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## **On the use of ancient theatres for modern performances: a scale model approach**

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Ancient theatres are widely used today for modern performances including drama, music and ballets. Despite the state of conservation of the stage, the scenery is seldom designed with little care about its acoustical efficiency. Moreover, depending on the specific venue, a sound system can be employed in the performance. To clarify the acoustical impact of all these elements in ancient theatres, different stage settings and a sound system were investigated by means of scale model measurements. The scale model is a 1:20 scale reproduction of the ancient theatre of Siracusa (Italy). It is conceived as modular structure so that different configurations of the cavea and of the stage can be reproduced. To investigate the stage-set effects, different groups of reflecting panels were arranged on the platform and an orchestra shell was tested too. Then, to simulate the sound system, two directional high frequency sources were assembled and optimized. The interplay of stage, sound system and theatre architecture was outlined by a comprehensive set of acoustical measurements.

## 1 Introduction

Ancient theatres are very striking places and for this reason they are widely used today as concert halls or drama theatres [1]. Apart from the state of conservation of the theatre and the presence of a stage wall, the modern stage setting is designed mainly for scenographical purposes, disregarding its acoustical efficiency. Moreover, a sound system is used very often to amplify the actors or some musical performances.

To investigate the interaction between the theatre architecture and both the stage set and the sound system, a 1:20 scale model of the ancient theatre of Siracusa (Italy) was used. In fact, a scale model can take into account all the wave effects, including comb filtering and scattering from the steps of the cavea, that are not considered by a ray tracing model but are fundamental in this type of theatres.

## 2 Tuning the natural acoustics

The scale model was firstly used to define some typical stage sets which allow to enhance the acoustics of the bare theatre for the needs of a musical performances or a play.

In these case the basic requirement is not to use a sound system but to make the most of the natural acoustics with passive devices.

The scale model in the bare configuration is shown in Fig. 1, only the cavea is present and there are no surfaces useful for first reflections as the stage building or gallery in the upper part of the cavea (typical of roman theatres). This condition is representative of most of the ancient theatres that remains nowadays and obviously is unfavorable for the acoustics in a large part of the cavea. In particular, as detailed in the following, the reverberation time in this condition is very short, the strength is very low and the clarity is too high.



Fig.1 The scale model of Siracusa theatre in the bare configuration (cavea only).

The aim is to add to the impulse response some useful reflection close to the direct sound which contribute to

increase the sound level and the perception of the reverberation which in this configuration is produced only by the scattering of sound on the cavea steps. So, objectively, the scope is to make the reverberant tail longer, reduce the clarity and rise the strength.

Since music and drama have very different scenographic requirement and it was not possible to design an unique arrangement. For this reason the three configurations described below were fixed up, and are reported in Fig. 2:

1. *Orchestra shell*: design of an orchestra shell having dimensions 16m x 7.6m x 7.4m (in real scale) consisting of three side walls and a roof and containing diffusive elements. The roof angle can be adjusted to maximize the listening zone coverage.
2. *Trap. Large*: eight reflective screens 2m large and 3m high (in scale) were arranged in a trapezoidal shape.
3. *Trap. Small*: following the same plan of the previous configuration, 8 smaller modules 1m large and 3m high were used.

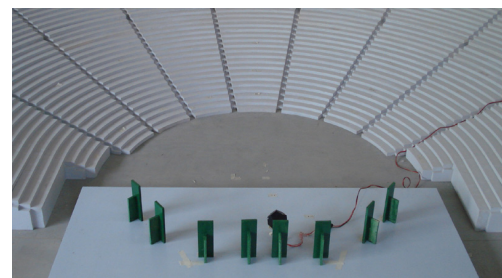
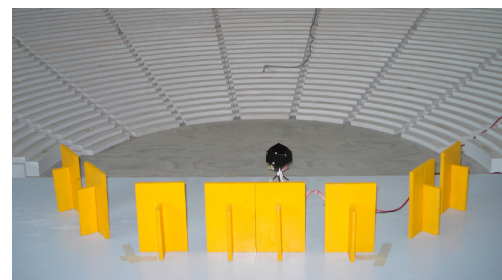
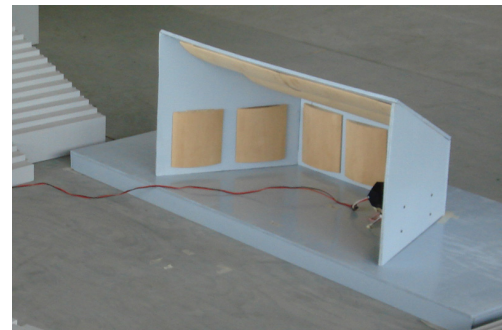


Fig.2 The three configurations of the stage.

Practically, the stage sets described above for the drama configurations could be built also using solutions which do not interfere with the stage set. For example, transparent screens made of rigid polycarbonate panels can be used.

## 2.1 Acoustical measurements

To characterize the three stage sets as well as the basic configuration of the theatre in term of acoustical parameters, an extensive set of acoustical measurements was taken. The measurement chain is the same described in [2] and include a miniaturized dodecahedron and a 1/4" microphone. This set-up allows to cover a frequency range up to the 2kHz octave band in full scale since the air absorption becomes too high over this frequency band.

Three positions for the source and 11 receivers on the right part of the cavea (and a control position on the left side) were defined. To obtain the impulse responses a convolution technique was adopted, using exponential swept sine as excitation signal and rescaling the obtained IR in the time domain.

The impulse responses were then processed and the acoustical parameters were calculated. The spatial average of results over all receivers will be shown as a function of frequency from 125 Hz to 2 kHz together with the "mid" (the average of the 500 Hz, 1 kHz and 2 kHz octave bands). The standard deviation from the mean value is also reported. Moreover, some results will be presented as a function of source-receiver distance.

In the following the most significant results will be shown and discussed considering only the source S1 placed at 5 cm (1 m in real scale) from the edge of the stage and 5 cm from the symmetry axis of the theatre.

### Reverberation

In Fig. 3 the reverberation time measured for the different configurations of the stage is shown. The bare configuration (cavea only) has a short reverberation, slightly higher at middle frequencies. The introduction of an orchestra shell produces some effects mostly at middle frequencies ( $T_{30}$  increases about 0.3 s at 500 Hz) but very little changes are visible at lower and higher frequencies.

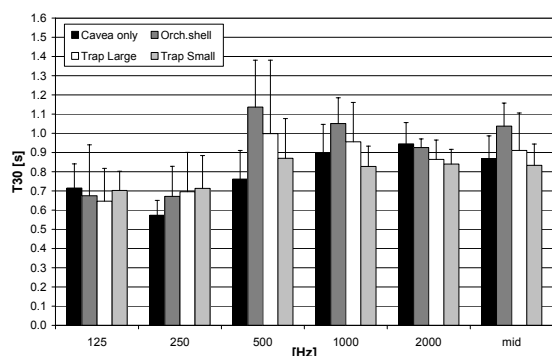


Fig.3 Reverberation time  $T_{30}$ .

The trapezoidal configurations increase the reverberant tail only at 250 Hz and 500 Hz but have a different impact in the other frequency bands.

Moreover, it can be noted that as the trapezoidal configurations are used for drama, the short reverberation is not so critical and the results can be considered satisfactory.

### Strength

Fig. 4 shows the  $G_{mid}$  parameter as a function of source-receiver distance together with the linear regressions for each configuration. As one can expect the strength is very low in the bare condition and in order to increase the parameter the small panel are not enough: the large ones are needed. In fact, using the larger reflecting panels the improvement with respect to the bare configuration varies from 2 dB in the positions farthest from the stage up to 5 dB in the closer ones.

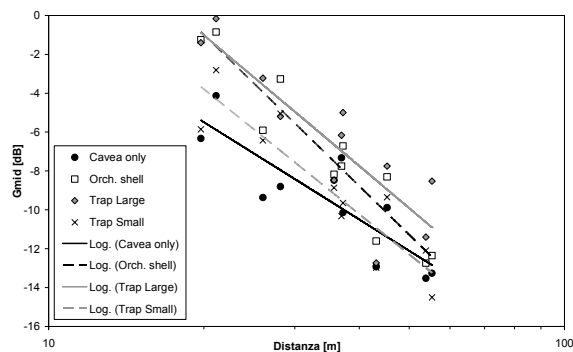


Fig.4 Sound Strength as a function of distance.

Although the orchestra shell has an effect similar to the large panels in a large part of the cavea, its performance is not as good as the panels in the farthest positions. Two reasons can explain this behaviour. Firstly the reflection from the shell roof should be optimized and directed towards the higher rows of steps in the cavea also when the source is positioned in the frontal part of the stage. Secondly the typology of reflection is actually different. In fact, the reflection from the shell are diffuse, as required for performers, and the sound energy is much more spread.

### Clarity

The analysis of Clarity parameters  $C_{50}$  and  $C_{80}$  is useful to understand the change in the impulse response produced by the stage configurations. In Fig. 5 the spatial average of  $C_{50}$  (up) and  $C_{80}$  (down) is shown together with the standard deviation. In both cases the values in the bare condition are very far from a possible optimal range. The sound is too dry especially for the musical signal. The improvement produced by the stage sets is very pronounced for  $C_{50}$ .

In this case, without considering the orchestra shell which is not compatible with a drama stage-set, the best solution is still the large panel configuration, as the clarity is 1 dB lower than using the small panels. Anyway, the overall values of  $C_{50}$  are slightly high and comparable with those of a position in the first rows in a closed theatre.

An improvement is visible also analyzing the  $C_{80}$  parameter with reference to the orchestra shell. The clarity decrease of more than 10 dB and many positions the parameter is close to its optimal range. Also in this case the parameters takes values similar to those found in the first rows of a concert hall.

In Fig. 6 the Clarity parameters are reported as a function of source-receiver distance together with the linear regression for each configuration of the stage. From the analysis of the graphs some interesting considerations can be added to the previous ones. Firstly, in the bare condition, the clarity

increases when increasing the distance from the source. Adding a few reflections from the stage set make the regression line flatter. Moreover, as seen before, for the drama configuration the large panels works better than the smaller ones.

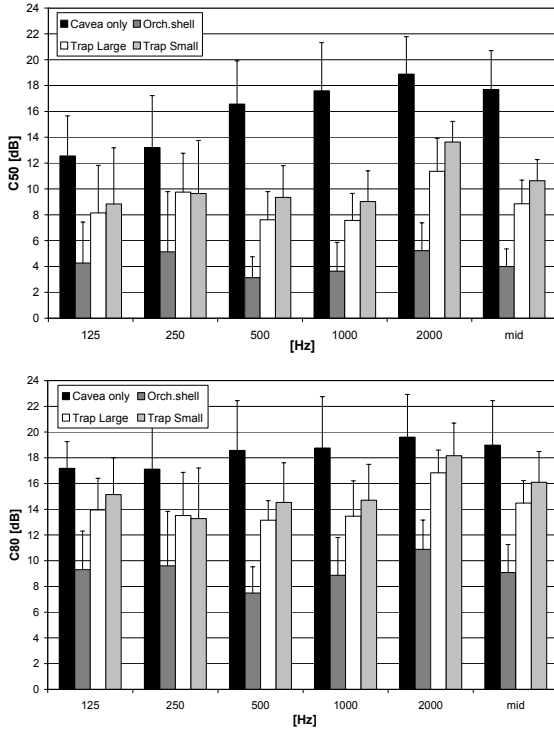


Fig.5 Clarity C50 (up) and C80 (down) as a function of frequency.

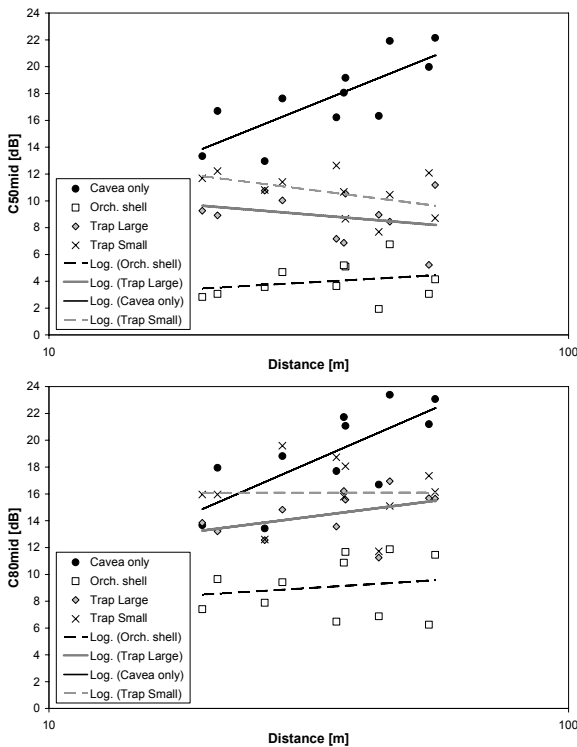


Fig.6 Clarity C50 (up) and C80 (down) as a function of source-receiver distance.

### 3 The sound system and the theatre

In this phase of the work the interaction between a sound system and the ancient theatre has been studied. In this case the modularity of the model was exploited allowing to create different configurations of the theatre simply adding or removing some parts as the stage building or the gallery in the upper part of the cavea.

#### 3.1 Design of the sound sources

Two directional sound sources in scale were designed and optimized to simulate a PA system in the ancient theatre. The two units are 25 cm high (4 m in real scale) and each one utilizes two drivers: a dome tweeter for the lower frequencies and a ribbon tweeter for the higher ones. The source is shown in Fig. 7.

The frequency response was optimized using a passive crossover and an equalization via software of the swept sine signal, obtaining a range of use from 1 kHz to 75 kHz.

The directivity of the source was measured too and the results are reported in Fig. 8 for the horizontal and the vertical planes. In can be seen that the aperture of the source in the vertical plane for the 32 kHz and 64 kHz frequency bands is limited to 15°-20°.



Fig.7 The sound source for PA system.

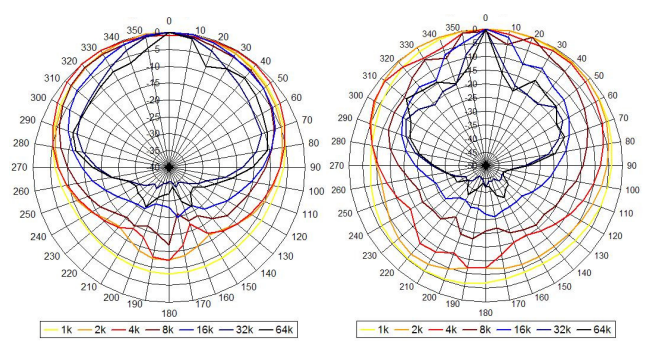


Fig. 8 Directivity of the source: horizontal plane (left) and vertical plane (right).

#### 3.2 Positioning the sources in the theatre

The coverage of the cavea was optimized taking into account the directivity and the distance between the two sources which were placed on the edge of the stage at a distance of 80 cm (16 m in real scale) from each other.



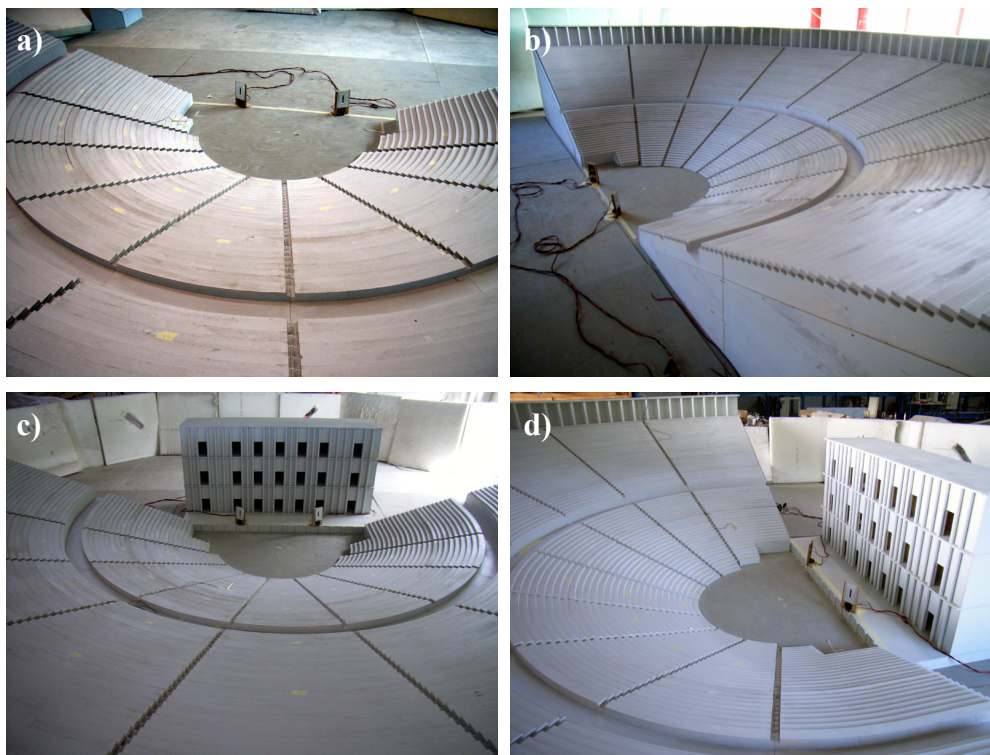


Fig. 9 The four tested configuration of the theatre: a) cavea only, b) gallery, c) stage building, d) stage + gallery

For this reason the resulting orientation is  $30^\circ$  in the horizontal plane with respect to the symmetry axis and  $5^\circ$  in the vertical plane. The sound system was positioned in four different configuration of the theatres that are shown in Fig.9: the bare condition described above and three configurations obtained adding the gallery, the stage building and both structures. In his case 30 receivers were positioned in one half of the cavea and 6 in the other half. The convolution technique by means of an exponential swept sine signal was used and the main acoustical parameters were calculated from the IR.

### 3.3 Acoustical measurements

#### Reverberation

The reverberation time relatively to the bare configuration is shown in Fig. 10. The directivity of the sources makes the reverberation very short in most of the measurements positions and produces longer values moving towards lateral positions.

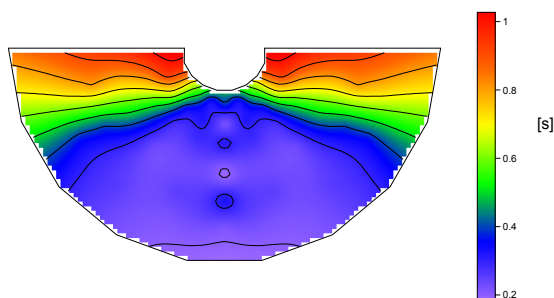


Fig. 10 Spatial distribution of T30 in the "cavea only" configuration.

Comparing this results with the reverberation time measured whit an omni directional sound source in the

same theatre ( $T30_{mid} \sim 0.75$  s [2]) the average values are different and the variability is very high. In Fig. 11 is shown the reverberation time measured in the four the configurations.

The jump in the reverberation due to the addition of the gallery and the stage building is clearly visible: this two architectural elements, in fact, define a "closed" space increasing the energy circulation and making the reverberant tail longer.

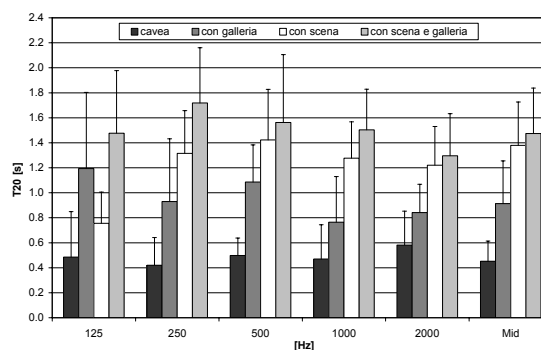


Fig. 11 The reverberation time T20.

#### Sound level

In this case the sound level does not correspond to the sound strength as a directional sources cannot be effectively calibrated with IR. In Fig. 12 the spatial distribution of sound level is shown: the values are relative to a given reference, so the absolute values are not important but depend from the sound power output of the system. Anyway the levels are uniform in the cavea and this indicates a good design of the PA system. Obviously the levels change with the distance and there are about 18 dB difference between the closer and the farthest positions.

Moreover, in Fig. 13 the contribution of different architectural part to the sound level is shown. The addition

of the gallery does not give a significant support but the introduction of the stage building makes the regression line flatter and give about 2 dB more in the farthest positions.

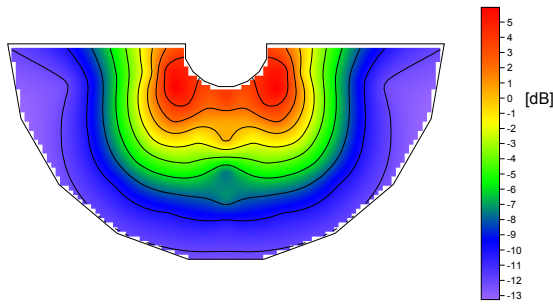


Fig. 12 Spatial distribution of the sound level (cavea only).

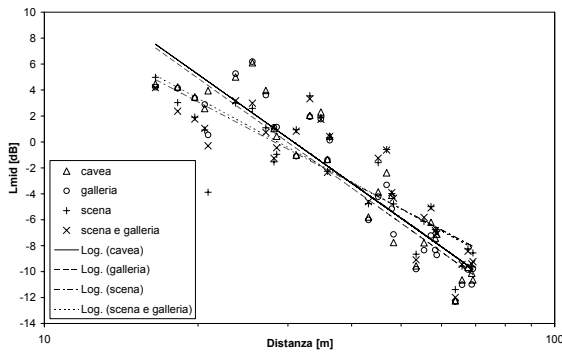


Fig. 13 Sound level in the four configuration of Fig. 9.

Considering the results found in [2] we have to note that in this case the sources are not omnidirectional. So, a solution could be the adoption of reflective screen in the upper part of the cavea but carefully avoiding any echo near the stage.

**Clarity**

In Fig. 14 the spatial distribution of C50 is shown in the “cavea only” configuration. The result are very similar for C80. It can be noted that the Clarity has a great variability as this parameters are strongly affected by the splitting of direct sound. In the lateral position the signals from the two loudspeakers arrive with a delay close to the integration limit (50 ms) but in the central position this delay is shorter. To compensate this problem a cluster system could be designed to preserve the uniqueness of the direct sound but this solution would probably be too invasive for an ancient theatre.

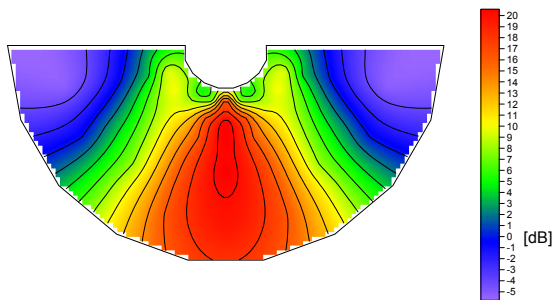


Fig. 14 Spatial distribution of the C50 (cavea only).

As visible in Fig. 15 the values of C50 (an those of C80 not reported) are always very high as the direct sound is outstanding. The addition of the architectural elements

makes the reverberant tail a bit richer and lower the parameter of a few dBs. Anyway the variability is still pronounced and the value are higher than using an omnidirectional source.

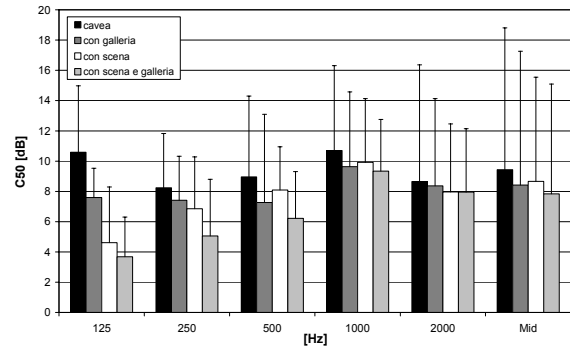


Fig. 15 Value of C50 in the four configurations.

**4 Concluding remarks**

In Tab. 1 the measured data were analyzed dividing the cavea in four sectors: central lower, central upper, lateral lower and lateral upper. The values for the gallery and the stage building are the differences respect to the cavea only configuration. In can be noted that the presence of the stage building affect all the listening position with positive effect on the acoustics (the differences are always positive). On the contrary the gallery has a minor effect which is localized in the central part of the cavea only.

		C50 [dB]	C80 [dB]	Lmid [dB]	RT20 [s]
Cavea	C l	15	20	2	0.4
	C u	20	24	-9	0.2
	L l	10	8	4	1
	L u	0	-2	-12	0.6
Stage building	C l	-8	-12	-1.5	+1
	C u	-6	-10	+1	+1.5
	L l	+2	+4	+1	+0.2
	L u	+4	+2	+1	+0.2
Gallery	C l	-2	-3	0	+0.2
	C u	-6	-10	+0.5	+1
	L l	0	0	0	0
	L u	0	0	0	0

Table 1 effect of architectural elements on the sound system. C: central, L: lateral, u: upper, l: lower.

**References**

[1] P. Chourmouziadou and J. Kang, “Acoustic evolution of ancient Greek and Roman theatres”, Applied Acoustics, doi:10.1016/j.apacoust.2006.12.009 (2007).  
 [2] A. Farnetani, N. Prodi, R. Pompoli, “On the acoustics of ancient Greek and Roman theatres”, J. Acoust. Soc. Am. (2008), in press.