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THE ERATO PROJECT AND ITS CONTRIBUTION TO OUR UNDERSTANDING OF THE ACOUSTICS OF ANCIENT GREEK AND ROMAN THEATRES

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Abstract. The ancient Greek and Roman theatres are famous for the excellent acoustics. However, it is not generally well known that different kinds of theatres were built, for different purposes and with different acoustical conditions. One of the aims in the ERATO project has been to investigate the acoustics of the open air theatres and compare to the smaller, originally roofed theatres, also called odea (from Greek: *Odeion*, a hall for song and declamation with music). The method has been to make computer models of the spaces, first as they exist today, and adjust the acoustical data for surface materials by comparison to acoustical measurements from some of the best preserved examples, namely the Aspendos theatre in Turkey and the South theatre in Jerash, Jordan. Next step was to complete the computer models in accordance with archaeological information, to make virtual reconstructions of the spaces. The acoustical simulations have given a lot of interesting information about the acoustical qualities, mainly in the Roman theatres, but the earlier Greek theatre has also been studied in one case (Syracusa in Italy). It is found that the Roman open-air theatres had very high clarity of sound, but the sound strength was quite low. In contrast, the odea had reverberation time like a concert hall, relatively low clarity, and high sound strength. Thus, the acoustical properties reflect the original different purposes of the buildings, the theatre intended mainly for plays (speech) and the Odeon mainly for song and music.

1 INTRODUCTION

The main objectives of this research are identification, virtual restoration and revival of the acoustical heritage in a few, selected examples of the theatre and the roofed odeum in a 3D virtual environment. The amphitheatres with their clearly different purpose were included in this project. The virtual restitution integrates the visual and acoustical simulations, and is based on the most recent results of research in archaeology, theatre history, clothing, theatre performance and early music.

This paper will focus on the acoustical results. The acoustical simulations were made with the room acoustic software ODEON ver. 7.0, developed at the Technical University of Denmark.

2 THE SELECTED THEATRES AND ODEA

Five spaces have been selected for virtual reconstruction in the ERATO project: Three theatres, see Fig. 1, and two odea, see Fig. 2. Acoustical measurements were made in the best preserved theatres in Aspendos and Jerash. In the theatre of Syracuse and the two odea the state of preservation was not sufficient to make acoustical measurements meaningful.

The Odeon in Aosta was selected because this is the only known example where some of the outer walls still exist in full height. The Odeon in Aphrodisias was selected because there was very good and detailed information available from the archaeological excavations, and many of the interior details like statues and marble floor in the orchestra still exist.

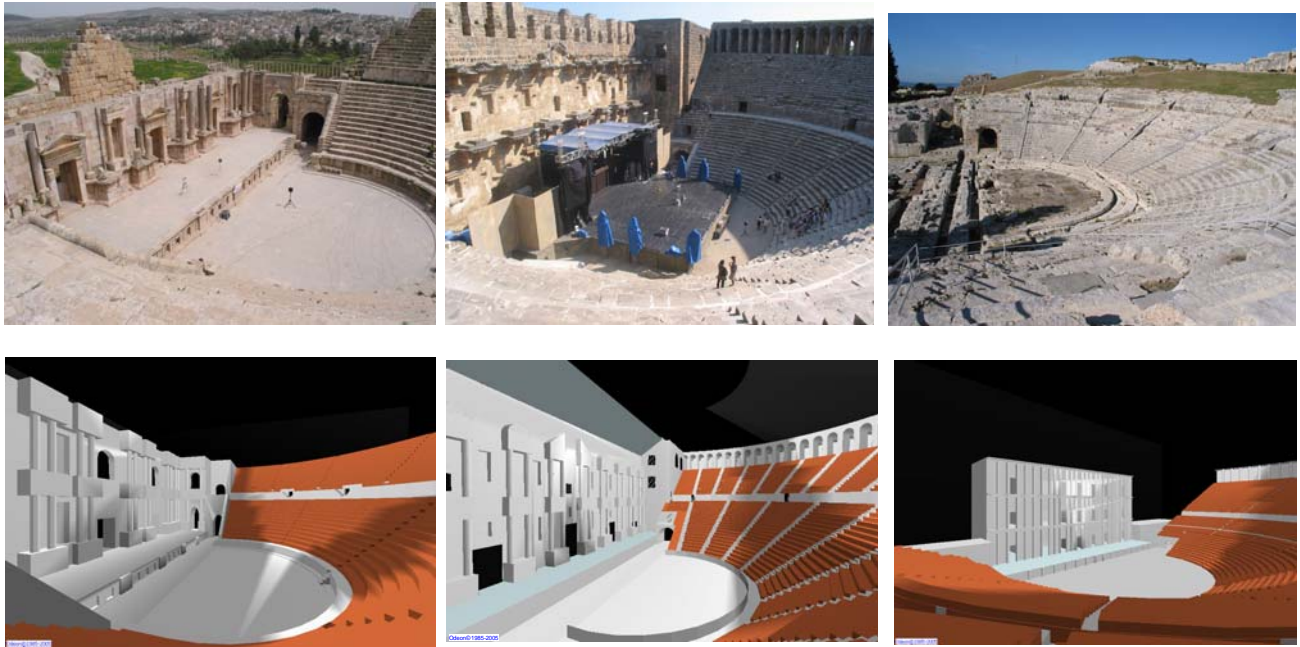


Figure 1. Above: Photos from the three selected theatres, below: View from computermodels, reconstructed for the Roman period. Left: Jerash, Middle: Aspendos, Right: Siracusa.



Figure 2. Above: Photos from the two selected odea, below: View from computermodels, reconstructed for the Roman period. Left: Aosta, Right: Aphrodisia.

3 ROOM ACOUSTICAL PARAMETERS

The following room acoustical parameters have been calculated in order to give an impression of the acoustic environment in the five theatres of the project.

The EDT (Early Decay Time) parameter has not been analyzed in depth since there have been large variations in the calculation values in certain open-air theatres. The reason is that the sound field in the open-air theatres is very far from diffuse and the calculations require a certain number of reflecting surfaces to calculate a reliable energy decay curve. If the reflection paths are few (as in the case of the Syracuse theatre in its present state) the EDT is difficult to predict giving too large variations.

The selected room acoustical parameters analyzed here are the following (for a more detailed description of each parameter see [1]):

- Reverberation time T_{30} : This parameter give us an indication of the reverberance of the room by the number of seconds it takes for a sound to decay to inaudibility after being stopped. Reverberance gives a richer sound and liveness preferable for performance of music but unfavourable for the representation of speech. The optimum reverberation time for symphonic music in a concert hall at mid frequencies is between 1,7-2,3 s.
- Strength G : The sound strength G is the level of the perceived sound in a room compared to the level in free field at 10 m from the source. This relative sound pressure level will generally be greater in a more reverberant room giving the sense of louder sound. It is recommended that the strength in a concert hall is greater than +3 dB.
- Clarity C_{80} : This is the balance between the early and late arriving energy, using a delay of 80 ms to separate the two parts. The larger this value, the more distinct the speech and music will be, separating the initial sounds from the diffuse ones and making the discrete sounds stand apart from each other. In a complete diffuse field this parameter has a perfect correlation with the reverberation time. But in a sound field which is not completely diffuse it can provide new meanings. Recommended values in a concert hall are between -1 and 3 dB.
- Speech Transmission Index STI : This represents the degree of amplitude modulation in a speech signal. It shows the distortion in speech signals caused by reverberation, echoes and background noise. STI can take values between 0 and 1, and the speech conditions are considered acceptable for values greater than 0,5.

In order to get reliable results all the simulations were carried out with 3 source positions and 15 receiver positions. This means 45 data sets for each parameter in each of the 8 frequency bands except in the Aphrodisias Odeon in its present state which uses 3 source and 6 receiver positions.

4 ACOUSTICAL RESULTS IN OPEN-AIR THEATRES

The open-air theatres have been used for popular theatre plays and music with an audience representing all social classes. These theatres had a substantially higher background noise from the surroundings and the weather (rain, wind, etc.) making the acoustics somehow poorer compared to the acoustics in the Odea.

The open-air theaters studied in this project have suffered less degradation through time than the Odea. The original materials of these open-air theaters have mainly been hard stone and a few wooden structures.

4.1 Aspendos, Jerash and Syracuse

These three theatres differ in shape and size as well as in cavea slope. In the Roman time, the Aspendos and Syracuse theatres had a colonnade behind the last rows of the cavea and the Aspendos theatre had a Velum (sunscreen over the audience area) made of sail.

In table 1 are shown the acoustical parameters for the three theatres in their different configurations and the cavea diameter to get an idea of the size of each theatre.

Table 1. Calculated parameters in different configurations of the theatres (empty and fully occupied) and their cavea diameter. The parameter values are averaged over all source-receiver positions and over mid-frequencies 500-1000 Hz in 1/1-octave bands

	T30 (s)		G (dB)		C80 (dB)		STI		Cavea Diameter (m)
	Empty	Full	Empty	Full	Empty	Full	Empty	Full	
Aspendos Roman	1,95	1,59	-2,34	-4,36	1,17	4,08	0,53	0,61	95,5
Aspendos Present	1,89	1,53	-4,37	-6,09	2,68	6,53	0,60	0,70	95,5
Aspendos Present (Stage)	1,77	1,43	-4,49	-6,05	4,42	8,27	0,63	0,71	95,5
Jerash Roman	1,54	1,06	-0,72	-3,05	3,46	6,88	0,62	0,70	87,8
Jerash Present	1,21	0,86	-1,18	-3,29	5,98	9,85	0,67	0,75	87,8
Syracuse Roman	1,81	1,67	-6,69	-8,24	4,07	8,25	0,62	0,70	138,6
Syracuse Present	1,25	0,97	-10,60	-11,61	12,88	18,12	0,88	0,93	138,6

The table shows that the difference in reverberation time between empty and full is about 0,3 - 0,4 s generally in all theatres, Jerash having a slightly bigger difference. The reverberation time when full seems to be more adequate in the roman reconstructions than in the present models.

The overall strength is the highest in Jerash and lowest in Syracuse, partly due to the different slopes and their great difference in cavea diameter.

The clarity is exceptionally high in all the theatres despite the levels of reverberation, and this is due to the lack of roof that make the field more like free field than a diffuse field. As a consequence of this, the STI values are also remarkably high in theory if we neglect the background noise from outside the theatres.

4.2 Reverberation Time T_{30} vs. Frequency

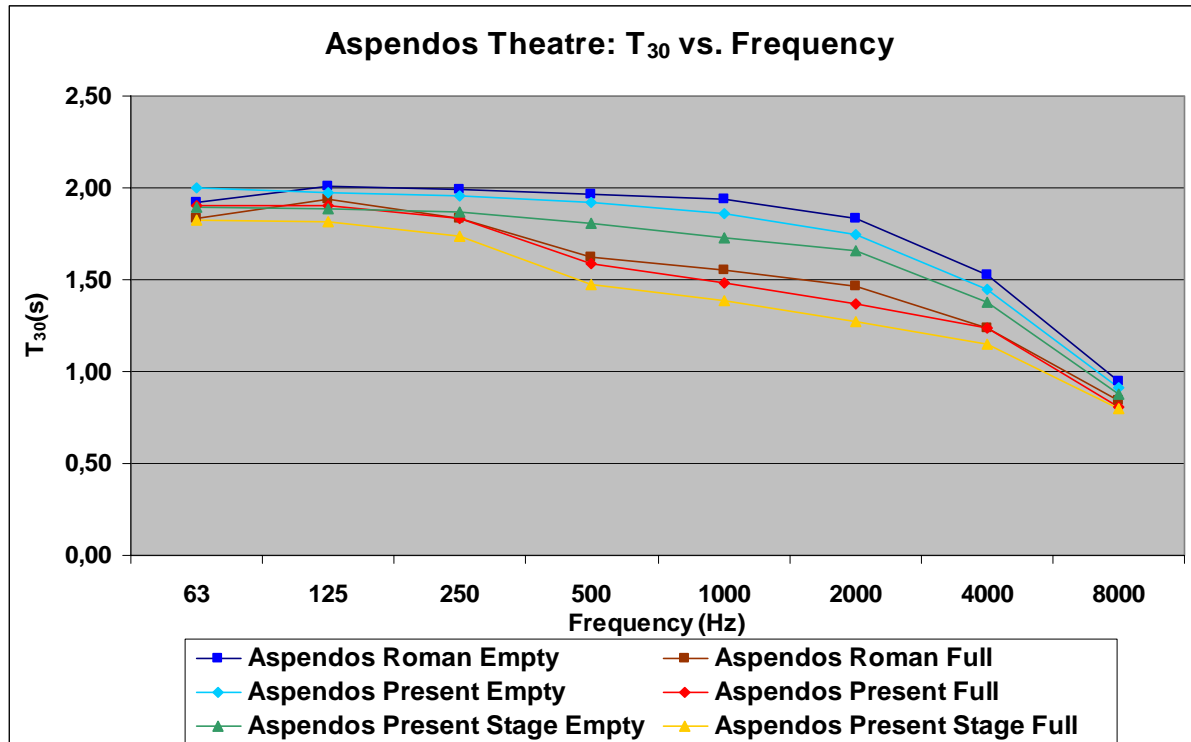


Figure 3. Calculated reverberation time T_{30} as a function of frequency in different configurations of Aspendos Theatre. The parameter values are averaged over all source-receiver positions.

We see in Fig. 3 that for the Aspendos theatre in present state, the modern stage provides a decrease of reverberation time at mid-frequencies, and in the case of the Roman reconstruction (with added velum and stage canopy) there is only minor difference in reverberation.

From Table 1 it is seen that in Jerash theatre the reconstruction of mainly the frons scaenae results in an increase of the reverberation time of around 0,3 s. It is also seen that the Syracuse theatre in the Roman era had around 0,6 s longer reverberation than in the present stage. This is mainly due to the frons scaenae but also the colonnade provided some reverberation.

4.3 Strength G vs. Distance

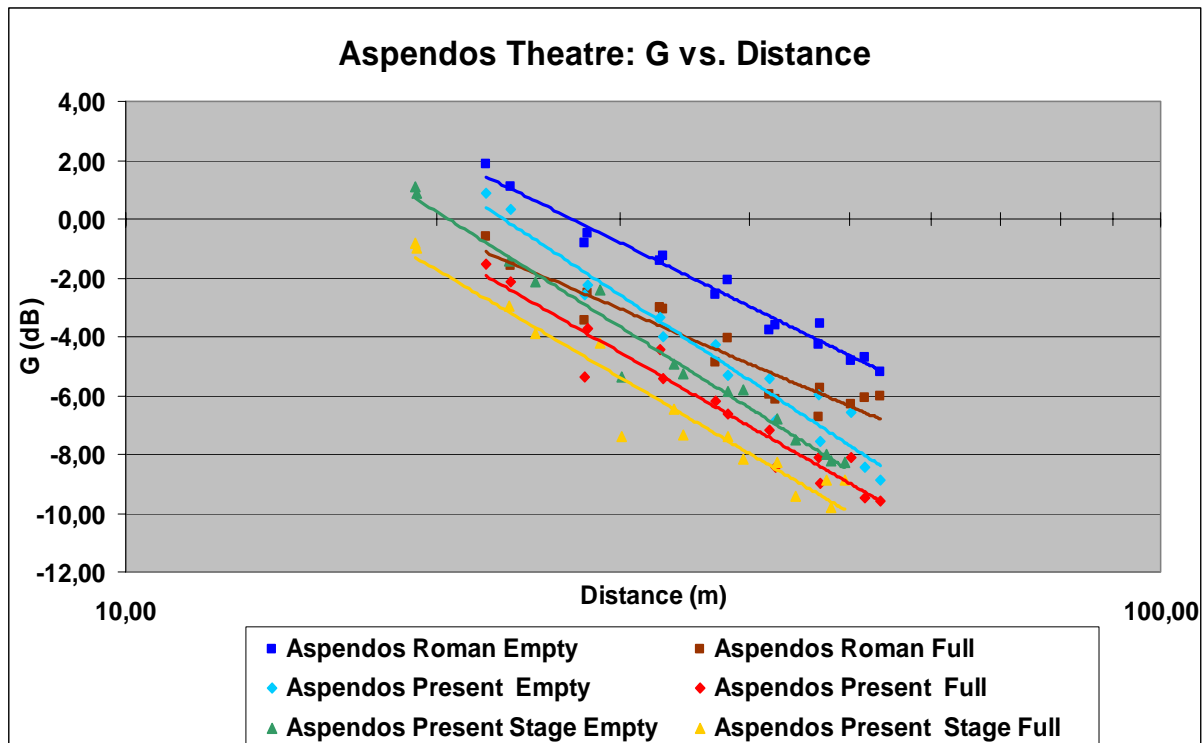


Figure 4. Calculated strength G in different configurations of Aspendos theatre. The parameter values are for one source position and averaged over mid-frequencies from 500-1000 Hz in 1/1-octave bands.

In Fig. 4 is shown the strength G as a function of the distance from source to receiver in the Aspendos theatre. In general the strength is reduced by 2 – 3 dB when the theatre is occupied by an audience. In all cases the strength decreases with the distance, and the attenuation per distance doubling DL2 is around 4,5 dB in the full reconstructed version, and around 6,0 dB in the present condition of the theatre. For the other reconstructed theatres the results are similar.

5 ACOUSTICAL RESULTS IN ODEA

This type of theatres has the property of being closed rooms with wooden roof structures used for more intimate music and theatre plays and often only for an exclusive audience. They have been made of hard materials as stone or marble and they are assumed to have had open windows to the outside for lightning and ventilation. The open windows and the audience seated in the cavea have provided the main acoustical absorption in these buildings. These rooms have thus been over reverberant from an acoustical point of view if we compare them to today standards.

5.1 Aosta & Aphrodisias Odeon

The Aosta and Aphrodisias odea differ mainly in their volume and in their shape. The outer walls of the Aosta Odeon follow a rectangular shape whereas in Aphrodisias Odeon the shape is semicircular following the seating area.

The Aosta Odeon in Roman time had almost double the volume of Aphrodisias Odeon as reconstructed, mainly due to the difference in ceiling height.

Table 1. Calculated parameters in different configurations (empty and fully occupied) of each odea, and cavea diameter. The parameter values are averaged over all source-receiver positions and over mid-frequencies from 500-1000 Hz in 1/1-octave bands.

	T30 (s)		G (dB)		C80 (dB)		STI		Cavea Diameter (m)
	Empty	Full	Empty	Full	Empty	Full	Empty	Full	
Aosta Roman	5,97	3,49	7,14	4,26	-5,28	-2,41	0,36	0,43	59,6
Aphrodisias Roman	4,02	1,62	10,45	5,45	-4,21	1,86	0,38	0,55	45,6
Aphrodisias Present	0,37	0,24	6,42	3,95	15,19	23,21	0,85	0,90	22,5

By comparing the reverberation times of the two odea in Roman time it is seen that Aosta has a longer reverberation time, mainly caused because of the greater volume.

The ruins of the Aphrodisias Odeon in the present have too little surfaces to provide a reverberant field for satisfactory acoustics as it is seen from the table. Aosta Odeon has not been reconstructed in its present state since there is only one wall standing.

In the reconstructed models of the Roman era both odea are over reverberant when they are empty. The Aphrodisias Odeon has a reverberation time T30 when full, which is comparable to the optimum for modern concert halls of similar volume. The Aosta Odeon seems to be over reverberant even when full.

The strength G of both Odea is seen to have optimum values both when empty and full. The clarity C80 of Aosta Odeon is too low mainly because of its high reverberation whereas Aphrodisias has an adequate clarity. The STI values show that the Aphrodisias Odeon is satisfactory for speech when full whereas the Aosta Odeon is just bearable. It has to be mentioned that the background noise level of the audience is not known and has probably caused lower speech intelligibility.

Overall, the calculation results of the reconstructed model of Aphrodisias Odeon have shown an excellent acoustic ambience comparable to modern halls. It is a hall that mainly has been optimal for music but also good enough for theatre plays and chorus.

The Aosta Odeon is less adequate for spoken performances but still acceptable for music.

5.2 Reverberation Time T_{30} vs. Frequency

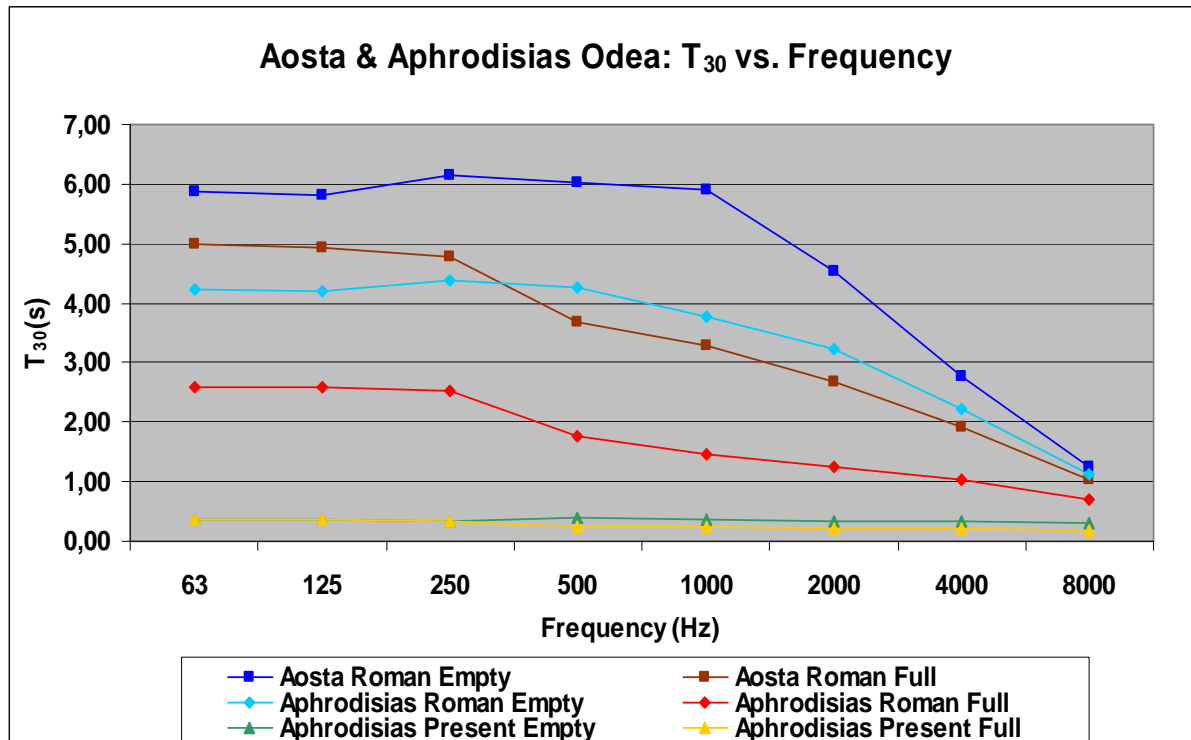


Figure 5. Calculated reverberation time T_{30} as a function of frequency in different configurations of Aosta and Aphrodisias Odeon. The parameter values are averaged over all source-receiver positions.

From figure 5, showing T_{30} as a function of frequency, it is seen that T_{30} decreases with increasing frequency in all the Odea in the Roman configuration. For the Odea fully occupied it is seen that T_{30} decreases most notably at low and mid frequencies, which is due to the absorption from the people. For the 4000-8000 Hz frequency bands there is not a big difference between empty and occupied, and this is due to the air absorption at high frequencies.

5.3 Strength G vs. Distance

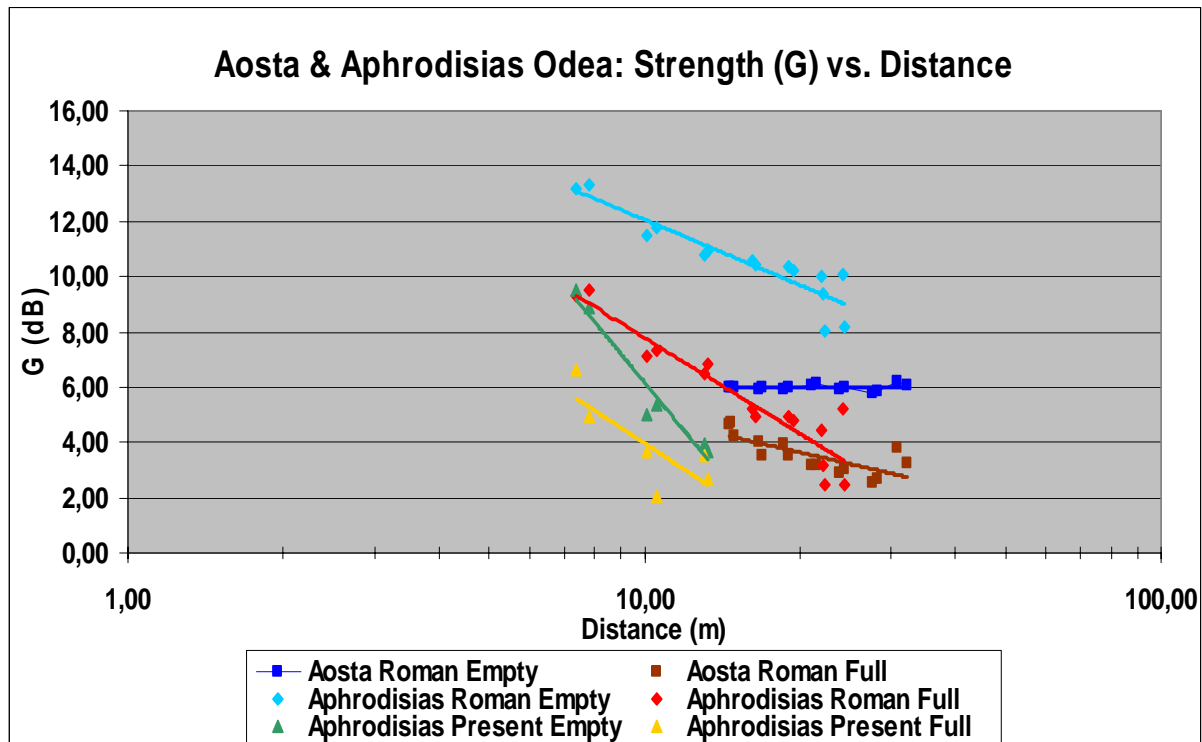


Figure 6. Calculated strength G in different configurations of Aosta and Aphrodisias Odeon. The parameter values are for one source position and averaged over mid-frequencies from 500-1000 Hz in 1/1-octave bands.

Figure 6 shows that G decreases with distance from the source in all the odea. For the case of Aosta Odeon in empty state the G parameter seems to be almost constant with distance. This shows that a more or less diffuse sound field is obtained in this highly reverberant room.

In all the odea it is seen that the strength decreases when the room is full due to the reduced reverberation time.

6 DISCUSSION

The acoustic simulations of the reconstructed spaces show a clear difference between the theatres and the odea. In the theatres the reverberation times are surprisingly long, even with a full audience it is around 1,6 s in the theatres with a colonnade. In Jerash without a colonnade reverberation time is significantly shorter, and this raises the question if it is possible that also the Jerash South theatre had originally a colonnade? The reverberation in the Roman theatres can be explained from the big frons scaenae in closed connection with the auditorium and the surrounding colonnade. This allows high order sound reflections even without ceiling.

In the odea the reverberation time depends strongly on the ceiling height and the size of the windows, which contribute some sound absorption to the spaces. In general there is no firm information available about the ceiling height, and in the case of the Aphrodisias Odeon a moderate height of around 15 m has been assumed, leading to a quite moderate reverberation time of around 1,6 s with audience. However, in the case of Aosta the ceiling height is 21 m, which is defined by

the walls that are still standing, and this leads to a considerably longer reverberation time of around 3,5 s with audience. While the shorter value in Aphrodisias is similar to the reverberation time in a modern concert hall, the longer value in Aosta is more similar to that of a modern church.

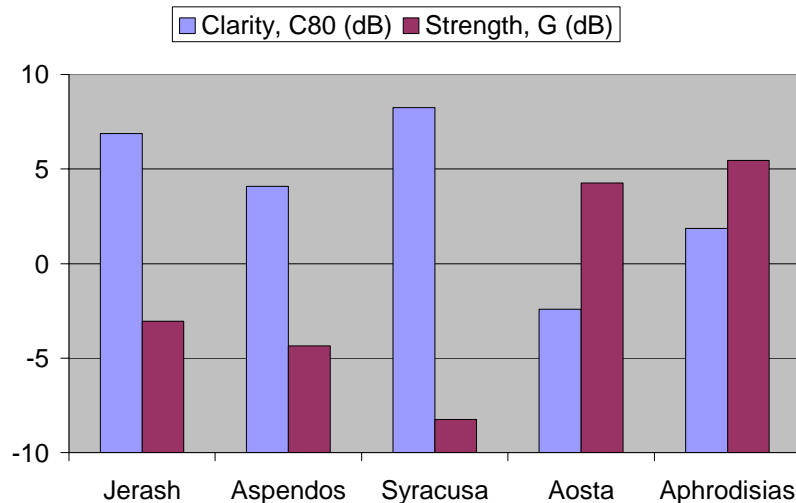


Figure 7. Comparison of the Clarity and the Strength in the reconstructed theatres and odea with a full audience. Average values at mid frequencies for all source-receiver positions.

The acoustics of the reconstructed open-air theatres can be characterised by a very high clarity and a rather low strength of sound, see Fig. 7. The sound strength decreases with distance, and more so if there is no colonnade. The acoustics of the reconstructed odea are quite different with a rather low clarity and a high strength of sound. The sound strength does not decrease much with distance.

7 CONCLUSION

The results of the acoustic simulations in the reconstructed theatres and odea confirm the assumption, that they were dedicated for different purposes. The theatres with very high clarity of sound were excellent for plays (speech), whereas the odea with a higher sound strength and more reverberant sound were excellent for song and music from weaker instruments like the lyre or chitäre.

8 ACKNOWLEDGEMENT

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References

- [1] ISO 3382 – “Acoustics – measurement of the reverberation time of rooms with reference to other acoustical parameters”