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The Acoustics of Roofed Ancient Odeia: The Case of Herodes Atticus Odeion

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Summary
Ancient Greek / Roman odeia were semi-enclosed theaters that currently survive without their original roof sections. The work compares the acoustics of the well-preserved Herodes Odeion in its current open-air form to a detailed acoustic model reconstruction of its original roofed version and illustrates the significant differences in acoustics between the two spaces. It is shown that in their original state, the odeia had acoustics appropriate for music performances in contrast to their current open-air form that have acoustic properties appropriate for speech reproduction, similar to the larger open-air theaters of the time which were used specifically for ancient drama performances.

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1. Introduction

Odeion (plural: odeia) was an ancient Greek and Roman theater of smaller dimensions than the typical open-air ancient theater, being also partially roofed and suited to musical performances and song recitations. Hence odeia served different functions to the larger open-air ancient theaters that were used for theatrical plays (ancient drama) [1, 2]. Given that such roofed theaters were used for recitations of an ode (= song), they had mainly an entertainment function and were referred to as "a place of the ode", i.e. "odeion" (in Greek) or "odeum" (in Latin) [1, 2]. The term has being recently paraphrased to "odeon" to denote theater buildings, music halls and movie theaters.

According to the archeologists, the roofed section of such theaters was constructed from cedar wood and had semi-circular form, partially covering the marble "koilon" (the steeply-sloped seating section). In some cases, an elaborate timber roof covered all the seating area and the orchestra. The partially-roofed design along with the perimetrically-located windows allowed for natural lighting to reach the stage [2]. The design for the odeia evolved from the earlier and larger open-air theaters but it is unclear if the roof was added in order to protect the audience or it was built in order to assist the acoustics for music performances. This aspect was not discussed in ancient documents and has not been analysed in detail in contemporary textbooks [2], except in results presented in the ERATO project [3].

In all existing odea, such roofed timber structures have either collapsed or have been burned since ancient times [1] and hence these buildings are currently preserved as open-air theaters. For this reason, the specialised function of the odeia as buildings for music performances, is largely ignored or misunderstood, being considered as open-air ancient theaters. Given such misconception and given that odeia present possibly the earliest known form of roofed theaters dedicated to music performances in front of large audience, it is significant to examine here their acoustic properties and to describe the significant differences in their acoustics from their currently-preserved open-air form.

It must be noted that in the past, the acoustics of ancient Greco-Roman theaters were studied in [3, 4, 5, 6, 7, 8] and in [3, 9], the acoustics of ancient odea were discussed. To obtain a clear insight of the difference in acoustics between open-air and roofed versions, the well-preserved ancient Herodes Atticus odeon in Athens is studied here in its current open-air form and compared to an acoustic model reconstruction in its original roofed form.

The "Herodeion" as it is called by modern Greeks was built in the southern slope of Athens Acropolis in AD 161 by Tiberius Claudius Atticus Herodes, an important figure of his time who was a teacher and philosopher and who had inherited a great fortune from his father. When his wife Rigilla died, he built this roofed odeion for musical performances to honour her memory. His odeion became an important cultural center for ancient Athens and was used mainly for music and recital concerts. The ancient historian Pausanias describes it as the "most significant building of its kind..." (Paus.vii.20 §3). The odeion was burned in AD 267 but since the 50s has been restored to its current open-air form, today being used every summer mainly for music performances during the Athens Festival.

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Table I. Geometric properties of the Herodes odeion.

Radius of koilon (m)	38
radius of Orchestra (m)	9.5
Rows of seats	32
Height of side walls (roofed version) (m)	30
Extension of roof (roofed version) (m)	∼14.30
Audience capacity	∼5000

The paper is organised as follows: Section 2 presents the method employed for acoustic simulations and measurement of the odeion; section 3 compares the results between the simulations and measurements for the open-air form of the odeion and then examines the differences in acoustic properties between the open-air and roofed versions; conclusions and discussion are then presented in section 4.

2. Method

2.1. Overview

The work here is mainly concerned with the accurate acoustic modeling and analysis of the Herodes odeion, being a typical case for most other similar theaters and for this, a comparison between two versions were considered: (a) the currently preserved open-air structure and (b) a virtual reconstruction of the original roofed structure. To examine the accuracy of the model, a set of in-situ acoustic measurements was obtained, at the exact positions where results were derived via the corresponding model simulations. Given that simulations and measurements are in good agreement (as will be discussed later), any simulation results for the corresponding roofed version may be considered to be accurate to the exactness of the archeological data employed for the geometry and properties of the wooden roof section.

A current photograph of the odeion is given in Figure 1. Figure 2a,b gives the 3-D views of the open-air and roofed versions of the acoustic model employed for the study.

2.2. Description of the odeon

The steeply-sloped seating section (koilon) is well-preserved today and was constructed from marble and has a capacity of nearly 5000 spectators. In horizontal plan-view the koilon has sides that extend to a small extend beyond the semi-circle and is split into upper and lower sections via a middle aisle. (Figure 3a). The upper side of the koilon was leading to the upper aisle that was enclosed by the back wall. The properties of the odeion are given in Table I.

Unlike the Hellenistic period open-air theaters, the orchestra was semi-circular and was initially covered by marble. The stage house was a dominating 3-floor structure of 28 m height and 35 m length, of which only a 2-floor structure is partially preserved today. The façade was elaborate in design with many recesses, was decorated by coloured marble and statues of members of the Herodes family as well as of members of the emperor's court.

Figure 1. The Herodes odeion in its current state.

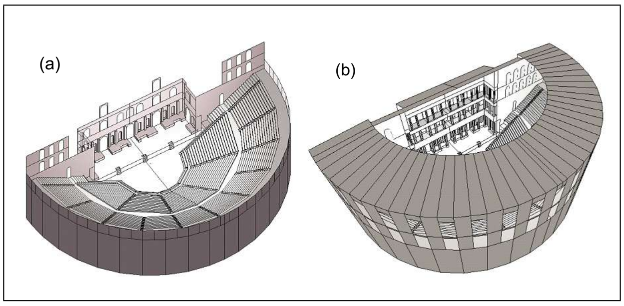

Figure 2. 3-D representation of the Herodes odeion acoustic model developed for the tests: (a) open-air version, (b) roofed version.

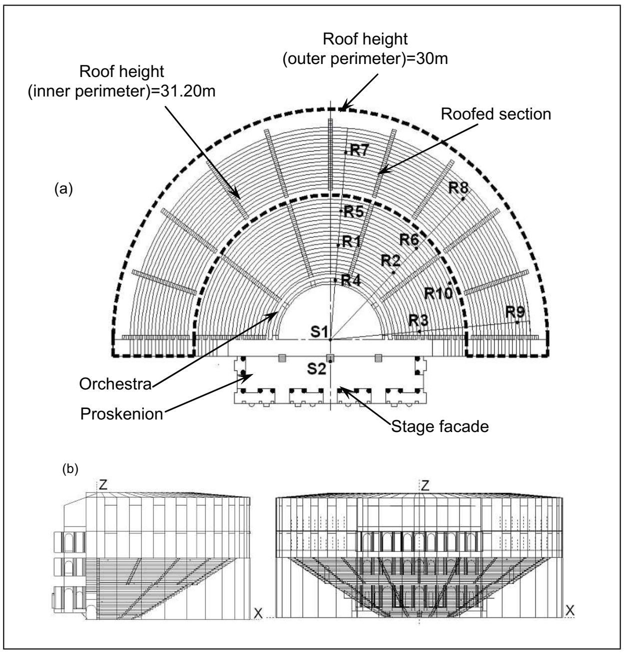

Figure 3. (a) plan view of the acoustic model with the tested source (S) and receiver positions (R); (b) sections of the model (roofed version).

The timber roof, of which evidence was also found during excavations, was semi-circular, clearly made in order to protect the seated audience and possibly to assist the acoustics of the music performances [1, 2, 10, 11]. This acoustic function of the added roof, as will be shown here,

Table II. Material properties (average values for all frequency bands) for the simulations of the Herodes odeion. Abs.: absorption coefficient, Scat: scattering coefficient.

Elements	Materials	Abs.	Scat.
Seating area	marble	0.013	0.55
Scene wall	porous stone	0.2	0.4
Proscenium floor	wood	0.1	0.5
Orchestra	mosaic	0.03	0.55

was a significant factor differentiating the functionality of the odeion from its open-air form. It should be also noted that during modern-day performances, the original orchestra surface is covered by a raised platform podium.

2.3. The acoustic simulations

The simulations were based on a collection of architectural drawings for the odeion, historical documents and other records related to the evolution and the functions of the building throughout its history [1, 2]. Based on these data, an electronic drawing of the building was generated using well-established design software (AutoCad v.2004) and the geometric data were then transferred to commercially available acoustic simulation software [12]. For all subsequent studies, a set of typical positions for the source (S_N) and the receiver (R_N, for $N = 1 \dots 10$) were defined, those being at various distances from the stage and at angles corresponding to central-arc listening positions ($\vartheta = 5°$), to middle-arc listening positions ($\vartheta = 45°$) and side-arc listening positions ($\vartheta = 85°$), as is shown in Figure 3a. For the model, the appropriate materials were defined obtaining data from the current state of the odeion and also from the archaeological evidence. The average values for all frequency bands of absorption and scattering coefficients are shown in Table III. The computer acoustic model was based on image / ray prediction [13] and was detailed [14] with approx. 3700 planes employed and approximately 900.000 rays used for the simulations. In order to simulate the acoustic measurement conditions, an omnidirectional source with level of 99 dB/1m was assumed, placed at a height of 1.7 m from the floor. The following alternative versions were studied:

a) the open-air version of the odeion, with source at the center of the orchestra (S_1),
b) the open-air version of the odeion, with source at the "proskenion" stage (S_2),
c) the roofed version of the odeion, with source at the center of the orchestra (S_1),
d) the roofed version of the odeion, with source at the "proskenion" (S_2).

Finally, given that currently the odeum is functioning with a raised platform (podium) on the original stage (orchestra), additional simulations were undertaken, to conform to this modern-day use of the building, i.e.

e) the open-air version of the odeion, with source at the raised platform extension (S_1),
f) the open-air version of the odeion, with source at the "proskenion" (S_2), but with the raised platform extension.

Given that currently background noise is usually high, the simulations were also considered such an alternative case, employing noise with features typical of the modern-day case, as is described in more detail in section 3. From these simulations, and for the frequency range 125–4000 Hz, the following well-established acoustic parameters were evaluated:

SPL (dB) the sound pressure level as sum of the 125–4000 Hz band components,
RASTI (%) the Rapid Speech Transmission Index, indicating speech intelligibility [15, 16],
T_S (ms) center response time and **EDT** (s) [17, 18],
D-50 (%) the Definition index and C-80 (dB), the Clarity index [17, 18, 19],
LEF (%) the Lateral Energy Fraction [18, 20, 21],
G-10 (dB) the response strength factor [18].

Figure 4. Typical source set-up for the acoustic measurements (source at position S_1 shown).

2.4. The acoustic measurements

Measurements were obtained using a combination of 2 opposite-facing self-powered loudspeakers to emulate an omnidirectional source placed at a height of 1.7 m from the floor and driven by sine sweeps from commercially-available measuring software running on a laptop, a high quality external sound card and omnidirectional measuring microphone (see Figure 4). Given that the modern-day environment around the theater can be noisy, the measurements were obtained at a time when such interference was as low as possible. The measured average ambient noise level was around 60 dB and the excitation signal was reproduced at an approximate SPL of 90 dB/1m. In all cases the reproduction gain was adjusted so that the SNR was kept above 28 dB.

Source and receiver positions were identical to the ones described in the previous section, as used for the computer simulations and shown in Figure 3a. However, measurements were obtained only for 5 receiver positions (R_1, R_2, R_4, R_7, and R_{10}).

Table III. Acoustic parameters (sum values for the 125–4000 Hz range) for simulated (S) and measured results (M) for the open-air version of the odeion and source at position S_1.

R_n	SPL (dB)		RASTI (%)		Ts (ms)		D-50 (%)		C-80 (dB)		G10 (dB)
(m from source)	S	M	S	M	S	M	S	M	S	M	S
R_1 (15.63)	90.2	90.0	68.9	77	27.5	24.0	82.9	88.3	9.5	10.3	2.1
R_2 (15.63)	90.2	89.0	70.2	74	25.5	28.9	85.5	85.2	9.6	9.3	2.2
R_3 (15.63)	90.0	–	69.2	–	24.5	–	81.2	–	10.1	–	1.9
R_4 (9.85)	94.8	93.4	73.3	80	20.4	19.1	89.0	92.1	11.7	12.3	6.7
R_5 (21.30)	86.4	–	60.4	–	34.8	–	78.2	–	7.5	–	-1.6
R_6 (21.30)	86.0	–	62.6	–	34.1	–	74.5	–	6.8	–	-2.1
R_7 (30.93)	83.3	84.6	58.3	67	35.1	35.1	77.8	78.5	7.8	7.7	-4.8
R_8 (32.81)	82.0	–	55.3	–	39.1	–	70.9	–	6.8	–	-6.1
R_9 (32.83)	82.1	–	57.6	–	38.8	–	70.6	–	5.5	–	-6.0
R_{10} (22.84)	86.2	83.8	63.8	64	29.7	49.6	79.9	69.1	7.3	5.7	-1.9

Table IV. The EDT (sum values for the 125–4000 Hz range) for all the receiver positions, for the simulated and measured results for the two versions of the odeion (open-air and roofed), with (+) and without (−) audience and source at position S_1.

R_n	open-air			roofed	
	S (−)	M (−)	S (+)	S (−)	S (+)
R_1	0.38	0.46	0.24	1.74	0.95
R_2	0.35	0.62	0.25	1.57	0.86
R_3	0.34	-	0.24	1.67	0.92
R_4	0.28	0.18	0.18	0.98	0.57
R_5	0.48	-	0.30	2.48	1.36
R_6	0.47	-	0.31	2.27	1.27
R_7	0.48	0.78	0.37	2.98	1.75
R_8	0.54	-	0.32	3.07	1.73
R_9	0.53	-	0.37	3.14	1.84
R_{10}	0.40	0.48	0.24	2.38	1.28
mean	0.42	0.50	0.28	2.22	1.25

3. Results

3.1. Comparison between simulations and measurements

Results for the open-air version of the odeion, with source at the center of the orchestra (S_1) are given in Table III.

As can be observed, a good agreement between simulation and measurements was achieved in most cases. Intelligibility according to RASTI appears somehow lower in the simulations as opposed to the measurements, noting though that the simulation results were obtained using an additive noise of constant level, which may differ to the variable noise present during the measurements.

3.2. The acoustics of the open-air version of the odeion

The odeion in its currently preserved open-air version has acoustics that are similar to the larger ancient theaters of the Hellinistic era, which were purposely build as open-air buildings for speech and theatrical performances [4]. In the case of the Herodeion, as can be deduced from the results in Table IV, the equivalent Reverberation Time value would have been RT ≈ 0.5 s, this low reverberance assisting good speech intelligibility. As was also discussed in [4], the sound field consists of

(a) the early reflections arriving from the floor of the orchestra, then from reflections from the rises behind the listener in the koilon, and then from reflections generated from the stage back wall (façade). These reflections arrive within a short interval after the direct signal (typically less than 30 ms), hence assisting intelligibility. In the simulations, these are described by 1st order reflections.
(b) later (2nd and 3rd order) reflections arriving for intervals 55–200 ms after the direct signal, generated by multipath reflections the opposite sides of the koilon, the orchestra floor / koilon façade / stage façade path. As was discussed in more detail in [4], such reflections are not assisting intelligibility, although rarely can be audible to the listener.
(c) The diffuse exponentially decaying field from reflections on the various elements of the koilon [22, 23].

In general there is a satisfactory agreement between the detailed structure of the simulated response and the measured impulse response (see Figure 5a-d). Any discrepancies may arise from differences in the details of the structure between the simulated version (where all surfaces have been modeled) and the current form of the structure where some of the façade structure has collapsed and some other modifications have been introduced on the stage platforms. Nevertheless, given that the exact comparison of simulated and measured versions was beyond the scope of this work, it appears that simulations for the roofed version can be considered as sufficiently trustworthy. Furthermore, the simulation results may assist in tracing the exact path of all reflections. From such detailed analysis of the simulation results it becomes clear that the main reflection multipath described by (b), above, affects mainly the central listening positions, whereas side positions receive also reflections from the opposite side of the koilon.

Measurements of the odeion, reveal that the frequency response (magnitude) for most listening positions exhibit the (expected) cancellation from floor reflection in the region of 200 Hz, as is shown in Figure 7a,b. However, given

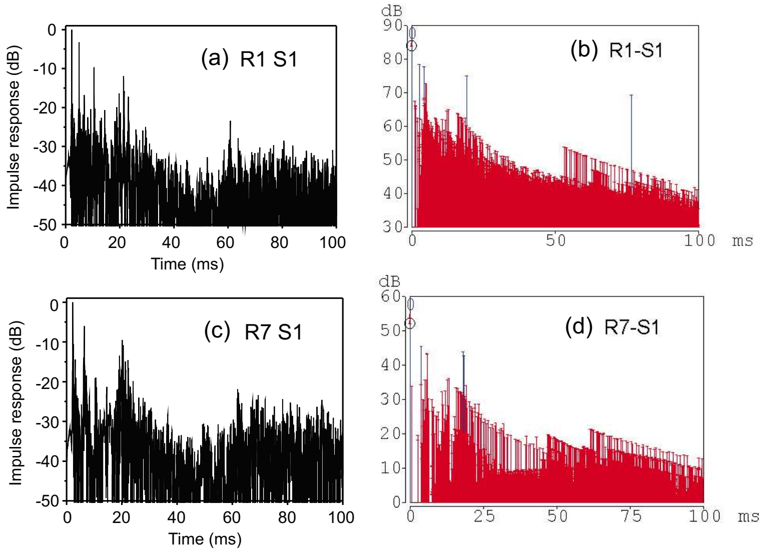

Figure 5. Typical odeion squared impulse responses for source at position S_1 and receiver at positions R_1 and R_7, shown in dB scale and up to 100 ms: (a), (c) measured results; (b), (d) simulated results.

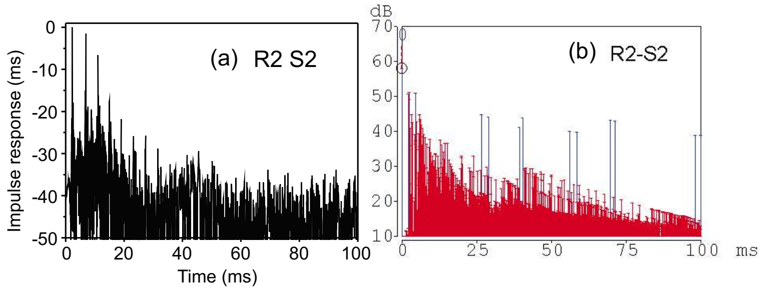

Figure 6. Typical odeion squared impulse responses for source at position S_2 and receiver at position R_2, shown in dB scale and up to 100 ms: (a) measured results;(b) simulated results.

that for modern-day performances a platform is added to the cover the stage floor (orchestra), a comb-like filtering effect is often appearing due to the multiple reflection paths generated by this additional platform, especially when the source is moved closer to the stage façade, i.e. in the position S_2, (Figure 6a,b). In such cases, stronger, periodic and delayed 2nd and 3rd order reflections are generated by multiple paths which include the stage floor (proskenion) and/or stage face, the elevated modern-day stage platform and the rises behind the listener in the koilon. In this case, intelligibility and spectral response deteriorate with respect to the case when the source is located on the orchestra.

3.3. Comparison to the roofed version of the odeion

For the roofed version, the results were obtained only from the acoustic model. In this case the volume of the semi-enclosed space becomes V = 9750 m^3.

Observing the echogram of the roofed version (e.g. see Figure 8), it is evident that the roof contributes to late reflections appearing approximately after 190 ms. The path of these reflections follows a reflection on the roof, then the back wall of the koilon and in some cases the rise behind the seats. These late reflections increase the overall reverberation of the odeion and it becomes apparent that the theater behaves more like an enclosed space with significant reverberance. The approximated frequency-averaged reverberation time of the empty roofed theater, as can be deduced from the results in Table IV is estimated to be RT $\approx$ 2.2 s, this value being reasonable given the volume of the theater and the low absorption of most surfaces. Table V gives the list of the evaluated acoustic parameters.

From these results and from Tables III, IV and V, it becomes evident that the acoustics of the roofed version of the odeion are not appropriate for speech communication and are more suitable for music performances. Figure 9 compares the simulated G-10 vs distance results of the roofed version of the odeion. Strength G-10 increases by an average of 3 dB for the roofed version, indicating an improved support for the reproduction of music and vocals.

Furthermore, from Figure 10 it is clear that speech intelligibility for the roofed version is approximately 20% worst, being marginal for most listener positions. Hence, it is reasonable to assume that this theater could not be easily employed for speeches and theatrical performances, especially given that the open theaters of the time were achieving near-perfect speech reproduction in all audience positions [4, 24]. Definition stays above 75% for all positions for the open-air version of the theater (see Figure 11, noting the good agreement between measured and simulated results), whereas for the roofed version the definition is reduced by 15% for the central near positions and

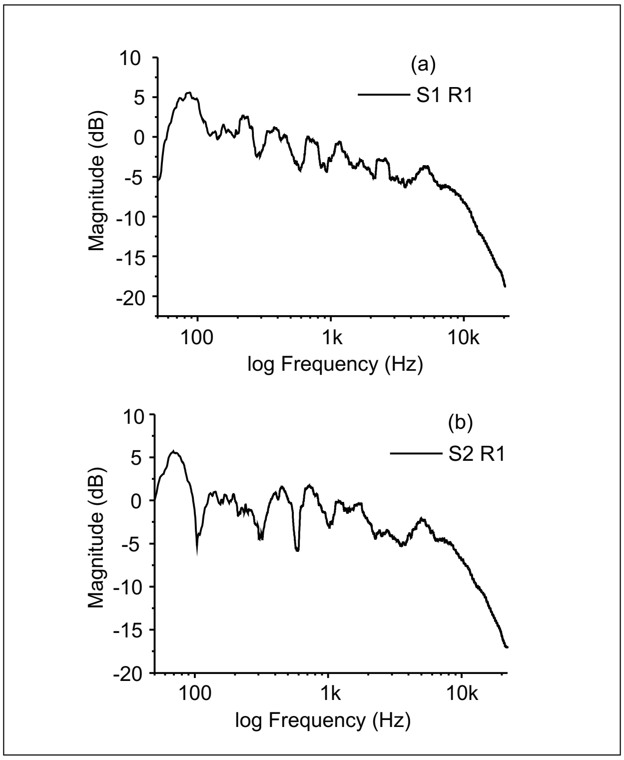

Figure 7. Typical measured odeion magnitude 1/10th octave-smoothed spectral response for receiver at position R_1: (a) source position at S_1; (b) source position at S_2.

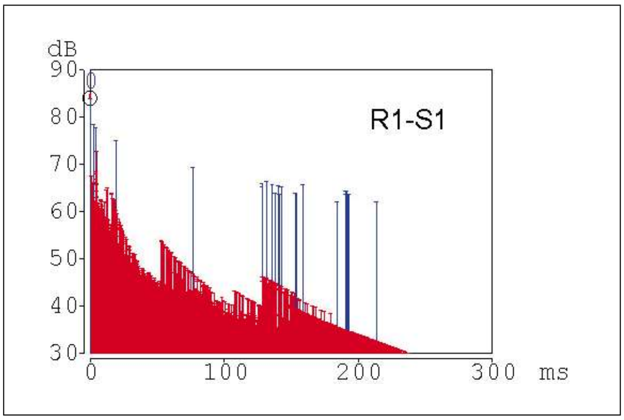

Figure 8. Typical simulated roofed odeion squared impulse response (shown in dB up to 300 ms for source at position S_1 and receiver at position R_1).

approx. 50% for the more distant positions. The C-80 criterion follows similar trends, the more distant positions having an approximate 10 dB reduction for the roofed version. Careful comparison of the results given in Tables V and VI. indicates that for the distant positions in the roofed odeion, there is an increase in the lateral reflection energy. Hence, as can be observed from the Figure 11a,b, the roofed version of the odeion, is more appropriate for music performances. Furthermore, Table IV shows a good agreement between the simulations and measurements for the (approximated) EDT values for the open-roofed case. This (position and frequency averaged) EDT value is close to 0.5 s, but it rises to 2.2 s for the simulated roofed version case and without audience present. With audience, this value is expected to fall to 1.25 s. Figure 12 shows the frequency dependence of the estimated and measured EDT values, for all cases studied.

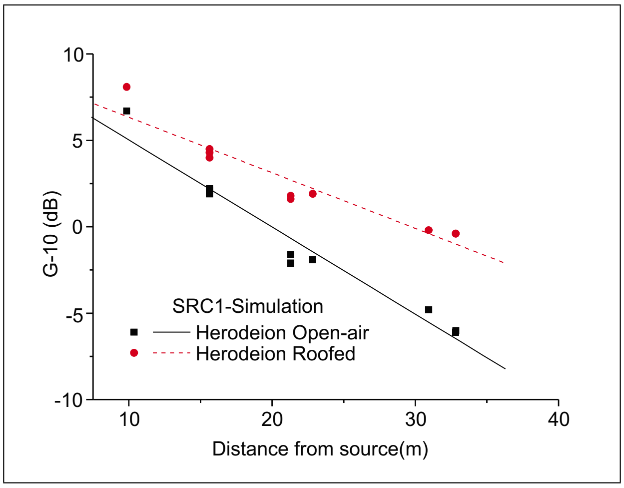

Figure 9. Variation of Strength Index G-10 with distance for the open-air version of the odeion, compared to the simulated roofed version. The source was located at the orchestra.

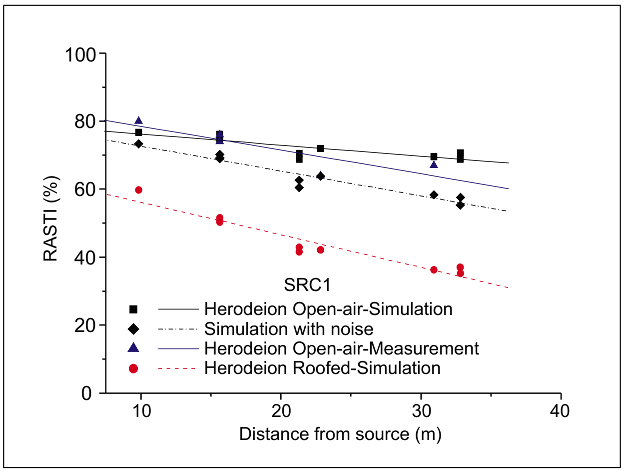

Figure 10. Variation of speech intelligibility (RASTI) with distance for the open-air version of the odeion (simulated and measured), compared to the simulated roofed version. The source was located at the orchestra and simulation results are also shown assuming 60 dB-SPL ambient noise.

4. Discussion and conclusions

For some time now it has been known that ancient Greek-Roman roofed theaters (odeia) were buildings with acoustics distinctively different to those of the contemporary open-air theaters whose acoustics are famed for speech reproduction. However, such differences had not been sufficiently illustrated by detailed results and hence the distinct functionality of each building had not been clearly identified. In the past, the limited knowledge of roofed odeia acoustics, has not allowed the experts to appreciate the dis-

Table V. Acoustic parameters (sum values for the 125–4000 Hz range) for simulated results for the roofed version of the odeion and source at position S_1.

R_n	RASTI (%)	Ts (ms)	D-50 (%)	C-80 (dB)	LFC (%)	G10 (dB)	SPL (dB)
R_1	50.7	126.1	52.0	1.5	18.8	4.0	92.0
R_2	52.4	113.6	57.6	2.3	19.8	4.3	92.3
R_3	50.5	121.5	51.4	1.8	26.8	4.5	92.5
R_4	60.6	71.2	72.3	5.3	25.1	8.1	96.2
R_5	41.1	179.8	37.4	-1.1	17.7	1.6	89.7
R_6	43.7	164.7	40.8	-0.7	19.2	1.8	89.9
R_7	37.4	216.3	25.9	-3.4	15.5	-0.2	87.9
R_8	37.1	222.4	22.0	-4.0	15.7	-0.4	87.6
R_9	29.8	227.3	20.9	-3.8	19.3	-0.4	87.7
R_{10}	42.7	172.3	36.1	-1.3	13.7	1.9	89.9

Table VI. Acoustic parameters (sum values for the 125–4000 Hz range) for simulated results for the roofed version of the odeion and source at position S_2.

R_n	RASTI (%)	Ts (ms)	D-50 (%)	C-80 (dB)	LFC (%)	G10 (dB)	SPL (dB)
R_1	45.7	142.2	44.3	0.9	29.8	3.0	91.0
R_2	49.7	123.0	48.3	1.4	23.8	3.5	91.5
R_3	47.9	126.4	47.5	1.4	23.2	4.0	92.0
R_4	53.3	103.7	55.3	2.7	26.0	5.5	93.5
R_5	42.2	170.1	35.9	-1.0	22.7	1.4	89.4
R_6	45.0	161.1	38.9	-0.7	20.9	1.5	89.5
R_7	35.9	201.2	26.5	-2.9	22.2	-	87.7
R_8	32.2	213.9	23.6	-2.9	18.4	-	87.4
R_9	34.2	229.8	20.2	-4.3	19.0	-	87.3
R_{10}	43.7	168.3	35.7	-1.8	19.8	1.6	89.6

tinct role that such buildings held in the antiquity, possibly being the earliest known venues for music performances for large audiences.

This work has derived detailed comparisons highlighting these differences, by examining the acoustics of the Herodes Atticus odeion (Herodeion) close to the Acropolis in Athens, Greece. A very detailed acoustic model for both the open-air and roofed versions was developed based on a collection of architectural drawings for the odeion derived from historical documents and other records, using acoustic simulation software. Acoustic measurements were also obtained from the odeion in its current open-air state, indicating a good agreement with the corresponding simulations. From this, it is safe to assume that any simulation results for the roofed version can be considered to be sufficiently accurate.

From the comparison between the open-air and roofed odeion simulations, it is apparent that in each case the building behaves acoustically in a completely different fashion:

The open-air odeion has acoustics that are fairly "dry", typical of a semi-open space, the equivalent reverberation time being in the order of 0.5 s. and the sound pressure level dropping by approx. 6 dB for each doubling of the source-receiver distance. Given that the odeion has a steeply angled seating positions (koilon), typical of many subsequent Roman-era odeia, the maximum source-receiver distance is less than 35 m and speech intelligibility is very good, even at the far listening positions;

The roofed odeion was an enclosed space of 9750 m^3 having an approximate reverberation time of 2.2 s. In this case the far-field sound pressure level was dropping less sharply with distance (approx. 3 dB for each doubling of the source-receiver distance) and speech intelligibility was poor especially for the more distant listening positions.

In more detail, speech intelligibility for the roofed version was found to be approximately 20% worst, being marginal for most listener positions. Hence, it is reasonable to conclude that in the ancient times the roofed odeion could not be easily employed for speeches and theatrical performances, given also that the open theaters of the time were achieving near-perfect speech reproduction for all audience positions. In contrast, the open-air form of the theater was not supporting well the reproduction of musical instruments and singing voice, over most listener positions. The comparison of the results given in Tables V and VI indicates that for the roofed odeion, there is an increase in the late lateral reflection energy, generated from multipath reflections arriving from the roof after 200 ms and subsequently reflected to other surfaces. Furthermore, the acoustic strength criterion for the roofed version is significantly higher, indicating good support for the acoustic reproduction of musical instruments and vocal performances for most listening positions. Hence, the acousti-

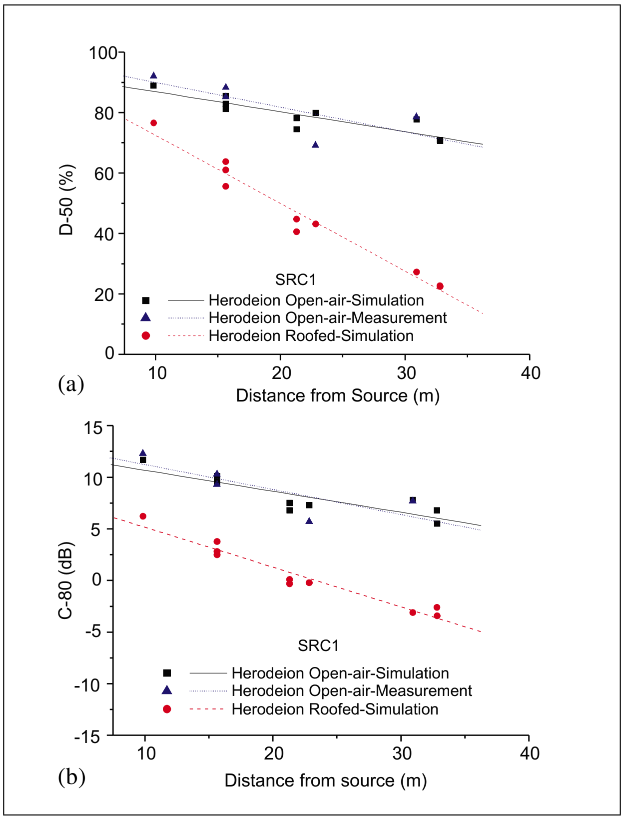

Figure 11. Variation with distance of: (a) Definition D-50, (b) Clarity C-80. The source was located at the orchestra.

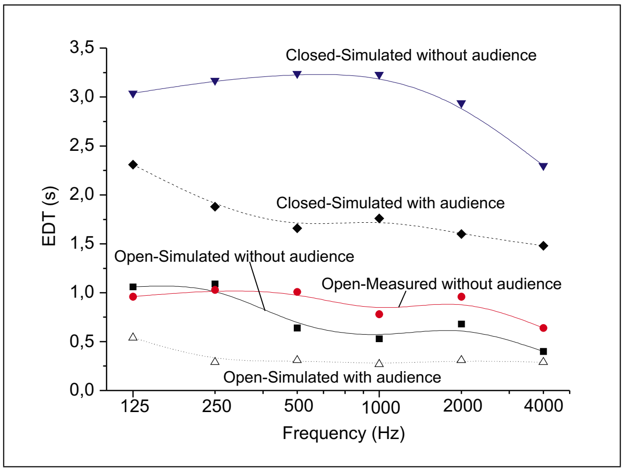

Figure 12. Variation with the frequency of EDT for the band 125–4000 Hz, for the receiver position R_7.

cal parameters of the roofed version of the odeion were more appropriate for such functions and were similar to many modern-day concert-halls of equivalent volume, although such halls would now have an approximate capacity of 1000 listeners, as opposed to nearly 5000 listeners for the odeion.

Such significant differences in acoustics and function between these spaces, may lead to the assumption that the roofed sections were added to the odeia in order to assist their use for music performances. Hence, following such a conjecture, some prior knowledge of building acoustics must be assumed in order to design a roof section that sufficiently differentiates the acoustics from the open-air theater structure. However, the question regarding the knowledge and practices in acoustic science available in the ancient Greek-Roman societies remains open. It is the opinion of these authors that further interdisciplinary research in ancient acoustic technology and science would help to clarify such issues and potentially benefit modern understanding of some aspects of building acoustics. In the face of this evidence, it is also useful for acousticians to account ancient Greek-Roman odeia as examples of the very early purposely-build buildings for music performances for large audiences and as the progenitors of the later-era concert halls.

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