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Measurement and analysis of the acoustics of the Roman theatre of Segobriga (Spain)

Álvarez-Corbacho, Ángel[1]
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla
Av. Reina Mercedes 2, 41012-Seville, Spain

Bustamante, Pedro[2]
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla
Av. Reina Mercedes 2, 41012-Seville, Spain

Galindo, Miguel[3]
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla
Av. Reina Mercedes 2, 41012-Seville, Spain

Girón, Sara[4]
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla
Av. Reina Mercedes 2, 41012-Seville, Spain

Zamarreño, Teófilo[5]
Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla
Av. Reina Mercedes 2, 41012-Seville, Spain

ABSTRACT

Segobriga (Cuenca) was the capital of the Celtiberia region. The specular gypsum of its mines, used as glass in windows, was exported across the whole Empire through the port of Cartago Nova (Cartagena). Its Roman theatre has one of the best conserved *cavea* of *Hispania*, although there is no *scaenae frons*. Its construction dates back to the year 79 A.D. In this work, experimental results and analysis are presented of impulse responses and of the values of the monaural and binaural acoustic parameters recorded in situ. These results correspond to the source-receiver combinations of three positions of the source, located in the *proscaenium* (2), and in the *orchestra* (1), and of 19 reception points, distributed across the *cavea*,

[1] arqangel@us.es
[2] bustamante@us.es
[3] mgalindo@us.es
[4] sgiron@us.es
[5] teofilo@us.es

the *proedria*, and the *proscaenium*. This theatre features as part of one of the study cases of a research project that aims to evaluate and revalue the acoustics of the principal Roman theatres of Spain.

Keywords: Roman theatre, theatre acoustics, ancient theatre
I-INCE Classification of Subject Number: 25

1. INTRODUCTION

Ancient theatres are public buildings of the utmost importance in the history of Western culture and in universal cultural heritage. These venues are mainly disseminated in coastal countries along the Mediterranean Sea, and in other regions and cities beyond, that belonged to the Roman Empire [1]. In addition to their archaeological interest, increasing attention has been paid to the acoustics of these performance spaces. Much of this interest is due to two research projects: ERATO [2] (Identification, Evaluation, and Revival of the Acoustical Heritage of Ancient Theatres and Odea), financed by the European Union; and, on a more local scale, the Italian project ATLAS [3], of national interest, and dedicated to safeguarding the acoustic and visual aspects of ancient theatres. The former project, with a duration of three years, was created in order to conserve and restore the architectural heritage of these buildings while also taking into account their acoustic characteristics. Within the framework of this ERATO project, the Roman theatre of Aspendos, Turkey, was studied, which is in a magnificent state of conservation [4].

Roman theatres are Greek in origin; they followed the earlier Greek seating pattern, but limited the seating arc to 180º, and also added a stagehouse (*skené*) behind the actors, a raised acting area (*proskenion*), and hung awnings (*velaria*) overhead to shade the patrons. The actors spoke from a hard-surfaced semicircle (*orchestra*) at the centre of the audience.

The acoustic principles used in such designs are signalled by Vitruvius [5], 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 an adequate sensation to the listener. Another prominent theoretical contribution in this regard is the work by Canac [6], who studies various geometries with image sources and shows how the first reflections in the orchestra and the back wall of the stage were significant in the amplification of the voices of the actors by supporting their direct sound.

Several papers deal with the evolution of open-air Greek and Roman theatres in the examination of the influences of the changes of forms and materials on their acoustics. These studies rely on acoustic measurement in the surviving remains of ancient theatres to support analyses with computer simulation [7, 8]. A single study with an analogous aim was based on measurements carried out in a reduced-scale physical model [9].

In another context, based on a computational model of a classical theatre, Declercq and Dekeyser [10] incorporate multiple diffraction orders and conclude that the rows of seats play a major role in the acoustics of the theatre, at least if 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. Hence 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, these authors show that such retro-dispersions better amplify the high frequencies, which are essential for speech intelligibility.

Other aspects that deserve mention that have been studied in these theatres include the state of knowledge and arrangements in the use of *velaria* in ancient Roman theatres in the past [11], and, through simulation models, their possible acoustic influence in three Italian open-air theatres.

Since ancient theatres are used in the modern age for a variety of cultural activities, virtual models were also adjusted to recreate the acoustic conditions by adding certain scenic elements in the theatre [12] or by including the presence of the audience in the *cavea* [13] to evaluate their influence on acoustic quality.

In Hispania (Spain), 22 Roman theatres are known. In a few of these theatres, only vestiges of the theatre remain but others remain in an excellent state of preservation, as is the case that concerns us: the Roman Theatre of Segobriga in the town of Saelices, Cuenca (Figure 1). In this work, the acoustic field of the theatre is described through a parametric analysis corresponding to three positions of the sound source as a consequence of an on-site measurement campaign. This theatre constitutes one of the cases of study of a research project financed by the Spanish government, carried out by the authors, that aims to evaluate and revalue the acoustics of the principal Roman theatres of Spain.

2. THE ROMAN THEATRE OF SEGOBRIGA

This is, without doubt, one of the most outstanding monuments of the Roman city of Segobriga. It constitutes one of the smallest Roman theatres, and one of the best preserved in Hispania, at least in terms of its tiers.

The theatre is located to the left-hand side of the entrance road that approached the main gate of the city. It is attached to the city wall, and, although it was located in the northern *suburbium*, it was perfectly integrated into the monumental centre through a square that linked the forum with the theatre.

Its ground plan is of a classical typology, with *cavea* endowed with *summum maenianium*, *orchestra*, *proscaenium*, a stage pit, and *frons scaenae* (not conserved). The constructive techniques used for its realization were those of *opus quadratum*, *opus vittatum*, and *opus caementicium*.

The theatre rises on the north slope of the hill on which the city was based. For its construction, the slope of the hill and natural rock were used to carve almost all the *cavea*. The *cavea*, of an almost semi-circular form, is of small size, 31.44 m in diameter. The *proscaenium* has a width of 7.5 m and a length of 62 m. The *pulpitum* is 25.60 m long, and the theatre had an approximate capacity of 2,500 spectators.

Figure 1. *Cavea of the Segobriga theatre (Saelices, Cuenca, Spain).*

According to a large monumental inscription whose remains have appeared among the ruins, the construction of the theatre must have begun in the time of Tiberius, was built in the time of Claudius or Nero, and was inaugurated in the time of Titus and Vespasian, around 79 AD.

The *cavea*, very well preserved, is divided into *cunei* or sectors by means of *scalaria*, stairs, and in three parts of different height that are separated by horizontal corridors and *baltei,* or small walls: the *ima*, *media,* and *summa cavea*. The first two are perfectly preserved, while the *summa cavea* is missing, which would have risen above a vaulted corridor under which ran the street that connected the two city gates. On top of this complex structure, the *summum moenianum* would have been erected.

The *orchestra*, almost semi-circular, preserves three steps for the seats of the authorities, the *proedria*, in front of which stands the *proscaenium*, which was made of wood and supported on stone pillars. The *murus pulpiti* was decorated with pilasters and ribbed in spiral semi-columns, upon which the *pulpitum* is located; this has two small lateral stairs to ascend from the *orchestra* to the *proscaenium.*

The stage front, *scaenae frons*, absent today, could have possessed a canopy and was decorated with columns and beautiful sculptures, presided over by the goddess Roma. It had: the usual three access doors, or *valvae*; the *valva regia* or central door; and the two *valvae hospitales,* or side doors.

3. EXPERIMENTAL METHODS

Measurements were carried out with the theatre without the presence of the public. There was no wind during measuring time (air velocity less than 0.5 m/s) and environmental conditions were monitored by means of measuring the temperature (range 27.9-44.3ºC) and relative humidity (range 17.2-44.4%) and by following the recommendations of the ISO 3382-1 standard [14].

The process of generation, acquisition, and analysis of the acoustic signal was performed by using the EASERA v1.2 programme, through an AUBION x8 multichannel sound card. In this venue, 3 source positions have been considered: two located in the *proscaenium*, and one in the *orchestra*. There are also 19 reception points, distributed

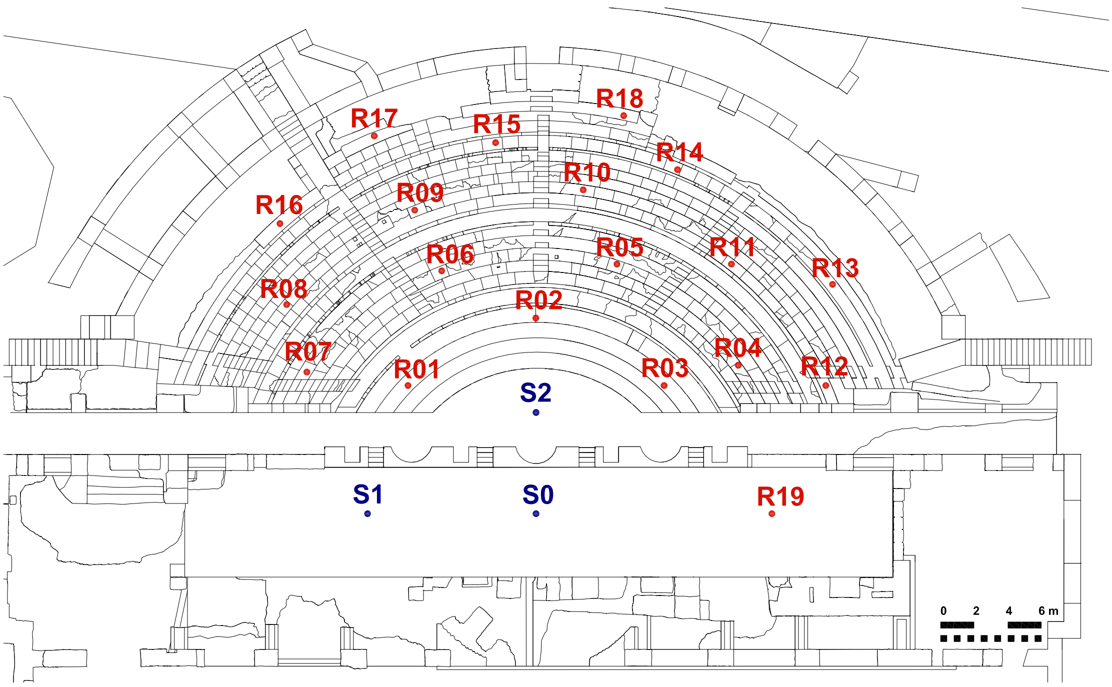


Figure 2. *Ground plan with the source positions (S) and receptors (R) shown.*

across the *cavea*, the *proedria*, and the *proscaenium* (see Figure 2). At each reception point, located at 1.20 m from the floor in all cases, the IRs were registered exciting the space with sine-swept signals, in which the scanning frequency increases exponentially with time. The frequency range, the level, and the duration of the excitation signal were adjusted so that the frequency range would cover the octave bands from 63 to 16000 Hz, and the impulse response to noise ratio (INR) would be at least 45 dB in each octave band to guarantee accuracy of certain parameters, such as T_{30}.

The generated signal was emitted through an AVM DO-12 dodecahedral sound source with a B&K 2734 power amplifier, for the three positions of the source located 1.50 m above the floor. At each reception point, IRs were captured by means of an Audio-Technica AT4050/CM5 microphone in its omnidirectional and figure-of-eight configurations connected to a Sound Field SMP200 polarisation source. The binaural IRs were obtained with a Head Acoustics HMS III torso simulator (Code 1323) and the B&K-2829 microphone polarization source. The background noise level was recorded with an SVAN 958 analyser, of SVANTEK. The B&K 4190 microphone was used with the B&K 2669 preamplifier and the B&K Type 2829 4-channel microphone power supply.

4. RESULTS AND DISCUSSION

Figure 3 shows the measured values of the reverberation time versus the frequency in octave bands for the three sources analysed and the standard errors to assess the spatial dispersion in each octave band. For all frequencies, short reverberation values are obtained in consonance with being an open space, as well as with the absence of the stage front. Longer values were found in the Spanish Roman theatres of Italica, (Santiponce, Seville), and Regina Turdulorum, (Casas de Reina, Badajoz) [15, 16]. Both theatres present, to a greater or lesser extent, a stage front and larger and smaller dimensions respectively than the Segobriga theatre. The two source positions located on the stage (S0 and S1) have the same behaviour. Only when the source is located within the orchestra S2, do the values of reverberation time decrease with the exception of the frequency band of 250 Hz. Similar behaviour between the various sound source positions have been found in other Roman theatres [15, 16]. The standard errors are low and minor when the source is placed in the *orchestra*.

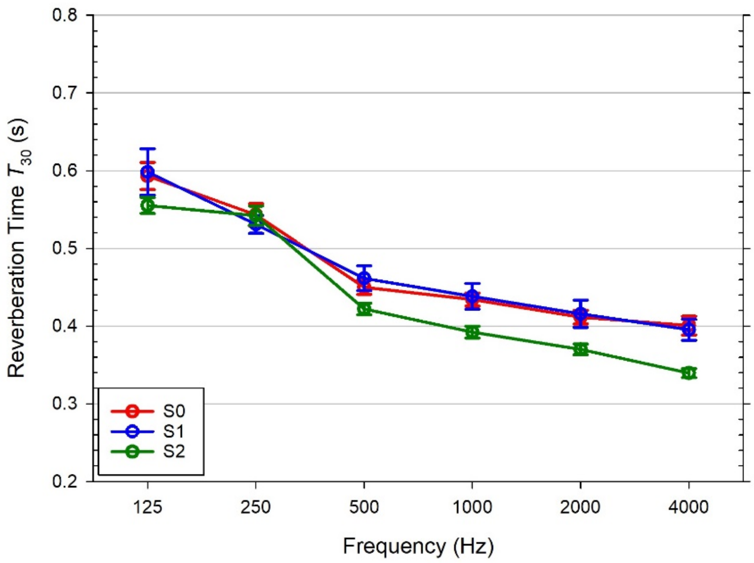


Figure 3. *Measured reverberation time T_{30} and standard error versus frequency octave band for the three sources.*

In order to show the suitability of the registered impulse responses, a typical broadband IR is presented in Figure 4 (a), corresponding to the combination of the sound source in the centre of the stage, S0, and the receiver 10. In Figure 4 (b), the Schroeder curve for the same source-receiver position filtered at 125 Hz is displayed, while in Figure 4 (c), the average of the effective decay range in all octave bands is shown with their associated standard errors to assess the spatial dispersion. In all cases, a sufficient range is obtained for a suitable calculation of the reverberation time T_{30}, with linear energy

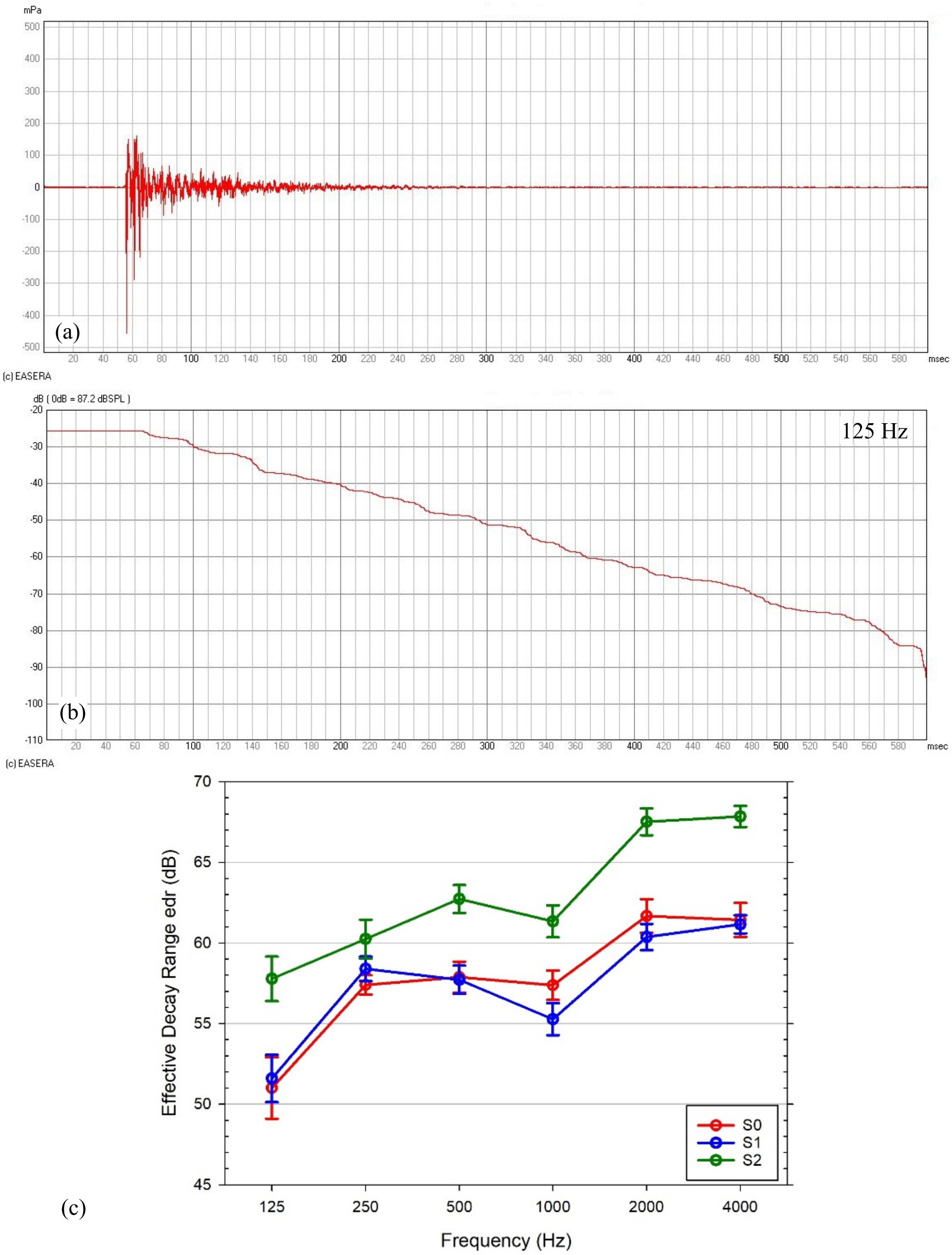
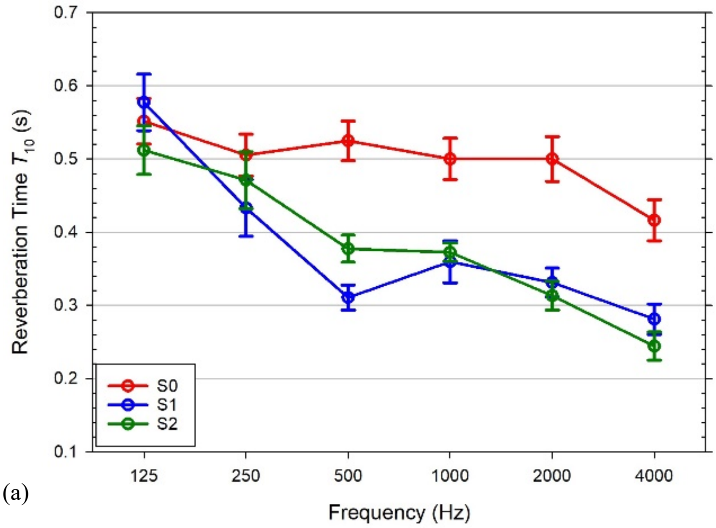
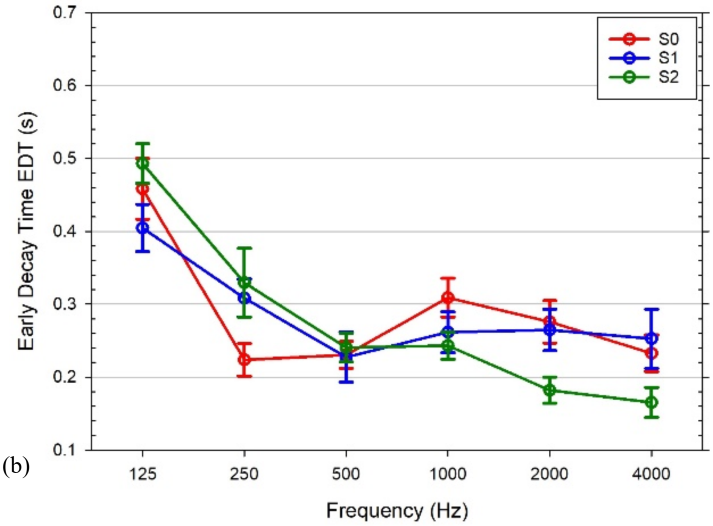


Figure 4. *(a) Impulse response (S0-R10 combination). (b) Schroeder curve at 125 Hz in the same position. (c) Effective decay range versus frequency octave bands and their standard errors.*



(a)



(b)

Figure 5. *(a) Measured reverberation time T_{10}, (b) Early decay time and their standard error versus the frequency octave band for the three sources.*

decays. The measured equivalent continuous sound level of background noise was 33.1 dBA.

Due to the importance of early reflections in these types of open spaces, the acoustic parameters related to the reverberation in the first 10 decibels of decay from the arrival of direct sound are analysed: T_{10} and EDT. In Figure 5, it is observed that the behaviour in these two parameters is moderately dependent on the location of the source. Assuming that the subjective quality of reverberation is more closely related to the values of EDT than is T_{30}, when comparing these two parameters with the average values in each octave band, we can conclude that listeners experience an even lower sensation of reverberation across all frequencies; this conclusion is again confirmed in two other Roman theatres in Spain that are analysed by our research group. In addition, when the source is located in the orchestra, the shortest values are found at only high frequencies.

In order to cover the remaining subjective qualities perceived by a listener, Figure 6 shows the average values for the various octave frequencies and the associated standard errors for clarity (C_{80}), definition (D_{50}), centre time (T_S), and early inter-aural cross-correlation coefficient ($IACC_E$) related to the clarity of the perceived sound for music and speech, for the first three parameters, and to the sense of spatiality for the latter parameter.

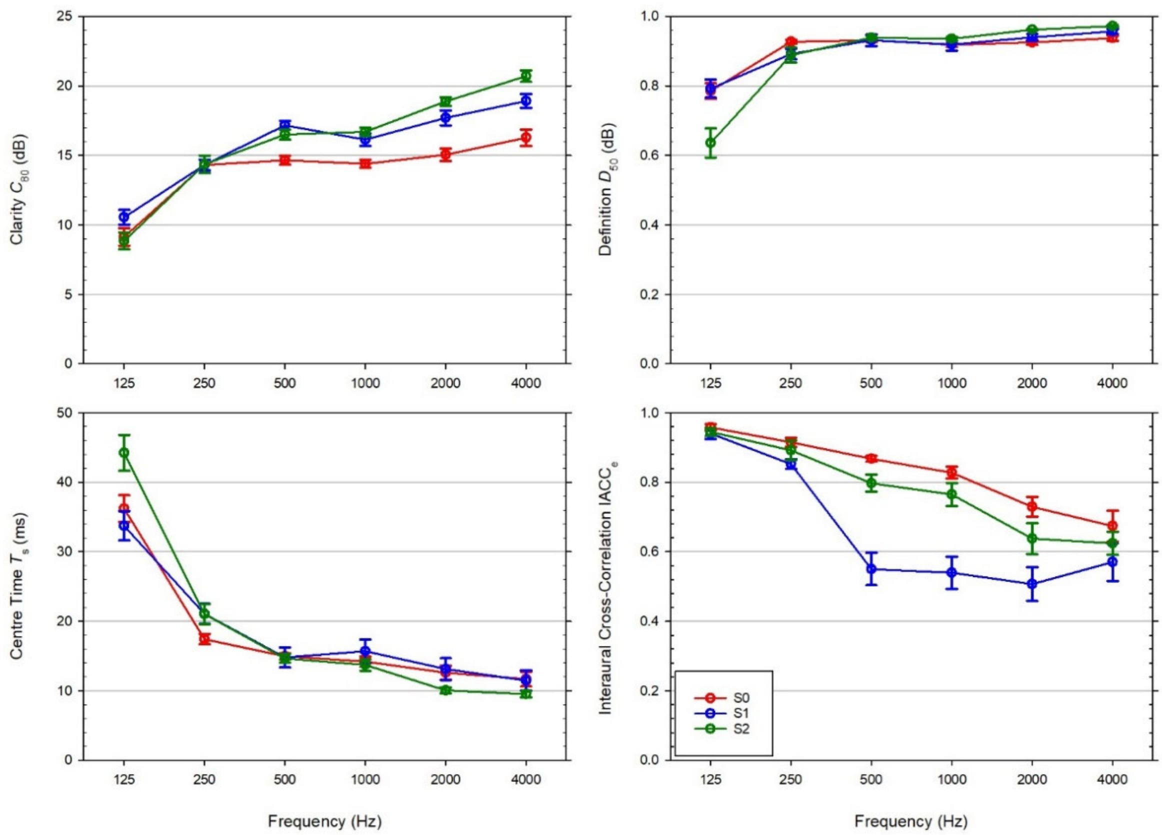


Figure 6. *(Top left) clarity parameter, (Top right) definition parameter, (Bottom left) centre time, and (Bottom right) early inter-aural cross correlation coefficient, all with their standard errors versus frequency octave band for the three sources.*

In all cases, and consistent with the short reverberation times, the excellent conditions presented by the theatre in its current configuration are verified, which logically do not correspond with those of its time. In addition, since these parameters are, by definition, closely related to early reflections, the measured values are dependent on source location, and therefore variations are obtained for each source position analysed. In particular, the greatest differences occur when the spatial sensation of the listener is analysed, which happens, logically, when the sound source is located on one side of the stage. However, in all cases, the signals that reach the public are very similar for either ear.

In order to quantify these differences, Figure 7 shows the absolute differences found in terms of the octave bands for each parameter studied, using the sound source located in the centre of the stage as a reference. These differences correspond to the absolute value of those measured for each source, divided by the corresponding value in each parameter of its differential threshold (JND) [14]. In this regard, it should be noted that the JND values used refer to venues whose reverberation times are longer than those obtained in the theatre. Therefore, in the absence of an adequate differential threshold for rooms with short reverberation times, the normative JNDs of the parameters that evaluate this subjective perception, corresponding to 5% of the measured values, give rise to large differences in the present study.

In the case of T_{30}, values are similar for each of the two positions of the sound source on the stage, and the differences appear, as indicated, when the source is placed in the orchestra. It is reasonable to assume that these differences would be less significant for a revised differential threshold. When we value the reverberation through the values

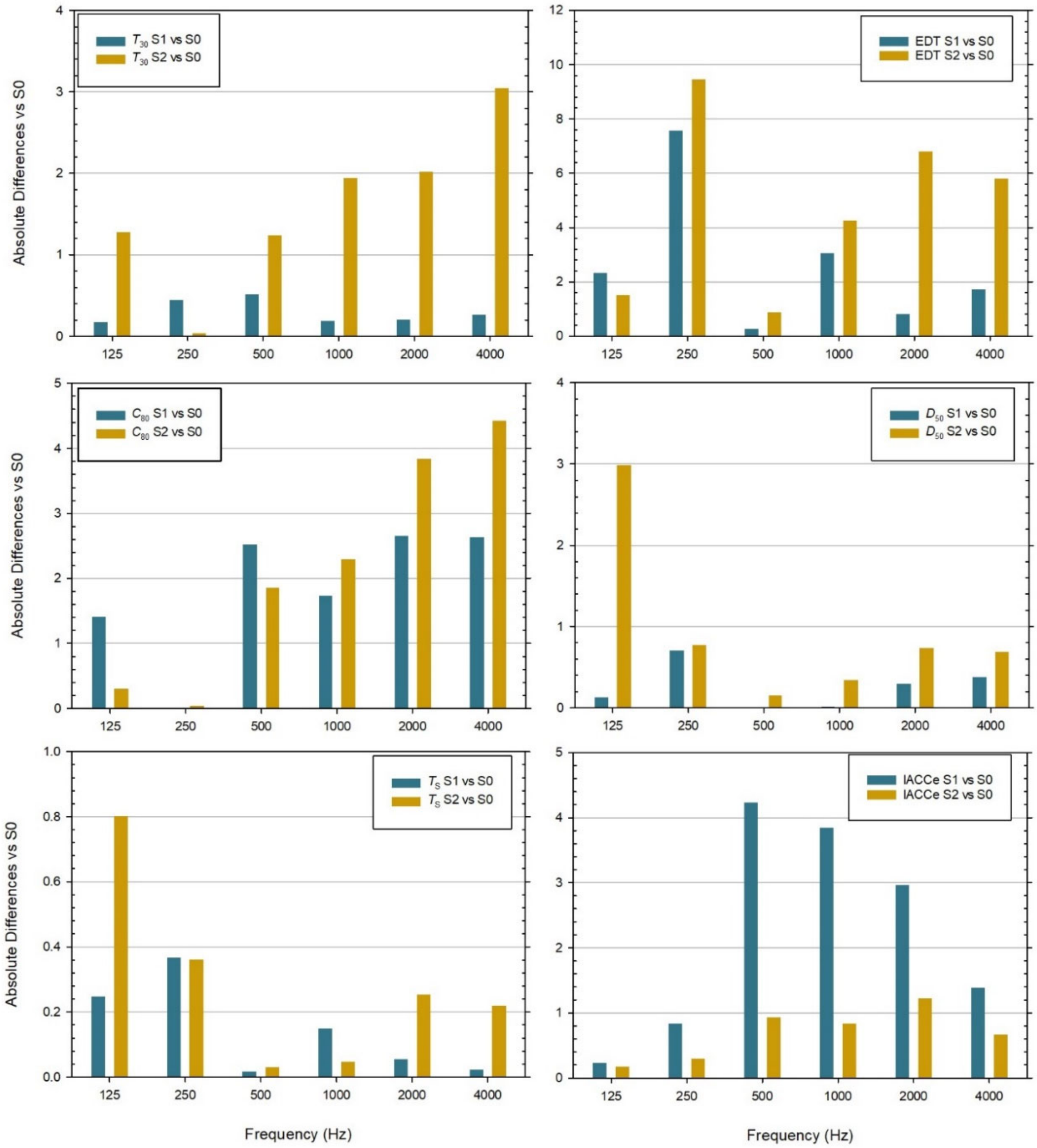


Figure 7. *Absolute differences between sources (S0 reference) expressed as values of JND versus frequency octave bands for the acoustical parameters analysed.*

of EDT, the differences between sources are more noticeable, especially, again when the source is placed in the orchestra.

The musical clarity finds differences greater than 1 JND (1 dB) at all frequencies except for the 250 Hz band and for the definition of the oral message at 125 Hz. However, differences less than 0.8 JND for the two sources at all octave bands are found for the centre time. These differences have the same tendency as for the clarity parameter.

In the case of the sensation of spatiality, listeners do not perceive differences between the source located in the centre of the stage and that located in the centre of the orchestra, but they do perceive differences superior to 1 JND when the source is situated on one side of the stage at medium and high frequencies.

Finally, in order to assess the behaviour of the theatre in its real configuration, the use of simulation techniques by means of specialized software will, in later studies, enable the acoustical importance of the presence of the stage front to be determined.

5. CONCLUSIONS

In this research the acoustic behaviour of the Roman theatre of Segobriga, (Saelices, Cuenca, Spain) has been described. In this type of open-air venue, with very short reverberation times, suitable conditions for the measurement of reliable impulse responses are achieved. Taking into account the current state, the measures of the acoustic parameters of the theatre reflect excellent conditions for the performance of cultural activities, as they occur today. The study of various positions of the sound source, both on the stage and in the orchestra, reflects the importance of its location, although the sound sensation for the audience, in general, involves no major differences. The greatest differences are, instead, revealed to be related to the sensation of spatiality.

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