# VIRTUAL ACOUSTICS OF THE ROMAN THEATRE OF ITALICA

**PACS**: 43.55.Ka

A. Álvarez-Corbacho; T. Zamarreño; M. Galindo; S. Girón
Instituto Universitario de Arquitectura y Ciencias de la Construcción (IUACC), Universidad de Sevilla. Av. Reina Mercedes 2, 41012 - Sevilla, España, Tel: +34 954556612, Fax: +34 954557892, E-mails: arqangel@us.es; teofilo@us.es; mgalindo@us.es; sgiron@us.es

## ABSTRACT

Classic outdoor theatres have special significance in the universal, cultural and architectural heritage. These scenic environments have undergone acoustic research in ERATO European project with basic purposes of recreation of associated intangible heritage and for their adaptation to contemporary cultural performances. In this work, the Roman theatre of the archaeological site of Italica (Seville) is studied by means of acoustic simulation, which responds to the classical scheme: cavea, orchestra, scenae, four-sided portico, and a capacity for 3,000 spectators.
Throughout this paper, the creation process, adjustment, and validation of the 3D model of the theatre for simulating its sound field is analysed, which is based on the experimental measurement of reverberation time. The initial model, once validated, is modified to assess the acoustic impact of various proposed interventions.

## RESUMEN

Los teatros clásicos al aire libre tienen muy especial significación en el patrimonio arquitectónico y cultural universal. Estos entornos escénicos han sido objeto de investigación acústica en el proyecto europeo ERATO, con fines básicos de recreación del patrimonio inmaterial asociado y para su adaptación a espectáculos culturales contemporáneos. En este trabajo se estudia mediante simulación acústica el teatro romano del conjunto arqueológico de Itálica (Sevilla), el cual responde al esquema clásico: cavea, orchestra, scenae, pórtico de cuatro lados, y un aforo para 3.000 espectadores.
A lo largo de la comunicación se analiza el proceso de creación, ajuste y validación del modelo 3D del teatro para la simulación de su campo sonoro, apoyado en los ensayos experimentales del tiempo de reverberación. Una vez validado, el modelo inicial se ha modificado con objeto de evaluar el impacto acústico de varias intervenciones propuestas.

## INTRODUCTION

Greek and Roman theatres are public buildings of great importance in the history of Western culture. Many of these spaces are used today for their original function with little or no adaptation. The exceptional achievement of former designers to provide such robust and outstanding scenic spaces has attracted architects and, in this framework, acoustics plays an essential role. In fact, both for its architecture and associated acoustics, Greek theatres can be considered the starting point of the history and design of the theatre. The ability of classical theatres to amplify speech in accordance with the polar pattern of the voice, in spite of the spherical divergence and the arrangement of the audience area, has fascinated acoustic researchers for decades. The acoustic principles used in such designs are signalled by Vitruvius [1], an engineer of ancient Rome, 2nd century BC, in whose writings he describes his own experience in the field of architecture. In his fifth book (V, III, 6), Vitruvius gives a basic interpretation of sound propagation, and describes a series of factors for the creation of a suitable sensation to the listener. Another prominent theoretical contribution in this regard is the work by Canac [2] (1967), who studies different geometries with image sources and shows how the first reflections in the orchestra and the back wall of the stage were important in amplifying the voices of the actors supporting direct sound.

Computational techniques have promoted the study of the acoustics of classical theatres. Accordingly, Declercq and Dekeyser [3], by means of acoustic simulation, model the Greek theatre of Epidaurus, incorporate multiple diffraction orders therein, and conclude that the sound is retro-dispersed from the *cavea* towards the audience, so that the public receives the sound, not only from the front, but also retro-scattered from behind. In addition, they show that such retro-dispersions amplify the high frequencies more; these are essential for speech intelligibility. The numerical model presented reveals that the rows of seats play an important role in the acoustics of the theatre, at least when it is not completely occupied by spectators, since they constitute a corrugated surface that works as a filter according to the periodicity of the rows of seats observed. Moreover, Farnetani et al. [4] study classical theatres with measurements in situ and in scale models. Based on the values of the sound strength, they propose that sound energy is mainly concentrated in the first part of the impulse response, including the direct sound, in the two outstanding reflections of the floor and the structure of the stage (if present), and of the first reflections contributed by the seven edges of the steps located behind the position of the microphone. Chourmouziadou and Kang [5] studied the evolution of the acoustics of theatres built in different eras, through computational modelling.

In this review, other contributions [6, 7] to virtual acoustics are highlighted, which provide information on the direct auditory sensation of the responses to speech and music of ancient Greek buildings. Although not currently preserved, these remain of great historical significance and their architectural features have been well defined in historical sources and archaeological research.

There are also several important milestones in current knowledge and its dissemination of the acoustics of classical theatres of antiquity, such as the European project ERATO, which responds to the acronym: Identification, Evaluation, and Revival of the Acoustical Heritage of Ancient Theatres and Odea [8], whose objective was to investigate the acoustics of classical outdoor theatres and odeons using virtual reconstruction by means of computational models of the spaces, made in accordance with the archaeological information available. Musical instruments of the time and short musical pieces were reconstructed and recorded in an anechoic environment to be auralised in these virtual environments. The result of this project is also a work of comparison of acoustic measurements and simulation in the best-preserved Roman theatre: the Roman theatre of Aspendos (Turkey) by Gade et al. [9]. Again, on a local scale, the Italian project ATLAS [10] stands out: a research project of national interest dedicated to safeguarding the acoustic and visual aspects of former theatres.

Two other events worthy of mention include, on the one hand, the International Congress held at the University of Patras (Greece), in September 2011, on the acoustics of ancient theatres [11]. Experts in acoustics and other fields of engineering are brought together to present and discuss all aspects and findings related to the acoustic properties of these unique ancient monuments, which are largely located around the Mediterranean region and are often used for public performances of theatre, drama, speech and music. On the other hand, the special section of volume 1 of the year 2013, of Acta Acustica United with Acustica journal [12] should be highlighted, which covers a wide range of themes and outstanding contributions of the Patras congress. For instance, Blauert [13] analyses the conceptual aspects of the qualitative acoustic experience in the theatrical spaces, and examines the processes of the areas of psychoacoustics, sensory psychology, physics, and communication sciences that contribute to the formation of sound quality. The study by Cocchi [14], with precise analysis both of acoustic science in antiquity and of the disposition of the Greek and Roman theatres, articulated with several historical antecedents on the behaviour of people, provides evidence that the design of these theatres was based on other reasons to that of meeting the best acoustic conditions for the audience. The contributions of Psarras et al. [15] and from Lokki et al. [16], both focus on the Greek theatre of Epidaurus. The former, through the analysis of the measures, and the latter, through acoustic simulation, reaffirm the exceptional acoustic quality of the theatre, particularly for the reproduction of speech. In addition, Economou and Charalampous [17] examine the role of sound diffraction at the edges of the multiple levels of the theatre, while Prodi et al. [18] present the influence of stage sets on the acoustics of a classic theatre based on scale models. Other pieces of research discuss the use of resonators (Polychronopoulos et al. [19]), and the role of masks in ancient theatres (Tsilfidis et al. [20]).

In this work, a 3D acoustic model has been created, using the CATT-Acoustic v9.0c software, of the Roman theatre of the archaeological site of Italica (Santiponce, Seville). This model has been refined based on the in situ measurements of the reverberation time, and through discussion of the influence of the dispersion coefficients of its surfaces for its validation. The influence of the detail in the model is analysed, and the case of an open model and a closed model with a maximum absorption cover is considered, as is the convergence of the results with the number of rays. A suitably modified version of this model will be used to simulate future interventions and different configurations from the past and the future, both from the parametric and sensorial point of view through auralisations.

## THE ROMAN THEATRE OF ITALICA

The theatre, apparently the oldest civil work in Italica, was built at the beginning of the Imperial era, in the time of Augustus, between the end of the first century BC and the beginnings of the first century AD. This date could be obtained with great reliability from the excavation of the landfills in the construction of the tiers (*cavea*). For more than the three centuries, in which it was kept in use, transformations of various kinds took place, due both to minor interventions or repairs, as well as renovation work and partial embellishment of the building.

The theatre occupied a somewhat peripheral area of the late republican city. The excavations carried out in the eighties and nineties of the last century show the full urbanization of the San Antonio hill area, where the theatre is located, at least since the Adrian period, through the consolidation of the road in charge of facilitating access to various points of the theatre as well as its communication with other sectors of the city. Following its discovery in 1937 (F. Collantes de Terán [21]), excavations began in 1971 and continued with several phases (Figure 1) throughout that decade.

Currently, the theatre is in use, and the performances of the International Dance Festival (since 1981, although not all editions) and the Greco-Latin theatre Festival have been held; in the spring of 2014, its eighteenth edition was held.

Its structure reponds to the usual structure in Roman Theatres, with the tiers (*cavea*) in a semi-circle around a central space called the orchestra (*orchestra*) and with a stage (*proscaenium*) closed by a high façade or front stage wall (*scaenae frons*) with orders of overlapping columns. The *parascenios* (*parascaenia*), the two bodies that flank the stage in the case of the theatre of Italica, fail to reach the monumentality that they acquire in other Roman theatres. Behind, the building opens into a portico square. The exterior finishing of the *cavea* was made with blocks of fossiliferous limestone, which also configures the finishing of the stands. On these stands, the steps of three radial stairs (*scalaria*) were

**Figure 1.** Excavations in the 1970s.

carved, which constitute the access to the different points of the *cavea*, which lacked internal distribution corridors (*vomitoria*).

Generally, Roman theatres are buildings of rather modest proportions when compared to amphitheatres and circuses. The semi-circular *cavea* of the Italica theatre measures 77.70 m in diameter, which delimits an *orchestra* of 26 m in length, and the length of the stage is 48.40 m. Its capacity can be estimated at about 3,000 spectators. As it is an archaeologically recovered space, a mixture between the original and the restored materials is presented (see Figure 2).

**Figure 2.** View of the theatre during the performance of in situ measurements.

## EXPERIMENTAL METHOD

Measurements were carried out in the theatre with the absence of the public. Environmental conditions were monitored by measuring temperature (around 25 ºC) and relative humidity (around 40%) and by following the recommendations of ISO 3382-1 [22]. Although the wind speed was not monitored, the smooth intermittent gusts were an inconvenience when recording impulse responses (IR).

The process of the generation of the exponential sweep signal, the acquisition, and the analysis of the IRs was performed with the WinMLS2004 programme through the Edirol UA-101 sound card. The generated signal was emitted by the AVM DO-12 dodecahedral source with a B&K 2734 power amplifier, for two positions of the source located at 1.50 m above the floor of the *proscaenium* and recorded at 25 reception points (Figure 3). These points were distributed across the *cavea* (18), the *proedria* of the *orchestra* (5), and in the p*roscaenium* (2). The monaural IRs were collected using a multi-pattern microphone (omnidirectional and figure-of-eight) AT4050/CM5 Audio-Technica connected to a 4-channel Sound Field SMP200 polarization source. The binaural IRs were obtained with a Head Acoustics HMS III torso simulator (Code 1323) and the B&K-2829 micro polarization source. In all cases, the microphone was placed at 1.20 m from the floor.

## ACOUSTIC MODEL AND SIMULATION

Acoustic simulation was carried out by using the CATT-Acoustic v9.0c programme [23], based on geometric acoustic algorithms. The model was constructed using the available graphic documentation and the data collected in situ. For the geometric survey, a three-dimensional model was generated through the SketchUp programme, and finally exported to CATT-Acoustic through the SU2CATT v 1.3 plugin.

Calculations were obtained with the TUCT v1.0h engine (The Universal Cone Tracer), which calculates the acoustic parameters from energy echograms (E) and/or B-format and binaural impulse responses (h) based on the evaluation of sound pressure. Specifically, algorithm 2 has been chosen. The geometric model, consisting of 1,081 plans, has dimensions of 48.5 x 34.5 m$^2$ in ground plan and a height of 7.85 m, which would enclose a volume of 7,770 m$^3$ (under the imaginary plane that rests on the its vertical limits), with a total area of 4,052 m$^2$ (Figure 3).

In order to adapt the acoustic conditions of simulation to those of the real situation, the model went through an iterative process of tuning in which the coefficients of the least-known materials were adjusted. The process concluded when the simulated reverberation times, at each octave band, spatially averaged, no longer differed by more than one JND (5%) of the corresponding values measured in situ. In this case, the calibration process was especially complex since it was an open space because the absorption of the upper closing plane dominated the remaining surfaces, and therefore the adjustment of the absorption coefficients produced no appreciable effects on the behaviour of the sound field. On the other hand, the geometry of the theatre, especially of the *cavea*, assumes that the dispersion coefficients are significant for all the octave bands. Precisely the adjustment of these dispersion coefficients constitutes the key to finally achieving the adjustment of the model. Table 1 shows the absorption and dispersion coefficients finally assigned to the surfaces, together with the colours shown in Figure 3 and the bibliographic references that served as a base.

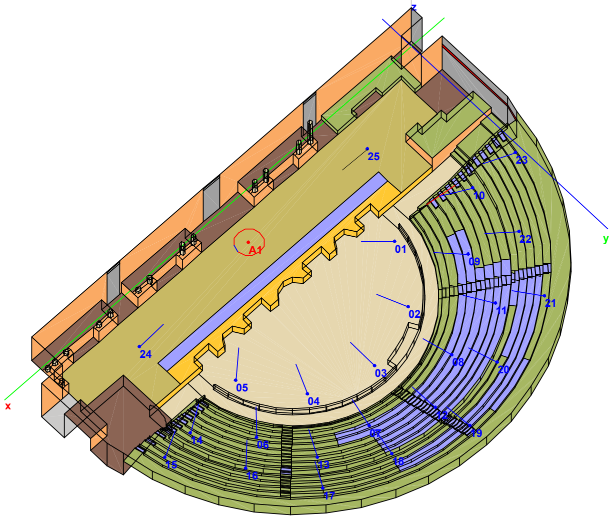

**Figure 3.** Computer model of the theatre in its current status.

**Table 1.** Areas, absorption (top) and dispersion (below) coefficients, at octave bands of the materials for the simulation.

| Surface, reference, | Area ($m^2$) | Area (%) | Colour (Fig. 3) | Absorption and dispersion coefficients 125 | 250 | 500 | 1k | 2k | 4k |
|---|---|---|---|---|---|---|---|---|---|
| Open space | 1,469.7 | 36.27 | | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| | | | | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| Stone wall, [24] | 990.5 | 24.44 | | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 0.07 |
| | | | | 0.65 | 0.60 | 0.55 | 0.40 | 0.35 | 0.35 |
| Stone wall, brick 40, [25] | 551.8 | 13.62 | | 0.08 | 0.08 | 0.14 | 0.16 | 0.18 | 0.25 |
| | | | | 0.65 | 0.60 | 0.55 | 0.40 | 0.35 | 0.35 |
| Orchestra floor, marble, [24] | 387.1 | 9.55 | | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| | | | | 0.35 | 0.35 | 0.45 | 0.40 | 0.45 | 0.50 |
| Stage floor, platform 50, [24] | 230.3 | 5.68 | | 0.10 | 0.07 | 0.07 | 0.07 | 0.07 | 0.06 |
| | | | | 0.35 | 0.35 | 0.40 | 0.40 | 0.50 | 0.40 |
| Tier panels, Phenlic, [24] | 197.6 | 4.88 | | 0.18 | 0.12 | 0.10 | 0.09 | 0.08 | 0.07 |
| | | | | 0.65 | 0.60 | 0.55 | 0.40 | 0.35 | 0.35 |
| Gravel wall 1, [25] | 127.4 | 3.14 | | 0.20 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 |
| | | | | 0.20 | 0.25 | 0.30 | 0.40 | 0.50 | 0.60 |
| *Murus pulpiti*, brick 2, [25] | 82.7 | 2.04 | | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.05 |
| | | | | 0.65 | 0.60 | 0.55 | 0.45 | 0.35 | 0.35 |
| Concrete, [24] | 11.1 | 0.27 | | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.05 |
| | | | | 0.65 | 0.60 | 0.55 | 0.40 | 0.35 | 0.35 |
| Steel, [24] | 3.9 | 0.10 | | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |

In Figure 4, the effect is shown of the modification of the dispersion coefficients in the simulation, mainly of the *cavea* zone on the spatially averaged reverberation time $T_{30}$. It is observed how, in the absence of dispersion, the simulated values of $T_{30}$ are almost three times those measured in situ; these values are reduced by almost a half when the dispersion coefficients increase to 50% of the final value that allowed the adjustment to be reached (differences less than 1JND with respect to the measured values). A similar behaviour is observed for the remaining acoustic parameters. The results correspond to the closed model (see below) and to a simulation with $10^6$ rays and a duration of the echogram of 1,200 ms, superior to the reverberation time measured in situ, and using the algorithm 2 of TUCT.

The aforementioned closed model was achieved by means of a maximum absorption surface as a cover (Table 1). In addition to this model, by taking advantage of the possibility of simulating non-closed spaces of CATT-Acoustic, simulations were carried out with the open space, whereby the aforementioned closing surface was eliminated, and the results of both models were compared with those measured experimentally. Figure 5 shows these results for four significant parameters related to different aspects of the perceived sensation: $T_{30}$ and especially EDT related to the reverberation; the centre time, $T_S$, related to the perceived clarity and the sound strength; and $G$, related to the perceived level. It is observed that the simulated values are very similar for the two models and, except in the first octave for certain parameters, in general, they differ by less than 1JND. As an exception, EDT appears, for which these differences are greater. Here the results also correspond to simulations with $10^6$ rays, a duration of the ecogram of 1,200 ms, and algorithm 2 of TUCT is used.

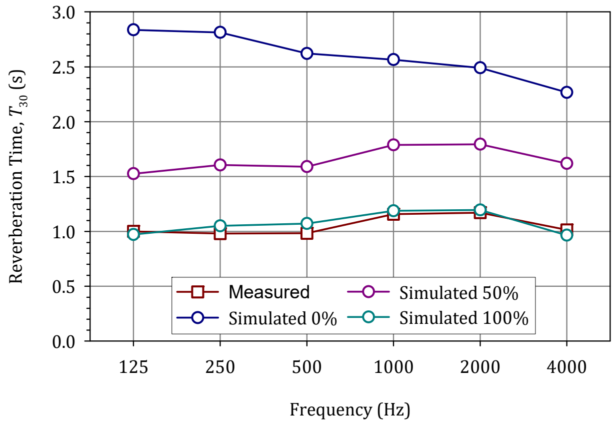


**Figure 4.** Effect of dispersion on the adjustment of the model for the simulation.

Another aspect investigated involved the convergence of the results with the number of rays used, both for the open and for the closed model. In this regard, it should be noted that the automatic estimate made by the software was 109,657 rays. Here, TUCT algorithm 2 has also been used with an echogram duration of 1,200 ms. To evaluate the results, the behaviour of the spectral averages suggested by [22] of the same parameters used in Figure 5, versus the number of rays, have been displayed in Figure 6, and tabulated in Table 2. In the case of reverberation times, vertical segments have been drawn whose length is equal to 1JND, both for $T_{30}$ and for EDT, while for the other two parameters, the vertical axis covers a range of 1JND in the environment of the simulated values. In each case, the regression line has been drawn. In terms of the associated JND, the largest dispersions appear for reverberation times (especially EDT) but always remain lower than 1JND.

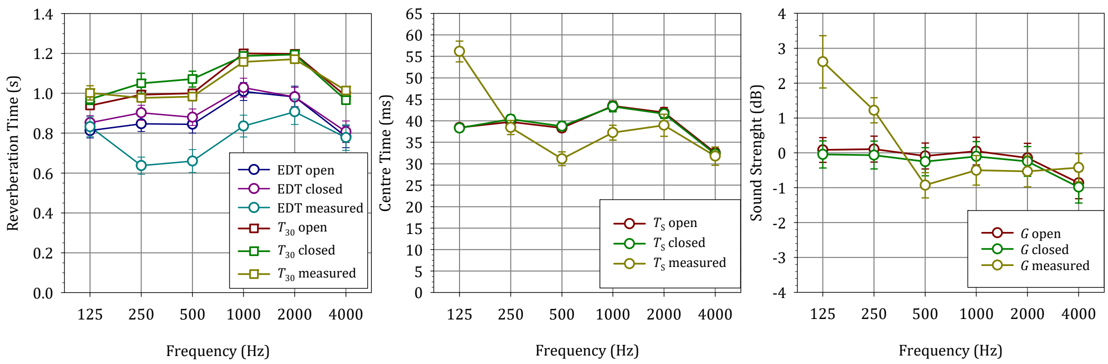


**Figure 5.** Comparison of the spectral behaviour, spatially averaged, of simulated parameters with the open and closed model and the experimental measures. Vertical bars value the spatial dispersion through the standard error.

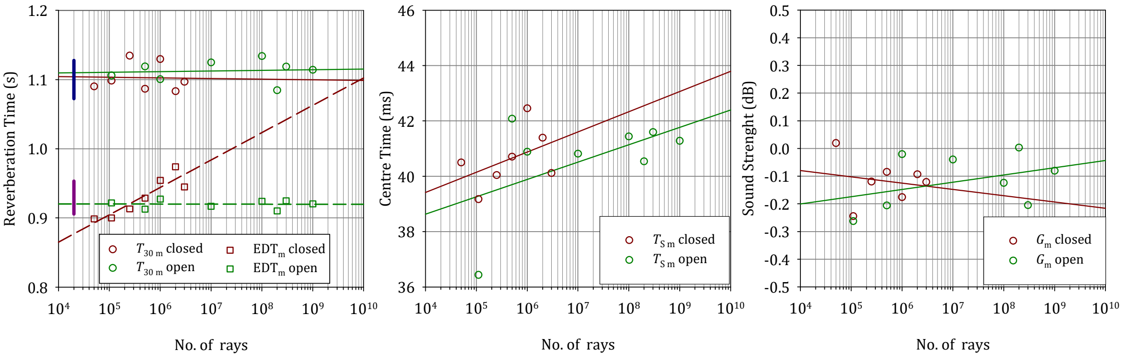


**Figure 6**. Behaviour of spectral averages, spatially averaged, of the acoustic parameters as a function of the number of rays for the open and closed model.

**Table 2.** Spectral average values (spatially averaged) for the closed building (C) and open (O) building as a function of the number of rays for the parameters omitted from Figure 6.

| No.of rays | | $5{\times}10^4$ | $11{\times}10^4$ | $25{\times}10^4$ | $5{\times}10^5$ | $10^6$ | $2{\times}10^6$ | $3{\times}10^6$ | $10^7$ | $10^8$ | $2{\times}10^8$ | $3{\times}10^8$ | $10^9$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_{80m}$ (dB) | C | 6.81 | 6.93 | 6.84 | 6.76 | 6.66 | 6.45 | 6.75 | --- | --- | --- | --- | --- |
| | O | --- | 6.86 | --- | 6.86 | 6.82 | --- | --- | 6.88 | 6.74 | 6.91 | 6.64 | 6.85 |
| $D_{50m}$ | C | 0.74 | 0.76 | 0.75 | 0.74 | 0.74 | 0.74 | 0.75 | --- | --- | --- | --- | --- |
| | O | --- | 0.75 | --- | 0.75 | 0.75 | --- | --- | 0.75 | 0.75 | 0.76 | 0.75 | 0.75 |
| $IACC_{Em}$ | C | 0.61 | 0.60 | 0.61 | 0.60 | 0.61 | 0.61 | 0.59 | --- | --- | --- | --- | --- |
| | O | --- | 0.62 | --- | 0.62 | 0.61 | --- | --- | 0.63 | 0.63 | 0.60 | 0.61 | 0.61 |

## CONCLUSIONS

In this work, the process of making and adjusting a 3D model to simulate the acoustic field in the Roman theatre of the Archaeological Complex of Italica in Santiponce (Seville) is presented and discussed. The model has been validated from the values of the reverberation times measured in situ, which has meant adjusting the dispersion coefficients of the surfaces of the model, since, for a plane with maximum absorption, the adjustments of the coefficients of absorption produce no appreciable effects on the values of the parameters. The effect of considering the open or closed model by means of a maximum absorption cover has been discussed, and it is shown that both models work properly, and obtain very similar spectral values of the spatially averaged acoustic parameters, and also a very similar spatial dispersion.

Finally, attention has been paid to the effect of the number of rays used in the TUCT calculation engine, both for the open and closed enclosure by the absorbent cover. It is clear that, from the number of rays automatically estimated by the software, the results converge properly, and hence the variations are, in general for all parameters, much smaller than 1JND. The detailed analysis of the point-to-point differences, the use of the generated model to evaluate other configurations (past or current), the presence of the public in the *cavea* and possible future interventions, both from the parametric and sensory point of view through auralisations, all constitute aspects to investigate in the future.

## REFERENCES

[1] Vitruvio Polión, M. *Los diez libros de arquitectura*, traducidos del latín y comentados por J. Ortiz y Sanz. Imprenta Real, Madrid 1787.

[2] Canac, F. *L'acoustique des théâtres antiques. Ses enseignements*. C.N.R.S. París 1967.

[3] Declercq, N. F.; Dekeyser, C. S. A. *Acoustic diffraction effects at the Hellenistic amphitheatre of Epidaurus: Seat rows responsible for the marvellous Acoustics*. J. Acoust. Soc. Am. **121(**4), 2011–2022 (2007).

[4] Farnetani, A.; Prodi, N.; Pompoli, R. *On the Acoustics of Ancient Greek and Roman Theaters*. J. Acoust. Soc. Am. 124(3), 1557–1567 (2008).

[5] Chourmouziadou, K.; Kang, J. *Acoustic evolution of ancient Greek and Roman theatres.* Appl. Acoust. 69, 514-529 (2008).

[6] Vassilantonopoulos, S. L.; Mourjopoulos, J. N. *Virtual acoustic reconstruction of ritual and public spaces of Ancient Greece.* Acustica 87(5), 604–609 (2001).

[7] Vassilantonopoulos, S. L.; Mourjopoulus, J. N. *A study of ancient Greek and Roman theater acoustics*. Acta Acust. united with Acust. 89, 123-136 (2003).

[8] Rindel, J. H. *Roman Theatres and Revival of Their Acoustics in the ERATO Project*. Acta Acust. united with Acust. 99(1), 21-29 (2013).

[9] Gade, A. C.; Lisa, M.; Lynge, C.; Rindel, J. H. Roman Theatre Acoustics; Comparison of acoustic measurement and simulation results from the Aspendos Theatre, Turkey. En Proceedings de International Congress on Acoustics ICA, Kyoto, Japón, pp. 2953–2956, 4-9 Abril 2004.

[10] Pompoli, R.; Gugliermetti, F. ATLAS: Un progetto di Ricerca di interesse Nazionale interamente dedicato alla fruizione, tutela e valorizzazione acustica e visiva dei teatri antichi. IV Congr. Naz. IGIIC, Lo Stato dell' Arte, Siena, 28-30 Settembre 2006.

[11] http://www.ancientacoustics2011.upatras.gr/ (visited 15/07/2014).

[12] Mourjopoulos, J. N.; Fausti, P. *The Acoustics of the Ancient Theatres*. Acta Acust. united with Acust. 99(1), Preface (2013).

[13] Blauert, J. *Conceptual Aspects Regarding the Qualification of Spaces for Aural Performances*. Acta Acust. united with Acust. 99(1), 1-13 (2013).

[14] Cocchi, A. *Theatre Desing in Ancient Times: Science or Opportunity*. Acta Acust. united with Acust. 99(1), 14-20 (2013).

[15] Psarras, S.; Hatziantoniou, P.; Kountouras, M.; Tatlas, N. A.; Mourjopoulos, J. N.; Skarlatos, D. *Measurements and Analysis of the Epidaurus Ancient Theatre Acoustics*. Acta Acust. united with Acust. 99(1), 30-39 (2013).

[16] Lokki, T.; Southern, A.; Siltanen, S.; Savioja, L. *Acoustics of Epidaurus – Studies with Room Acoustics Modelling Methods*. Acta Acust. united with Acust. 99(1), 40-47 (2013).

[17] Economuo, P.; Charalampous, P. *The significance of Sound Diffraction Effects in Simulating Acoustics in Ancient Theatres.* Acta Acust. united with Acust. 99(1), 48–57 (2013).

[18] Prodi, N.; Farnetani, A.; Fausti, P.; Pompoli, R. *On the Use of Ancient Open-Air Theatres for Modern Unamplified Performances: A Scale Model Approach.* Acta Acust. united with Acust. 99(1), 58 – 63 (2013).

[19] Polychronopoulos, S.; Kougias, D.; Polykarpou, P.; Skarlatos, D. *The Use of Resonators in Ancient GreekTheatres.* Acta Acust. united with Acust. 99(1), 64 – 69 (2013).

[20] Tsilfidis, A.; Vovolis, T.; Georganti, E.; Mourjopoulos J. N. *Function and Acoustic Properties of Ancient Greek Theatre Masks*. Acta Acust. united with Acust. 99(1), 82 – 90 (2013).

[21] Collantes de Terán, F. *Trabajos y hallazgos en Itálica (1936-1938)* Sevilla.

[22] ISO 3382-1:2009(E), Acoustics-Measurement of room acoustic parameters, part 1: Performance rooms, International Organisation for Standardisation, Geneva, Switzerland 2009.

[23] Dalenbäck, B.-I .L. CATT-Acoustic v9 powered by TUCT user manuals. Computer Aided Theatre Technique, Gothenburg (Sweden), (2011).

[24] Vorländer, M. *Auralization, fundamentals of acoustics, modelling, simulation, algorithms and acoustic virtual reality*. Berlin, Springer-Verlag, (2008).

[25] Physikalisch-Technische Bundesanstalt, line 514. http://www.ptb.de/en/org/1/17/172/datenbank.htm (visited 15/07/2014).