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ACOUSTIC CHARACTERISATION OF THE ROMAN THEATRE OF CARTHAGO NOVA

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Resumen

La ciudad (Qart Hadasht, que significa Ciudad Nueva) tras la dominación cartaginesa fue tomada por el general romano Escipión el Africano en el año 209 a. C. rebautizándola con el nombre de Carthago Nova. El teatro romano fue construido en tiempos del emperador Augusto que se lanzó a un ambicioso plan de urbanización y romanización de la ciudad. Con una capacidad en su origen de 7000 espectadores, es uno de los mayores de la Hispania romana. Fue construido con piedras calizas, mármoles locales y mortero y su ornamentación escultórica fue realizada en mármol pentélico blanco. En este trabajo se describe el procedimiento experimental para la medida y análisis de respuestas al impulso 3D para un análisis completo espacial de su campo sonoro en términos de magnitud, tiempo y dirección de las reflexiones junto con una caracterización paramétrica monoaural y binaural de este espacio clásico de acuerdo a la norma UNE-EN-ISO 3382-1:2010, considerando tres posiciones de la fuente sonora y 20 puntos de recepción de los micrófonos.

Palabras clave: Teatro romano, respuesta al impulso 3D, teatro antiguo al aire libre.

Abstract

Following the Carthaginian domination, the city (Qart Hadasht, which means New City) was taken by the Roman general, Scipio the African, in the year 209 BC, who renamed it Carthago Nova. The Roman theatre was built in the time of Emperor Augustus who launched an ambitious plan for the urbanisation and Romanisation of the city. With its original capacity of 7,000 spectators, it is one of the largest theatres in Roman Hispania. Built with limestone, local marble, and mortar, its sculptural ornamentation was created in white pentelic marble. This paper describes the experimental procedure for the measurement and analysis of 3D impulse responses for a complete spatial analysis of the sound field of this theatre in terms of magnitude, time, and direction of reflections, together with the monaural and binaural parametric characterisation of this classical performance space in accordance with the ISO 3382-1:2009 standard, through the consideration of three source positions and 20 microphone reception points.

Keywords: Roman theatre, 3D impulse response, ancient open-air theatre.

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1 Introduction

The Greek civilisation is the cradle of theatrical representation. In that period, plays composed of music, dance, and drama began to be performed with the objective of paying tribute to Dionysus, god of the Greek pantheon. Despite the religious origins of these pieces, they gained importance among Athenian society, and, little by little, established themselves as an important literary genre designed to transmit knowledge and ideas to the people. These plays were held in open-air theatrical structures.

The culture of Greece exerted a powerful influence on the Roman Empire, and spread through many of its territories in Europe. The Roman theatre is commonly interpreted as the continuity of the taste for Greek performances, which Roman culture included in its leisure activities of *ludi circenses*, *ludi scaenici,* and *munera*; the first took place in the circus, the second in the theatre, and the third in the amphitheatre. The imperial era of Roman civilisation witnessed not only the greatest upsurge in the construction of theatres, but also the export of the model from Rome to the provinces. In addition to being a symbol of Rome, the theatre must be recognised both as an instrument of the new imperial ideology with its stage for ceremonies and acts with a high symbolic content, and as a means for its political, religious, and propaganda content to be disseminated [1]. In fact, the Roman theatre identifies a whole series of transformations with respect to the old Greek-Hellenic structures according to this new conception and functionality.

The acoustic study of ancient theatres, especially those preserved, constitutes one of the most important case studies of heritage and historical acoustics. The earliest written records from the acoustics of these venues come from the Roman Vitruvius in the first century BC. He appears to base his geometric prescriptions for designing Greek and Roman theatres on an understanding of acoustics [2]. In his fifth book (V, III, 6), Vitruvius provides a basic interpretation of sound propagation, and describes a series of factors for the creation of a suitable sensation for the listener. The most valuable information on ancient classical auditoria is to be gleaned from the surviving examples in terms of the fan-shaped layout and the shape of the arena, which both became highly developed in classical times and have remained a constant point of reference in current design. Another prominent theoretical contribution in this regard is the work by Canac [3], 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 [4, 5]. A single study with an analogous aim was based on measurements carried out on a reduced-scale physical model [6].

Using another focus based on a computational model of a classical theatre, Declercq and Dekeyser [7] incorporate multiple diffraction orders and conclude that the rows of seats play a major 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. 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 have been studied in these theatres that deserve mention include the depth and the arrangements in the use of *velaria* in ancient Roman theatres in the past [8], 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 [9] or by including the presence of the audience in the *cavea* [10] to evaluate their influence on acoustic quality.

This paper describes the experimental procedure for the measurement and analysis of 3D impulse responses for a complete spatial analysis of the sound field of one of the best-preserved Roman theatres of the Roman province of Hispania, where 25 structures of Roman theatres are documented if present-day Portugal is included.

2 The conquest of Hispania

What started off at the end of the third century BC as a strategic invasion to cut off the Carthaginian supply lines that supported Hannibal's invasion of the Italic peninsula during the Second Punic War, soon became a conquering invasion, which, within some twelve years, had completely driven the Carthaginian forces out of the peninsula. However, it would still take almost two centuries for Rome to dominate the entire Iberian Peninsula, mainly due to the strong resistance that the peoples of the interior offered to the invaders. Two centuries of intermittent but extremely violent and cruel wars, left the pre-Roman cultures of Hispania almost completely exterminated. The Roman domination would last until the entry of the first barbarian tribes into Hispania, as early as the fifth century: during the seven centuries of Roman influence, a homogeneous population was formed in Hispania.
In the same way as Rome established its dominion over the Iberian Peninsula, it also imported its particular way of understanding life: its economy, its legislation, the infrastructures that allowed them to create and preserve an empire, and artistic manifestations of all kinds. Today, an important legacy is preserved: not only is it archaeological, but also cultural in the form of the Romance languages spoken in Spain and Portugal, as direct descendants of Latin.
The most important Roman cities had constructive elements of enjoyment and recreation in the form of a theatre, an amphitheatre, and/or a circus. The taste for performances was one of the many aspects that Rome exported to all provinces: there are 22 documented structures of classical outdoor theatres in present-day Spain.

3 The city of Carthago Nova

The south-eastern territory of the Iberian Peninsula has been recognised since antiquity as a strategic point for exploitation and trade. As early as Phoenician times, important mineral deposits were documented (lead, silver, zinc, etc.). This, together with the fertility of the territory and the presence of the coastline, makes the existence of ports a feasible option, and establishes this location as a fundamental point for ancient civilisations.
The city of Cartagena, located in this south-eastern territory, was founded as *Qart Hadasht* by the Carthaginian Asdrubal the Beautiful, in the year 227 BC, atop a previous Iberian or Tartessian settlement. The city, which had become for the Carthaginians the centre of their military operations, drew the attention of the Roman Empire, and became one of the main objectives of conquest in Hispania. It was therefore taken by the Roman general Scipio the African in the year 209 BC; renaming it *Carthago Nova* and granting it the status of a suburb. In 27 BC, the emperor Octavio Augustus included it in the imperial province *Hispania Tarraconensis* after the reorganisation of the territory. A few years later, by order of the emperor, the city, which already held the Amphitheatre, became involved in an urbanisation project from which the construction of the Forum and the Theatre emerged, both of large dimensions (Figure 1(a)).
From the second century onwards, as with other cities in Hispania, there was a slow economic and demographic decline in the city, causing the entire eastern sector of the city to be abandoned, including the forum, which left the city reduced to the sector spanning from the hill of "La Concepción" to the Pinwheel. One of the causes of the city's decline seems to lie in the exhaustion of the mining industry.

This decline was slowed down in the low empire when, in 298 AD, Emperor Diocletian divided the Tarraconensis province into three provinces (Gallaecia, Tarraconensis, and Cartaginensis), thereby establishing the capital of the Roman Carthaginensis province in the city of *Carthago Nova* (Figure 1(b)).

Figure 1 – (a) Plan of the archaeological remains of the city (adapted from www.arqueotur.org). (b) Territorial division of Diocletian in 298. Based on Arbaborix / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0).

The commercial activity of the city was reoriented towards the manufacture of *garum*, a fermented fish paste sauce, of which numerous remains of farms have been found all along the coastline. Towards 425 AD, the city was devastated and sacked by the Vandals on their way to Africa [11, 12].

3.1 The Roman theatre of Carthago Nova

The Roman theatre, built in the time of Emperor Augustus, between the years 5-1 BC, remained in use until the third century. With an original capacity of 7,000 spectators, it remains one of the largest theatres in Roman Hispania. The theatre typology confirms the model proposed by Marco Vitruvius, as in most of the Hispanic theatres, and consists of: the *Scaenae frons* (stage front) with double columns; the *Orchestra*, formed by a semicircle in front of the stage in which the authorities sat; the *Cavea*, in which the spectators stood according to their social rank of *ima*, *media*, or *summa*; the *Proscenium*, which consists of space in front of the stage; and the *Post scaena porticus* , made up of a porticoed courtyard behind the stage.
The diameter of the *cavea* is 87.6 metres; the *proscenium* has a length of 43.60 m, and was topped by a front articulated by exedrae. In front of the tiers of the stands, the *scaena frons* was situated, which can be restored, based on the analysis of the imprints and the architectural elements, with a plan articulated with three curved exedrae, and an elevation of 14.60 m in height with two orders, in which the combination of the reddish tones of the columns, the white of the capitals and bases, and the greys of the *podium* and entablature provoke a suggestive chromatic framework. In the back, the *post scaena porticus* is developed in a terraced manner and articulated with a double-arcaded gallery delimited by a powerful sandstone facing, which also serves as the perimeter wall of the portico onto which semi-circular paths open of 12 m in diameter.
The stands are projected by taking advantage of the natural slope of one of the highest hills in the city. The central part of the *cavea* is excavated into the rock of the hillside itself, while the lateral flanks include vaulted galleries. The theatre is incorporated within the historical centre of the city near

emblematic buildings and port facilities. The partial overlapping of the Old Cathedral on top of the Roman theatre is valued as one of the historical singularities of this archaeological site (Figure 2(a)). The traditional construction techniques generally used are *opus quadratum*, *opus vittatum*, and *opus caementicium*. The theatre was built with various materials: limestone, marble and sandstone from local quarries, of which the columns made of red travertine from Mula stand out, and especially all the sculptural ornamentation of the theatre made of white pentelic marble from Greece [13, 14].

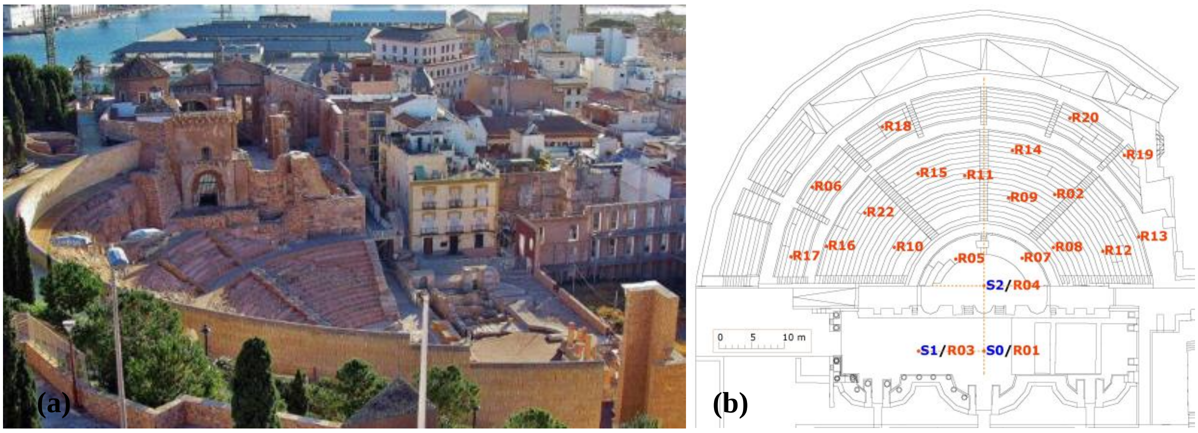

Figure 2 – (a) Aerial view of the Roman theatre in Cartagena (J. L. Sarralde, June 2019). (b) Ground plan of the theatre with the positions of the source (S) and receivers (R) displayed.

4 Experimental procedure

4.1 On-site measurements

Measurements were carried out on the theatre without the presence of the public and by following the recommendations of the ISO 3382-1 standard [15]. 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 (32°C) and relative humidity (49%). According to the dimensions of the theatre, and in order to carry out an exhaustive acoustic characterisation, 3 source positions were chosen (located in the centre of the stage (S0), on the left-hand side of the stage (S1), and in the centre of the *orchestra*, (S2)), and 20 microphones were distributed throughout the audience area, as shown in Figure 2(b).
In order to carry out the measurements in-situ, the following equipment has been used:

- The process of generation, acquisition, and analysis of the signal has been carried out with IRIS software and through the MOTU 4PRE HYBRID sound card.
- The excitation signal is a sweep of sinusoidal signals with a duration of 5.5 seconds and a frequency range from 63 Hz to 16000 Hz.
- The excitation signal was reproduced in the space using an AVM DO-12 omni-directional source located 1.50 m above the floor, previously amplified with a B&K 2734-type power amplifier.
- The Room Impulse Responses (RIR) were captured with the Core Sound TetraMic microphone array that allows temporal and spatial (3D) information to be incorporated.
- The binaural RIRs were captured with a Head Acoustics HMS III torso simulator (Code 1323) and a B&K-2829 microphone polarisation source. In all cases, microphones were placed at 1.20 m from the floor.

- The background noise level was recorded with a Svantek SVAN 958 analyser. The B&K 4190 microphone was used with a B&K 2669 preamplifier and the B&K 2829-type 4-channel microphone power supply.

4.2 Results and discussion

The impulse responses, obtained in-situ in the theatre, were analysed and processed in order to carry out a parametric and spatial study of its sound field.

Figure 3(a) shows the spatially averaged reverberation-time values in octave bands for each of the sources; the error bars of these values correspond to the standard error for the evaluation of spatial dispersion. The results of this parameter show that it is moderately high compared to other Roman theatres in Hispania, such as the Regina Turdulorum [16], (Casas de Reina, Badajoz) with a total spatial average value at mean frequencies of 0.63 s and an estimated capacity of 1,000 spectators, or that of Segóbriga (Saelices, Cuenca) [17], whose total average value at mean frequencies is 0.45 s, with a capacity of 1,500 spectators. The reason for this higher value of the parameter can be attributed to the fact that the Carthago Nova theatre has been rebuilt more than have the previous theatres, and the dimensions of its *cavea* and capacity are notably greater.

The first two sources (S0 and S1) are located on the stage and show similar behaviour, while for source S2, which is located in the *orchestra*, a decrease in the value of the reverberation time is observed in all frequency bands, although with a pattern of dependency on frequency equal to that of the two previous sources.

(a) (b)

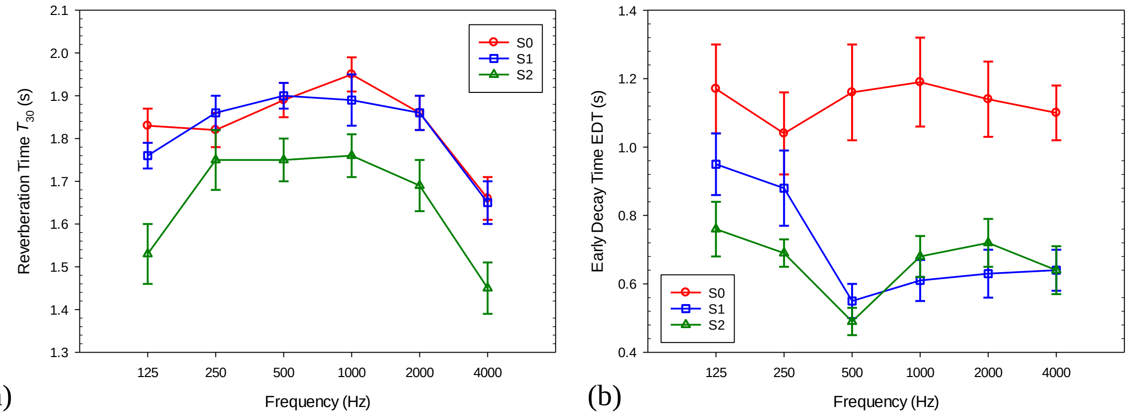

Figure 3 – (a) Measured Reverberation Time, T_{30}, and its standard error versus frequency octave band for the three sources. (b) Measured Early Decay Time, EDT, and its standard error versus frequency octave band for the three sources.

Another interesting value for analysis is that of the EDT. This value is an objective parameter that is subjectively correlated with the perceived reverberation of the room. By comparing the results of Figure 3(a) with those of Figure 3(b), it can be observed that the EDT values are lower than those of T_{30} in all octave bands, that is to say, the listener will perceive the room with an acoustic sensation of lower reverberation than that shown by the other objective time parameter, T_{30}. Regarding the EDT values, it can be appreciated that sources S1 and S2 follow a similar pattern, while for source S0 there is an increase in the order of 0.5 s at medium frequencies, which indicates a much livelier perception in the theatre for that source position. Spatial dispersion is greater for all the sources in this parameter than in reverberation time, especially for source position S0.

Another two acoustic parameters based on acoustic energy and related to the balance between early and late sound are the Centre Time (T_S) and Musical Clarity (C_{80}). Figure 4(a) shows the values of the T_S parameter, which enables the level of sharpness of the sound inside the room to be determined: if this value decreases, then the perceived sharpness increases. As can be observed, at the mid and high frequencies, the T_S value decreases, thereby presenting greater sharpness.

In Figure 4(b), the clarity of the perceived sound for music can be observed and the results of the parameter depend on the position of the source: the highest results at all frequencies are those of position S2; S1 presents a frequency pattern similar to that of S2; and values of C_{80} remain high in all frequency bands. In all cases, there are values above 5 dB (reference value for theatres) [18], and hence the musical clarity is *good* in this space on the stage.

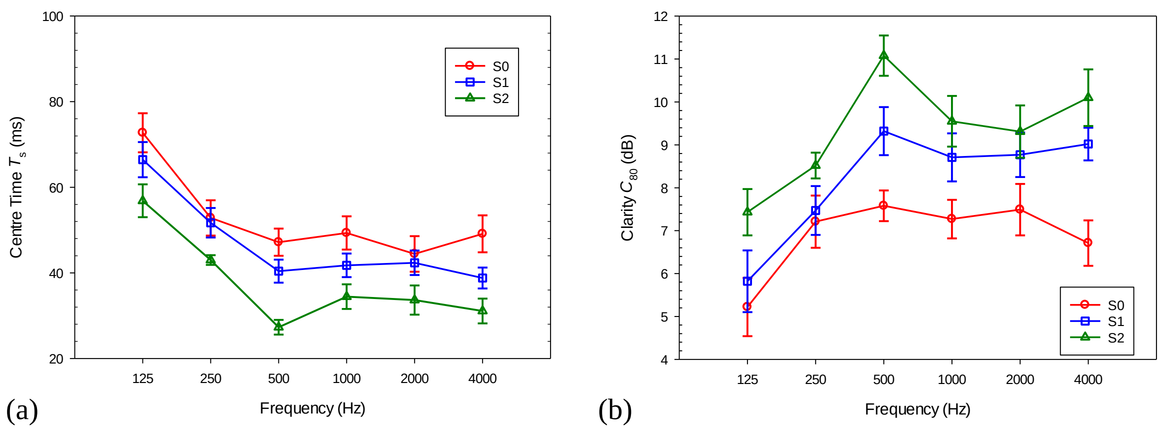

Figure 4 – (a) Measured Centre Time, T_S, and its standard error versus frequency octave band for the three sources. (b) Measured Clarity, C_{80}, and its standard error versus frequency octave band for the three sources.

An analysis is then carried out of the word definition parameters (D_{50}), which studies the ratio of the initial and total acoustic energy and the speech intelligibility parameter (STI).

Figure 5(a) shows the spectral dependence of the energy parameter in octave bands for the three positions of the sound source. The frequency pattern is the same as for musical clarity, with a strong decrease in the parameter at low frequencies and an increase at mid and high frequencies. According to its range of variation, since the values are above 0.6, the spoken message is perceived properly. The results of the STI parameter complete this analysis as a function of the source-receiver distance for the three sources, Figure 5(b). The results reveal independence from the distance for all the sources, with certain exceptions for the positions near the source, especially for sources S1 and S2. The majority of the locations studied in the *cavea* present a variation of the parameter ranging from 0.60 to 0.75 and therefore the intelligibility of the word can be classified as *good* throughout the space on the stage.

In Figures 6(a) and 6(b), the parameters associated to the sensation of spatiality of sound, J_{LF} and $IACC_E$, are analysed.

The J_{LF} parameter is the ratio between the energy that arrives laterally in the first 80 ms after the direct sound and the energy received in all directions in that interval. This is subjectively correlated with the apparent width of the source. The typical range, according to ISO [15], is from 0.05 to 0.35. Figure 6(a) shows that the results of the parameter even within the typical range are located in the lower values of the range, especially for the position of source S2 in the *orchestra*. The best results are obtained for source S1 at low frequencies.

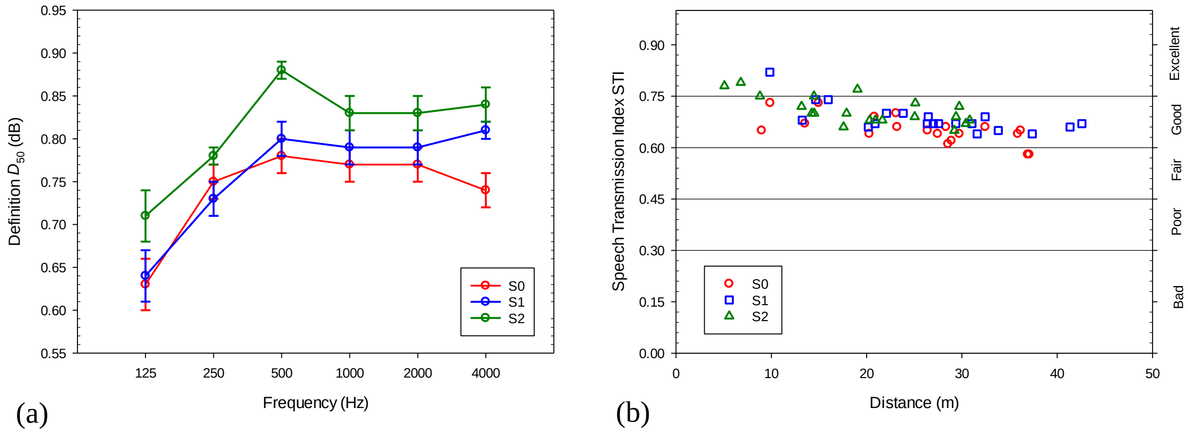

Figure 5 – (a) Measured Definition, D_{50}, and its standard error versus frequency octave band for the three sources. (b) Measured Speech Transmission Index, STI, versus source-receiver distance for the three sources.

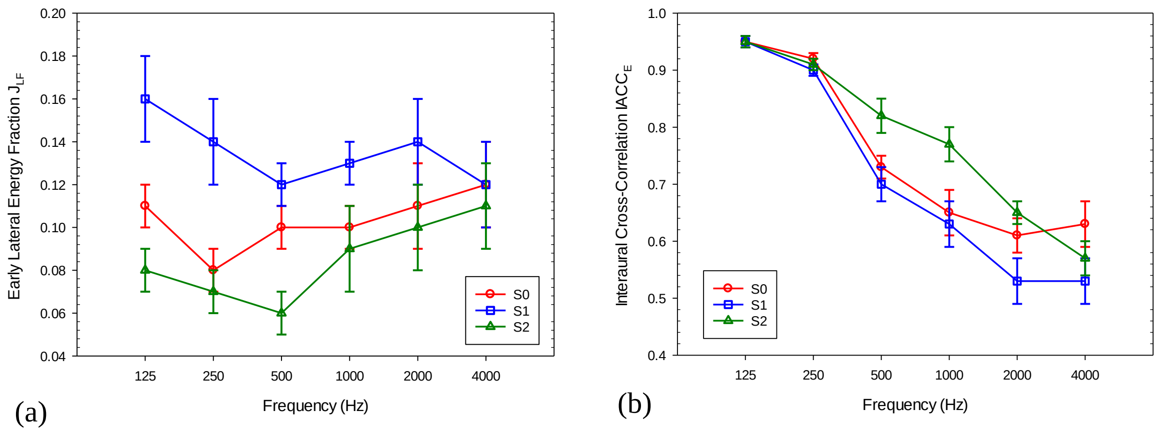

Figure 6 – (a) Measured Early Lateral Energy Fraction, J_{LF}, and its standard error versus frequency octave band for the three sources. (b) Measured Early Interaural Cross-Correlation coefficient, $IACC_E$, and its standard error versus frequency octave band for the three sources.

The $IACC_E$ parameter provides the correlation between the sounds that reach both ears, that is, it indicates the degree of similarity between the two signals in the initial 80 ms. For the $IACC_E$ to be 1, the signals must be the same; if it is 0, the signals are totally random. As shown in Figure 6(b), all values are above 0.5 and therefore, in all cases, the signals that reach the public are very similar for either ear, and there is no major subjective sensation of apparent source width, which is related to the value of (1-$IACC_E$).
Finally, the analyses of the values of Sound Strength (G) and the Late Lateral acoustic energy levels (L_J) are performed.

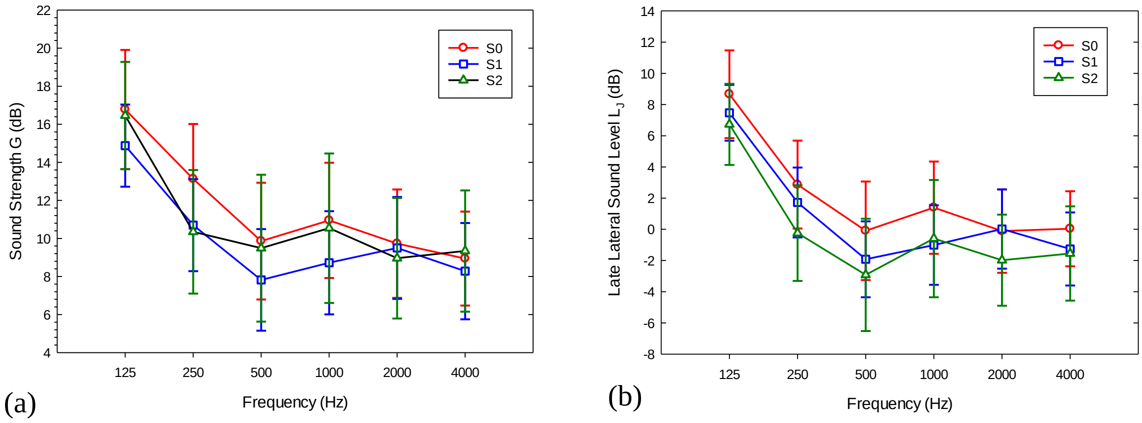

Figure 7 – (a) Measured Sound Strength, *G*, and its standard error versus frequency octave band for the three sources. (b) Measured Late Lateral Sound Level, L_J, and its standard error versus frequency octave band for the three sources.

The *G* parameter measures the degree of amplification produced by the room, and is defined as the difference between the total sound pressure level produced by an omni-directional source at a certain point in a room and the sound pressure level produced by the same source located in free-field conditions and measured at a distance of 10 m. According to the ISO standard [15], the typical range is from -2 dB to 10 dB. As can be observed in Figure 7(a), all values are within the typical range except at low frequencies, which have an amplification of between 5 and 7 dB.

The L_J parameter measures the degree of sound diffusion, that is to say, the enveloping sensation of the sound field perceived by the listener within the room. The range of typical values for this parameter according to the ISO standard [15] is from -14 to 1 dB. As with the *G* parameter, on observing Figure 7(b), all the values fall within the typical range except at the low frequencies that appear amplified between 5 and 8 dB. In both parameters, the spatial dispersion is large. This amplification in the two parameters may be due to the size of the Roman theatre and the high value of the reverberation time.

4.3 3D Room Impulse Responses

IRIS software [19] provides a plot of 3D impulse responses that shows sound energy arriving at the receiver position (the origin) as a series of vectors: the length of each vector indicates the level, the angle indicates the incoming direction, and the colour corresponds to the time of arrival.

The four tetrahedral cardioid signals from the TetraMic are converted into another 3D system called the first-order B-format. B-format encodes the pressure (omni-directional) and three particle-velocity (figure-of-8) signals in the X, Y, and Z directions. IRIS software identifies the relevant part of the recording for analysis: this runs from the onset of the direct sound to when the impulse response decays into noise. The octave–band-filtered B-format impulse response is then divided into a series of non-overlapping rectangular windows. The length of these windows is determined by the speech time intervals. The recommended resolution is 2 ms, which introduces a low frequency limitation, and therefore the plot only shows frequencies of 500 Hz and higher.

The RMS sound pressure level for each window is calculated. The “Level Reference” determines 0 dB for the direct sound. The dynamic range is selected at 40 dB and this may be adjusted in 10 dB increments. Vectors of levels less than -40 dB are ignored and are not displayed. The average direction of sound energy flow at each window is determined by using a sound-intensity technique: this is the product of pressure and particle velocity.

There are three options for colouring the spikes according to their time of arrival: red for the direct sound (0-2 ms) so that the direction of the red vector is the same as that of the source-receiver distance line; green (2-50 ms) and dark blue (50-80 ms) for the early reflections; and light blue (80-*Inf* ms) for the late reflections. *Inf* is the actual time that the IRIS software stops analysing the impulse response: the point at which the signal decays into noise.
The set of plotted graphs in Figure 8 shows the 3D RIRs for 3 receivers belonging to the *orchestra* (R07), the *ima cavea* (R11), and the *summa cavea* (R18) of the theatre, which were all filtered at the frequency of 1 kHz, for the three source positions.

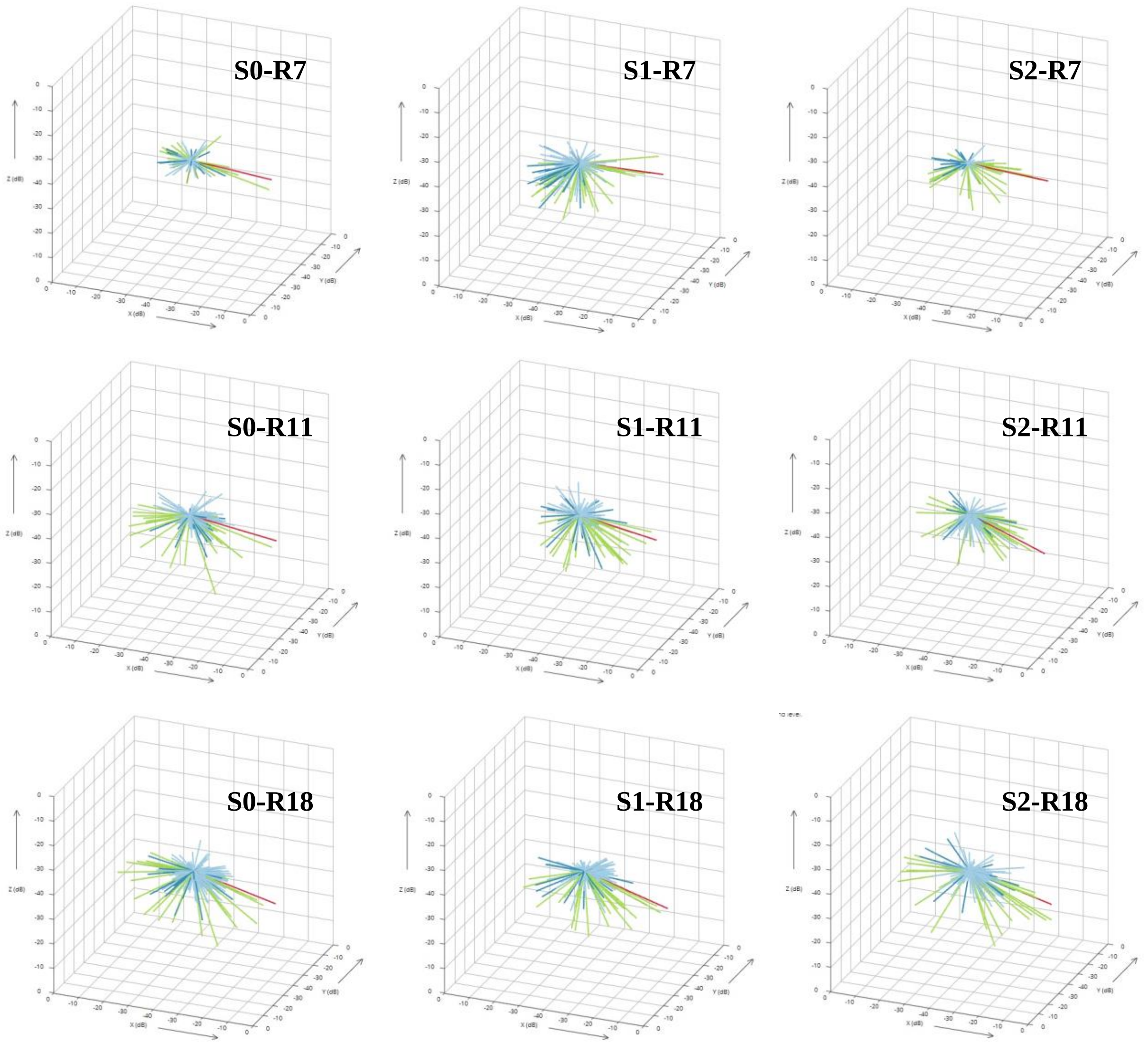

Figure 8 – 3D RIRs in 3 receivers belonging to the *orchestra* (R07), the *ima cavea* (R11), and *summa cavea* (R18) of the theatre, filtered at the frequency of 1 kHz, for the three source positions.

For all the cases, reflections in the 2-50 ms time interval, which is related to the intelligibility of speech, correspond to the contributions of the *orchestra* floor and the steps nearest to the *cavea*. These reflections are unevenly spatially distributed. For the S0 and S2 sources, centred on the *scaena* and in the *orchestra*, there is a clear trend of reflections from three directions (behind, below, and directly facing), and less contribution from the lateral directions, which is why these receivers register a less

immersive sound. This trend is less pronounced for the R7 receiver due to its location being less central.
By expanding the range to 80 ms, whose interval is related to musical clarity, the contribution of lateral reflections increases. For the remaining reflections, the late energy becomes more diffuse. The reduction of late response times, above all for the points nearest to the source and for source S2, validates the behaviour of T_{30} in terms of the source.
When the source is located on the side of the *scaena*, S1, the sensation of spatiality increases considerably in all cases, as reflected in the values of the parameters related to spatial sensation.
It must be taken into account that the 3D plots are intrinsically related to the location of the receiver within the enclosure, and that therefore the amount of energy within each interval and its spatial distribution remains unique. By way of example, Figure 9 shows the 2D diagrams that correspond to the S1-R18 combination in the 1 kHz octave band. As expected, most of the reflections beneficial for music clarity and word definition come from the left-hand side of the *cavea*.

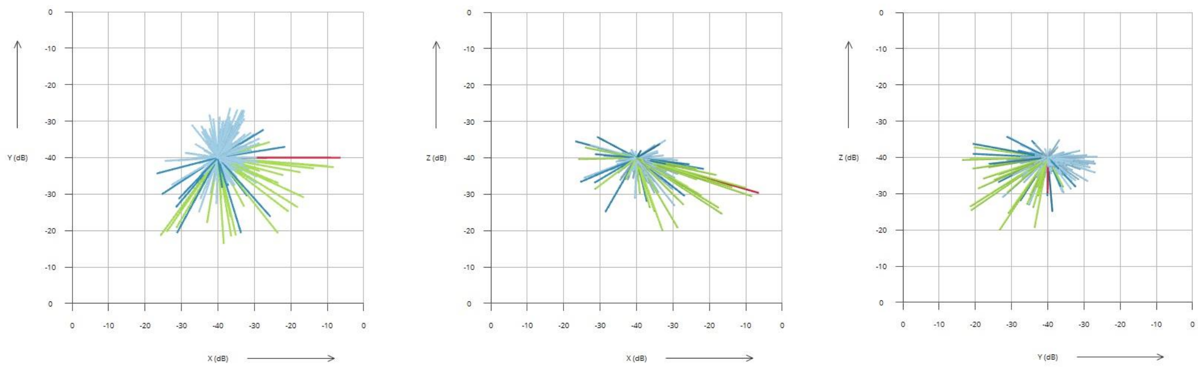

Figure 9 – 2D diagrams XY, XZ, and YZ for the combination S1-R18 in the 1 kHz octave band.

5 Conclusions

In this research, the acoustic behaviour of the Roman theatre in Cartagena has been described. To this end, the main temporal and energy acoustic parameters derived from the monaural and binaural impulse responses have been obtained for three positions of the sound source. The values of these parameters characterise the spectral behaviour and the spatial distribution of the sound field of the theatre. The parametric analysis described, and the pattern of the omni-directional and directional initial reflections, have been validated through 3D characterisation which provides the direction, temporal distribution, and energy of the reflections that reach the microphone, thereby achieving a better understanding of the behaviour of the sound within the enclosure. The results show great uniformity in the intelligibility of the word across the entire area of the audience of the *cavea* for the three source positions studied, and, in all cases, the intelligibility can be considered *good*. As for musical clarity, despite certain differences in the values of the parameter according to the position of the sound source, at all the positions, the values attained are either higher or of the order of that obtained in modern auditoriums, which guarantees the use of the venue for drama and classical music events.

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