PREDICTING THE ACOUSTICS OF ANCIENT OPEN-AIR THEATRES: THE IMPORTANCE OF CALCULATION METHODS AND GEOMETRICAL DETAILS

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ABSTRACT

For more than a decade now, computer simulations of sound fields in rooms have been widely adopted in research and for consulting purposes. Most computer simulations are either based on geometrical room acoustics or statistical methods, hereby neglecting diffraction and interference effects. The calculation algorithms in this type of simulations often combine the image-source method and the ray-tracing technique.
In this paper, the acoustics of an open-air roman theatre are investigated. This is a special case which sets up a challenge to these prediction methods. The absence of a roof and therefore of a reverberant field, demands high accuracy in predicting the early reflections. The energy dissipates quickly in this type of enclosures and there is little masking effect of the reverberation. The inverse cone shape of these theatres also puts serious limitations to the image-source method, where great areas are in the shadow zone of the mirroring surface.
Another aspect that has been shown to give very different results in this case study, is the geometrical detailing of the models. Although it has been pointed out in several studies that models with a limited number of surfaces give more accurate results, in this particular case the opposite is shown to be true.
The aim of this paper is to clarify some of the problems that can arise in this type of constructions, and give guidelines for how they can be overcome / avoided. Another objective is to emphasize that room acoustic computer simulations although very useful need careful consideration about the underlying calculation methods.

1. INTRODUCTION

The simulations of the acoustics of ancient roman theatres presented in this paper are part of a larger research project named **ERATO** (identification **E**valuation and **R**evival of the **A**coustical heritage of ancient **T**heatres and **O**dea) part of the European Commission Fifth Framework INCO – MED Programme.
One of the objectives in this project is to provide a virtual reconstruction of the acoustics in the Roman period in its large open-air theatres and in smaller roofed theatres (Odea).

Computer models of the theatres have been designed based on plans, pictures and information provided by archaeologists and architects involved in the project. The acoustic simulations were run in these models using the ODEON 7β software which is based on geometrical acoustics.
In room acoustic computer simulations the simulated sound field is usually predicted within an enclosure where all surfaces reflect the sound. In this paper the acoustics of an open-air theatre is simulated by replacing the open-air area with a large totally absorptive surface.

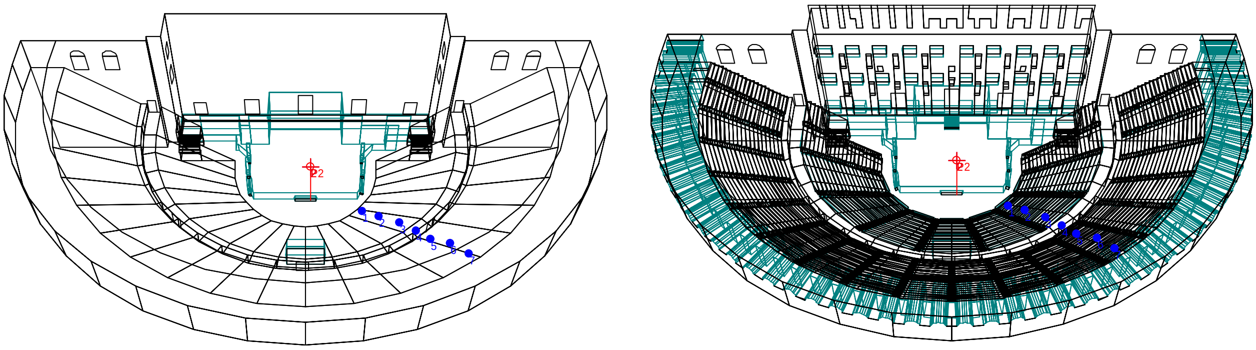
2. METHODS

2.1. Computer modeling

The Odeon program uses a hybrid calculation method, where early reflections are calculated by combining the image- source and a ray tracing method. The late reflections are calculated using a ray tracing process, which generate diffuse secondary sources. In this process rays are sent from the source position detecting image sources up to a certain reflection order and then detecting secondary sources on the surfaces of the room. The secondary sources radiate with a directivity that follow Lamberts Law and an intensity contribution attenuated mainly by the distance and the reflections in the path from source to receiver. [1,2]

The transition order (T.O.) at which the calculation method changes from image-source to ray tracing can be adjusted according to the complexity and shape of the room. If T.O. is set to 0 the calculation method used for all reflections will be the secondary source / ray tracing method.

The Aspendos roman theatre has been modeled and simulated in different levels of detail in order to study the importance of the geometrical details for the acoustics. In figure 1 are shown two versions of the same theatre in a simple and a detailed model.



a. **b.**

Figure 1*: The Aspendos Roman theatre with a performance stage.* ***a****. Simple computer model.* ***b.*** *Detailed computer model. The dot on the stage is the source and the dots on the seating area are 7 receiver positions.*

In the simple model (362 surfaces) the seating area (cavea) is shaped as sloping surfaces and the back wall (proscenium) behind the stage is modeled as a plane surface. In the detailed model (6049 surfaces) the cavea is defined with seat rows and stairs, a colonnade behind the last row and a more detailed proscenium.

As we found out in the in-situ measurements, the Aspendos theatre is used for performances most of the year, so a modern wooden stage and stage house were placed on the orchestra and proscenium area. For the computer models to be compared with the measurements this stage had to be included in the simulations.

The modeling procedure was the following:

1. Theatre dimensions and geometrical details were measured from plans and pictures.
2. Geometrical elements were divided into groups taking into account surface size and shape. These groups were assigned different diffusing characteristics following the principles described in [3].
3. Surface properties as absorption and scattering coefficients were estimated from available data.
4. First predictions were made to get an overview of the acoustics in the theatre.
5. In-situ acoustical measurements and evaluation of the materials of the theater were necessary to get more information on surface properties. The absorption and scattering coefficients of the surfaces in the model were readjusted in order to match the measured room acoustical parameters. The reverberation time was considered to be the most important parameter and was used as a reference in the model calibration.

The surface characteristics of the theatre were calibrated on the detailed model using a Transition Order 0. Average values for all frequency bands are presented in Table 1 for the different groups of surfaces:

Group	**Materials**	**Absorption coefficient**	**Scattering coefficient**
Seating area	Hard Stone	0.05	0.7
Proscenium	Porous Stone	0.2	0.4
Colonnade	Porous Stone	0.2	0.2
Performance Stage	Wood / Polystyrene	0.2	0.2

Table 1: *Surface characteristics.*

The scattering coefficients for the cavea were estimated taking into account the small fittings of the seat rows and the cracks and fissures caused by erosion. In a similar way the erosion and details on the proscenium meant a high scattering coefficient.
Most of the materials in the Aspendos theatre have little absorption so the scattering coefficients had to be further increased in order to match the measured parameters.

Simulations were carried out on these models changing the transition order with the purpose to study the influence of the calculation methods on the results. The transition orders were set to 0, 2 and 5 and the number of rays used was 500000 in both models.
Calculation time in this type of rooms is considerably longer than for traditional rooms such as concert halls. However the calculation time was less than 1 minutte per receiver position on a 3 GHz, Pentium 4.

2.2. Measurement procedure

Room acoustic measurements were made with the DIRAC software and a laptop PC. A two channel microphone with omni and figure 8 patterns and an omni directional dodecahedron loudspeaker with power amplifier were connected to the system via an external Edirol UA-5 sound card. The impulse responses were stored in the hard drive and later calibrated and analyzed.
The measurement positions were chosen as points along two radial lines in the seating area. For the results presented here, the source position was placed 1m left of the center line and about 13m from the proscenium wall. The same positions were used in the simulations as shown in the line of receiver positions in Fig. 1.

3. RESULTS AND DISCUSSION

The simulated reverberation time of the Aspendos theatre is presented in Figure 2 as an average of the T_{30} values for one source position and 7 receiver positions.

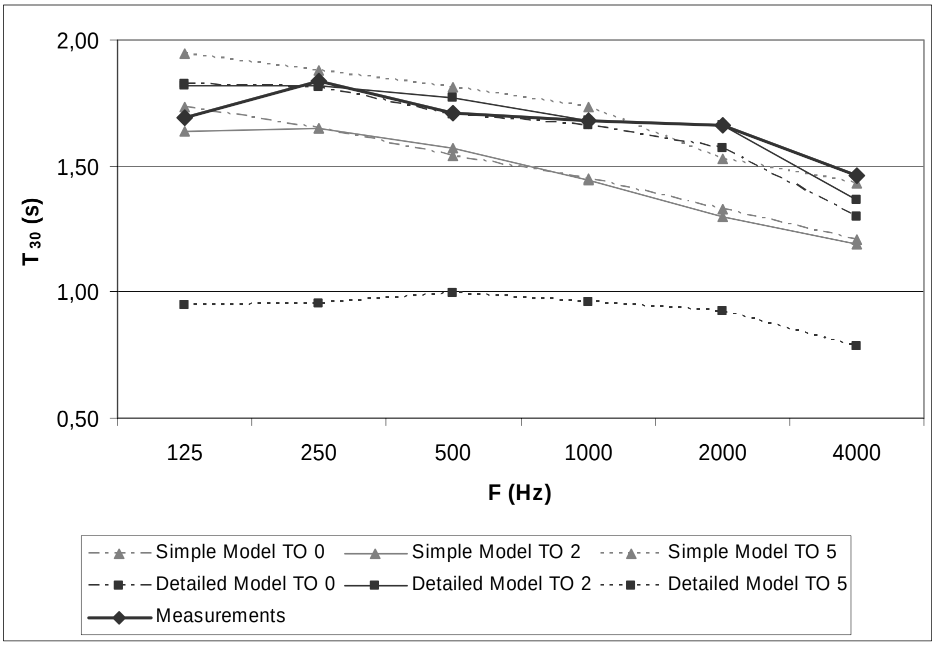


Figure 2: *T_{30} values of the Aspendos Theatre*.

The simulated early decay time of the Aspendos theatre is presented in Figure 3 as an average of the *EDT* values of one source position and 7 receiver positions.

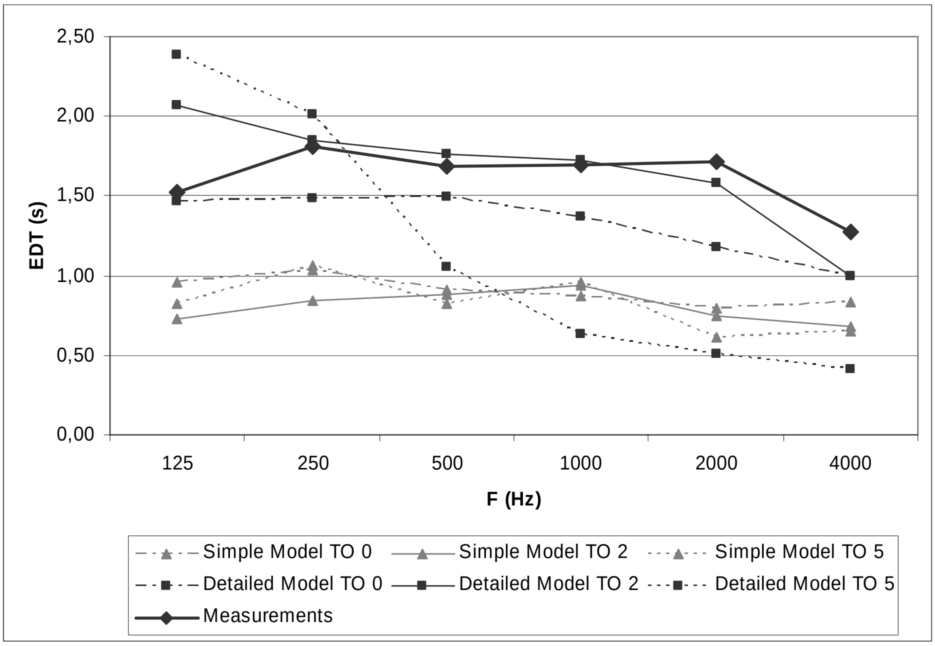


Figure 3: *EDT values of the Aspendos Theatre*.

The figures show curves of simulations using different transition order in both the simple and the detailed model and a reference curve with the measured values.

The T_{30} graph shows that for the simple model a better estimate is achieved with a high transition order (5) whereas the better estimates for the detailed model occur when it is simulated with a lower transition order (0 and 2). The detailed model gives a large error when using a higher transition order as 5.

For the simulated *EDT* the simple model seems to underestimate this parameter to a great degree regardless of transition order. For the detailed model the best results are obtained when using a transition order of 2. For a higher transition order then 5 the error becomes much larger.

A comparison of the simulations with the measured values for T_{30} and *EDT* shows that the detailed model yields the best results when used with a transition order 2.

Other room acoustical parameters where also studied to verify the agreement with the measurements, and the degree of error was evaluated following the formula:

$$Error = \frac{\left|AP_{measured} - AP_{simulated}\right|}{JND}$$

where:

$AP_{measured}$ is the measured value of the current acoustics parameter
$AP_{simulated}$ is the simulated value of the current acoustic parameter
JND is the subjectively just noticeable difference for the selected acoustic parameter [5]

Table 2 shows the definition of one JND for each acoustical parameter and the simulation errors in JND. The error is shown for an average of one source position and 7 receiver positions at the 1000 Hz octave band calculated on a detailed model with a transition order 2.

Acoustic parameter	**EDT**	**T30**	**SPL**	**C80**	**D50**	**Ts**	**LF80**
JND	5 %	5 %	1 dB	1 dB	0.05	10 ms	0.05
Error in JND	2.77	1.02	0.9	0.67	1.27	0.64	0.85

Table 2*: Average deviation in JND's between measured and simulated room acoustic parameters.*

The error for most parameters is around one JND compared to measurements.

The results show the importance of the details when creating models of a roman outdoor theatre and the fact that using the image-source method at low order reflections and then using the secondary source ray-tracing calculation method gives the best results. This is consistent with previous simulation results on rooms with many surfaces [4].

Shankland [6] has previously shown the importance of the detailed geometry in the seating area of a theatre and that the scattering from the seats has a considerable effect on the perceived sound at a listener position.

The edge diffraction contribution in a room with many sharp edges as the stone seats provide has a considerable influence on the acoustics of these theatres.

One of the reasons for the detailed model to give better results is that definition of the rows on the cavea horizontal reflections between cavea and proscenium. The sound will in this case bounce back and forth between the vertical seat rises and the proscenium wall. These reflections will arrive at a listener position with a large delay and attenuation but will nevertheless contribute to a long reverberation time. This is illustrated in Figure 3 showing the sections of different cavea shapes.

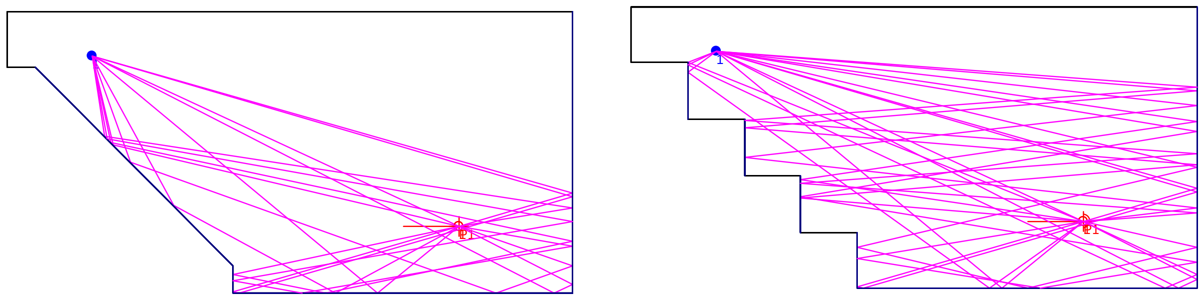


Figure 4: *Reflection paths in a simple and detailed cavea.*

When the cavea of the theatre is modeled as sloped surfaces the theatre will resemble the shape of an inverse cone. This shape will tend to direct most of the reflections towards the open sky and therefore the energy will dissipate quickly leaving few late reflections.

The diffraction and scattering effect from the empty seats is not usually considered important in computer simulations of roofed theatres. Many strong reflections from the roof and side walls mask the much lower energy coming from scattering and diffraction. But in the case of the open-air theatres fewer strong reflections are present and the gaps between strong reflections in the impulse response have to be filled in with scattered energy in order to get a smoother decay curve. An abrupt decay curve with a few strong reflections makes it very difficult to estimate any acoustic parameter and can be misleading.

In rooms resembling open-air theatres with an inverse cone shape the image-source method seems to give larger errors than the ray-tracing method after the first few reflection orders.

In the image-source method the number of sources up to a given order in a closed room with N walls increases exponentially [7].

When we simulate rooms with open roof and sloped surfaces, the first order mirror images will be treated as usual but after a few reflections most of the image-sources will be mirrored above the roof surface. As the roof is treated as totally absorbent the images will have no energy contribution for a receiver position inside the theater if they only are visible through the roof surface. That means that with a higher order the image source reflections will not grow exponentially but decrease. This will result in a decay curve dominated by a few strong reflections and therefore a low correlation coefficient that can give misleading results when calculating acoustical parameters.

Table 3 shows the number of reflections created by an image source for each reflection order hitting a receiver in the simple and the detailed model when using a Transition Order of 5.

Reflection order	**1**	**2**	**3**	**4**	**5**
Simple Model Reflections	3	4	6	6	1
Detailed Model Reflections	3	6	7	6	4

Table 3: *Number of reflections vs. reflection order*

Both in the simple and the detailed model the number of reflections decreases after the 3-4th reflection order.

As the number of reflections decreases with higher order there is less reflection density in the impulse response and also less scattered energy, thus the edge diffraction becomes more important for the later part of the decay curve than in roofed theatres.

4. CONCLUSIONS

A roman theatre has been studied through computer simulations providing useful information on its acoustical properties and on how simulations can become more accurate when applying the appropriate calculation method for these rooms.

It has been shown that in simulations of open-air roman theatres the definition of the seating area has a big impact on the acoustics of the room. A detailed seating area with rows and steps allows horizontal reflections between seat rises and proscenium resulting in higher accordance with measured data.

Regarding calculation methods the simulations have shown that using an image-source method up to 2nd order reflections and then changing to a secondary source ray-tracing method yields the best results.

The majority of the room acoustical parameters have been predicted with an accuracy of one JND when comparing with measurement data and only short calculation times are needed despite the large amount of surfaces.

In open-air theatres the image-source calculation method gives large errors when used at higher order reflections. The reason is that most images will be mirrored above the roof surface which is treated as totally absorptive. This will result in a decay curve dominated by a few strong reflections and a low correlation coefficient.

The scattering and diffraction from the sharp edges of the stone seats in an open-air theatre play an important role for the acoustics as opposed to roofed theatres where this is masked by roof reflections.

The scattering effect of the seats has been simulated to a certain degree but the edge diffraction contribution is still a task to be solved.

The ERATO project will continue in the future with simulations of other open-air theatres and roofed theaters (Odea).

5. ACKNOWLEDGEMENTS

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