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THE SIGNIFICANCE OF SOUND DIFFRACTION EFFECTS IN PREDICTING ACOUSTICS IN ANCIENT THEATRES

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Abstract
This paper examines the effect of sound diffraction in predicting sound propagation in ancient theatres. Few simulation studies to date concerning ancient theatre acoustics were conducted with diffraction effects. While sound diffraction effects in ancient theatres are known qualitatively, rarely have they been quantitatively documented. In this paper, the ancient theatre of Kourion in Cyprus was acoustically modeled and simulated, in a commercially available software application which handles also sound diffraction to high orders. Sound measurements were also taken at the theatre for comparison purposes. All analyses were conducted in the frequency domain. Comparison of results of the variation of sound pressure level with distance and frequency shows that the contribution of sound diffraction is significant. It is proposed that future acoustical simulations of ancient theatres should include sound diffraction effects.

Keywords
Ancient Theatres, Diffraction, Prediction, Software, Propagation

1. Introduction

There is nothing mysterious about the shape and thus the acoustics of ancient theatres. People then had used common sense to make sure that when a performance took place in the orchestra, the audience could see and hear the performers. They had placed the audience at equal distances from the performer; thus, they had created the circular shape of the theatre. They then had raised the seats in order to provide uninhibited view for all. They had also used the necessary minimum step depth to accommodate seating and movement of audience, in order to avoid increasing the distance between the audience and performer. Since sight lines are affected by step depth, a reasonable depth also kept theatre height to a minimum. After having solved the audience seating arrangement, other structures had been added (such as the scene and proscenion) which contributed to the acoustical properties of the theatre. Once the shape of the theatre was finalised, other techniques were used to enhance the acoustical properties of the space [1].

This paper examines, sound diffraction effects at the steps of ancient theatres and how significant these effects are in predicting their acoustical properties. In order to examine the significance of such effects, sound measurements were taken at the ancient theatre of Kourion in Cyprus which were then compared to simulations by modelling Kourion in a commercially available software application which also handles sound diffraction to high orders.

Kourion was first built during the Hellenistic era, in the 2nd century B.C. It later took on the form of a Roman theatre. The theatre is well preserved today, and is used as a venue for music and theatre performances. Since the theatre does not have a scene construction, spectators have an open view overlooking the sea below.

Sound measurements at Kourion were the apex of a series of preparatory work since the place is a monument, and the effort was to secure valid measurements during one visit only. The Kourion measurements scenario was "rehearsed" at a recently built open theatre in the fashion of ancient Greek theatres. In order to validate both hardware and software to be used in the final Kourion measurements, sound measurements were taken inside a hemi-anechoic chamber prior to the Kourion measurements. Description of the preparatory work done may be found at http://research.mediterraneanacoustics.com/1.aspx.

2. Previous Work

Ancient Greek Theatres are well known for their acoustical properties [2]. Past studies explain that exceptional acoustics of ancient theaters are entirely due to their geometrical shape. Their shape allows a full line of sight from all places for the audience in the scene, perfect transmission of sound and a reduced absorption of the audience. There are also significant contributions due to early reflections and sound diffusion [3]. There are several attempts to simulate this acoustic behaviour and analyse the reasons of excellent acoustic performance of theaters [4, 5]. However, none of them analyses the significance of diffraction in the acoustics of theatres. On the other hand, there are attempts to explain diffraction effects in ancient theatres which use simulation techniques without comparing results to measurements, and which conclude that diffraction effects change the acoustic properties of theatres [6]. The combination of calculating diffraction effects with the use of an acoustics simulation software and on site sound measurements will assist in a deeper understanding of diffraction effects in ancient theatres.

Diffraction in an ancient theatre is a case of multiple diffractions over multiple edges. Extensive research has been conducted over the last decades, and there exists a solid mathematical background for the calculation of the diffraction effect over multiple edges [7-11]. In this paper, Olive Tree Lab – Terrain was used for the simulation and calculation of diffraction effects. OTL – Terrain implements a sound propagation model based on the above work and its accuracy was validated based on further scientific findings [12, 13] and hemi-anechoic chamber measurements mentioned in this paper.

3. Definitions

Sound diffraction is commonly understood as the bending of sound around objects (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 [14- 16]. Therefore, the term "diffraction effects" used in this paper, denotes the scattering of sound both in the illuminated and shadow zones of an obstacle.

Excess Attenuation (EA) is the spectrum of the ratio of the total sound level at a receiver to the direct sound that would be present in the absence of an object(s) or environment [17]. One may think of it as the transfer function of the environment between the source and the receiver, how the environment alters direct sound.

4. Ray Equivalency Theorem by Panagiotis Charalampous

4.1 Theorem

Assuming a circular curve C with central angle $< \pi$, a line L crossing the plane of C perpendicularly at the center of C, a point P on L and a point O not on L, there is only one diffraction ray connecting C, P and O, crossing C at point F. This ray is equal to the diffraction ray connecting the tangent at F, P and O (Figure 1).

4.2 Axioms

(1) Each diffraction ray is the shortest ray connecting a source, an edge and a receiver.
(2) Angle of incidence of a diffracted ray on an edge is equal to the angle of diffraction.
(3) The angle of incidence of any radius on the perimeter of a circle is 90^o.
(4) Assuming a circular curve C with central angle $<\pi$, a line L crossing the plane of C perpendicularly at the center of C, for any point P that is not on L there is only one tangent T on C where the angle between P, the projection of P on T (PP) and any point on T not equal to PP is equal to 90^o.

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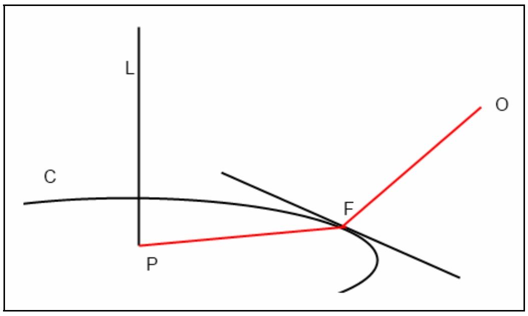

Figure 1 – Ray Equivalency theorem

The above is a ray acoustics theorem which is the result of P. Charalampous' work on this paper. It has an application in circular open theatres provided there are no structures (scene, proscenion, and others) which could introduce sound reflections and diffractions, other than from the cavea. It is applied by extruding a cavea section into a three-dimensional space. In ray acoustics this model is equivalent to the actual semi-circular model (Figure 3).

5. Geometry

Modelling Kourion theatre was a crucial part of the acoustical simulation process as the accuracy of the geometrical model determines the accuracy of the results. There are limitations to the accuracy of the model since, as the picture shows below, surfaces modelled as smooth are in reality highly uneven due to erosion (Figure 2).

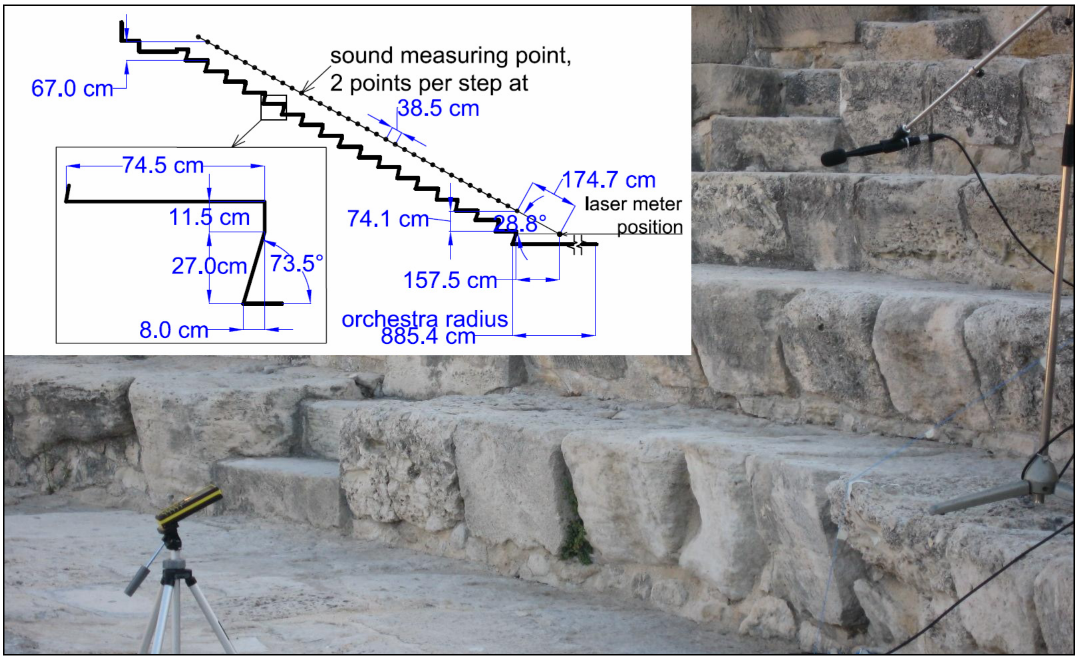

Figure 2 – Drawing of a section of the cavea over which sound measurements were taken. The picture shows the 1st step microphone position and the erosion of the theatre structure.

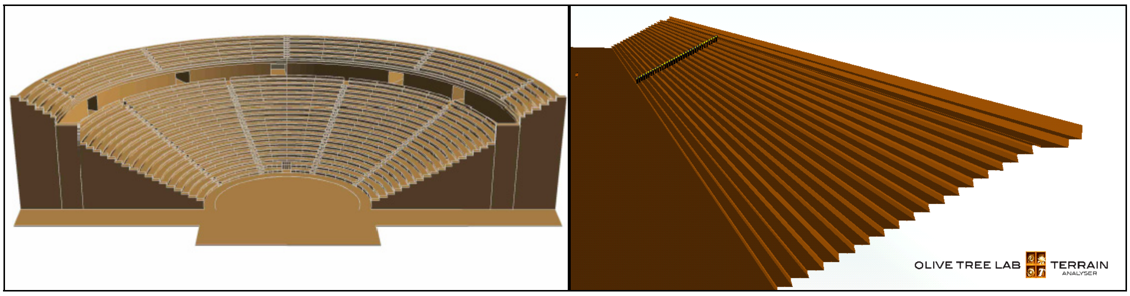

Figure 3 – On the left a model of Kourion (as it was originally built) and on the right, the equivalent model used in the simulations.

5.1 Description of modelling spaces under study

The following describes the methodology followed in geometrically modelling Kourion and the open theatre of The Heritage School in Limassol, where preparatory sound measurements were also taken before the final measurements at Kourion.

A section of the cavea was used for the acoustical simulations, which was documented as follows. Firstly, the exact centre of the orchestra was defined and then its radius was measured. The cavea is divided by columns of smaller steps for audience movement up and down the theatre. Sound measurements eventually were taken at the centre line between two steps-columns at a height where an audience would be seated. Using a laser distance metre (for Kourion and a tape measure for the Heritage), the section of the theatre was created by measuring the dimensions and inclination of each audience step at the centre line of the audience area under study (Figure 4).

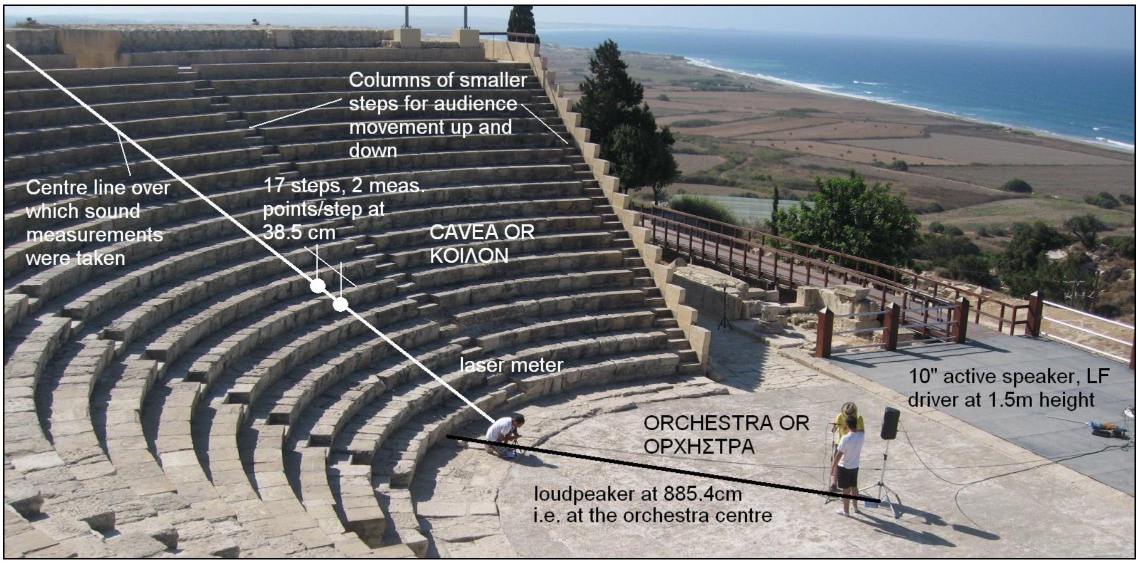

Figure 4 – A photograph of Kourion during sound measurements. Information on sound measurements and geometrical modelling is also given in the photograph.

Once the section was constructed and based on the ray equivalency theorem above, a three-dimensional model was created by the extrusion of the section. Mathematically this model is equivalent to the actual semi-circular model (Figure 3).

6. Measurements

Due to limited time availability of the Kourion Theatre, sound measurements were taken at two additional spaces in order to ensure that during the final Kourion measurements a solid measurements protocol would be established, especially with regards to the location of the microphone within the cavea. Additional measurements were taken to (a) validate OTL – Terrain and to discover the “signature” of diffraction from a step-like structure (b) validate the proposed ray equivalency theorem above and (c) decide the type of source to be used for the Kourion measurements.

6.1 OTL – Terrain validation

To validate the accuracy of Olive Tree Lab – Terrain, sound measurements were taken at the Cyprus University of Technology hemi-anechoic chamber. Furthermore, in anticipation of a complex sound transfer function from sound measurements at Kourion, the hemi-anechoic measurements were used to discover the “signature” of diffraction from a step-like structure. (For more information please see http://research.mediterraneanacoustics.com/2.aspx).

6.2 The Heritage School Theatre, Measurements, Results, Ray Equivalency theorem

The next step was to establish a protocol of measurements to be choreographed at Kourion, to determine whether the source would be suitable for the measurements at Kourion and to provide evidence that the ray equivalency theorem applies.

Theatre geometry was established as described in Paragraph 5.1. Sound measurements were taken at three step heights (1st, 7th and 13th out of total of 13) at two cavea positions, i.e., on two different rays over the cavea from the centre of the orchestra, as seen in figure 5, to offer evidence for the ray equivalency theorem proposed above (Paragraph 4). The source used was a two way 10” active constant directivity speaker unit (70 Hz to 18 kHz of unknown cross-over frequency). With the use of an acoustic measurement software application [18], the driver was fed with a sine sweep sound within the frequency range of 50 Hz to 20 kHz.

The Heritage School Theatre measurements resulted in finalising a measurement protocol. The 10” speaker of the two way speaker unit was meant to be used as an omnidirectional source, up to 1500 Hz. However, measurement and calculation results show that this limit could be a lot higher with the contribution of the horn driver. This claim cannot be substantiated since there are no directivity data on the speaker unit. Measurement results have also shown that the 10” speaker suffered from diffraction effects from its cabinet. In order to further examine this in more detail, additional measurements were conducted elsewhere to be used subsequently to minimise as much as possible this effect in the Kourion measurements, by time windowing or other methods. This, however, was not possible; therefore, Kourion results are contaminated with the loudspeaker cabinet sound diffraction contribution. The additional measurements resulted also in a reference curve which was subsequently used to remove the spectrum bias of the speaker from the measurements.

Furthermore, the Heritage School Theatre experience has shown that the use of a measuring tape to measure distances, especially to locate the position of the microphone in the cavea was not accurate enough, therefore, the use of a laser distance meter was eventually employed for the Kourion measurements.

Lastly, sound measurements results on two cavea rays offer evidence for the ray equivalency theorem (Figure 5).

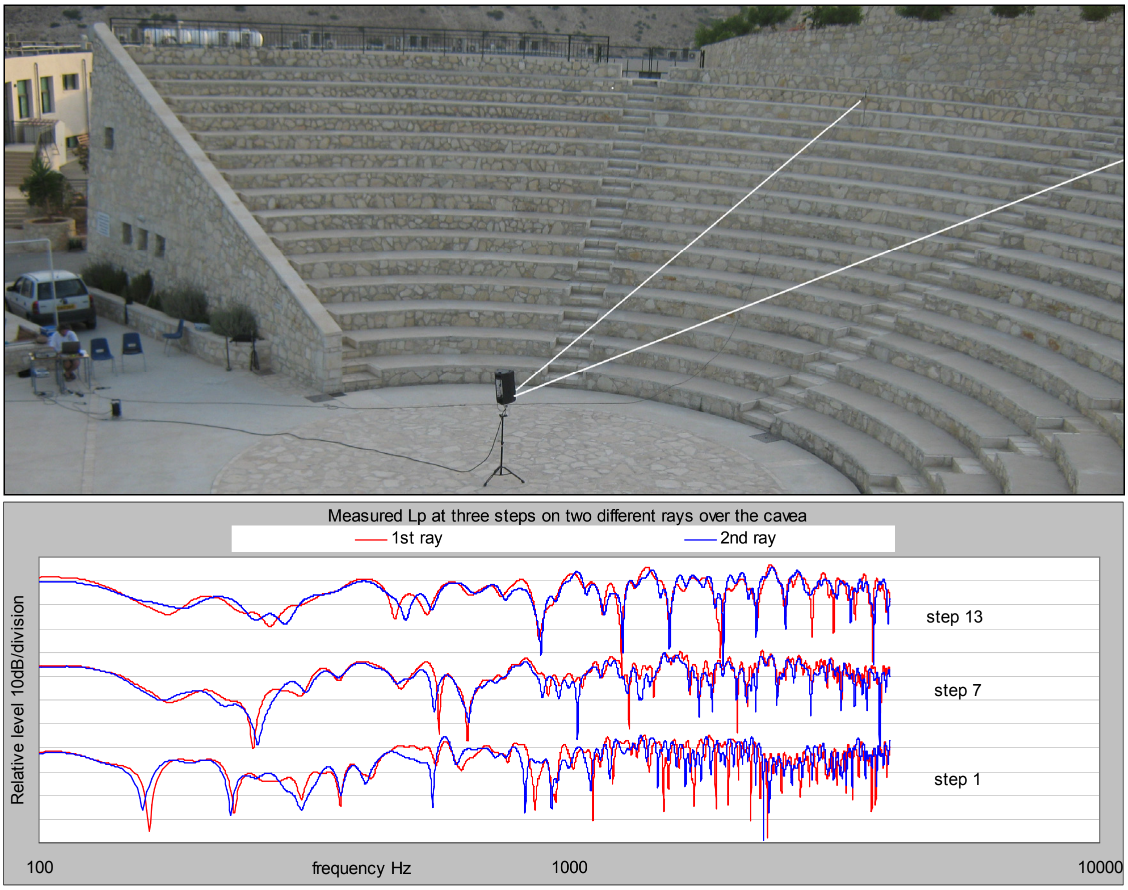

Figure 5 – The two cavea rays over which sound measurements were taken at The Heritage School Theatre on steps 1 (S-R dist. 6.311m), 7 (S-R dist. 11.845m) and 13 (out of 13, S-R dist. 17.583m) to provide evidence for applying the ray equivalency theorem proposed above (Paragraph 4). Sound measurement results are also shown.

6.3 Kourion

Kourion being a monument receives a lot of visitors throughout the day and one needs a permit by the Department of Antiquities in order to carry out any work there. Faced with these facts and in order to secure minimum meteorological effects (which were monitored with a portable weather station) [19], measurements took place between 6.30 am and 9.00 am.

Before visiting Kourion, the microphone positions for each measurement were established using a detailed section of the theatre. A laser meter was used to position the microphone in the orchestra with its beam at the centre line, as shown in figure 4, corresponding to a height of a seated person (75 cm above each step). Its beam was used to position the microphone at intervals of 38.5 cm, corresponding to approximately two measuring points on each step at heights which varied (step dimensions are irregular) between 70 and 103 cm above the steps. Each microphone position height was then measured from the level of the corresponding step.

7. Acoustic simulations in commercial software

7.1 Olive Tree Lab – Terrain

OTL – Terrain is a sound prediction software application which simulates and predicts outdoor sound propagation in the frequency domain to a resolution down to 1 Hz. It takes into account geometrical spreading, atmospheric absorption, and atmospheric turbulence. What makes OTL – Terrain unique is that it does away with sound absorption coefficient and deals instead with spherical wave reflection coefficient and complex ground and object impedance. It also predicts reflection from objects based on Fresnel zones. Lastly and most importantly it applies ray acoustics concepts to calculate scattering of sound, including in shadow zones, of what is usually coined as diffraction of sound. Currently, all sources in OTL – Terrain are considered to be point omnidirectional sources [20].

8. Results, comparison between measurements and simulations

The results of Kourion measurements are shown below in terms of Excess Attenuation (EA) versus frequency and EA versus distance. Excess Attenuation was used in the presentation of results since sound pressure levels are biased by sound source and microphone response. For EA analysis the sound measurements were corrected for distance attenuation. In all simulations, 2nd order reflections were used, the maximum order detected by OTL – Terrain for all 35 receivers and a 2nd order sound diffraction. The analysis was carried out in 1 Hz resolution between 50 and 10000 Hz. A third party commercial software was used with the semicircular geometry as a model to verify that only 2nd order reflections are possible in the theatre.

8.1 EA vs Frequency – results of measurements and simulations with and without 2nd order diffraction effects.

Figure 6 shows in graphical form the Excess Attenuation results extracted from the Kourion measurements, as well as the simulation results, with and without diffraction. They help demonstrate the effects of including sound diffraction simulations. Due to limited space, results are presented in one graph in relative levels and shifted in level for presentation purposes. The results refer to the 7th step from the orchestra (S - R distance, 13.234 m).

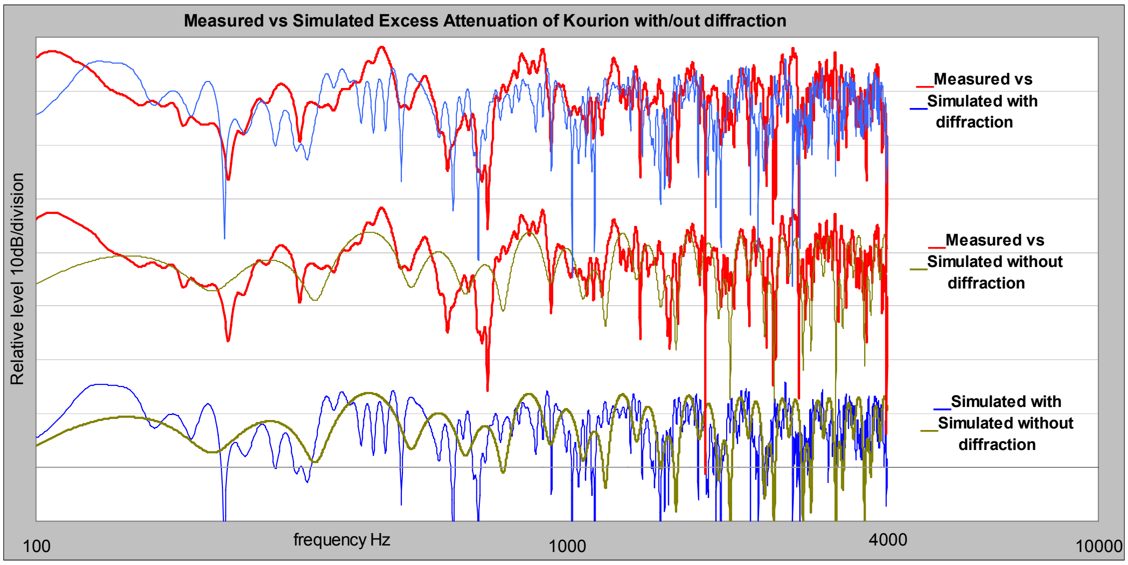

Figure 6 – EA results extracted from Kourion measurements, compared to simulation results, with and without diffraction, in relative levels.

8.2 EA vs Frequency - results of measurements and simulations with 2nd order diffraction effects, at three steps.

Figure 7 shows in terms of EA the results from sound measurements and simulations with 2nd order diffraction at three steps. The 3rd (close to the orchestra), 7th and 14th step out of total of 17 steps at Kourion. Source - Receiver distances are 10.043 m, 13.234 m and 18.405 m respectively. For presentation purposes, the curves are shifted in level, while the Y-axis represents relative levels. Sound measurements were corrected for distance attenuation. The frequency axis is linear to show differences more clearly.

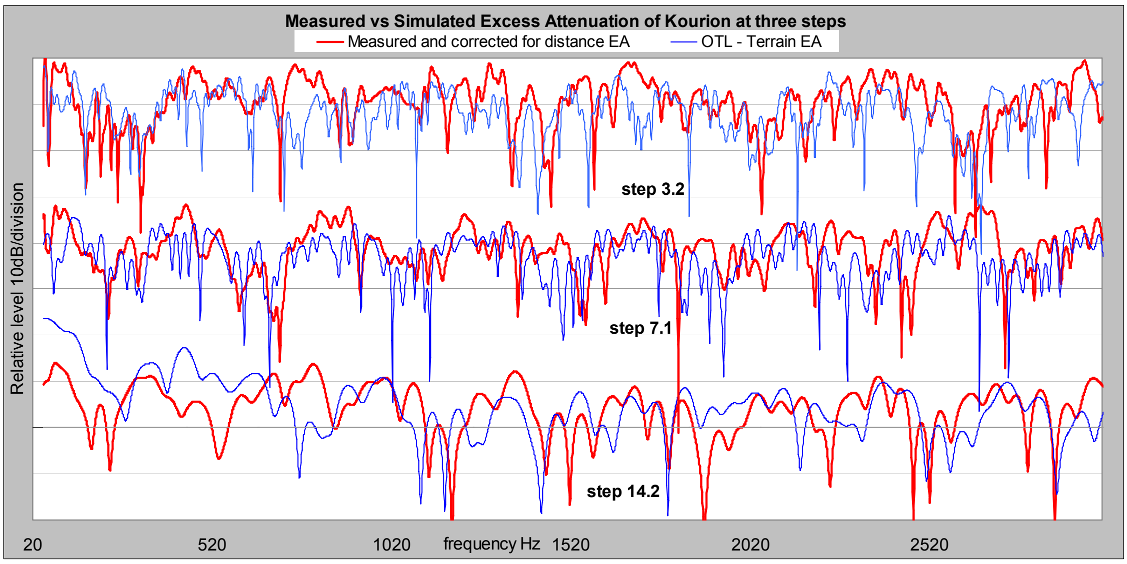

Figure 7 – Sound measurements and simulation results with 2nd order diffraction at three Kourion steps, 3rd, 7th, 14th, out of total of 17.

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8.3 EA vs Distance

To visualise how sound is filtered as it propagates over the cavea, Excess Attenuation is plotted against distance (at intervals of 38.5 cm) in 1/3rd octave bands. Figure 8 shows EA extracted from measurements and simulation results with and without diffraction. Again, for presentation purposes the curves are shifted in level, while the Y-axis represents receivers' distances from the source as they are located on a section of the cavea.

Figure 8 – EA against distance (at intervals of 38.5 cm) in 1/3rd octave bands. Sound measurements versus simulation results with and without diffraction.

Figure 9 shows the above Excess Attenuation results versus distance and frequency: Left measured, middle simulated with diffraction, right simulated without diffraction. Arrows show increase in frequency and distance values.

In addition, figure 10 shows the total relative sound pressure level (in 1/3rd oct. bands) versus distance plotted on a logarithmic axis. Also shown in dashed lines, are the theoretical distance attenuation trends of arbitrary values for comparison purposes.

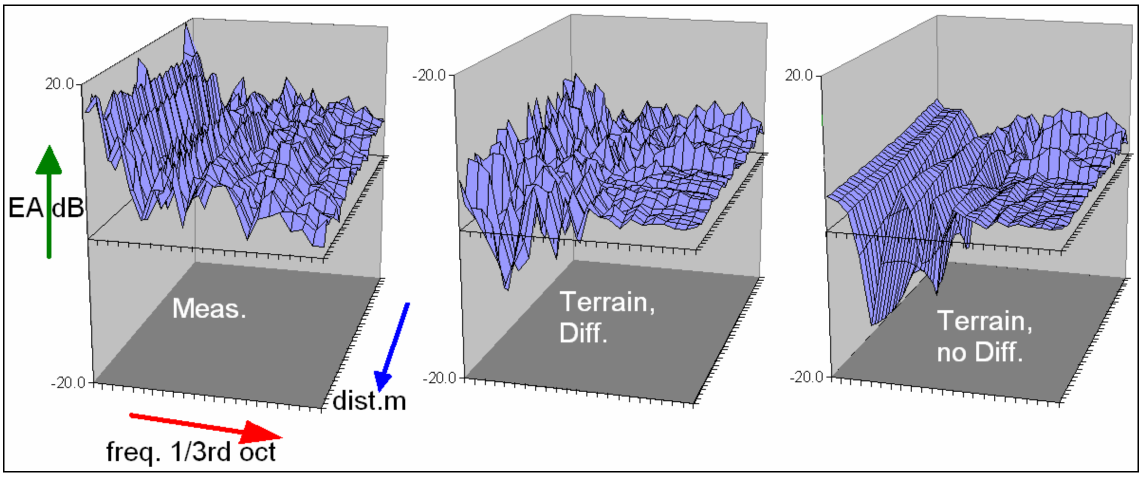

Figure 9 – Excess Attenuation results versus distance and frequency (in 1/3rd oct. bands). Left - measured, middle - simulated with diffraction, right - simulated without diffraction.

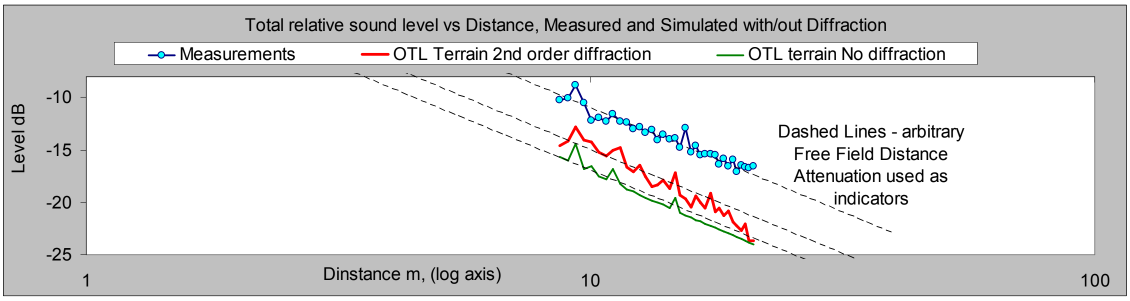

Figure 10 – Total relative sound pressure level (in 1/3rd oct. bands) versus distance (log axis). Blue curve with points - measured, heavy red curve - simulated with diffraction, green curve - simulated without diffraction.

9. Discussion

The objective of this paper has proven to be challenging in many ways. Many factors had to be considered, such as what type of noise source to use, the accuracy of modelling a real structure, the accuracy of sound measurements in relation to simulations, and to what degree could meteorological conditions affect sound measurement results. Unknown factors also have made the comparison of measurements with predictions daring, especially with regards to high resolution frequency analysis. Overall, this paper experience has demonstrated how various factors may have unpredictable effects on final results.

A great deal of effort had gone into establishing beforehand the parameters which would eventually affect sound measurements and simulations results. The directivity of the source turned out not to be as important as initially thought. A source factor which was not anticipated and yet had contaminated sound measurements results was diffraction from the loudspeaker unit cabinet. This factor effectively turned one sound source into many sources introducing interference effects in the transfer function response by distorting the results (see more information on this at http://research.mediterraneanacoustics.com/3.aspx).

Meteorological conditions (atmospheric turbulence) have also proven not to be a major factor. Although OTL – Terrain calculates atmospheric turbulence, simulations have shown that even a very mild turbulence effect dampened high frequencies more than the sound measurements have shown. In the end calculations were carried out without atmospheric turbulence.

Erosion also turned out not to be as effective as was initially thought. Measurements taken and simulations of the first steps of the theatre, made out of the original stones which are heavily eroded, showed the best results.

The most crucial factor, to which all results are very sensitive to, is the geometrical relationship between structures, sources and receivers. This was established early on during the preparatory work, which is why a lot of detailed modelling was introduced (see individually each step where measurements were taken http://research.mediterraneanacoustics.com/4.aspx). Bottom curves of figure 7, the step furthest from the orchestra, show the least matching results between measurements and simulations.

Figure 11 shows the effect of shifting the source laterally off orchestra centre by 10 cm in the OTL – Terrain model. Shifts in line with the receiver are not as sensitive as lateral shifts. This is because at long distances diffraction is more sensitive to left – right shifts rather than shifts towards or away from the receiver, since it is a function of angles at the diffracting edge. Lateral angles seem to be affected more than angles in the vertical plane of the edge. The graph (at the first step of The Heritage School Theatre) is an indicator of how things could vary if a positioning error is introduced.

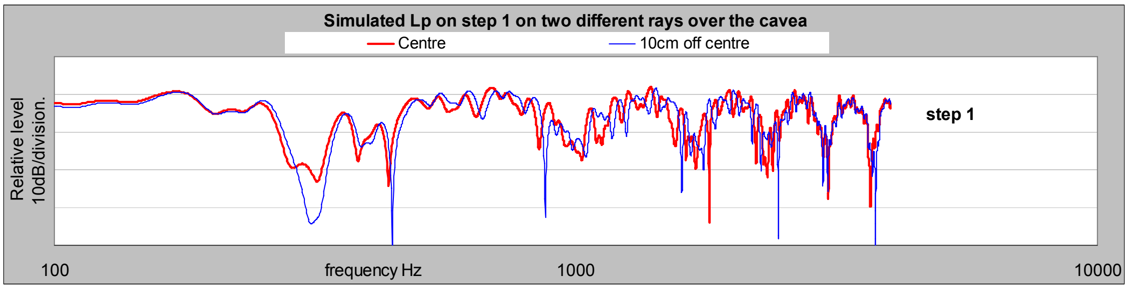

Figure 11 – Frequency response change due to a lateral shift of the source by 10 cm off the orchestra centre, simulated.

Bearing the above in mind, the results of the simulations are in good agreement with sound measurements. As mentioned previously, Excess Attenuation was used in the presentation of results since sound pressure levels are biased by sound source and microphone response.

With regards to how important diffraction effects are in ancient theatre simulations, this paper shows that they are vital. They provide the finer structure of the response of the theatre. Theatre response without diffraction, gives a rougher response structure which indicates areas where reflections are important, it omits details especially in the low frequencies and ignores interference effects due to diffraction. Furthermore, without diffraction, sound level contributions from the theatre structures are underestimated. Simulations of open spaces without diffraction, assume that energy is concentrated in the route of a particular ray, while with diffraction or scattering, a ray which eventually would be lost to the environment offers part of its energy to the theatre before vanishing. In effect, sound diffraction, provides a more diffused field and most probably yield reverberation times one would not anticipate in achieving in open spaces. Such a claim cannot be substantiated unless all analyses are conducted in high frequency resolution.

10. Conclusion

There is a definite and solid conclusion which can easily be drawn from the above: Sound predictions and simulations could come close to real life sound fields provided they include sound diffraction effects. Simulations with sound diffraction in high frequency resolution analysis provide the finer structure of sound fields; provide the missing details from calculations without diffraction effects; unveil the structure of diffused sound field; and provide the inevitable increase in sound level as a result of more sound contribution in the initial part of the time envelope. It is known that for engineering purposes 1/3rd or 1/1 octave bands might be adequate, however, for sound analysis purposes, a high resolution analysis is compulsory. The study of open spaces such as ancient theatres by the method of simulation, is much more demanding than closed spaces since acoustical effects are more evident due to the non returning waves escaping into the environment, i.e., they do not linger on and cover up details in the response of sound fields. Sound diffraction enhances sound diffusion and has a greater effect on low rather than high frequencies.

This paper is limited in examining the acoustical properties of ancient theatres without audience. The acoustical properties of ancient theatres with audience, including diffraction effects, could be the subject matter of future work. It remains to be seen to what degree diffraction effects in a theatre with audience alter its sound field. Any additional work should also be carried out in the time domain as well since certain psychoacoustical phenomena and criteria, may be refined or redefined based on parametric studies using simulations with sound diffraction.

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