the early reflections (b) and the diffuse field (d), since the late reflection group (c), were mostly suppressed due to the high slope of the koilon. Typical position and audience dependent variations in the echograms can be observed in Figures 2a, 2b and 2c.

4.2. Sound pressure level

It is obvious that for each receiver position, the overall sound pressure level (SPL) will be due the contribution of all previously described sound field components. Typical SPL vs distance results for the three angular positions are shown in Figure 3. In the same figure, the expected direct sound level for the same speaker (a directional human source generating 73 dB-SPL/1 m), is also plotted for comparison.

From these results it is evident that for Epidauros and Dodoni, there is a small increase of SPL (approx. 4 dB) due to the contributions of the reflected and diffuse sound field components (b), (c) and (d) (see previous paragraph),

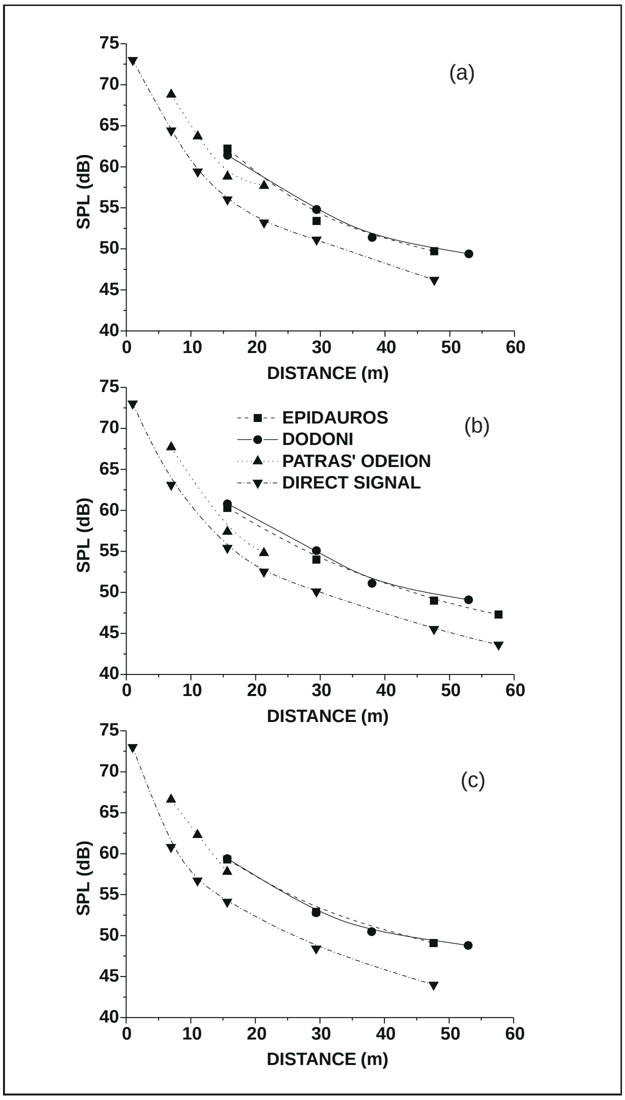

Figure 3. SPL vs distance for the 3 theaters (without audience), and corresponding direct signal level, for: (a) $\theta_1 = 5°$, (b) $\theta_2 = 45°$ and (c) $\theta_3 = 85°$.

above the direct sound level, independently of the receiver distance.

As expected from the previous paragraph, for Patras' Odeion, these contributions were smaller, the SPL being mainly comprised from the direct sound. Further tests, when the contribution of the koilon was removed from the simulations (by rendering it fully absorbent), have indicated that for the Epidauros and Dodoni theaters, approximately 2 dB-SPL increase over the direct sound was due to reflections from the orchestra and a similar level increase due to reflections/scattering generated from the koilon. Audio Demo 6 in Appendix A2 gives an aural example of these tests.

Generally, the SPL vs distance results for both Epidauros and Dodoni exhibit similar trends (Figure 3) and the listener distance affects in a rather predictable way the total sound pressure level, this being attenuated by the square law with doubling the distance. Therefore the overall SPL distribution resembles that of a direct field, with the addition of an offset level due to the reflections and diffusion. Furthermore, given the distances involved in these theaters, the overall SPL is not usually falling more than 30 dB from the source level. Assuming a human speaker generating 73 dB-SPL/1 m and located at the theater's orchestra and provided that ambient noise due to outside sources or the audience is low (for most simulations the case of low-level ambient was used as noise floor), a plausible scenario given that Epidauros and Dodoni are located at rural areas, a sufficient level of intelligibility can be guaranteed by this signal to noise ratio condition. This will be discussed in more detail in a later section. Clearly, intelligibility can suffer when audience noise increases, as will be shown later. Especially for Patra's Odeion, which is located within the busy modern city, high levels of noise interference are expected which can depend on many external factors related to community activities.

This reflected energy contribution is reduced when the theaters are full of audience, due to the increased absorption from the koilon. This total SPL reduction was found to be in the order of 1–2 dB (see Tables IV, V and VI). Audio Demos 3 and 5 in Appendix A2 illustrate these effects.

A complementary approach to evaluate the level parameter is via the G-10 (Strength factor) criterion (Tables IV, V and VI). The G-10 = 0 dB-SPL for the ancient Greek-period theaters, was found to correspond to approximately $d = 18$ m for most positions (for the theaters empty) and it is reduced to approximately $d = 16$ m when these are full of audience. Hence a significant increase of the distance for which the total level would be equal to the direct sound distance is introduced by the theater's sound field, this being in partial agreement with the observed approximate 4 dB total SPL increase due to reflections / diffusion additionally considering that a directional sound source, was used for these tests.

The sound field of Patras' Odeion, taking into account the dominance of the direct signal and the shorter distances involved due to its smaller size and the steeper koilon inclination for this theater, exhibits a reduction in G-10, this being G-10 = 0 dB for approximately $d = 15$ m (for empty theater) and $d = 14$ m (for full audience theater).

4.3. Source Clarity (C-80) and Definition (D-50)

This type of sound field, as discussed above, has great benefits when the known acoustic quality parameters are examined. Considering the Definition (D-50) and Clarity (C-80) criteria, it can be observed (Tables IV, V and VI) that all theaters exhibit remarkable performance, especially for central-arc and middle-arc locations, irrespective of the listener to source distance. When empty, and for $\theta_1 = 5°$ and $\theta_2 = 45°$, both Epidauros and Dodoni achieve nearly distance-independent D-50 in the region of 95%, whereas C-80 is above 15 dB. For the side-arc seating positions, D-50 and C-80 drop significantly for both theaters (by up to 20% and 10 dB, respectively), due to the build-up of late reflections at these positions generated from koilon side multiple reflections. This late energy build-up can generate some image "blurring" (Audio Demo 1 in Appendix A2) as can be also observed by the Ts criterion (Tables IV, V and VI), which increases by at least 15 ms for such side seating angles.

When the theaters are full of audience, D-50 further improves to a distance-independent 100% for central / middle-arc positions and 90% for side-arc positions. However, C-80 appears to be less sensitive to audience absorption. Significantly, when the theaters were studied with the addition of stage / backstage (skene, proskenion, paraskenion) and provided that the speaker was located at the orchestra position S1, these acoustic parameters were degraded (due to the arrival of late reflections from this back structure) and Epidauros' acoustics appeared to be significantly inferior to Dodoni. This is in agreement with [4] where it is noted that the use of a temporary stage house in Epidauros for contemporary ancient drama performances, did not enhance the acoustic quality due to the "blurring" effect of these late reflections. However, by placing the speaker at the position S_2 (on the stage), although both definition and clarity criteria for all theaters were overall reduced by approximately 15% and 10 dB, Epidauros was found to exhibit a clear advantage with respect to other theaters, for all receiver positions (Audio Demo 4 in Appendix A2).

For the Roman-period theater, both C-80 and D-50 seem to drop faster with distance, due to the absence of late arriving reflections and the dominance of the direct field. This trend becomes more obvious for moving the source to the S_2 position.

Comparing now the relative trends of these criteria for the two classical-era theaters (Tables IV and V) it is evident that Epidauros has superior definition for distant central and middle-arc positions than Dodoni, which can be easily traced to earlier arrival times of reflected energy (see the corresponding Ts results, Tables IV and V), this being a function of koilon size and shape. However, this trend is reversed for the side-arc positions, where, late- arriving lateral reflections (from the more enclosing-shaped koilon) shift the Ts value, thus inhibiting acoustic quality and eventually reducing intelligibility (Audio Demo 1 in Appendix A2). As was previously stated, for the case when the stage house is included and the speaker is on stage, Epidauros has again superior definition and clarity to the other theaters (especially when the theater is full of audience), independently of listener position. This can be accounted by the relative reduction of the contribution of the multiple path reflections (group c) and the corresponding increase of the early reflections (group b).

4.4. Spatial aspects of sound field

As is known, the optimal distribution of lateral reflections can enhance the perception of source size and introduce a sense of spatial comfort and listening intimacy [10, 23]. As can be seen from the results for the theaters (Tables IV, V and VI), these structures generate a moderate but perceptually significant level of lateral energy, so that they introduce a unique sonic character, which perceptually can be differentiated from other fully open spaces. Furthermore,

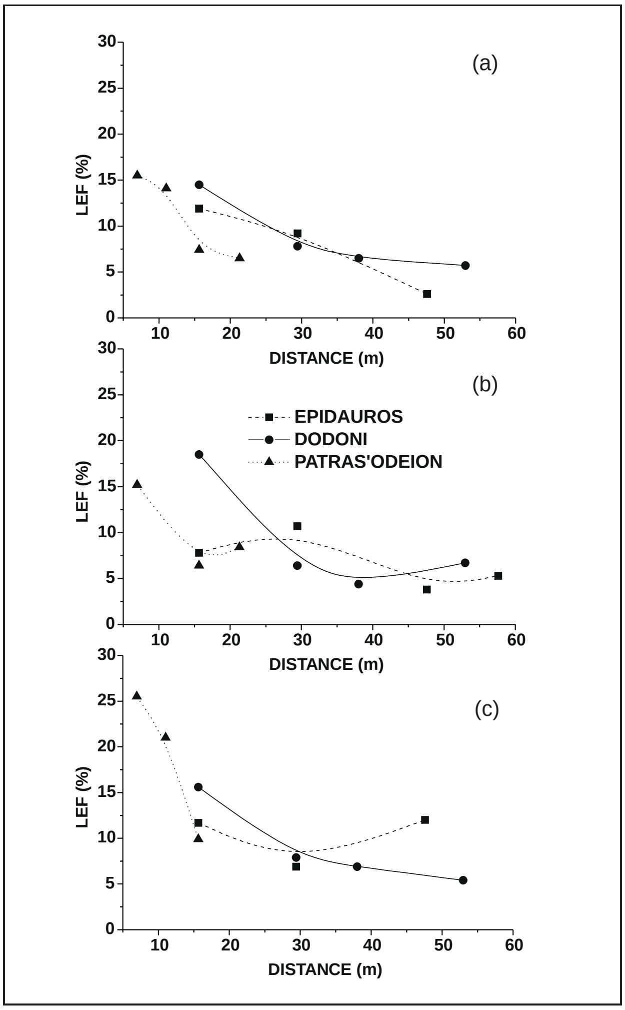

Figure 4. LEF vs distance for the 3 theaters without Audience, for: (a) $\theta_1 = 5°$, (b) $\theta_2 = 45°$ and (c) $\theta_3 = 85°$.

as was suggested in [4], the spatial properties of the scattered, diffuse-field reflection components can influence to significant degree the acoustics of Epidauros and other ancient theaters. Such reflections (component d of the sound field, see paragraph 4.1), appear to arrive at the listeners at progressively narrower angles with increasing distance from the source, as was also discussed in [4] and can be verified by the Lateral Energy Fraction (LEF) results shown in Figure 4.

Such effect, combined with early arrival times, can be beneficial to speech definition and intelligibility at these more distant positions [19], especially since overall SPL is reduced in a proportional fashion at these more distant locations. As can be also observed from the audio examples (see Audio Demo 2 in Appendix A2), listener positions at the lower koilon seats close to the orchestra, receive a rather excessive lateral reflection energy which is progressively reduced for seats at more distant positions up the koilon, where better clarity is achieved due to LEF reduction.

Significantly, Epidauros exhibits a more progressive reduction in lateral reflection energy with distance, except for the side-arc angles. At these side-arc positions in Ep-

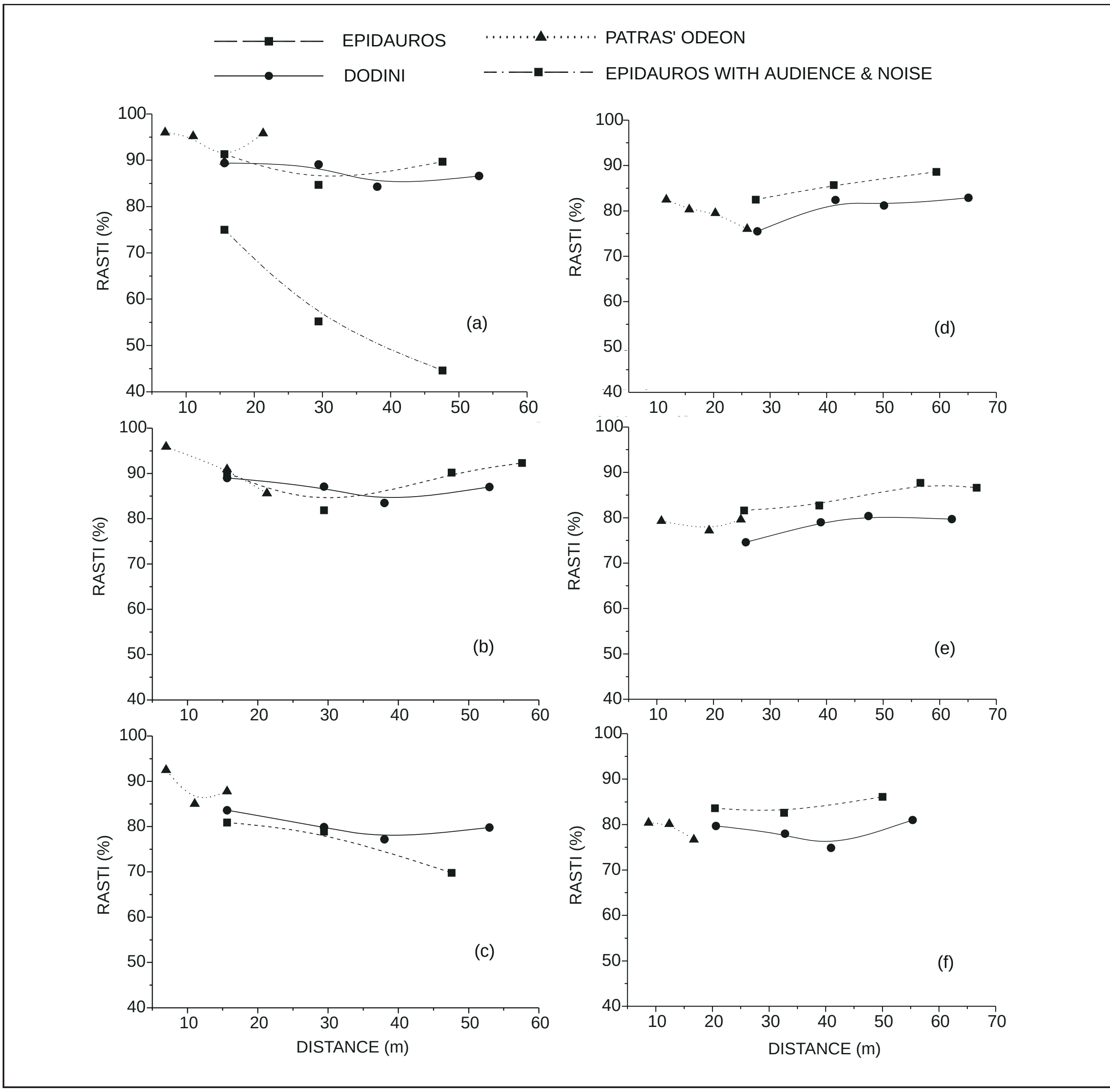

Figure 5. RASTI vs distance for the three theaters, (a)–(c) source at S_1, without audience, (d)–(f) source at S_2 with audience, for: (a),(d) $\theta_1 = 5°$; (b),(e) $\theta_2 = 45°$; (c),(g) $\theta_3 = 85°$. (a) includes RASTI estimated for Epidauros with audience noise (see Table refA.2.5).

idauros, as well as for most other positions in Dodoni, LEF variation with distance does not exhibit a decreasing trend and such proportionally larger lateralisation of the scattered reflections can account for acoustic image "blurring" and definition / intelligibility reduction, as is also evident from the corresponding auralisation examples (Audio Demo 2 in Appendix A2).

When the theaters are full of audience (see also Tables IV, V and VI), LEF further decreases with distance [4], so that intelligibility as well as the other previously discussed criteria relatively improve and become even more distance-independent, assuming the audience is not noisy.

Hence, reflection spatialisation for Epidauros is optimal, being "distance normalised" and superior to the other theaters for center and middle – arc positions, although the highly enclosing koilon sides appear to increase reflection angles and thus inhibit sound quality, for these extreme side-arc listening positions. Significantly, it was also found that for the case of source at S_2 with the use of stage and for full audience condition, spatialisation is becoming more optimal, especially for the case of side-arc positions of Epidauros, hence reducing the previously discussed negative trends for such audience locations.

4.5. Speech intelligibility

The ancient Greek theaters and especially Epidauros are famous for their good speech intelligibility, as was proved by in-situ tests [4] and is all too often verified by casual tests performed by the visitors of this theater. The tests here have confirmed this property through the RASTI criterion (Figure 5 and Tables IV, V and VI). In all cases, assuming a low ambient noise (Table III), RASTI was found to be above 70% and nearly independent of source–receiver distance (Audio Demo 2 in Appendix A2). For middle-arc and central-arc positions RASTI was even higher, in the region of 90%, but for the side-arc positions RASTI was lower, again, due to the late energy build-up of multiple reflections, which as was also discussed in the previous paragraph, seems to affect more Epidauros than Dodoni, 'though Epidauros appears to have better intelligibility for the central-arc positions, especially when full of audience. Furthermore, the reduced contribution of low-level late reflections observed for the $\theta = 45°$ position, results to an increase in intelligibility with distance for both ancient Greek theaters for these regions. For most configurations, the Roman-period theater also exhibits perfect intelligibility, though the lack of supporting early reflections seem to reduce RASTI with source / receiver distance at a higher rate than for the classical period theaters. Nevertheless, for the shorter source / receiver distances of this Roman theater, due to its smaller size and high koilon inclination intelligibility is above 70% for all positions. However, ambient noise was found to dramatically reduce RASTI, as can be observed in Figure 5(a) for Epidauros, when a typical noisy audience signal was considered whose SPL values are given in Table IV. In this case it was found that for the distant positions, RASTI was below 50%.

For the case of the speaker at S_2, when the stage structure is included (Figures 5d, 5e, 5f), rather remarkably, both Dodoni and Epidauros appear to have RASTI improving with distance and Epidauros shows a clear advantage over the other theaters (Audio Demo 4 in Appendix A2).

4.6. Acoustic quality

The preceding analysis gave an account of the overall sound field energy and the objective acoustic performance trends. However, in order to subjectively evaluate the unique acoustic character of each theater, more tests were performed, based on controlled auralisation experiments. During these tests, different impulse response components were successively removed prior to speech signal convolution, by rendering the corresponding reflective surfaces fully absorbent. Apart from the obvious contribution of the early reflections (group b in paragraph 4.1), which as is well known reinforces the level of the direct signal, it was found that a characteristic and unique contribution was related to the diffuse reflection component (group d), as can be observed in Audio Demo 6 in Appendix A2. This diffuse field has an exponentially decaying structure, an approximate overall duration of 100 ms and a dense multiple scattered reflected sound structure, which in principle reinforces the direct sound by enhancing the source's level and tonal properties.

From the study of the corresponding echograms, it was found that for Epidauros, a proportionally higher degree of such diffuse components were present which had a longer and smoother exponential decay than for the other theaters, a feature which may be contributing towards the unique acoustic character of this theater (Audio Demos 3 and 5 in Appendix A2).

5. Discussion

Purpose of this work was to investigate by controlled predictions, comparisons and listening tests, the acoustical performance of ancient Greek open theaters and Roman Odeion. A secondary task was to examine the dependence of the performance metrics on the geometrical shape and other architectural features of these structures.

It was found that although these spaces do not generate any proper reverberant field and in consequence their sound pressure distribution is reduced away from the source in a similar rate to a direct field, the reflections generated by the orchestra and the enclosed sloped semi-circular seating area ("koilon"), introduce a measurable source signal level amplification. Hence, the theater sound field is due to the combination of the direct signal, some early specular reflections, diffusely scattered reflections, and in some cases, discrete, low-amplitude late reflections, resulting to overall T_{60} values below 0.2 s (Table VII). This sound field is beneficial to speech intelligibility, acoustic quality and perceived sense of intimacy and communication. However it is clear that the absence of proper reverberation makes these spaces inappropriate for music performances, although solo instruments and chanting performances may be accommodated.

It was also found that early diffuse reflections play significant role in the acoustic and perceived quality in such theaters. These components are mainly generated by the initial scattering of the early specular reflections typically, one from the orchestra floor and the other from the back risers of the unoccupied seats close to the receiver (note that in Epidauros seat risers were backwards slopped by approximately 10°), or, (when present) audience heads which in turn generate multiple early-arriving scattered components to adjacent areas, i.e. around each listener position. Under certain combinations of early reflection angle, relative to the specific receiver location, a fraction of these secondary diffuse sounds are "refocused" to the corresponding listener position. In general this results to a narrower arrival angle for listener positions higher up the koilon. Clearly each theater's koilon radius, slope and aisle / tier dimensions, are affecting the microstructure of these scattered reflections and ultimately affect the theater's acoustic quality. It is evident from all tests that the diffuse components arrive from wider angles at positions near the orchestra (as was also discussed with respect to the LEF parameter), where acoustic quality suffers from this excessive effect, rendering source image wide and its tone to be coloured. In contrast for positions higher up the koilon, image becomes more focused as this effect is reduced (Audio Demo 2 in Appendix A2) so that the diffuse energy assists clarity and speech communication.

It was also found that each of the 3 theaters tested, due to variations in size and shape had measurable performance differences and perceived sound quality (Audio Demos 3 and 5 in Appendix A2). Of these 3 theaters, Epidauros, featuring double slope koilon, side koilon extensions and a well conceived ratio between orchestra size, koilon dimensions and slope and stage house positioning (when this was in use), has confirmed its fame for its good acoustics, exhibiting a fine balance between architectural form and speech communication function.

In comparison, Dodoni is a significantly larger theater with larger koilon radius and height and a stage house being located further back from the orchestra. Although the total SPL of this theater and level of reflected energy is very similar to Epidauros (see Tables IV, V), speech communication and perceived quality are different to Epidauros. These differences can be traced to the koilon size and aisle dimensions which are responsible for proportionally larger delays for the center-arc and far distances / middle-arc positions (see Tables IV and V). This results to less uniform diffusion for these audience areas so that intelligibility and sound quality are inferior than to Epidauros. In contrast, extreme side-arc positions in Dodoni have better acoustic performance, since for such positions the highly enclosing Epidauros koilon, generates greater delays from multiple reflections and introduces some source “blurring” (Audio Demo 1 in Appendix A2). Significantly, the fine integration of the stage house in Epidauros, in contrast to the distantly located stage structure of Dodoni, ensures spectacular advantages of the first theater for speakers located on this structure (Audio Demo 4 in Appendix A2).

Patras’ Odeion illustrates the architectural changes occurring during the transition of these open theaters to the Roman era, with significantly smaller sized and highly inclined koilon, half-circle orchestra and large, elaborate stage house structure, a form which later led to the medieval and renaissance semi or fully closed theaters [1, 2]. In this case, the high inclination dictates far shorter source / receiver distances than for the ancient period theaters, hence facilitating direct signal transmission. Nevertheless, reflections and diffusion plays a smaller role here, their overall contribution being insignificant in level increase and image spatial expansion. Hence, most acoustic criteria are more distance – dependent than for the earlier theaters, albeit their overall effect being moderated by the inherently short distances involved. This lack of support from reflections results that Patras’ Odeion has lower RASTI performance than Epidauros (with the use of the stage house) for compatible conditions, i.e. for speaker on the stage and the theater to be full of audience.

Some additional aspects were also highlighted by the study:

- When ambient / audience noise intrudes into the mid-frequency ranges, then intelligibility will suffer significantly, especially for listener positions in the upper gallery sections.
- Off-axis, side-arc listener positions receive a number of late, multipath reflections which under certain conditions (very loud speech passages) may be audible above the noise floor, provided that noise and audience absorption is not severe.
- In all cases and especially for Epidauros, assuming a speaker located at the center of the orchestra, facing the theater’s axis, side-arc listener positions had inferior acoustics to other positions.
- Increasing audience absorption (e.g. for full-audience theaters) improves speech intelligibility and the other metrics, especially for distant listener positions.
- The use of the stage house (this being an integral feature of the Roman theaters) has different effect on the acoustics of Epidauros and Dodoni. For actors speaking from the orchestra, for both theaters and especially for Epidauros, the acoustics seem to be adversely affected by the stage house reflections. This effect is dramatically reversed for actors located on the stage (as was the case for later-period ancient drama performances), when Epidauros exhibits a remarkable advantage over the other theaters, especially when full of audience, with intelligibility improving for distant listener positions.
- For Epidauros, a more uniform reduction of the lateral reflected energy with distance was observed, than for the other theaters, except for the extreme side- arc positions, this effect being related to the unusual highly enclosing side koilon sections.

From these results it can be concluded that the more balanced and distance independent acoustic performance of Epidauros and to a lesser degree of Dodoni, is a consequence of the theater’s geometric shape alone, other factors such as temperature gradient which were not examined here, possibly acting in synergy to these purely path-related acoustic factors. This shape results to generation of early reflections and a uniform decaying early diffusion, which although low in overall level, (the equivalent Reverberation Time value being less than 0.2 s), are supporting the direct signal and hence enhancing speech communication and perceived signal quality. In addition, it was also verified that for most listening positions, total SPL reduction with distance is linked to a corresponding reduction of lateral reflected energy component, hence further assisting source definition, focusing and perceived signal coherence for such more acoustically adverse positions.

Hence, this study has verified that these theaters have remarkable acoustic performance, which should be considered as an achievement of ancient acoustic technology. Historic evidence suggests [2], that conscious acoustic design decisions were involved in these theaters’ construction, so that speech communication and quality, together with uninterrupted sight lines, would be optimised for such large audiences (for a more extensive discussion on the writings of Vitruvius, see Appendix A1). In contrast to that, the authors have reported [12] that closed public buildings of the same era were not thus optimised for speech communication, though their acoustics could be utilised for other public or ritual functions.

In conclusion, this work indicates that the acoustic principles implemented in the ancient theaters can challenge many aspects of contemporary acoustic and architectural design. These theaters, although they could accommodate large audiences (up to 17000 people, that is, a significant portion of the local ancient community population), they still could provide neutral acoustics with reverberance equivalent to that of a small studio and introduce to the listeners a desired sense of intimacy and acoustic comfort, allowing good intelligibility even at distant positions. Their functional and discrete integration to the environment (being appropriately chosen to fit existing hill slope recessions), assists both visual and aural speaker / audience communication and their method of construction has ensured that for 2500 years now, they have remained operational to communities so further apart in time.

Appendix

A1. Historic evidence on ancient theater design

A useful account of the design principles employed in such ancient designs is given by Vitruvius [2], an engineer in ancient Rome, living approximately during 2nd century BC, his writings being later published in many languages. In those, he describes the architectural design and method of construction of Greek and Roman theaters.

In the 5th book (V, III, 6), Vitruvius gives a basic interpretation of sound propagation, describing sound as a “flow of air travelling from the source and creating an appropriate sensation to the listener”. He also refers to sound as 3-D outwards propagating waves (making a comparison to 2-D sea waves), whose path may be interrupted by reflecting objects, thus creating some interference. Based on this analysis, he explains that ancient Greek and Roman architects designed theaters to achieve good acoustics by taking into account of a number of different factors:

(a) The seat height and koilon slope were designed so that sound propagating upwards to reach the listeners in harmony (without reflecting interference) and in a clear way. To this effect, he mentions that the diazoma (aisle) width should not exceed the height of the seats, so that the sound wave would always “touch” the edges of the tiers and reach the listeners in the upper aisles in a way that “..the ending of the words would be clearly perceived”.

(b) A high priority was given to the proper choice of site, which should have good acoustics, without unwanted echoes from nearby reflecting obstacles. By reference to ancient Greek authors, Vitruvius describes the alternative modes of acoustic behavior of reflecting sites, as follows: (i) acoustically dissonant sites (“katechountes”), (ii) reverberant sites (“peri-echountes”), (iii) echoic sites (“antiechountes”) and (iv) acoustically consonant sites (“synechountes”). Theater sites were chosen to meet the last condition.

(c) In Roman theaters, specially designed brass resonating chambers (vases) were employed, placed on the koilon with their opening facing the orchestra and Vitruvius gives an account on the method of their design and placement. These were tuned in harmonic intervals, following the principles of ancient music theory, as was previously described by Aristoxenos, so that the speaker’s voice tone would be shaped by these acoustic filters. This may be considered to be more of an acoustic effect than as a method to assist intelligibility, ‘though the likely voice amplification would improve communication if audience or other noise was present.

(d) Many environmental factors were also taken for the choice of site and the theater’s orientation. Such factors related to avoidance of unhygienic locations, windy and sites exposed to sunlight, etc. Possibly, environmental noise, if was systematically present at specific locations, would be also taken into account.

A2. Audio Demonstration List

(WAVE file names are shown in bold letters)

Audio Demo 1 (AD1)

Comparison of listener angle θ_N for the three theaters (source at S_1, theaters empty of audience, no stage-house).
AD1Epidauros: Epidauros, receiver at R_1, R_2, R_3
AD1Dodoni: Dodoni receiver at R_1, R_2, R_3
AD1Patras: Patras, receiver at R_1, R_2, R_3

Audio Demo 2 (AD2)

Comparison of listener distance R_N for the three theaters (source at S_1, theaters empty of audience, no stage-house).
AD2 Epidauros: Epidauros, receiver at R_1, R_4, R_7
AD2 Dodoni: Dodoni, receiver at R_1, R_4, R_{14}
AD2 Patras: Patras, receiver at R_{12}, R_1, R_5

Audio Demo 3 (AD3)

Comparison of the 3 theaters for receiver at same distance (source at S_1, theaters empty of audience, no stage-house). **AD3:** Epidauros receiver at R_1; Dodoni receiver at R_1; Patras receiver at R_1.

Audio Demo 4 (AD4)

Comparison of the 3 theaters for receiver at same distance (source at S_2, theaters full of audience, with stage-house included). **AD4:** Epidauros receiver at R_1; Dodoni receiver at R_1; Patras receiver at R_1.

Audio Demo 5 (AD5)

Comparison of the 3 theaters for receiver at same distance (source at S_1, theaters full of audience, stage-house not included). **AD5:** Epidauros receiver at R_1; Dodoni receiver at R_1; Patras receiver at R_1.

Audio Demo 6 (AD6)

Comparison of receiver at position R_1 for Epidauros with the effects of orchestra and koilon removed (source at S_1, empty of audience, no stage-house included). **AD6:** Direct signal; signal without koilon (contribution from orchestra only); signal for full theater (contribution from orchestra and koilon).

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References

[1] M. Bieber: The history of the Greek and Roman theater. Princeton University Press, Princeton, New Jersey, 1961.
[2] VitruvII: De architectura. Harvard University Press, Cambridge, Mass., 1931. Lib V, translated by Frank Granger.
[3] A. Gergan, W. Müller-Wiener: Das Theater von Epidauros. W. Kohlhammer Verlag, Stuttgart, 1961.
[4] S. R. Shankland: Acoustics of Greek theaters. Physics Today (1973) 30–35.
[5] F. Canac: L'acoustique des théâtres antiques. Editions du Centre National de la Recherche Scientifique, Paris (1967) 151–161.
[6] J. Moir: Ancient acoustics. Audio annual (1967) 46.
[7] G. E. Tzekakis, G. Schubert: The acoustical design of a new open air theater in Thessaloniki, Greece. J. Acoust. Soc. Am. **105** (1999) 1043.
[8] M. Cognini, A. Farina, R. Pompoli: L' acoustica dell' anfiteatro Romano Arena di Verona. Atti della Conferenza Internazionale "Acoustics and recovery of spaces for music", Ferrara, 1993, 27–28.
[9] G. Cambourakis: Oiniades theater assessment. Dept. of Archaeology Report, Univ. of Vienna, 2001.
[10] J. Blauert: Spatial hearing: The psychophysics of human sound localization. MIT Press, Cambridge USA, 1997.
[11] http://www.wcl.ee.upatras.gr/ audiogroup/ AncientAcoustics/ index.html.
[12] L. S. Vassilantonopoulos, N. J. Mourjopoulos: Virtual acoustic reconstruction of ritual and public spaces of Ancient Greece. Acoustica **87** (2001) 604–609.
[13] http://www.culture.gr.
[14] S. I. Dakaris: The hieron of Dodoni, the theater (in Greek). Archeology Bulletin **16** (1966) 7–40.
[15] Catt-Acoustic v7.0b: User's manual. Gothenburg, Sweden, 1998.
[16] B. J. Allen, A. D. Berkley: Image method for efficiently simulating small-room acoustics. J. Acoust. Soc. Am. **65** (1979) 943–950.
[17] B.-I. Dalenbäck, M. Kleiner, P. Svensson: A macroscopic view of diffuse reflection. J. Audio Eng. Soc. **42** (1994) 793–807.
[18] ISO 3382-1997(E): Acoustics-measurement of the reverberation time of rooms with reference to other acoustical parameters. 1997.
[19] L. Cremer, H. A. Müller, T. Schultz: Principles and application of room acoustics. Volume 1. Applied Science, London, 1982.
[20] H. Kuttruff: Room acoustics. Third edition. Elsevier Applied Science, 1991.
[21] T. Houtgast, H. J. M. Steeneken, R. Plomp: Predicting speech intelligibility in rooms from the modulation transfer function. I. General room acoustics. Acustica **46** (1980) 60–72.
[22] T. Jacobsen: The RASTI method for objective rating of speech intelligibility. 12th ICA, 1986, paper E10–1.
[23] M. Barron, H. A. Marshall: Spatial impression due to early lateral reflections in concert halls: the derivation of a physical measure. Journal of Sound and Vibration **72** (1981) 211–232.
[24] L. Cremer: Early lateral reflections in some modern halls. J. of the Acoustical Society of America **85** (1989).
[25] I. B. Dalenbäck: The importance of diffuse reflection in computerized room acoustic, prediction and auralisation. Proc. Inst. Of Acoust. **17** (1995) 27–34.