The Significance of Sound Diffraction Effects in Ancient Theatres – Measurements and Simulations with and without Audience

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Summary

This paper examines the acoustics of ancient Greek-Roman theatres and the significance of sound diffraction effects taking place in the cavea. In a previous paper " The Significance of Sound Diffraction Effects in Simulating Acoustics in Ancient Theatres", it has been demonstrated how significant sound diffraction effects are in enriching the sound field in an ancient theatre by taking into account diffraction effects in an empty cavea. Sound diffraction is a scattering effect which disperses sound in many directions thus it allows listeners to perceive the sound of performers from the many scattering edges in the cavea before escaping to the surroundings. In essence unlike sound reflections, which are very few in open theatres, sound diffractions yield a precious part of the performers sound energy back to the audience thus creating a semi-diffused field. The theatre under study is a private school theatre, in the style of an ancient Greek theatre, where sound measurements were taken in 2011 with an empty cavea. For this paper, sound measurements were repeated there, with and without audience. The latter reveals more realistic conditions during performances. Sound measurements are compared to 3D wave-based geometrical acoustics simulations. The 3D theatre acoustical model was validated against sound measurements and wave interference effects analysis has shown that sound absorption and diffraction effects by an audience, provide indeed better speech acoustics.

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1. Introduction

In 2011 measurements were taken in the ancient theatre of Kourion to investigate the effect of edge diffractions on the acoustical properties of ancient theatres [1]. Due to the ancient theatre being a monument it was not possible to take controlled sound measurements of the theatre whilst being occupied by an audience, in order to investigate whether the scattering effect of an audience in open ancient theatres indeed provide for their excellent acoustical qualities of ancient theatres [2] .

In continuation to the previous paper by the same authors [1] this paper examines the effect of audience on the sound field in ancient theatres. To study the significance of these effects, sound measurements were taken at the open theatre of the Heritage Private School (Figure 1), a recently built theatre in the style of ancient Greek theatre. The measurement results were then compared with the results of an acoustical 3D model of the theatre in Olive Tree Lab-Suite (OTL-Suite) [3], Figure 2.

The paper is organised as follows: Section 2 reviews previous work done on ancient theatre acoustics and sound diffraction. Section 3 defines and comments on the acoustical terms used in the paper while Sections 4 and 5 refer to the geometrical and acoustical modelling methods used. Section 6 presents a description of the sound measurement protocol used at the theatre. Sections 7 and 8 present sound measurements and simulation results, followed by Section 9 with discussion of the results and Section 10 with conclusions.

Figure 1. The theatre with 432 pupils.

2. Previous Work

In 2013 Acta Acustica United with Acustica published a special issue (Vol. 99, Issue 1) dedicated to the acoustics of ancient theatres [4] as a result of the Conference on The Acoustics of ancient Theatres [5]. Ancient theatres have long been the subject of speculation, but only until recently has technology developed adequately to allow the investigation of the exact nature of their acoustic quality, in particular the importance of early reflections and edge diffractions.

While early reflections do make a significant contribution to the sound field inside the cavea of an ancient theatre, most of their energy is either absorbed by audience or escapes to the environment. In contrast, diffractions on edges of the cavea scatter in all directions, hence they direct much of the performers' sound energy back to the audience before escaping to the environment. Therefore, any analysis of the acoustical performance of ancient theatres must include edge diffraction phenomena [1].

An early account of the nature of the acoustic quality of ancient theatres was provided by Shankland [2] who emphasised the importance of early reflections and edge diffractions.

To the authors' knowledge there haven't been many sound measurements performed in an occupied theatre. In 2001 [6], sound measurements were taken at Epidauros with the theatre occupied with 300 and 3000 spectators. These were compared to earlier measurements [7] of the empty Epidaurus in 2004, investigating mainly the audience effect on room acoustical parameters.

In the past decade or so, more research was done on edge diffractions, however these studies were only concerned with empty theatres and were based on either computer simulations or scale model measurements [8],[10],[11]. The work presented here aims to investigate the sound scattering effects of a typical ancient theatre in both its occupied and empty state using simulations and measurements.

3. Definitions and how to interpret results

Sound diffraction is commonly understood as the bending of sound around the edges of objects (in the shadow zone) but, in fact, it is governed by the same physical process as is the scattering of sound due to an obstacle or an inhomogeneity in its path [12],[13],[14]. Therefore, the term “diffraction effects” as used in this paper, denotes the scattering of sound in both the illuminated and the shadow zones of an obstacle. Furthermore, for brevity the term sound diffraction(s) loosely used, denotes sound edge diffraction(s). When an object shields the sound path between source and receiver, the impulses of the diffracted paths are positive, while when there is direct sound between source and receiver, the diffracted paths produce negative impulses [15].

Excess Attenuation (EA) is the magnitude spectrum of the ratio of the total sound level at a receiver to direct sound [16]. EA may be thought of equivalent to Transfer Function (TF) in the sense that it calculates the filtering effect a space has on direct sound. It is a frequency domain measure which can be used to assess the sound quality of the space being analysed since it is independent from the spectral characteristics of a source. In terms of EA analysis, usually, good sound quality environment has an overall flat and relatively rough EA curve. While a single reflection at proximity from an object could offer a flat EA curve without comb filtering, this does not imply rich sound, which is characterized by sound scattering which makes an EA curve relatively rougher but overall flat. In other words, the inevitable comb filtering effect, embellished with sound diffraction make EA look rougher with usually shallower dips and consequently the sound field is richer. However, when consecutive sound diffractive edges combine, like in rows of seats, they create what is called the seat dip effect which filters out sound at specific frequencies which may lie in the range between 100-300 Hz. On the other hand, high peaks in EA signify resonances, therefore isolated higher levels in EA indicate sound enhancement which depending on the space could be useful or undesirable.

Like EA, Impulse Response (IR) fully describes a sound field in the time domain. Furthermore, it demonstrates how the sound field of an environment evolves with time. One may visualize and detect the arrival of sound reflections and diffractions. When sound comparable in intensity with direct sound arrives at a time longer than 50ms [17] then such a sound is perceived as a distinct echo. IR is the most important diagnostic tool to remedy acoustical defects.

Wave Based Geometrical Acoustics WBGA extends GA to accommodate for impedance surfaces, complex pressure summation, spherical wave propagation, and with the use of the image source method, can account for the phenomena of reflection, diffraction, refraction, transmission and others. It has been shown [18] that in rectangular rooms WBGA is as accurate as the BEM. This paper presents calculations using OTL-Suite [3], a sound propagation software application which employs WBGA in a 3D simulation environment.

4. Modelling of the open theatre of the Heritage Private School

The modelling of a space for simulation purposes determines the accuracy of the simulation results. Previous work has shown that even a variation of just 10 cm can have a significant effect on the final sound field [1].

The open theatre of the Heritage Private School consists of 15 rows of seats, each on average 0.37 m high and 0.91 m deep. The radius of the Orchestra is approximately 6.18 m while the entire radius of the theatre is approximately 19.85 m, with an arc spanning 220 degrees. The theatre capacity is of the order of 1500 people. During measurements 432 students acted as spectators. Each individual audience member was modeled as a trapezoidal shape with base dimensions of 0.50 x 0.30 m and top dimensions of 0.20 x 0.20 m. The trapezoid was 0.80 m high corresponding to the typical dimensions of a sitting human torso.

The modelled audience were roughly located according to pictures taken during measurements.

5. Modelling software application used for acoustical simulations

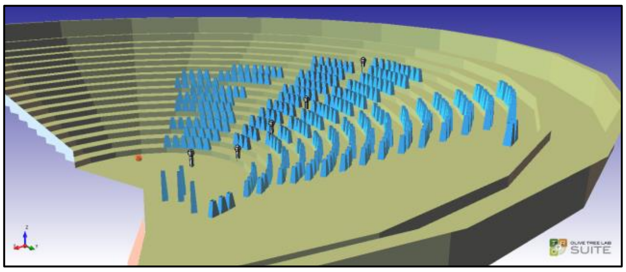

Figure 2. 3D acoustical model of the theatre with 432 pupils.

For the acoustic simulations OTL-Suite was used, which incorporates Wave Based Geometrical Acoustics (WBGA) in its calculation engine.

OTL-Suite calculates Excess Attenuation according to the following expressions. The time factor $e^{-j\omega t}$ is suppressed throughout.

$$EA = 20\log\left[\frac{p_{total}}{p_{ff,total}}\right], \tag{1}$$

$$p_{total} = \sum_{b=1}^{L} p_{t,b}, \tag{2}$$

$$p_{t,b} = \sum_{i=1}^{n} p_{1,b} \frac{e^{jkR_i}}{R_i} D_{i,total} Q_{i,total} \alpha_{R_i}, \tag{3}$$

where p_{total} is the total sound pressure at a receiver, of all the propagation paths from all sources, L is the number of sources, p_{tb} is the total sound pressure at a receiver, of all propagation paths from a source b, n is the number of paths from source to receiver, k is the wavenumber, R_i is the path length between a source and receiver, $p_{1,b}$ is the sound pressure of a monopole source at 1 m in free field conditions,

$$Q_{i,total} = \prod_{j=1}^{m} Q_j, \tag{4}$$

$$D_{i,total} = \prod_{l=1}^{s} D_l, \tag{5}$$

where Q_j is the partial spherical wave reflection factor of reflection j [19] (including Fresnel zone finite size reflection correction [20]), within path i, m is the number of partial reflections within path i, D_l is the partial spherical wave diffraction factor of diffraction l within path i [21], s is the number of partial diffractions within path i, α_{Ri} is the atmospheric attenuation within path i according to ISO 9613-1 [22],

$$p_{ff,total} = \sum_{b=1}^{L} p_{ff,b}, \tag{6}$$

$$p_{ff,b} = p_{1,b} \frac{e^{jkR_b}}{R_b} \alpha_{R_b}, \tag{7}$$

where $p_{ff,total}$ is the total sound pressure at a receiver, of all sound propagation paths from all sources in free field (FF), p_{ff} is the free field sound pressure at a receiver from source b.

In all simulations third order reflections (even though the maximum number of reflections detected was 2) and first order diffractions were used. A Fresnel zones correction was used to account for reflections from finite sized facets such as the modelled theatre steps. The analysis was done in 0.5 Hz resolution from 0.5 to 10000 Hz in order to also calculate the IR of the model.

The 3D model walls, were assigned acoustic impedances using the Delany-Bazley (DB) model [23] while the audience were modeled according to the Allard and Johnson (AJ) methodology [24]. All theatre surfaces were modelled as hard with a flow resistivity of 20,000kPas/m^2 (DB), while the material on the audience was modelled as a multilayered system (AJ). Audience impedance used in the calculations are shown in Figure 3. For easier interpretation, their equivalent statistical sound absorption coefficients are also shown, however, they were not used in any of the calculations.

6. Sound Measurements

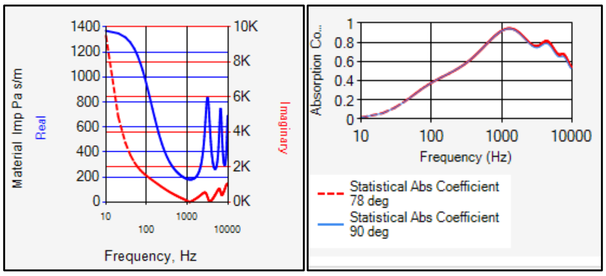

Figure 3. Audience surface impedance used. Equivalent sound absorption coefficients.

The main challenge of this paper was to perform sound measurements with and without the presence of a seating audience in the cavea of the open theatre while ensuring that the measurement conditions (microphone positions and source positions, atmospheric conditions etc) were the same throughout the measurement period. Sound measurements were taken on March 7th 2018 between the hours 11.40 and 12.00.

Five microphone locations were chosen, one in the Orchestra, and four on Steps 1, 4, 7 and 13 of the theatre while the Source was placed in the center of the Orchestra. Measurements of all five microphones were taken simultaneously using a ZOOM R24 multitrack recorder, avoiding having to move a single microphone at each measurement location. This was to ensure that after taking measurements of the empty theatre, there was no movement of the microphone positions once the audience arrived to take the measurements of the full theatre. Furthermore, since the audience were secondary school children, measurements had to be carried out in the minimum span of time to avoid movement and noise from the audience.

The source was a two-way 10” active speaker (the same used in 2011 measurements). The signal used was a log-frequency sine sweep which ranged from 50 to 20000 Hz based on the IR measurement technique by Farina [25]. A portable weather station was used to measure atmospheric conditions throughout the session. During measurements temperature varied from 18.6 °C to 19.3 °C, humidity was around 70% while wind was less than 3m/s.

6.1. Calibration of Multi Track Recorder

Because different microphones and preamplifiers were used for different microphone locations the individual gains of the preamplifier of each channel on the multitrack recorder was calibrated with the aid of an acoustic calibrator.

6.2. Microphone Setup

In order to align all the microphones along the same line of sight with the loudspeaker, a string was stretched from the front of the loudspeaker to the last step of the theatre. The mic stands were each individually adjusted so that the microphones were 0.67 m above the step floor and 0.70 m away from the forefront of the next step above, the position of a seated person.

The microphone of the orchestra was placed 3.07 m away from the loudspeaker and 1.55 m above the ground. The microphones used were omnidirectional Behringer ECM8000 Measuring Condenser Microphones.

6.3. Post-processing of results

After the measurements were taken the IR was calculated by dividing the Fourier Transform of the measured output signal by the Fourier Transform of the input signal used.

For the extraction of the EA from the IRs measured onsite, the Fourier Transform of the IR measurements were divided by the Free Field (FF) spectrum. The FF spectrum was obtain from the orchestra microphone measurements, which was located 3.07 m away from the acoustic centre of the loudspeaker and used as reference measurement for the direct sound. The direct sound distance was adequate to window out the much longer surrounding reflections, and thus establish the FF source spectrum at 3.07 m.

To obtain the EA of each microphone measurement the frequency response of the measurement in question was divided by the frequency response of the isolated direct path of the reference measurement. The level of the resulting frequency response was adjusted to account for the distance attenuation, L_d given by equation 8 below:

$$L_d = 20\log_{10}\left(\frac{R_2}{R_1}\right) \qquad (8)$$

where R_1 is the length of the reference distance (3.07 m) while R_2 is the length of the direct path between the loudspeaker and the microphone at each location.

7. Results, comparison between measurements and simulations

Below three types of results are given: The IR, EA and speech parameters (determined from measurements only). Please note that the comparison of the results of EA for Step 1 (Figure 4) between measurements and calculations, show the effect of the High Frequency (HF) unit of the loudspeaker when added coherently to the Low Frequency (LF) unit of the cabinet, which is manifested as an increase at 2.5kHz. For all the other calculations, the inclusion of the HF unit in the simulations was not performed due to the very long calculation times needed especially when the theatre was with audience.

The figures below show the measured versus the calculated EA and IR for steps 1 and 13 (closest and furthest respectively, to the source) when the theatre was empty and with audience. These validation graphs are presented to demonstrate that the calculations are very close to the measurements and thus the 3D model can be used to calculate sound distribution in the theatre (see next section) as in a real setting. Also shown are the some EA results in 1/3 oct. bands.

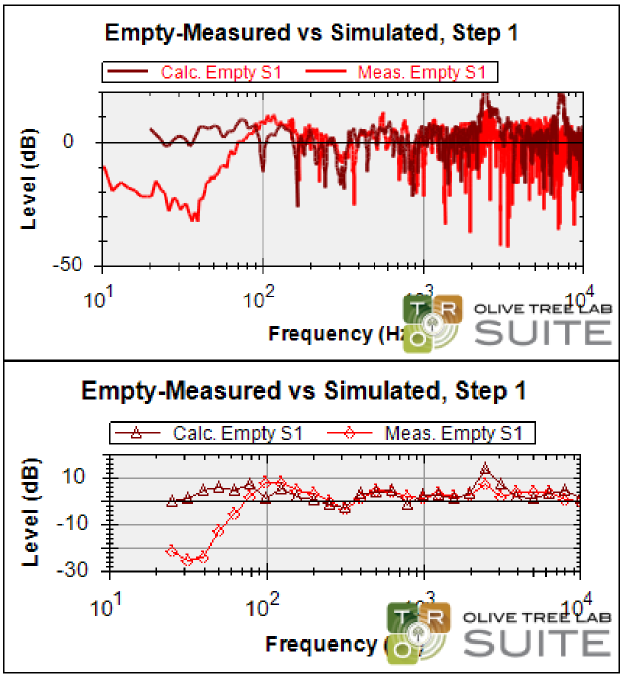

Figure 4. EA of empty theatre, measured vs simulated in high freq. resolution and 1/3 octave at Step 1.

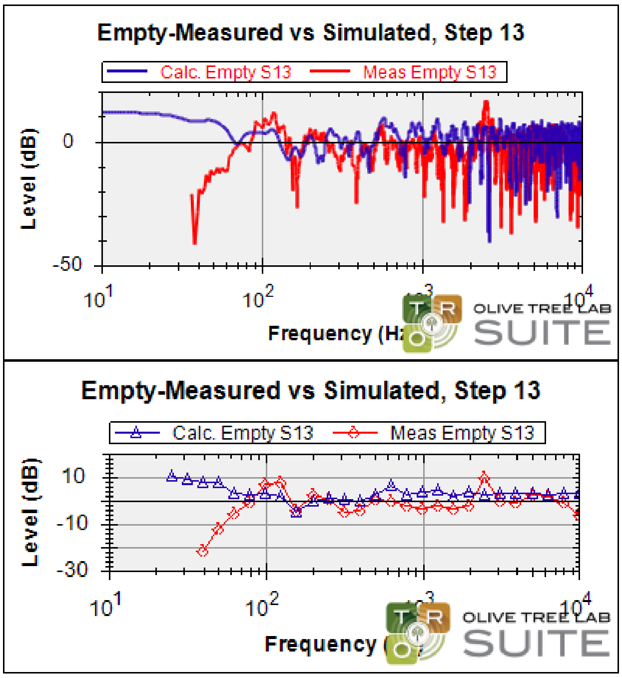

Figure 5. EA of empty theatre, measured vs simulated in high freq. resolution and 1/3 octave at Step 13.

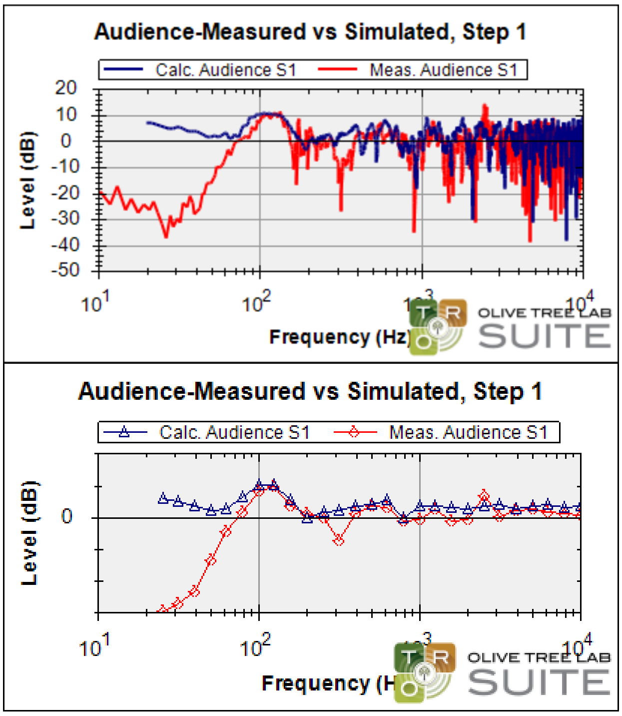

Figure 6. EA of occupied theatre, measured vs simulated in high freq. resolution and 1/3 octave at Step 1.

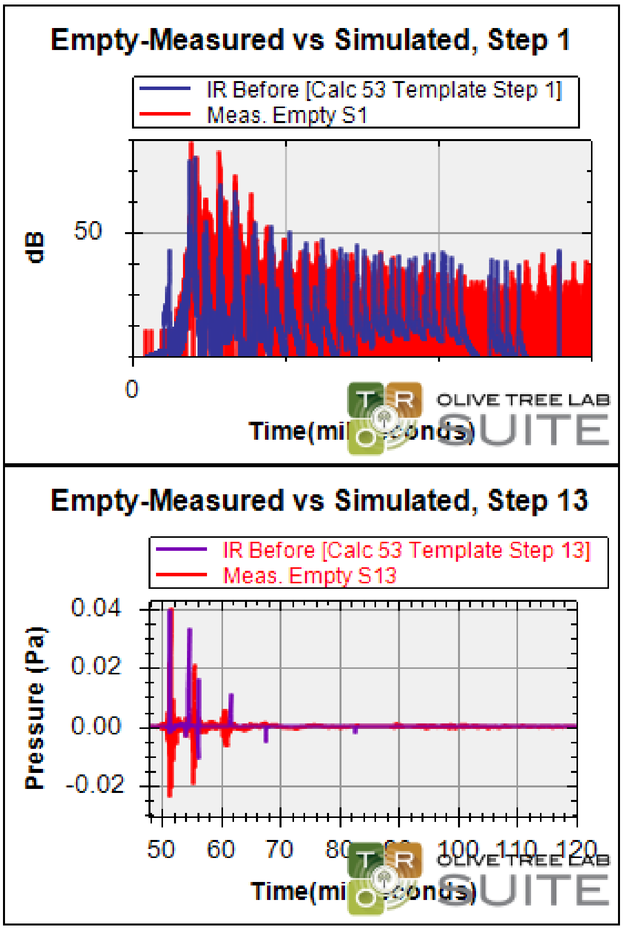

Figure 7. IR of empty theatre, meas. vs sim. at Steps 1 & 13

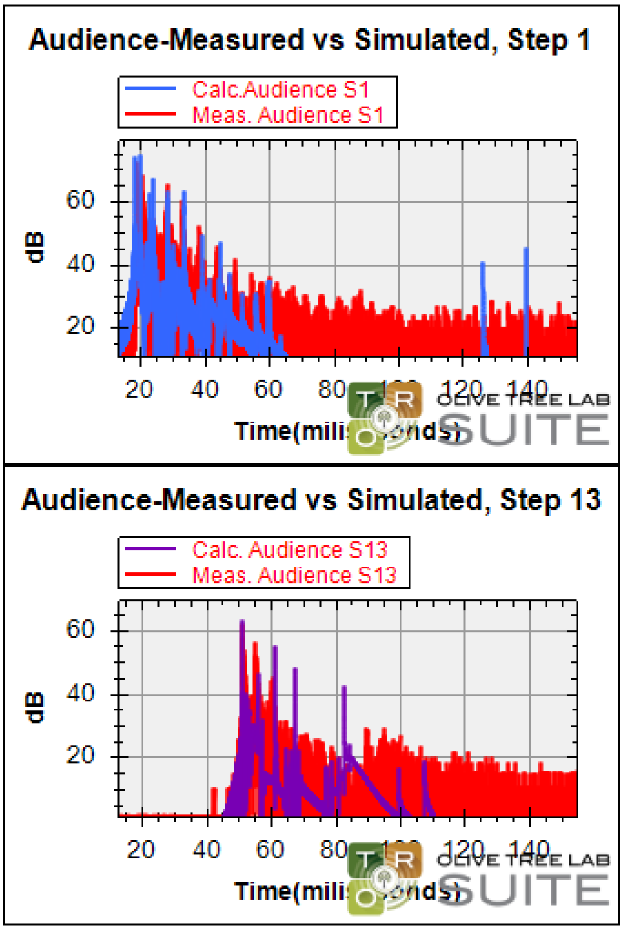

Figure 8. : IR of occupied theatre, meas. vs sim. at Step 1 & 13.

The following figures show the IR for all microphones in envelope Energy Time Curves (ETC) graphs displaying clearly reflections and diffractions from the cavea with and without audience.

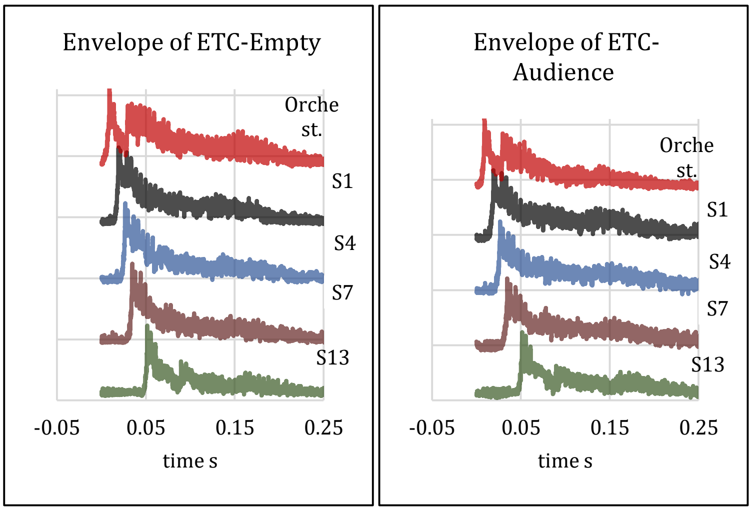

Figure 9. ETC of empty vs occupied theatre.

The following table, show derived speech parameters from sound measurements when the theatre was and empty and with audience.

Broadband	C50 (dB)		D50 (%)	
	EMPTY	AUDIENCE	EMPTY	AUDIENCE
Orchestra	18.4	24.0	98.58	99.6
S1	21.0	25.3	99.2	99.7
S4	21.1	25.4	99.2	99.7
S7	20.5	25.2	99.1	99.7
S13	19.0	20.5	98.8	99.1

Table I. Speech clarity & definition, with and without audience.

8. More results from simulations

The power of acoustical modelling is that once the model is calibrated, one can simulate conditions which cannot be performed in real life, for example, what is the sound field in a theatre without the effect of sound diffractions, i.e., just from reflections. Figure 11 shows plots which may be considered as a type of a cavea sound mapping based on polar plots calculated within the 3D model. A virtual microphone rotates at a height of a sitting person above the edge of each step within the cavea and produces polar plots such as the ones shown in Figure 10 below. The polar plots investigate the following sound field conditions: (a) The field of an empty cavea is made up of just reflections (b) The field of an empty cavea is made up of reflections and diffractions (c) The field of a cavea with audience is made up of reflections and diffractions. All polar plots represent SPL and the direct sound was excluded from the calculations.

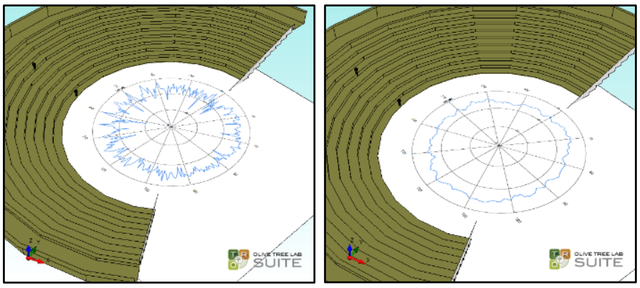

Figure 10. Polar plots of sound distribution at Step 1 in empty theatre. L: reflections & diffractions, R: reflections only.

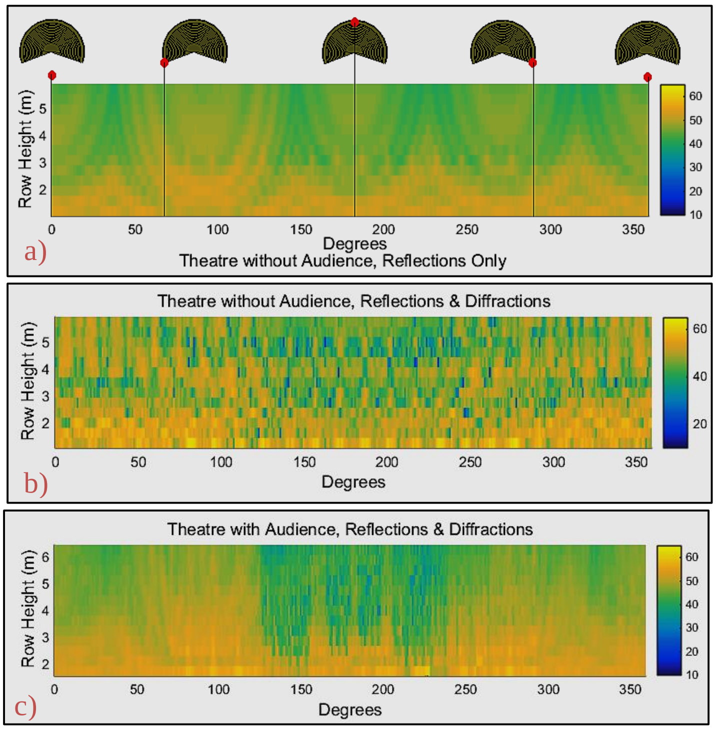

Figure 11. Sound distribution & directivity in cavea. a) reflections only-empty, b) reflections & diffractions – empty, c) reflections & diffractions – occupied

Based on each polar plot, the sound diffusion coefficient is calculated according to ISO 17497-2:2012 [26]. The results for each step for the above sound field conditions are given in Figure 12.

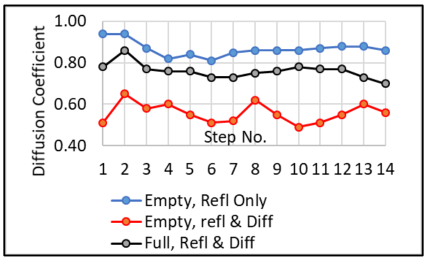

Figure 12. Diffusion coefficient in empty & occupied cavea.

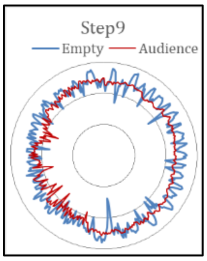

Fig 13. Polar plot at Step 9 with & without audience, reflections & diffractions.

9. DISCUSSION

This paper is mostly concerned with the mechanisms of sound propagation within open air ancient theatres from which some acoustical attributes of the acoustics of these spaces may be deduced. Since ancient theatres cannot have a fully developed diffused field, no attempt is made to derive any parameters whose premise is built on a sound diffused field such as RT, EDT etc.

Since sound measurements cannot cover all possible source-receiver combinations, the open air theatre model was calibrated against sound measurements in order to further investigate sound distribution within the space. The measured EA and IR were used for the calibration of the sound field within the open theatre acoustical model. The orders of reflection, diffraction and reflection between diffractions used, was kept on purpose to a minimum, in order to avoid long calculations especially with audience in the cavea. For example, a calculation with 3 orders of reflection, 2 orders of diffraction and 1 order of reflection between diffractions, for 2 sources (LF & LF speaker units) and 1 receiver with audience in the cavea, was estimated to last 15 days. Therefore, all calculations, with and without audience, were carried out with 1 source, 3 orders of reflection and 1 order of diffraction without reflections in between diffractions.

There are many aspects of the measurements and simulation one could discuss, however, due to limited space the following were reviewed, with and without audience: (a) EA and IR, (b) speech quality, (c) cavea sound distribution linked to directivity. Please note that any conclusions reached here are based on this particular case of how the audience was seated in the theatre. A denser seating arrangement would offer different results and probably additional conclusions.

EA & IR: From the results, it is apparent that the calculated versus the measured results trends match well. Calculations at Step 13, which is the furthest measuring point from the source, demonstrate as expected, more deviations from measurement results since the accuracy of measurements and simulations deteriorate with distance. More elaborate calculation settings already discussed above, could have provided better results both in EA and IR as in reference [1], however time limitations would not allow such calculations. EA and IR in this paper were merely used to validate calculations against measurements.

Speech: From Table I, one may conclude that all measured speech parameters improve with audience, not significantly, but enough to demonstrate that late sound energy decreases with the presence of audience. This is also substantiated from Figure 9 where the envelope of the measured Energy Time Curves (ETC) become smoother with the presence of an audience. This is to be expected since audience absorb and scatter sound (to a certain degree). This is corroborated by Figures 11b and c which show the calculated cavea sound distribution, as discussed below.

Cavea sound distribution and directivity: Figure 11 show cavea sound distribution and intensity favoured in certain directions (directivity). Please note that the direct sound does not participate in the calculations. The imaginary yet informative scenario of Figure 11a of an empty cavea, where the sound field is made up of sound reflections only, from the orchestra (Figure 14 Left) and the back of the step (Figure 14 Right) structures, highlight a periodic sound distribution over the cavea depending on step row height and horizontal angle. Based on this periodicity, at row heights greater than about 3 m, one could even select with some precision particular areas where sound would be louder. Front rows, as expected, have in general higher intensities than back ones due to distance attenuation. At the same time, they have more pronounced interference effects. Overall, and in conjunction with Figure 11a, it is evident that there are no pronounced directivity patterns.

In the case of the empty cavea but calculated with reflections and diffractions, one observes a lot of sound scattering manifested with interference phenomena where intensity changes rapidly, from point to point. One is also able to observe cavea directivity features with more intensity towards the opening of the cavea, between 290 and 70 degrees (the orchestra arc opening). Again it was to be excepted that sound would “flow” from the cavea to the surroundings. This demonstrates that there is sound energy to be “harnessed” by introducing an orchestra supporting structure to return sound back to the cavea. Calculations not shown here, have demonstrated that just a 5 m high vertical wall at the orchestra opening increases the sound pressure level in the cavea by an average of 3 dB.

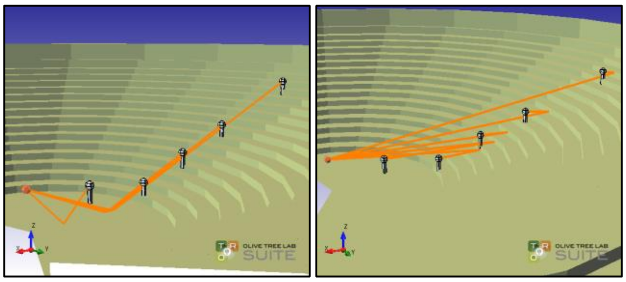

Figure 14. L: reflections from orchestra. R: reflections from steps.

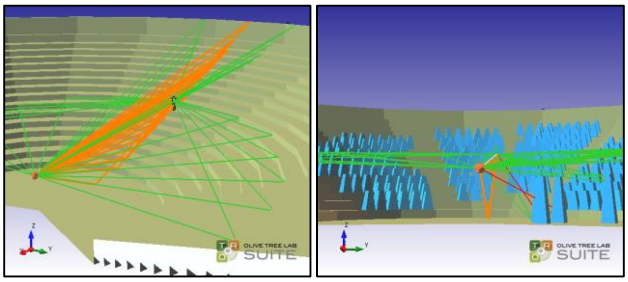

Figure 15. Highlighted reflections & diffractions L: available reflections and diffractions in an empty cavea at Step 7. R: noticeably reduced ref & diff due to the presence of audience.

Finally, the presence of sound absorptive and at the same time sound scattering, audience smooths out the very irregular sound distribution at the steps. Furthermore, as the height of the audience row increases, sound distribution seems to resemble the sound field with just reflections in the cavea (Figure 11a). An explanation in this particular 3D model, may be visualized in Figure 15, where they show that the presence of audience, cut-off sound diffractions from reaching higher or lower audience steps and at the same time provide scattering, (nonetheless less pronounced than the steps), from the bodies of an absorptive audience. Furthermore, reflections from the orchestra reach only front rows. Rows further back from the orchestra have less chances of receiving orchestra floor reflections due to obstructions offered by audience seated in the lower rows. In this particular case where a great part of the cavea was empty, reflections mixed with additional scattering from audience, smooth out the effects of steps diffraction in the unoccupied area of the cavea as Figure 13 shows.

Lastly, any presence of audience, eliminates the reflections from the back of the cavea steps.

10. Conclusions

The work has shown that the presence of audience, indeed assists speech and theatrical performances. This was demonstrated by measurements and simulations. This is due to the mechanisms of sound absorption and diffraction from audience. The presence of audience decreases late sound energy thus increasing speech clarity. Since an audience is sound absorptive, it scatters sound less pronounced than step edges. Still, simulations show that sound diffraction or scattering from an audience, provide for a more even sound distribution within the cavea. Polar Plots indicate that sound level distribution in an empty cavea is susceptible to interference effects and thus not uniform. Furthermore, all calculations show that useful sound energy escapes to the surroundings especially in the direction of the orchestra. This suggests that ancient theatres utilized the proscenium not only for staging effects but also for preserving useful sound energy.

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References

[1] P. Economou, P. Charalambous: The Significance of Sound Diffraction Effects in Simulating Acoustics in Ancient Theatres. ACTA Acustica United with Acustica **99** (2013) 48-57.

[2] R. Shankland: Acoustics of greek theatres. Physics Today **4** (1973) 30-35.

[3] P. E. Mediterranean Acoustics Research & Development Ltd. (SD): Olive Tree Lab-Suite. https://www.mediterraneanacoustics.com/olive-tree-lab-suite.html.

[4] ACTA Acustica United with Acustica **99** (2013).

[5] The Acoustics of Ancient Theatres Conference, Patras, Greece, 2011, http://www.ancientacoustics2011.upatras.gr/.

[6] S. Psarras, P. Hatziantoniou, M. Kountouras, N-A. Tatlas, J. N. Mourjopoulos, D. Skarlatos: Measurements and Analysis of the Epidaurus Ancient Theatre Acoustics, ACTA Acustica United with Acustica **99** (2013) 30-39.

[7] S. Vassilantonopoulos, T. Zakynthinos, P. Hatziantoniou, N-A. Tatlas, D. Skarlatos, J. Mourjopoulos: Measurement and analysis of acoustics of Epidauros theatre (in Greek). Hellenic Institute of Acoustics Conference, Thessaloniki, 2004.

[8] N. F. Declercq, C.S. Dekeyser: Acousticc diffraction effects at the Hellenistic amphitheater of Epidaurus, seat rows responsible for the marvelous acoustics. J. Acoust. Soc. Am 121 (2007) 2011-2022.

[10] N. Prodi, A. Farnetani, R. Pompoli: On the Use of Ancient Theatres for Modern Unamplified Peformances: A Scale Model Approach. ACTA Acustica United with Acustica **99** (2013) 58-63.

[11] T. Lokki, A. Southern, S. Siltanen, L. Savioja: Acoustics of Epidaurus – Studies With Room Acousticcs Modelling Methods. ACTA Acustica United with Acustica **99** (2013) 40-47.

[12] A. Pierce: Acoustics – An introduction to its physical principles and applications. Acoustical Society of America, New York, 1994.

[13] P. Morse, U. Ingard: Theoretical acoustics. Princeton University Press, Princeton, 1986.

[14] J. Keller: Geometrical theory of diffraction. J. Opt. Soc. Amer. **52** (1962) 116-130.

[15] R. R. Torres, P. Svensson, M. Kleiner: Computation of edge diffraction for more accurate room acoustics auralization. J. Acoust. Soc. Am **109** (2001) 600-610.

[16] K. Attenborough, K. M. Li, K. Horoshenkov: Predicting outdoor sound. Taylor and Francis, New York, 2007.

[17] L. Cremer, H. A. Müller: Principles and Applications of Room Acoustics Volume 1. Applied Sciences Publishers, Essex, 1978.

[18] Y. W. Lam: Issues for computer modelling of room acoustics in non-concert hall settings. Acoustical Science and Technology Journal **26** (2005) 145-155.

[19] T. T. F. W. Embleton, J. E. Piercy, G. A. Daigle: Effective flow resistivity of ground surfaces determined by acoustical measurements. J. Acoust. Soc. Am. **74** (1983) 1239-1244.

[20] C. S. Clay, D. Chu, S. Li: Secular reflections of transient pressures from finite width plane facets. J. Acoust. Soc. Am. **94** (1993) 2279-2286.

[21] E. Salomons: Sound propagation in complex outdoor situations with a non-refracting atmosphere: Model based on analytical solutions for diffraction and reflection. ACTA Acustica United with Acustica **83** (1996) 436-454.

[22] ISO 9613-1:1993: Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere.

[23] E. Delany, E. N. Bazley: Acoustical properties of fibrous absorbent materials. Applied Acoustics **3** (1970) 105-116.

[24] J.F. Allard, N. Atalla: Propagation of Sound in Porous Media. Wiley & Sons Ltd, West Sussex, 2009.

[25] A. Farina: Simultaneous of Impulse Response and Distortion with a Swept-Sine Technique. AES Convention, Paris, France, 2000.

[26] ISO 17497-2:2012: Acoustics – Sound-scattering properties of surfaces – Part 2: Measurement of the direction diffusion coefficient in a free field.