

VIRTUAL ACOUSTIC RECONSTRUCTION OF THE ROMAN THEATRE OF PALMYRA

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ABSTRACT

In this paper, the creation process, adjustment, and validation of the 3D model of the Roman theatre of the monumental Syrian city of Palmyra is analysed in order to simulate its sound field. Given the impossibility of carrying out on-site measurements, the acoustic simulation is based on a 3D model made from photogrammetry, blueprints, and photographs obtained from the web and from the previous studies of the group on the Roman theatres of Itálica (Seville, Spain) and Regina Turdulorum (Badajoz, Spain). Due to the special shape of the cross-section of the *cavea* of this theatre, a study has been carried out on the influence of the dispersion of reflected sound in the objective acoustic parameters.

RESUMEN

En esta comunicación se analiza el proceso de creación, ajuste y validación del modelo 3D del teatro romano de la ciudad monumental siria de Palmira para simular su campo sonoro. Dada la imposibilidad de realizar medidas in situ, la simulación acústica está basada en un modelo 3D realizado a partir de fotogrametría, planimetría y fotografías obtenidas de la web y en los trabajos anteriores del grupo sobre los teatros romanos de Itálica (Sevilla, España) y Regina Turdulorum (Badajoz, España). Debido a la especial forma de la sección de la *cavea* de este teatro, se ha realizado un estudio de la influencia de la dispersión del sonido reflejado en los parámetros acústicos objetivos.

THE CITY OF PALMYRA

According to Plinio's testimony [1], the city of Palmyra, located in the Syrian steppe, benefitted from its location between the Euphrates River and the cities of western Syria (Homs, Damascus, Bosra) and the Mediterranean coast (Figure 1).

Palmyra was originally a settlement located in an oasis called Tadmor in the northern part of the Syrian Desert. Although the Roman province of Syria was created in 64 BC, the inhabitants of Tadmor (Arabic name of the same Aramaic word "Palmyra"), mainly Arameans and Arabs, remained semi-independent for more than half a century, benefitting from their control of the caravan routes between the Roman coast of Syria and the empire of Parthia to the east of the Euphrates, which enabled them to provide the Roman Empire with goods from all directions. Palmyra was strategically located on two of the most important trade routes of the ancient world: one stretched from the Far East and India to the head of the Persian Gulf, while the other route (the Silk Road) extended all over the Eurasian continent up to China.



Figure 1. General map of Palmyra. (Drawing from Thibaud Fournet).

Under the Roman emperor Tiberius (14-37 AD), Tadmor was incorporated into the province of Syria and adopted the name Palmyra, "city of date trees" (Figures 2 and 3). After the Roman invasion of Nabataea in 106 AD, Palmyra replaced Petra as the leading Arab city in the Near East and its most important commercial centre. Around 129 AD, during the reign of Hadrian, Palmyra ascended to the rank of a free city, and in 212 AD to that of a Roman colony. With the founding of the Sasanian Empire of Iran in 224 AD, Palmyra lost control of the commercial routes, but Septimius Odaenathus, head of a prominent Arab family that was an ally of the Roman Empire, directed two campaigns against the Sasanians and drove them out of Syria. When Odaenathus was assassinated in 267 AD, his Arab queen, Zenobia, declared herself Augusta (Empress) and ruled in the name of her son, Vaballathus. Zenobia established Palmyra as the capital of an independent empire and expanded its borders by conquering Lower Egypt, Syria (region), Palestine, Anatolia and Lebanon. Her government did not last long however: in the year 272 AD, Emperor Aurelian reconquered Palmyra and captured Zenobia. To celebrate his triumph, he paraded its queen, Zenobia, dressed in jewels and fettered in gold chains so heavy that she needed servants to move them. 'The haloed prisoners of greatness constituted solid proof of the splendour of victory', writes Mary Beard [2].



Figure 2. Theatre of Palmyra in the Decumanus. (National Geospatial-Intelligence Agency, Bethesda, MD, USA).



Figure 3. Theatre of Palmyra in the Decumanus. On the left the Tetrapylon. (www.historiayarqueologia.com).

That date marked the end of Palmyra's great prosperity and the beginning of its decline, but not its demise. Palmyra never regained its previous power, but did remain a major city. With the passage of time it became a bishopric and the city sent a bishop to the Council of Nicea in 325 AD and again in 351 AD to the council of Chalcedon.

The recognition of the splendour of the ruins of Palmyra by travellers in the seventeenth and eighteenth centuries [3] contributed greatly to the later revival of classical architectural styles and urban design in the West. The first excavations of Palmyra were made in 1902 by Otto Puchstein and in 1917 by Theodor Wiegand. In 1929, the director general of antiquities in Syria and Lebanon, Henri Arnold Seyrig, began excavating the ruins and convinced the villagers to move to a new village built by the French near the site. The relocation was completed in 1932; the old Palmyra was ready to be excavated while its villagers settled in the new town of Tedmur. The excavation of the site, interrupted by the Second World War, resumed shortly after the end of the war.

Since 1980, it has been registered as an archaeological site on the Unesco World Heritage List. On 20 June, 2013, Unesco included all the Syrian heritage sites on the list of endangered World Heritage Sites to warn of the risks to which they would be exposed due to the Syrian civil war [4].

THE ROMAN THEATRE OF PALMYRA

The unfinished theatre of Palmyra [5] dates back to the 2nd century AD. It was built in the centre of a semi-circular arcaded square that opens to the south gate of Palmyra (Figures 3 and 4). The square, completely flanked by columns, measuring 82 by 104 m, is located southwest of the city's Decumanus, which runs from the monumental arch, access gate in the southeast of the city, to the Tetracylon, in the northwest of the city (Figure 3).

Its stage front, in carved stone, has the royal vault located in a wide curved recess and two *hospitularium* doors in shallow rectangular recesses. It also has two additional doors at the ends of the *scaenae frons*. The wall of the stage therefore has five entrances through which actors acceded to the stage. The sides of the *scaenae frons* are closed by walls (*versurae*) that also have access doors that led to the stage from the rooms or side basilicas; their columns are of Corinthian order. The *Decumanus*, flanked by columns, functions as a type of *porticus post scaena* (Figure 5).

Its *proscenium* has ten curved niches, nine rectangular niches and two access staircases to the *pulpitum* from the orchestra. This large number of niches is a characteristic of the second and third centuries, especially in the East. The *pulpitum* dimensions are 45.5 m x 10.5 m.

The unfinished tier, executed in carved stone, only has the *ima cavea* of 12 rows, divided into 11 *cunei* by 10 staircases. It had a planned diameter of 92 m. The theatre has a central corridor in the *cavea* that bisects it (Figures 5 and 6) and allows direct access from the exterior square behind the theatre into the *orchestra* (Figures 5 and 6). This access must have been for the exclusive use of the most influential spectators of Palmyra who would sit in the *proedria* of the theatre and for those who occupied the lowest seats in the *ima cavea*. In other words, it complemented or replaced the *aditus maximi* as a means of privileged entry. The *aditus maximi* of the theatre, with its main entrances, is 3.5 m wide and leads to the *orchestra* paved in

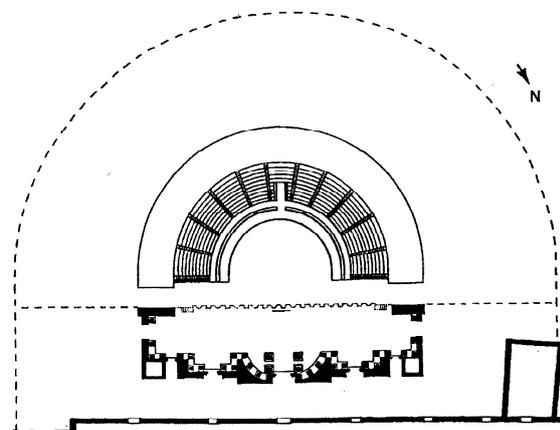


Figure 4. Ground plan of the Roman Theatre of Palmyra.
(F. Sear. Roman Theatres. An Architectural Study).

carved stone, with a diameter of 23.50 m. It is bounded by a wall (*balteus*) of 20.30 m in diameter, which forms a *praecintio* of 1.60 m in width (Figures 6 and 7).

In the 1950s, the theatre was cleared of sand and later underwent restoration work. It should be noted that the theatre of Palmyra, studied by Puchstein between 1902 and 1917, is highly reconstructed rather than restored and, therefore, has been the object of many academic concerns regarding the historical authenticity of the current structure of the building [6].

It served as the venue for the annual festival of Palmyra, hosting performances of folk music until the beginning of the civil war in Syria.



Figure 5. The Roman theatre of Palmyra. Colonnade of the *Decumanus*. Top left: the *Tetrapylon*. (www.flickr.com/photos/newpalmyra).

EXPERIMENTAL METHOD

In order to adapt the acoustic conditions of simulation to those of a real situation, the model has been adjusted using the absorption and dispersion coefficients of the materials used in the acoustic studies of the Roman theatres of Itálica [7] and of Regina Turdulorum [8]. In both theatres, acoustic measurements were made in situ with the theatres unoccupied. In both measurements, the environmental conditions were monitored by measuring temperature and relative humidity, and the recommendations of ISO 3382-1:2009(E) [9] were followed.

The process of generating the frequency exponential sweep signal to excite the theatre, the acquisition, and the analysis of the IR were carried out with the WinMSL2004 programme in Itálica and with Dirac 5 in Regina Turdulorum through the Edirol UA-101 sound card. The signal generated was emitted by the AVM DO-12 dodecahedral source with a B&K 2734 power amplifier, the sources were located at 1.50 m above the floor of the *proscenium* and in the *orchestra*, and were recorded at the reception points distributed by the *cavea*, the *proedria* of the *orchestra* and in the *proscenium*. The monaural IRs were collected using a multi-pattern microphone (omnidirectional



Figure 6. Cavea of the Roman theatre of Palmyra.

Photograph from Bernard Gagnon, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=12198409>



Figure 7. Wall of the stage. Roman theatre of Palmyra.

Photograph from Guillaume Piolle, CC BY 3.0, <https://commons.wikimedia.org/w/index.php?curid=11304940>

Table 1. Geometry of the theatres [5].

Theatre	Orchestra diameter (m)	Cavea diameter (m)
Regina Turdulorum	19.60	64.00
Palmyra	23.50	46.82
Italica	25.40	75.76
Jerash South	19.91	76.00
Syracuse	21.40	138.50
Aspendos	23.87	95.48

and figure-of-eight) Audio-Technica AT4050/CM5 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 a height of 1.20 m from the ground.

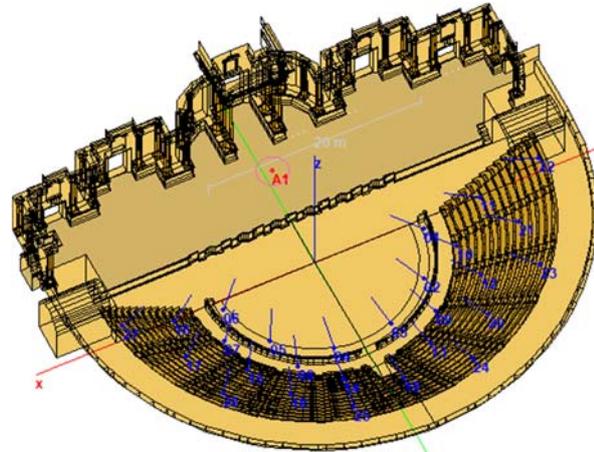


Figure 8. Computer model of the theatre of Palmyra.

Table 1 contains a summary of the geometry of the three theatres. It also shows the three theatres studied in the ERATO project.

ACOUSTIC MODEL AND SIMULATION

The acoustic simulation has been carried out using the CATT-Acoustic v9.1a programme [10], based on geometric acoustic algorithms. The model is constructed from photogrammetry, planimetry, and photographs obtained from the web. For the geometric survey, a three-dimensional model has been generated by the SketchUp programme, and exported to CATT-Acoustic through the SU2CATT v 1.3 plugin. The final model consists of 5,629 plans.

The simulations were carried out by considering the case of an open model, with the source centred on the *proscenium*, and by recording the signal at the 27 reception points distributed across the *cavea* (Figure 8).

The meteorological conditions used for the simulation have been taken from the 2013 publication ASHRAE Handbook-Fundamentals [11]. Table 2 collects the data used:

Table 2. Meteorological conditions of the simulation.

Temperature (°C)	Relative Humidity (%)	Pressure (Pa)	Air density (kg/m ³) [12]
22.4 °C	51	96,560	1.13

Results have been obtained with the TUCT v2 (The Universal Cone Tracer) calculation engine, which calculates the acoustic parameters from energy (E) and/or B-format and binaural impulse responses (h) based on the evaluation of sound pressure. In the simulation process, complete simulations were launched with 1,000,000 rays and an echogram duration of 1,500 ms, superior to the estimated reverberation time of 1,000 ms, and used the TUCT algorithm 2.

Table 3 shows the absorption and dispersion coefficients finally assigned to the surfaces, the associated colours in Figure 9, and the bibliographic references used.

Table 3. Coefficients of absorption (top) and dispersion (below), at octave bands, of the materials for the simulation.

Surface, [reference]	Colour (Fig. 9)	Absorption and dispersion coefficients					
		125	250	500	1k	2k	4k
Land, [13]		0.15	0.35	0.40	0.50	0.55	0.80
		0.20	0.25	0.30	0.40	0.50	0.60
Stone, [14] (Dispersion Italica theatre)		0.02	0.03	0.03	0.03	0.04	0.07
		0.61	0.61	0.57	0.44	0.37	0.33
Stone, [14] (Dispersion Regina theatre)		0.02	0.03	0.03	0.03	0.04	0.07
		0.55	0.58	0.62	0.62	0.60	0.56
Stone Cavea, [14] (Dispersion Italica theatre)		0.02	0.03	0.03	0.03	0.04	0.07
		0.61	0.61	0.57	0.44	0.37	0.33
Stone Cavea, [14] (Dispersion Regina theatre)		0.02	0.03	0.03	0.03	0.04	0.07
		0.55	0.58	0.62	0.62	0.60	0.56
Stone columns, [14]		0.02	0.03	0.03	0.03	0.04	0.07
		0.35	0.35	0.45	0.40	0.45	0.50

Table 4 shows the results of the calibration process for the values of T_{30} spatially averaged for the source centred in the *proscenium* and in Figure 9 these values are displayed.

Table 4. Results of the calibration. Values of T_{30} (s), spatially averaged, at octave bands.

Frequency (Hz)	125	250	500	1000	2000	4000
Measured values Italica	1.00	0.98	0.98	1.16	1.17	1.01
Measured values Regina Turdulorum	0.69	0.66	0.64	0.64	0.63	0.56
Palmyra simulated values coef. Italica	0.98	0.92	0.92	1.01	0.98	0.89
Palmyra simulated values coef. Regina	0.96	0.92	0.90	0.89	0.84	0.76
Simulation difference (%)	1.33%	-0.48%	2.21%	12.73%	14.61%	14.01%

It can be observed (Figure 10) that the differences obtained between the two simulations (referred to the values of the simulation carried out with the coefficients of Italica theatre) are less than 5%, that is, lower than 1 JND, in the bands 125-500 Hz. The most significant differences lie in the bands 1000-4000 Hz, whereby they are close to 3 JND for 2000 Hz for the reverberation time T_{30} since, in these bands, the most notable differences appear in the dispersion coefficients.

ANALYSIS AS A WHOLE

Figure 11 shows the spectral behaviour of the differences between the simulated values using different material dispersion coefficients, spatially averaged corresponding to the energy and bin-aural acoustic parameters. In order to compare the differences in the various parameters, they have been expressed in terms of their respective JND.

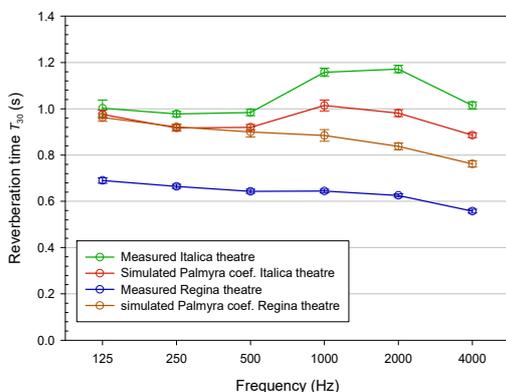


Figure 9. Spectral behaviour, spatially averaged, of T_{30} values. Vertical bars value the spatial dispersion through the standard error.

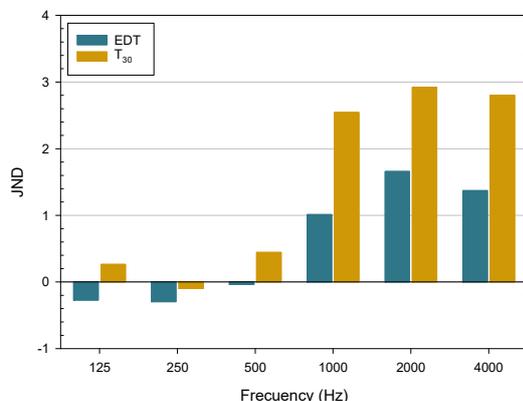


Figure 10. Spectral behaviour of the differences between the spatial average of simulated values of the acoustic parameters T_{30} and EDT.

We can see that these differences, for all parameters, are kept below ± 1 JND for all frequencies.

Figure 12 shows the value of the sound strength G_m , at an average of 500 and 1000 Hz, versus source-receiver distance. We see that both have a linear drop with a slope of -0.48 dB/m and correlation coefficients r^2 equal to 0.84 and 0.87, respectively. The simulated values remain about 6 dB above the trend marked by the theoretical value of G for a free field (Figure 12).

This drop was not observed in the C_{80m} and T_{sm} parameters, as happens in closed enclosures. The simulated values of these parameters remain between 4-8 dB and 30-55 ms, respectively.

Table 5 summarizes the values of the acoustic parameters, spatially and spectrally averaged in accordance with ISO 3382-1 [9], of the unoccupied theatres, from the ERATO project [15] and those of Italica, Regina Turdulorum, and Palmyra. Only acoustic measurements have been carried out in Aspendos, Italica and Regina Turdulorum, the remaining measurements are simulated by computer.

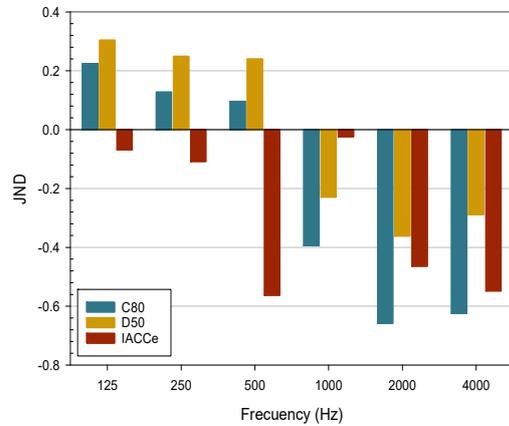


Figure 11. Spectral behaviour of the differences between the spatial averages of simulated values of the acoustic parameters: C_{80} , D_{50} , and $IACC_E$.

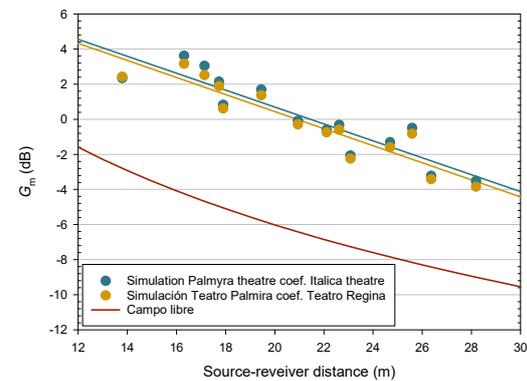


Figure 12. Variation of the spectral simulated value of G_m (average of 0.5 and 1 kHz) against source-receiver distance.

Table 5. Values of the acoustic parameters of theatres from ERATO project and those from Italica, Regina, and Palmyra spatially and spectrally averaged in accordance with ISO 3382-1.

	T_{30m} [s]	G_m [dB]	C_{80m} [dB]		T_{30m} [s]	G_m [dB]	C_{80m} [dB]
Aspendos	1.89	-4.37	2.68	Italica	1.07	-0.71	8.09
Jerash South (*)	1.21	-1.18	5.98	Regina Turdulorum	0.64	-0.10 (*)	10.62
Syracuse (*)	1.25	-10.60	12.88	Palmyra coef. Italica (*)	0.97	0.17	6.33
				Palmyra coef. Regina (*)	0.89	-0.08	6.48

(*) Values obtained by simulation.

CONCLUSIONS

The historical, archaeological, architectonic, and heritage value of the Roman theatre of Palmyra, Syria, has been documented from bibliographic bases, and the acoustic behaviour of the aforementioned theatre has been characterised. A 3D model has been developed for the simulation of the sound field. This theatre has been simulated using the coefficients of absorption and dispersion of the materials used in the acoustic studies of the Roman theatres of Italica and Regina Turdulorum, whose models were adjusted by testing dispersion coefficients for the different materials, especially in the cavea.

We analysed the spectral behaviour of the acoustic parameters T_{30} , EDT, C_{80} , D_{50} , and $IACC_E$, spatially averaged and, where appropriate, the variation with the source-receiver distance of the

spectral parameters G_m , C_{80m} , and T_{Sm} . In this respect, it has become clear that the G_m values present an attenuation with distance that is approximately linear, however, similar behaviour has not been observed with other parameters (such as those of clarity), which in closed spaces usually appear.

Several of the parameters (simulated), spatially and spectrally averaged in accordance with ISO, have been compared with the values published for three theatres investigated in the ERATO project, and for Italica and Regina Turdulorum, and show that parameters from Palmyra are similar to other analogous classical spaces.

One aspect to be studied in the future would involve the use of models generated for sensory evaluation through auralisations.

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