Acoustics of ancient Greek and Roman theatres in use today

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1. Introduction

In the Mediteranian area a large number of open, ancient Greek and Roman theatres are still today facing a busy schedule of performances including both classical and contemporary works of dance, drama, concerts, and opera. During the EU funded "Erato" project and a subsequent master thesis project, extensive measurement data have been collected from four well preserved theatres, which represent different stages of enclosing the audience in an open air environment. The purpose of the present paper is to present and compare the acoustic characteristics of these theatres and to discuss their potential in the light of acoustic performance requirements for modern use.

2. The theatres studied

The theatres dealt with are: The two theatres in Epidaurus, Greece, of which the smallest one was not discovered until the 1970's, and the two Roman theatres Aspendos in Turkey and the south theatre in Jerash, Jordan. As seen in the pictures below, neither of the Greek theatres have a skenae wall, as was typical for the later Roman theatres seen in the bottom of the Figure.

Figure 1: Pictures from the two Greek (top) and two Roman (bottom) theatres investigated.

Besides the high skene wall in the Aspendos theatre, we here also find a columnade behind the cavea, which – as we shall see later - contributes to generation of late reflections in the space. In fact, with all parts of the structure still standing in full height, the Aspendos Theatre is the best preserved of all Roman Theatres.

The stage arrangements seen in the two Greek theatres (particularly elaborate in the small theatre) were installed temporarily for certain performances that took place in the summer season 2006. Also the Aspendos theatre was equipped with a large mobile stage during our measurement visit in 2003. Most modern performances in the Greek as well as in the Roman theatres make use of the orchestra as stage area.

The seating area (cavea) in the Greek theatres covers an angle of more than 180 degrees, whereas in the Roman theatres this angle is limited to 180 degrees. Besides, the orchestra in the Greek theatres normally covers a full circle (as seen in the large theatre to the left, whereas this area in Roman theatres is half circular. Another typical difference is that the slope of the cavea is normally steeper in the Roman theatres.

3. Objective acoustic data

The room acoustic measurements carried out in the Aspendos and Jerash theatres were part of a large, international, research project called "ERATO": "identification, Evaluation and Revival of the Acoustical heritage of ancient Theatres and Odea" funded by the European Union,[1] whereas the measurements in the two Greek theatres were part of a master thesis project carried out by the second author of this paper.

The measurements to be presented here concentrate on room acoustic parameters described in ISO 3382: Reverberation Time, T (evaluated over 30 dB of the decay), Early Decay Time, EDT, Clarity, C80 and Sound Strength, G. Among these, the variation of G with source receiver distance is believed to be a key parameter in these open spaces which beforehand were expected to generate little reverberant energy.

The "Dirac" software installed on a portable PC was used for the acoustic measurements. A two channel microphone with omni and Fig. 8 capsules (AKG C34) and an omni directional dodecahedron loudspeaker with power amplifier were connected to the system (via an external Edirol UA-5 sound card). The Dirac system was calibrated in a reverberation chamber at DTU (for the sake of the G-measurements) both before and after the trips to Turkey and Jordan, while free field calibration on the sites was used for the measurements in Greece. [2]

The measurement positions in Aspendos and Jerash were chosen as points along each of two radial lines in the cavea. One line was placed in the left side of the theatre (seen from the audience) about 65° off the center line whereas the other line of receivers points formed an angle of 35° on the right side of the centre line. For the measurements in the Greek theatres, the receiver positions were also arranged along radial lines; but all together the points here were more evenly distributed over the left half of the seating area (as seen from the stage). Three or four source positions were used in all theatres. These were located in the

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[1] This project aimed at virtual restoration of ancient open and roofed Roman theatres and the primary purpose of the measurements in the Aspendos Theatre was to calibrate a room acoustic simulation model (created in ODEON). This model was used to auralize the sound in virtual presentations of what theatre goers might have experienced in ancient times. See the Erato web-page: WWW.OERSTED.DTU.DK/~ERATO for further details.

[2] As we did not trust the calibration process of the Dirac system completely, in Aspendos we also measured G directly by means of steady state noise and a B&K 2260 sound level meter with octave filters. However, apart from deviations in the 125 Hz octave, the two systems gave similar results (within about one dB).

orchestra as well as in the proscenion areas. In total, impulse responses from 30 to 45 source-receiver combinations were recorded in each of the theatres.

Reverberation Time

The position averaged values of Reverberation Time (T30) versus frequency for all four theatres are shown in Figure 2 below. In the case of the Aspendos theatre, we also had the opportunity to do a few measurements in the (half) occupied theatre. It is seen that the occupied values are only about 0,1-0,2s lower than in the empty theatre. That this is the case is not so surprising, since with a totally “absorbing ceiling” the relative increase in absorption area caused by the audience is not very large. Besides, even if fully occupied, late reflections could still propagate undisturbed above the audience between the skene wall and the wall/ceiling surfaces in the columnade.

In the case in the Greek theatres without skene wall and columnade, it is likely that the change in reverberation time between empty and occupied will be larger than in the Roman theatres, as here the only possible source of the reverberation is the highly scattered reflections of the stone seating itself. Anyway, we observe that in the empty state we have significant duration of reverberation in all four of these open theatres, and the decay rates are lower the more the cavea is fenced in by a high skene wall and an eventual columnade.

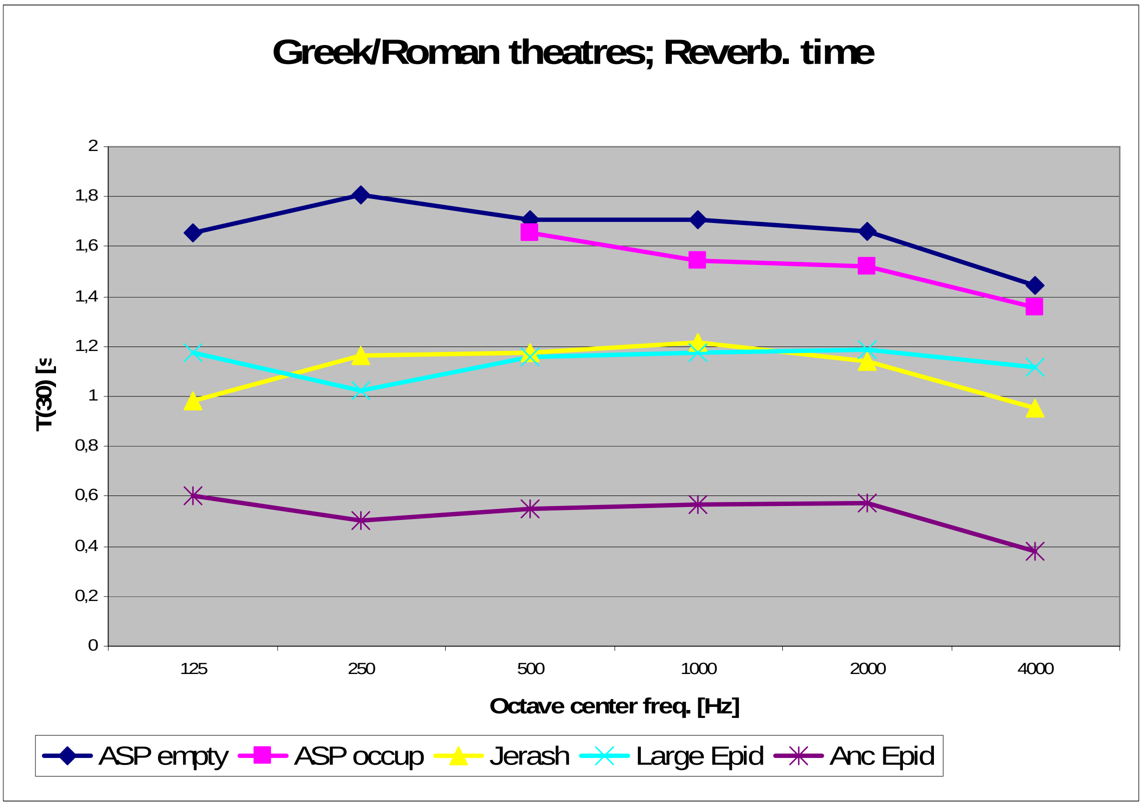

Fig. 2: Measured Reverberation Time versus frequency in the Aspendos, Jerash & Epidaurus Theatres; average over 30 – 45 source receiver combinations in each theatre.

In Jerash which has a skene wall and in the large Epidaurus, which does not have such a wall, the T values are almost equal. This must be caused by the much larger dimensions in Epidaurus.

Early Decay Time, EDT

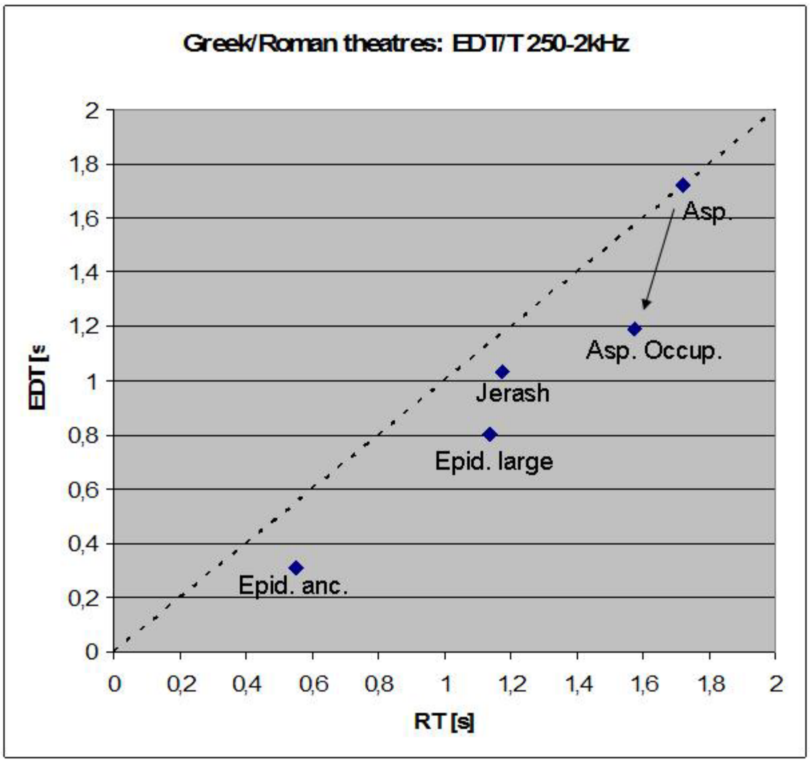

Fig. 3: Measured Early Decay Time versus measured Reverberation Time in the four theatres; average over 30 – 45 source receiver combinations and the 250-2000 Hz octave bands.

Not unlikely most roofed halls, EDT in these open theatres is also generally found to be slightly lower then T. However, in all cases except Aspendos (empty), the difference is between 0.2s and 0.4s, whereas in roofed halls EDT is in general only about 0,1s lower than T. Already this indicates that the levels of the reverberant sound in the open theatres are fairly low.

Clarity, C

That the level of the reverberant energy is very low indeed is further illustrated by comparing the measured values of Clarity with the expected values, C_{exp}, based on the measured reverberation time and the existence of diffuse sound field (which is of course not the case). C_{exp} is given by:

$$C_{exp} = 10 \times Log_{10}\left(\exp\left(\frac{1.104}{T}\right) - 1 \right) dB$$

Fig. 4 shows that in all four cases the measured value of Clarity (C80) is between 4 and 8 dB higher than expected.

From experience in normal roofed halls, it is known that a large width, a wide angle between side walls and steeply sloped seating are all factors that cause C to be higher than predicted by C_{exp} [1]; but even this can not explain the highest of the C values measured.

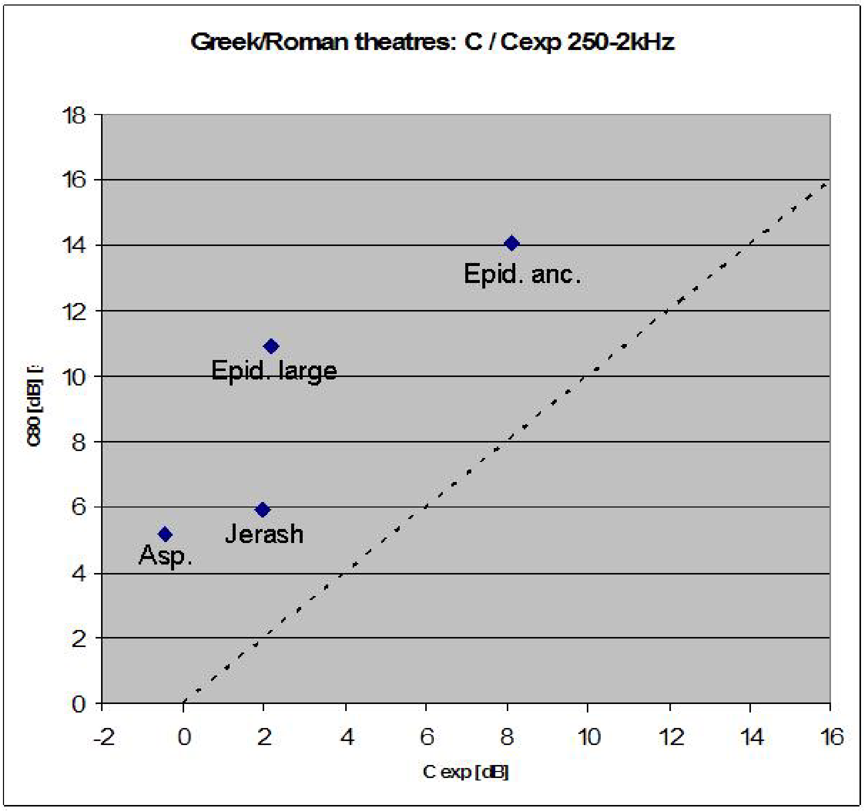

Fig. 3: Measured Early Decay Time versus the expected value according to diffuse field theory and the measured Reverberation Time in the four empty theatres; average over 30 – 45 source receiver combinations and the 250-2000 Hz octave bands.

Anyway, the sound is always very clear in the open theatres and reverberation is mainly perceived when loud and/or impulsive sounds are generated. Consequently, also intelligibility is high – if just the signal to noise ratio is sufficiently high as well.[3]

Strength, G

In all four theatres, the level varied strongly with distance from the source. One example is shown in Fig. 4, in which measured (and simulated) G values for one particular source position in the Aspendos theatre is shown as a function of distance. The lower curve corresponds to the theoretical behavior of G with distance in a free field. It is seen that the measured level is at least 2-3 dB louder; but the attenuation with distance is almost as steep as for the direct sound alone, that is far steeper than the about 1 dB per 10m which, according to Barron's revised theory [2], would have been expected beyond the critical distance (equal to about 12 m) in a closed room with similar volume (about 80,000 m^3) and reverberation time (1.75s). Also the seat averaged reverberant level is lower than the -2 dB predicted according to empirical models based on experience in concert halls [1].

An attenuation with distance as steep as in a free field was observed in all four theatres, while the offsets relative to the free field condition differed depending on presence and distance to reflecting surfaces in the different theatres (and probably on calibration procedure and accuracy as well).

[3] Background noise is an important issue in open theatres. Fortunately none of the four theatres studied here are placed in busy city centers where traffic noise disturb the performances and the performances disturb the neighbors, so our challenges during the measurements were mainly grasshoppers and tourists.

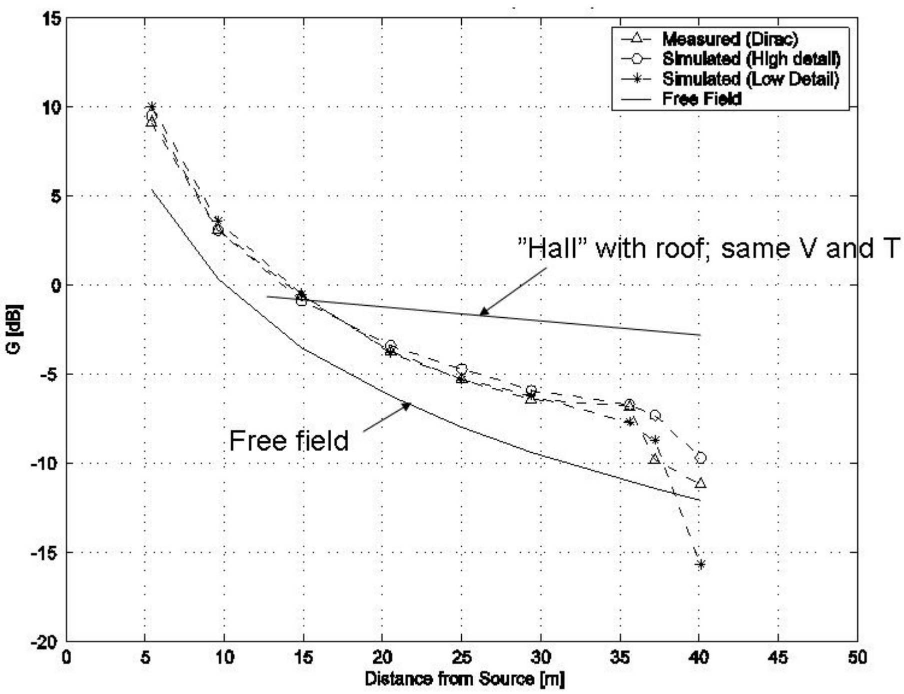

Fig. 4: Measured (and simulated) Strength at 1000 Hz versus distance in the Aspendos Theatre. Source in orchestra close to first row. Lower, full line curve corresponds to G in free field. Upper, straight line corresponds to Barron's revised theory.

With the observed sound level distribution in the open theatres, eventual problems with background noise will first appear in the more distant seats. Not least for this reason, use of amplification can be well motivated in many cases.

In summary, the natural acoustics of the open theatres are characterized by a non vanishing reverberation time and rather low sound levels decreasing with distance as steeply as in free field. On the other hand, the low level of late reflected sound in particular implies that Clarity and - if the ambient noise level is sufficiently low - the intelligibility are higher than expected considering the measured reverberation time and experiences from closed rooms.

4. Objective effects of introducing a stage enclosure

Many modern performances in open theatres make use of a stage set raised behind the performers. While the main reasons for their installation may well be artistic, the stage set will also have an acoustic effect if its surfaces are made from sound reflecting materials. This is particularly the case in Greek theatres not having a skene wall already. The positive effects will be higher level and longer reverberation time suiting un-amplified events in particular. However, as seen below, one must be aware of the distance from the source to the reflecting surface not being too large.

This was illustrated by installing a stage set or "shell" in computer models of the large and small, ancient Epidaurus theatres as shown in Figure 5. In both cases the models represented the empty conditions of the theatres as measured. For the large theatre, the distribution of reverberation time (at 100 Hz) and Speech Transmission Index when the source is placed in the centre of the orchestra are shown in Fig. 6. The upper part of the picture shows distributions of T (left) and STI (right) without the stage enclosure. The range from low to high T/STI values is represented by a blue – green – yellow – red colour scale. It is seen that particularly low values of both parameters are found in the seats placed nearly 90 degrees off the centre line. For these seats the impulse responses recorded with the source placed in the centre of the orchestra

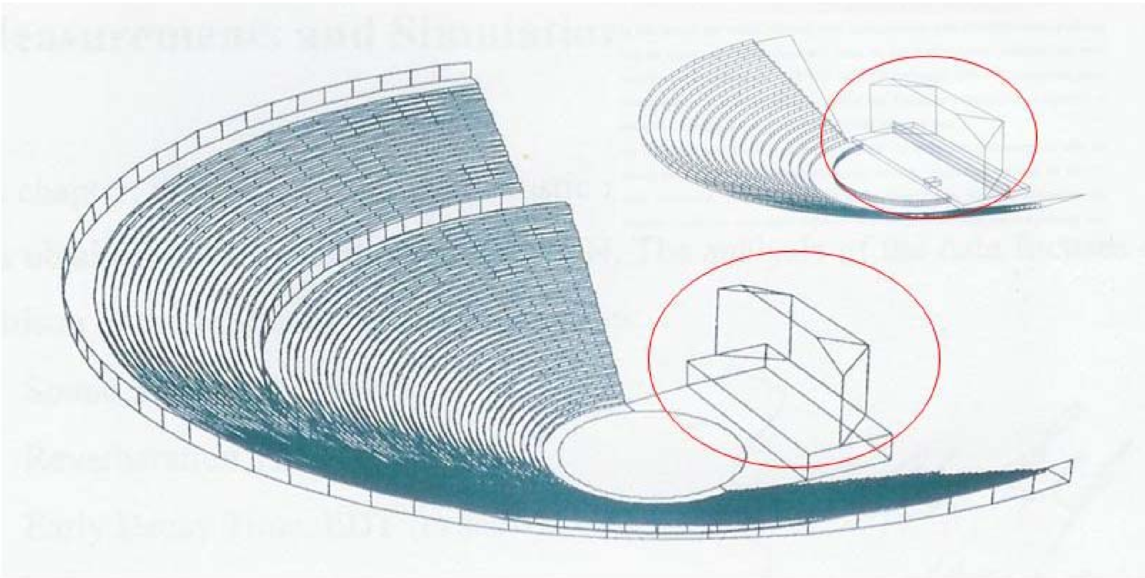

Fig. 5: Wire frame models of Odeon models of the Large and Ancient Epidaurus Theatres used for simulation of the effect of introducing a stage enclosure (encircled in red).

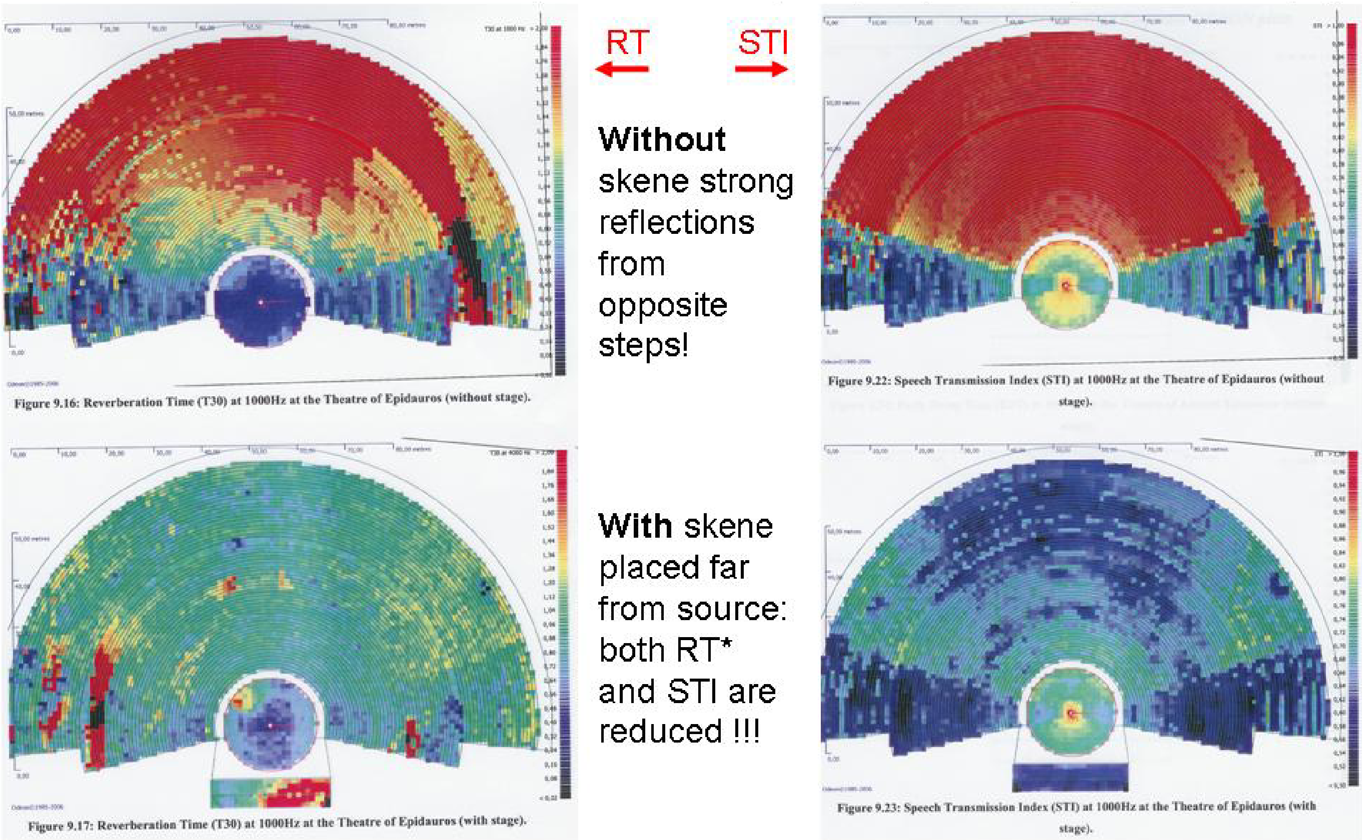

Fig. 6: Distribution of simulated values of Reverberation Time (left) and Speech Transmission Index (right) in an ODEON model of the Large Epidaurus Theatre without (top) and with (bottom) a stage enclosure as shown in Fig. 5. The simulations correspond to the conditions without audience.

are characterized by containing late reflections from the seating steps placed directly behind the omni directional source. With these reflections being delayed more than 80 ms and being much stronger in level than the later arriving reverberation, the effect is an increased slope of the decay after these reflections have arrived as well as reduced clarity and intelligibility.

The effect of installing the stage set placed about 20 m behind the source is similar as seen in the lower part of Fig. 6. Now both T and STI are low in all listening areas, and severe echoes are observed! In fact EDT increases at the same time as T decreases.

It should be added that these effects were also observed in the measured data. In particular, the EDT values in the Jerash theatre increased considerably when the source was placed in the orkestra in stead of on the proskenion, and the effect of the opposite steps towards the sides was also clearly seen in the large Epidaurus measurements.

In other words, for a stage set installation to provide useful early reflections and perhaps also a desired increase in reverberation time in these theatres, their large dimensions must be taken into account and the sound sources (actors/musicians) must be placed close to the reflecting surfaces.

5. Subjective effects of loudspeaker amplification

In the two Greek theatres, the measurements were supplemented by dummy head recordings made during amplified as well as unamplified performances of plays (primarily Greek drama).

Back in the laboratory, these recordings were presented over headphones to listeners who were asked to compare pairs of recordings with respect to “intimacy” and impression of the perceived “size” of the theatre space. Thus, no questions were asked regarding the obvious possibility for amplification to increase the sound levels. Neither the clarity or intelligibility were judged, as these aspects will strongly depend on the particular sound system installation rather than on the acoustics of the theatre itself. The stimuli pairs presented contained all four combinations of large/small and amplified/unamplified.

Pair 1	Large / Non Amplified	Large / Amplified	No difference
Which is more "intimate" for you?	9,1%	81,8%	9,1%
Which theatre seems larger to you?	90,9%	9,1%	0,0%
Pair 2	Small / Non Amplified	Small / Amplified	No difference
Which is more "intimate" for you?	0,0%	100,0%	0,0%
Which theatre seems larger to you?	81,8%	9,1%	9,1%
Pair 3	Small / Non Amplified	Large / Amplified	No difference
Which is more "intimate" for you?	18,2%	72,7%	9,1%
Which theatre seems larger to you?	63,6%	27,3%	9,1%
Pair 4	Large / Non Amplified	Small / Amplified	No difference
Which is more "intimate" for you?	18,2%	81,8%	0,0%
Which theatre seems larger to you?	100,0%	0,0%	0,0%
Pair 5	Large / Non Amplified	Small / Non Amplified	No difference
Which is more "intimate" for you?	27,3%	63,6%	9,1%
Which theatre seems larger to you?	36,4%	27,3%	36,4%
Pair 6	Large / Amplified	Small / Amplified	No difference
Which is more "intimate" for you?	0,0%	90,9%	9,1%
Which theatre seems larger to you?	63,6%	9,1%	27,3%

Amplification =>

- more intimate/ less large

- makes the large theatre seem smaller and more intimate than the small theatre (without amplific.)

Same ampl. condition: Large theatre always felt larger and less intimate than the small theatre

Figure 7: Subjective results regarding the use of amplification in the two Greek theatres.

The results shown in Fig. 7 repressent the percentage of times the acoustics in a recording is judged “more intimate” and “larger” than the other recording in the pair listed in the same row of the table. It is seen that the two subjective aspects considered are largely complementary as could be expected.

The main results are quoted to the right in the figure. It is clear that the theatres are judged more intimate and the apparent size shrinks when the performance is amplified. It is even found that the large Epidaurus when amplified is judged more intimate than the smaller one without amplification, although the former seats about 7 times more people.[4] Finally it is seen that for the same amplified or unmplified condition, the large theatre is judged larger and less intimate than the small theatre.

As intimacy and sound levels are obvious issues in open theatres with large stage-listener distances and little reverberation, it is clear that well designed sound systems can have an important role in many types of modern performances.

6. Conclusions

It has been found that the acoustics of the ancient open theatres are characterized by a substantial duration of the reverberation when empty, in which case reverberation time values between 0.5s and 1.7s have been found. When occupied, the T values will be lower, particularly in the Greek theatres without a reflecting Skene wall or a raised building structure behind the audience.

With extremely high clarity compared to the measured reverberation times and levels that are higher than in free field; but still decreasing about 6dB per doubling of distance, the acoustics in these theatres are different from conditions in free field as well as from normal closed rooms.

Modifications of the acoustics like installation of a stage shell or a sound system may be used to increase levels, intelligibility and/or reverberance according to the needs of each particular performance; but the large dimensions of these spaces as well as the positioning of the natural sound sources and loudspeakers must be given proper consideration in order to avoid echoes or other defects.

Acknowledgements

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References

[1] Gade, A. C., *"The influence of basic design variables on the acoustics of concert halls; New results derived from analysing a large number of existing halls"* Proceedings of the IOA, Vol. 19, Pt. 3, 1997.

[2] Barron, M.F.E. and Lee, L.-J., *``Energy relations in Concert Auditoria''*, J. Acoust. Soc. Am. Vol. 84 (1988). p. 618-628.

[4] It should be mentioned that the ratio between the source receiver distances for the recording positions in the two theatres was equal to the ratio between the linear dimensions of the two theatres. That is, the same realtive positions about half way between the stage and the last row were compared.