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STUDIES OF EPIDAURUS WITH A HYBRID ROOM ACOUSTICS MODELLING METHOD

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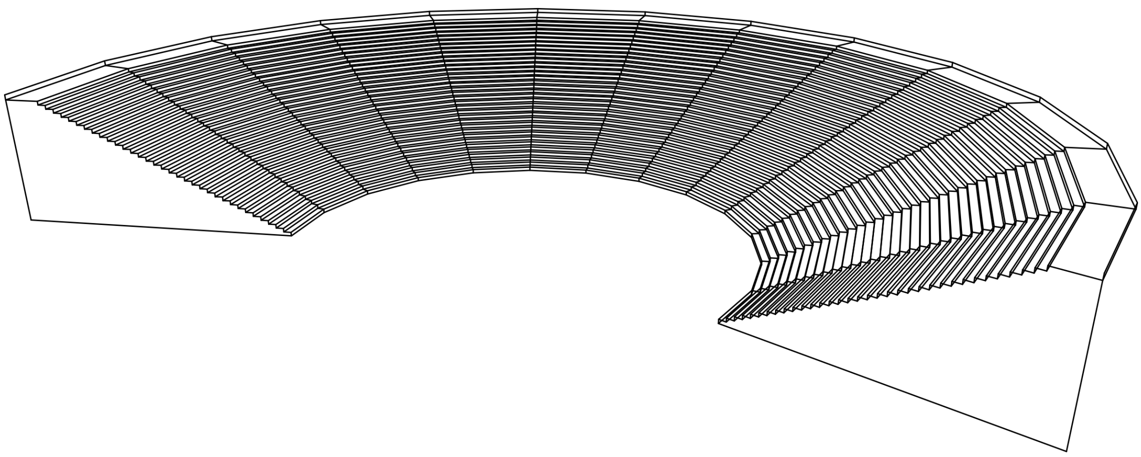
Abstract (max 300 words)

The 3D model of Epidaurus is simulated with a hybrid room acoustics modelling method. The low frequencies up to 500 Hz are simulated with a 3D FDTD method to be able to predict the wave-based phenomena such as diffraction and interference. The high frequencies are predicted with a beam tracing method. The early part of the computed impulse responses is analyzed to find the reasons for incredible acoustics of ancient theatres.

The prediction results are visualized with various methods both in the time and frequency domains. The results suggest the direct sound, the floor reflection, and the scattered energy from the seating area are all so close together in time that the total integrated energy is merged to one perceived sound source. The early part of the impulse response does not suffer from severe seat-dip effect as is typical in most of the concert halls. The presented analysis brings more information to raise the current understanding of the acoustics of ancient theatres.

Keywords

FDTD, beam tracing, room acoustics, speech intelligibility, auditorium acoustics



1. Introduction

This study concentrates on simulation and analysis of sound propagation in an Epidaurus model within first 50 ms after the direct sound. With speech, produced by an actor on stage, such very early energy is integrated to the direct sound due to the *Haas effect*. Therefore, it is assumed that this early energy is one of the main reasons for the incredible amplification of sound and high speech intelligibility in the Epidaurus theatre. First, a few earlier studies are summarized and then the early sound field is studied with several simulations.

Declercq and Dekeyser [1] performed acoustic simulations on an Epidaurus model using a geometric-based acoustic modelling method incorporating multiple orders of diffraction. They concluded that the sound is backscattered from the cavea to the audience making the audience receive sound from the front, but also backscattered sound from behind. In addition, such backscattering amplifies high frequencies more than low frequencies, thus the seat rows act as a high-pass filter due to second order diffracted sound. The cross-over frequency of such filtering depends on the periodicity of seat rows and in Epidaurus it is around 500 Hz. Thus, their explanation for great acoustics is that high frequencies, i.e., frequencies at which the information in speech is, are amplified more than low frequencies. Such low frequency attenuation is important to attenuate the wind noise as well.

Farnetali et al. [2] studied ancient theatres with measurements both in-situ and in scale models. The study presents reverberation times in different styles of theatres, though Epidaurus was not considered. However, in theatres with similar construction the reverberation time is around 1.0 second. Based on sound strength values Farnateli et al. propose that the sound energy is mainly concentrated on the first part of an impulse response, including the direct sound and the two outstanding reflections from the floor and stage building (when present). In addition, there were early reflections that correspond exactly to seven step edges behind the microphone position. The rest of the dominating early energy could not be identified to any particular part of the geometry. Interestingly, Farnateli et al. could not exactly correlate the wave theory of scattering [1] with the experimental results.

Chourmouziadou and Kang [3] studied the evolution of acoustics for the theatres constructed in different eras. With computer modelling they simulated impulse responses and they show the results with room acoustical parameters. Without seeing impulse responses it is quite hard to find information about the effects of the geometry to different parameters. Finally, they concluded that they found good correlations with computer modelling and measurements. However, it might be questionable whether the room acoustics parameters, which are based on the diffuse field assumption, can be really used to judge the acoustics of ancient theatres.

2. Simulations

Here, sound propagation in the model of the lower cavea of the Epidaurus was simulated with a 3D finite-difference time domain (FDTD) method and a beam tracing method. The low frequency simulation was implemented as a standard rectilinear (SRL) FDTD scheme as presented in [4]. Here, the model of Epidaurus, presented in figure 1, is so large that the sampling frequency of the mesh has to be limited to 5 kHz. That means that frequencies up to 500 Hz do not suffer from the dispersion problems of the rectilinear FDTD scheme. The internodal distance was 0.119 m, resulting in the 3D mesh of 23,582,364 nodes. The boundaries of the model had all the same wall impedance weighting of α = 0.001, representing hard material. The open-air free field conditions were approximated by setting a bounding box around Epidaurus to have α = 0.95, i.e., highly absorbing boundaries.

The high frequency sound wave propagation was simulated with a beam tracing implementation [5], an efficient algorithm for identifying valid image sources. The image sources were searched up to order of 3. Unfortunately, no diffraction or scattering were included in the modelling, thus the results show only the specular reflection paths. However, together with low frequency simulations the specular paths allow us to explain how sound propagates over the corrugated audience seating area in Epidaurus model.

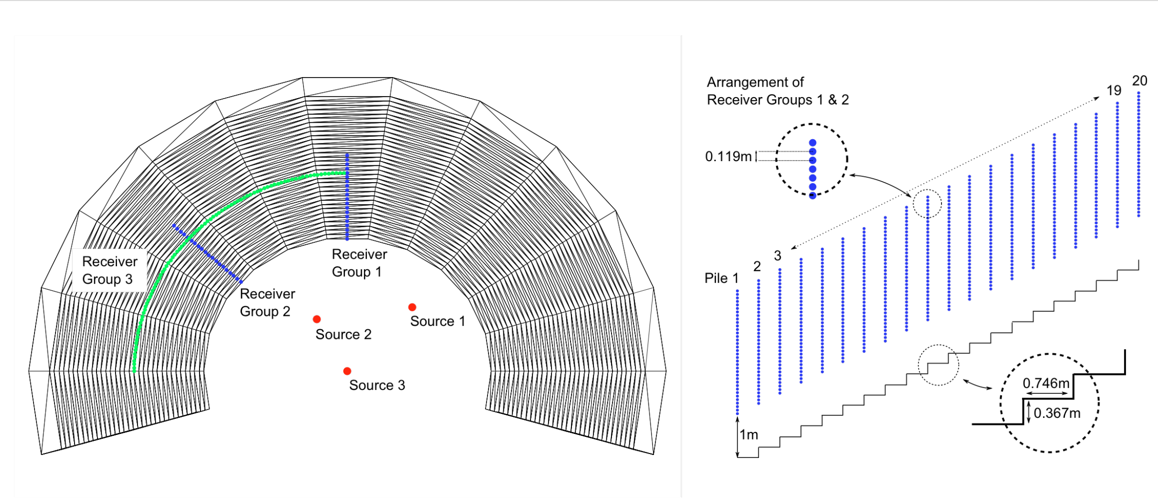


Figure 1 – Epidaurus model and source and receiver positions used in the simulations.

2.1 Results with the Epidaurus model

The simulation results from both modelling methods are presented in figure 2. The time-energy 3D FDTD and beam tracing responses from receiver groups 1, 2 and 3, shown in figure 1, are given for 3 source positions (height 1.37 m) in each column. The first two columns provide responses from the 20 lowest receiver positions, 1 m above the seat edge. The blue, 3D FDTD responses, were low-passed with 5th order IIR filter with a cut off frequency of 400 Hz to remove any dispersion and aliasing artefacts introduced by the method. The red lines are the beam tracing results. The last column plots group 3, 91 receiver positions at row 15. The simulations reveal:

- The direct sound and floor reflection from the stage are integrated together at low frequencies when the source is far enough. In high frequency simulation the direct sound and the floor reflection can be distinguished.
- The backscattering of the direct sound from the seat rows behind the receiver positions is clearly seen. In low frequency simulations several backscattered wavefronts are seen. In high frequency simulations, without any diffraction, there is usually only one specular reflection and it is from 2nd, 3rd, or 4th row behind the receiver position.

These results confirm the backscattering theory proposed earlier with simulations [1] and measurements [2].

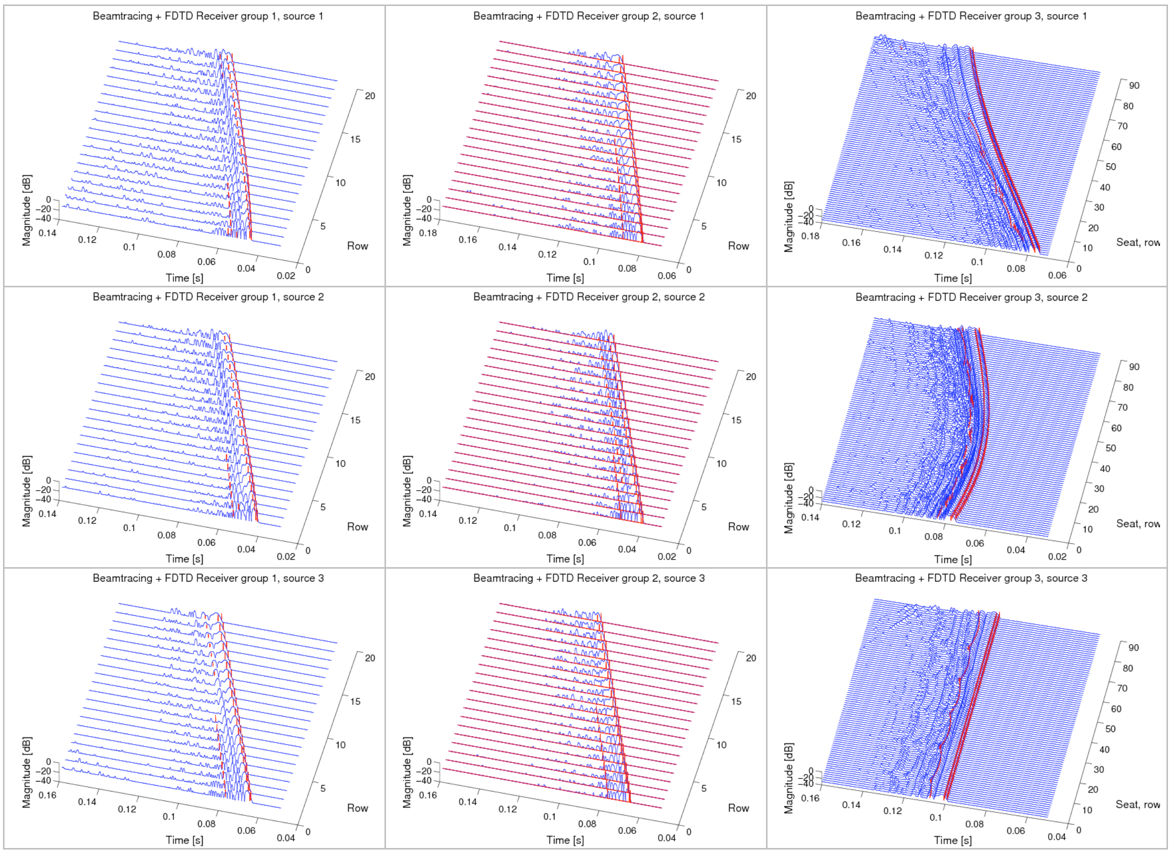


Figure 2 – Beam tracing (red) and 3D FDTD (blue) simulation results on all receiver positions from all three source positions, see figure 1.

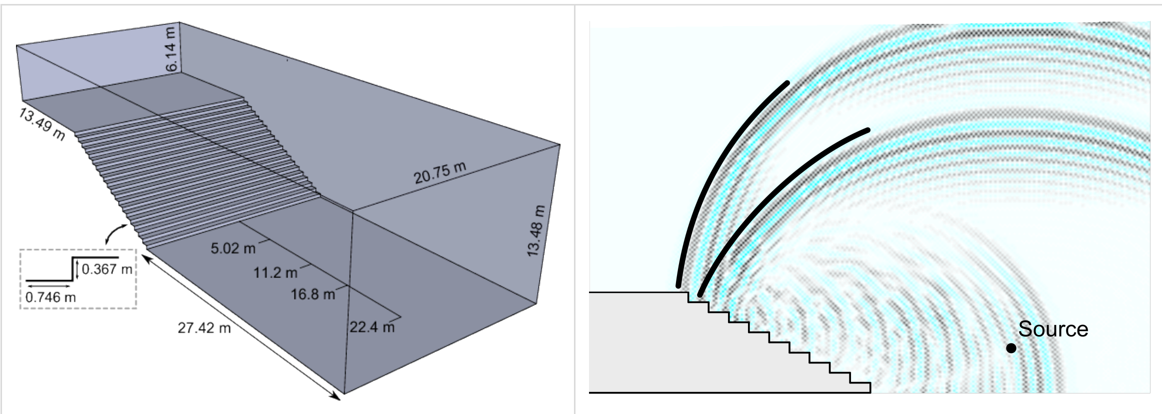


Figure 3 – Left: simplified 3D staircase model. Right: Model A with source at 5 m distance. The black lines are showing the direct sound and the floor reflection.

2.2 Simplified staircase model with different source distances

To study the backscattering effects in detail, we did a new rectilinear staircase model with 20 seat rows, shown in figure 3. Three versions of it consist of A) only 10 rows, B) only rows from 11 to 20, C) 20 rows. Such models let us study the contribution of scattering from the seat rows in front and behind of receivers separately. In addition, different source distances were used to see the contribution of floor reflection to the frequency response. Two examples of simulated wavefronts are illustrated in figure 3. The backscattering of sound from all seat rows is clearly seen.

With reference to figure 4, model B (columns 3 and 4) the comb filter introduced by the floor reflection is clearly seen. As the source moves further away the distance difference between the direct sound and the floor reflection gets smaller shifting the attenuated frequencies higher. This is important because at distances over 15 m, the fundamental frequency of male speech (around 120 Hz) is not attenuated at all. In contrast, the level is 6 dB higher due to the floor reflection. Model A (columns 1 and 2) show that when stairs exist in front of the receiver position, the scattered energy from the stair edges reduces the comb filtering. In addition, the frequencies below 200 Hz are emphasized even more. Thus, at the fundamental frequency of the male voice, the floor reflection and stairs amplify considerably the direct sound. Finally, model C is shown in figure 5 and for all sound source distances. There is a dip in the frequency response around 180 Hz that we attribute to the scattering from the seat rows. However, the interference dip due to the floor reflection is not seen. The overall level of the first 15 ms at 100 Hz is about 10 dB higher than the level of the direct sound alone. In addition, with more distant sound sources the low frequency level is the same at every seat.

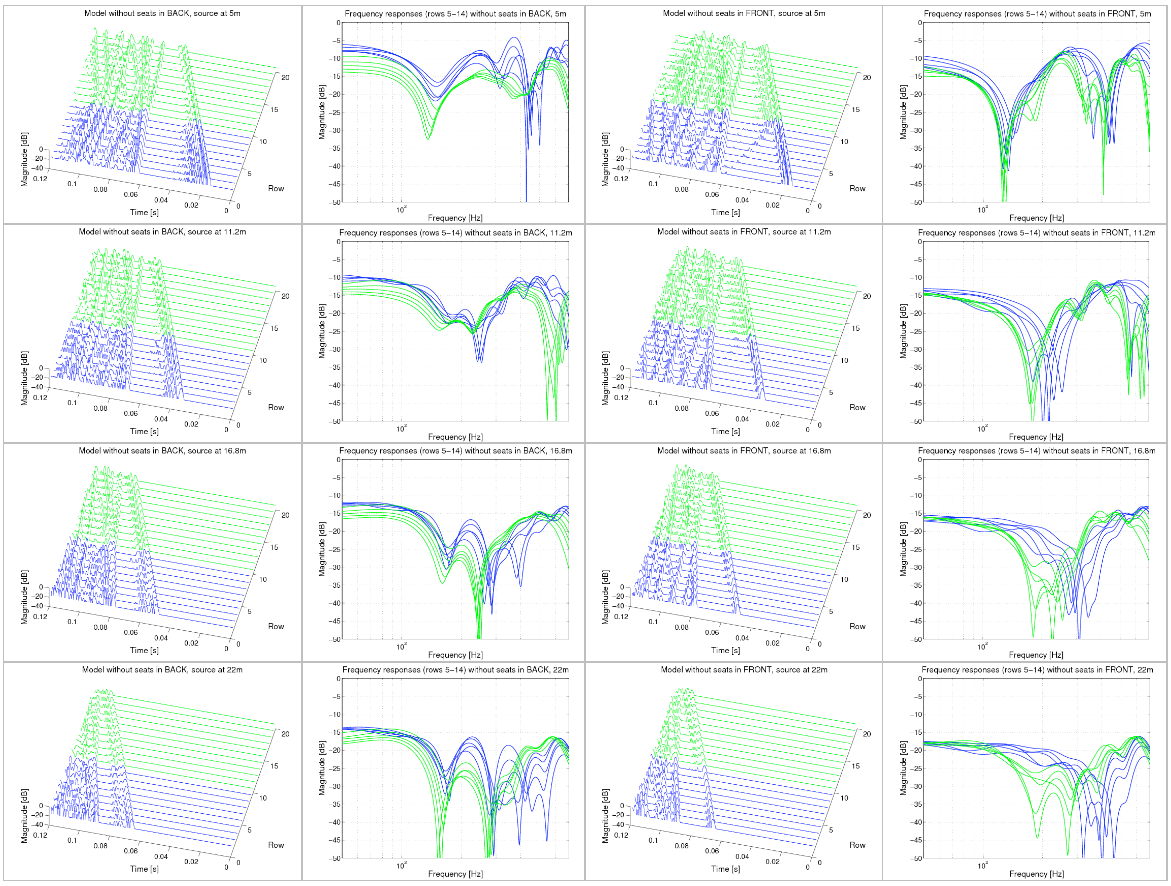


Figure 4 – FDTD simulations of staircase models. Columns 1 and 2 show 20 and 10 receiver positions, respectively, (see figure 1) in the model with only 10 seat rows. Columns 3 and 4 show responses with the model having only rows from 11 to 20. The frequency responses are computed by windowing the first 15 ms of the impulse responses.

3. Discussion, conclusions and future work

This paper proposes that the high speech intelligibility and strong sound of the Epidaurus theatre is due to the integration of the direct sound, the floor reflection, and the forward and backscattering of the seating area. The analysis both in the time and the frequency domains shows that the direct sound is relatively flat when it is compared to the situation in modern concert halls, in which the seat dip effect attenuates severely the low frequencies [4,6]. Therefore, the fundamental frequency of the male speech is amplified well in the Epidaurus. The backscattering from several seat rows behind the listener can be considered as multiple early reflections, which are all integrated to the direct sound due to the Haas effect. The height of the long smooth seat rows is high enough to give wideband reflections on the frequency range of formants in speech, i.e., from 500 Hz to 4 kHz. The later reflections from the curved surfaces of cavea were not studied in this paper, but we assume that they still slightly increase the perceived loudness. In addition, they contribute to the perceived reverberation. However, based on our understanding they do not reduce the speech intelligibility because the early part of the impulse response is so strong. The proof of this assumption is left as future work.

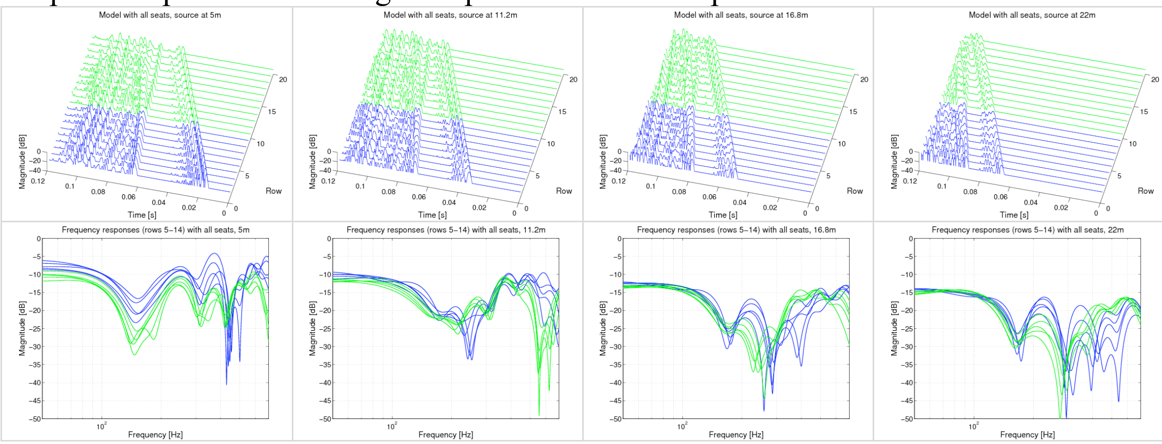


Figure 5 – FDTD simulations of a staircase model with 20 stairs. The frequency responses are computed by windowing the first 15 ms of the impulse responses.

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