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INVESTIGATION OF THE ACOUSTICS OF THE ANCIENT THEATRE OF EPIDAURUS

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1. Introduction

The ancient theatre of Epidaurus is one of the finest open air theatres in the world, in terms of acoustic and architectural qualities. Various aspects of its design, materials' and geometric features have been scientifically investigated aiming at understanding the role of each in the acoustics of this theatre. As far as acoustic parameters are concerned past and more recent studies have focused on measuring several of them in the field without taking into account the special characteristics of an ancient drama performance namely the actors' positions and orientations on stage, the unique role of the chorus and the voice level fluctuation. In addition it is known that ancient drama was based on speech and that intelligibility is an important parameter for the assessment of ancient theatre acoustics. Given the above, measurements of the parameter STI and of the associated clarity index (C80, dB), as well as measurements of the RT(sec) and EDT(sec) have been performed on the simulated acoustic field of the constructed 3d model of the Epidaurus theatre and in the field. Estimated values of the reverberation time in the case of full theatre, were also carried out with EASE software. The results from comparison between the actual and the computer simulated acoustic field, lead us to various conclusions which concern the architectural design of the theatre and its features as well as the role of the actors' locations and orientation on stage.

2. Literature review

2.1 Available studies on the Epidaurus theatre

The acoustics of ancient Greek theatres has always been a subject of high scientific interest. Epidaurus theatre is located in a quite hilled site in Peloponesos which is free from the common noisy obstructions of an urban environment. However it seems that this theatre has succeeded in attenuating not only the residual sounds of noisy audiences and the unwanted effects of low frequency sounds, but also the drawbacks associated with the maximum distance of 70m between stage front and most remote seats.

The already completed studies on Epidaurus theatre [26, 6, 5, 21, 25, 9, 8] cast some light on the important design features that play a major role to this theatre's acoustics.
First of all Vitruvius' study of the acoustics of Greek theatres has lead to the formulation of design guidelines for the audience area. The latter clearly demonstrates the important role of the seating space on the overall acoustics. The intrinsic acoustic qualities of any site, were also considered to be of great significance for the acoustic quality of an open air theatre [1]. Following this line of thought, Cremer L. [7] proved the positive impact of the reflected sound from the orchestra floor, by arguing that raising the stage (3-3.6m in the cases of Priene and Epidaurus theatres, 1-1,2m in the case of the Theatre of Dionysus), is actually worsening the acoustics. Shankland [21] by measuring word articulation in the Epidaurus theatre, among other Greek theatres, has provided evidence of the very good intelligibility (72%) at the back of the theatre on the axis of its symmetry. More recent studies of the ancient theatre of Epidaurus carried out field measurements of acoustic parameters and offered a qualitative analysis of the most important architectural features that influence the acoustic quality [8, 9, 10, 25]. By comparing the results with field measurements in other ancient Greek as well as Roman theatres, the aforementioned studies, provided insight on the qualitative impact of architectural features on the acoustics of ancient theatres.

2.2 Acoustic measurements

2.2.1 Acoustic field simulation

There is extensive literature on mathematical models for the estimation of parameters' values and an increased scientific interest on the subject of prediction methods of acoustic parameters' values in open air theatres. A recent study [15] has proved and justified that detailed 3d models, in the case of open-air theaters, are in high accordance with measured data than simplified 3d models.
On what concerns the available software, there is a number of programs like ODEON, EASE, CATT, RAMSETTE with which predictions of room acoustic parameters' values can be made for different constructions of a building's elements. The user can easily alter any of the finishing surfaces or construction of an element (wall, floor, ceiling) in a space, and calculate the intended acoustic parameter.
As far as EASE is concerned, it is an acoustic simulation software designed for the Windows operating system that provides sound system designers a useful tool for the prediction of the performance of a sound system in a given venue[27]. In the latest version, custom Speaker DLLs (Dynamic Link Libraries) allow designers to use proprietary information in order to simulate proprietary line arrays without the manufacturer having to release proprietary control information to the public. Thus engineers are free to change the parameters of those speakers for aim, distance and frequency, just like in real life. Finally with the new version it is possible to compute the Direct SPL (Sound Pressure Level) field for any speaker model or speaker DLL [28].

2.2.2 Field measurements

Extensive research since the 1900 has identified the parameters that are considered to play a vital role to the control of the acoustic performance of a space [3]. Eight studies sum up the early scientific research on the objective measures of acoustics (Sabine (1900), 2, 24, 3, 22, 14, 11, 19, 6].

All the above mentioned studies share the notion that the control of five objective measures is most important for the design of places for speech, namely the clarity index (C80, dB), the Early Decay Time (EDT, sec), the early lateral fraction (L_f), the reverberation time (RT, sec) and the STI (Sound Transmission Index). STI was introduced by Tammo Houtgast and Herman Steeneken in 1971 [12], and is implemented as a measure of the ability of a transmission channel to carry out the characteristics of speech regardless of the spoken language. In other words it predicts the likelihood of syllables, words and sentences being comprehended.

3. Aims of study

The current study aims at providing new insight on the importance of the actors' various locations and orientations on stage, on what concerns the overall acoustics of the Epidaurus theatre. The results from the on site measurements and from those conducted on the electronic model, are expected to offer insight on the interpretation of this theatre's optimum acoustics. This study takes into account all aspects of the ancient drama performances.

4. Methodology

4.1 Acoustic field simulation

First of all existing architectural drawings of the ancient theatre of Epidaurus along with restoration drawings and photos of the remnants, provided us with all necessary information about the geometry and dimensions of the theatre. Based on the above, an electronic model for the Epidaurus ancient theatre was built using AUTOCAD. The three-dimensional model was exported as .dxf file and imported into EASE after the necessary alterations were made to it according to the requirements of the program. In order to perform the simulation, the positions of the sound sources were defined as shown on table 1. The actors were simulated by loudspeakers with the appropriate directivity and response curve (Tab. 2) and the audience defined in the model reproduces the noise effect of 25-30 whispering spectators. It is believed that if the audience noise becomes greater, intelligibility deteriorates rapidly, especially for the more remote seats or those behind the actor. An extensive series of reflections were obtained in order to obtain the impulse response and subsequently to estimate all parameters' values.

Table 1- Positions and types of sound sources

Source	Speaker Model	x [m]	y [m]	z [m]	Horizontal [°]	Vertical [°]
S1	MAN LOUD	0	0	1.7	180	16
S2	MAN LOUD	0	-6.75	1.7	180	16
S3	MAN LOUD	0	-17	4.5	180	16
S4	MAN LOUD	-4	0	1.7	90	16
S5	MAN LOUD	-4	-6.75	1.7	90	16
S6	MAN LOUD	-4	-17	4.5	90	16
S7	MAN LOUD	-18	-12	1.7	90	16
S8	MAN NORM	0	47.4	18.5	0	-10
S9	MAN RAISED	0	10	1.7	180	20

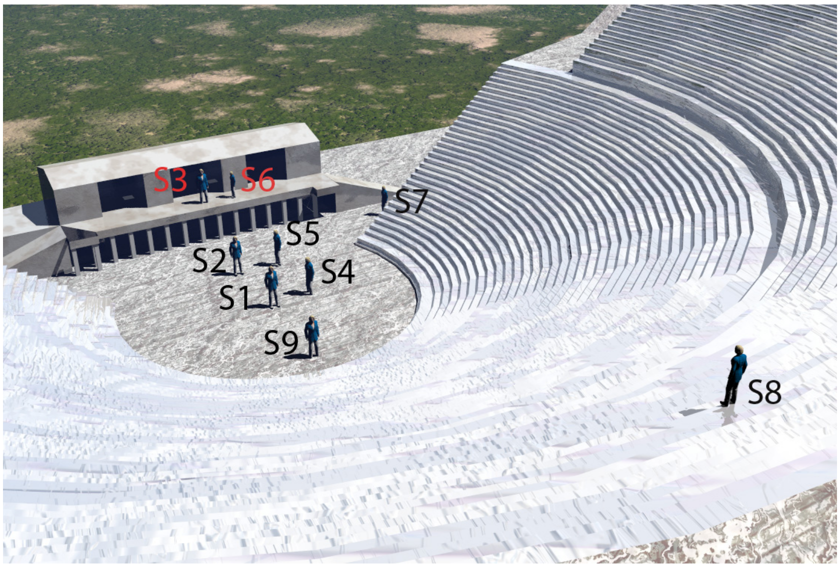


Image 1- Positions of sound sources on the theatre model

Table 2- Sound Pressure Levels in dB at 1 m distance from the source

	Hz	Male loud voice	Male normal voice	Male raised voice
Standard Frequencies (Hz)	100	57	49	51
	125	57	49	51
	160	59.67	51	49
	200	62.33	53	51
	250	65	55	56
	315	67.33	56	55
	400	69.67	57	58
	500	72	58	60
	630	71.67	55.67	58
	800	71.53	53.33	53
	1000	71	51	54
	1250	69.67	49.67	53
	1600	68.33	48.33	51
	2000	67	47	47
	2500	64.67	45.67	47
	3150	62.33	44.33	43
	4000	60	43	44
	5000	57	41.33	40
	6300	54	39.67	41
	8000	51	38	38

4.2 Field measurements of physical acoustic parameters

For the on site measurements of physical parameters (reverberation time(Sec), EDT(sec), Clarity Index (C50, C70, dB) the nine source positions (Image 1) that were utilised for the acoustic simulation were preserved. Then for each position values of each parameter were obtained in 30 different locations at the audience area as it is demonstrated in images 2, 3. Gun firing and loudspeakers were the selected sound sources for the theatre excitation. At a next stage, the obtained recorded signals were analyzed in order to compare them with the results from the simulation of the 3d model in EASE. The necessary equipment for the completion of the measurements comprised of JBL EON loudspeakers, the B&K 2250 Sound analyzer, Behringer ECM 8000, Beyer MM1 and B&K 4134 microphones. Finally the analysis of the obtained data was made with software DIRAC 3.0.

Image 2- *STI for source position S1*

Image 3 – STI for source position S3

5. Results

5.1 Acoustic field simulation

The computed STI on the basis of the electronic model for various source-receiver locations, confirms that speech intelligibility is 'good' to 'very good' throughout the theatre (fig.1, 2, 3, 4).

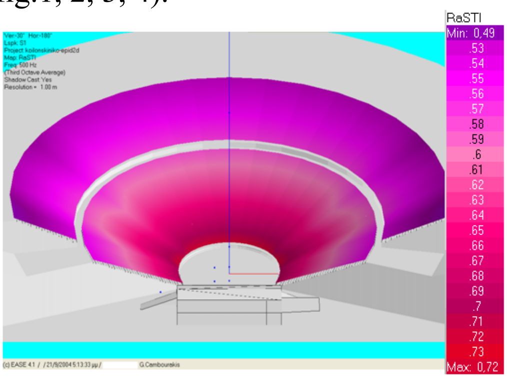


Figure 1- STI for source position S1

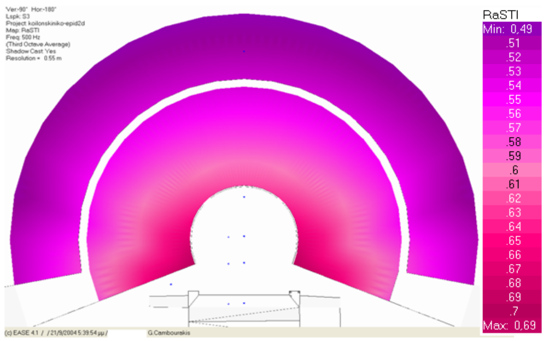


Figure 2 – STI for source position S3

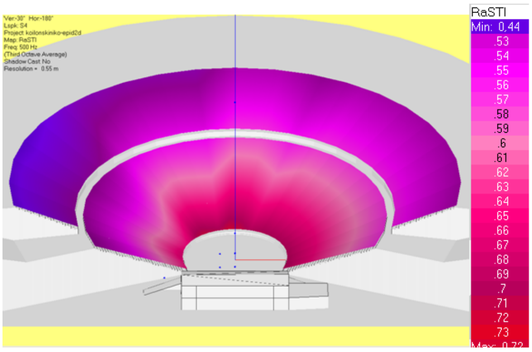


Figure 3- STI for source position S4

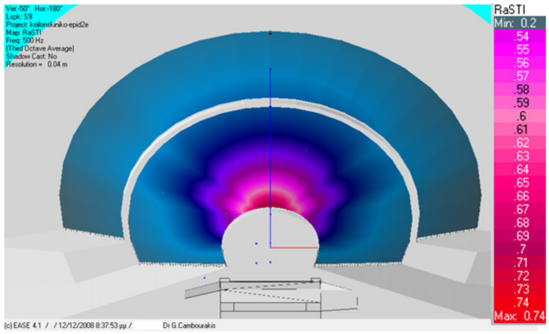
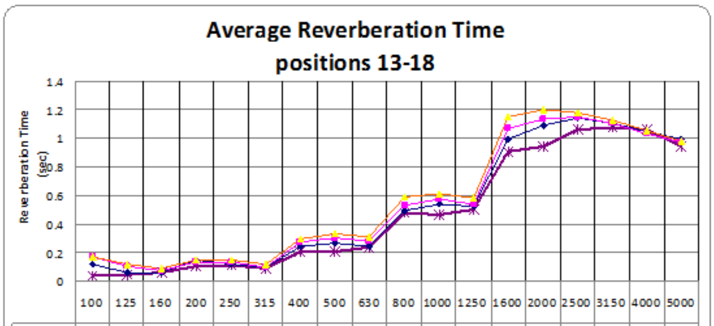


Figure 4 – STI for source position S9

5.2 Field measurements

In terms of the field measurements of acoustic parameters, the obtained RT values (fig.5) as well as the measured sound spectrum (fig.6) demonstrate first a clear amplification at mid frequencies (where speech spectrum falls) and secondly attenuation of low frequency sounds (where most unwanted noises register).



	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
EDT	0.03	0.04	0.06	0.1	0.11	0.09	0.21	0.21	0.23	0.48	0.46	0.5	0.9	0.95	1.06	1.08	1.06	0.94
T20	0.12	0.06	0.06	0.15	0.12	0.09	0.24	0.27	0.24	0.5	0.54	0.52	0.99	1.09	1.14	1.1	1.05	1
T30	0.17	0.1	0.07	0.14	0.13	0.09	0.27	0.3	0.28	0.53	0.58	0.54	1.07	1.14	1.15	1.1	1.03	0.97
T40	0.17	0.12	0.09	0.15	0.15	0.12	0.3	0.33	0.31	0.59	0.61	0.58	1.15	1.2	1.18	1.12	1.05	0.98

Figure 5- Measured RT(sec) and EDT (sec) values average over positions 13-18

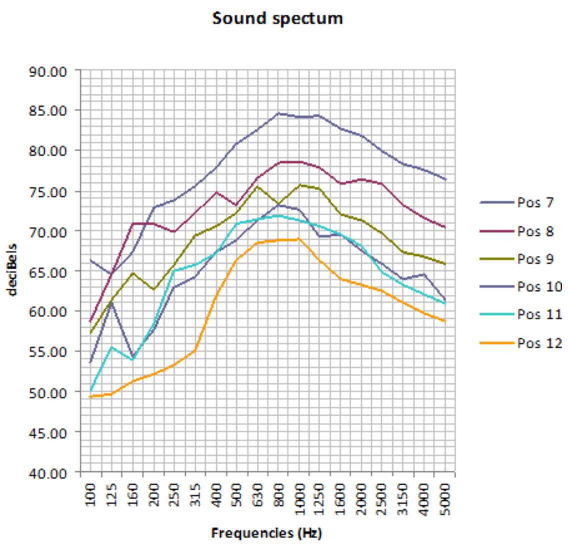


Figure 6 - Measured Sound Spectrum for positions 7-12

The measured STI (fig.7) is in good agreement with the STI computed on the basis of the electronic model whereas all measured values for the clarity index) C80, C70, dB) confirm clarity of speech throughout the theatre.

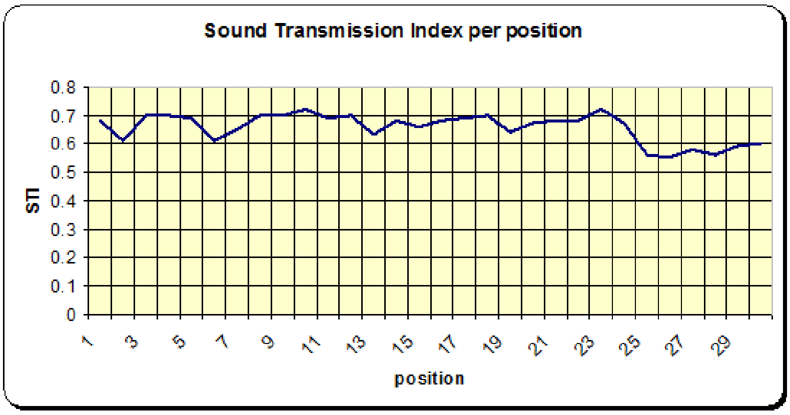


Figure 7- Measured Sound Transmission Index

6. Discussion

The results of the acoustic field simulation in terms of STI values, have clearly demonstrated that overall speech intelligibility is optimum for the majority of the seats. Since, intelligibility depends heavily on the actor's voice strength and his articulation it is evident that audience noise has to be as low as possible so that intelligibility attains useful values.
On what concerns the in-situ measurements, as Fig.6, depicts, the frequency response in most of the seats is bell shaped and its maximum value is observed around 1000 Hz (the frequency of maximum sensitivity of human ear). Therefore it is concluded that all frequencies below 400 Hz are attenuated while the voice critical frequencies (300 to 2000 Hz) are boosted. Since most unwanted noises of an audience have frequencies in the lower registers, most of them are attenuated improving intelligibility dramatically (Fig. 7). Overall it can be stated that the measured values are better than those predicted by the EASE model for the source S1 (the actor is standing in the center of the <orchestra>). Furthermore, a detailed analysis of the obtained values in each of the 30 audience positions that were used for the measurements, shows that the main factors contributing to the extraordinary acoustics of Epidauros theatre are its architectural symmetry and the scattering effect from the inner stepped surface of the <koilon>.

7. Conclusions

With the completion of both stages of this study we concluded that the speech intelligibility was found to be 'good- very good' throughout the audience area and that there's sound reinforcement in the middle frequencies region where speech sounds register. In addition the theatre attenuates all low frequency sounds where most unwanted noise register. In terms of the various actors' locations and orientations on stage, the obtained good STI values, permit us to allege that although there are fluctuations in this parameter's values, the values throughout the theatre are always greater than '0.5' which determines a space's intelligibility as 'good'.

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