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Acoustics of Epidaurus – Studies With Room Acoustics Modelling Methods

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Summary

The 3D model of Epidaurus is simulated with two room acoustics modelling methods. The low frequencies up to 1000 Hz are simulated with a 3D FDTD method able to predict the wave-based phenomena such as diffraction and interference. The high frequencies are predicted with a beam tracing method. The early parts of the computed impulse responses are analyzed to explain the well-known acoustics for speech in the ancient theatres. The prediction results are compared to real measurements and visualized with various methods both in the time domain and in the frequency domain. The results suggest that when an actor was on the stage (which does not exist anymore) his direct sound was supported by several early reflections from the ground, from the stage, and from the staircases of the audience area. All this early energy is assumed to fuse well with the direct sound resulting in a strong voice being perceived at every seat in the audience.

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1. Introduction

The capability of the ancient theatres to amplify speech has been fascinating researchers of acoustics for decades. Many different explanations have been proposed to explain why even at the back row speech is clear and well audible. The speech intelligibility is very high all over the huge audience area [1]. This article contributes to the series of explanations by studying one of the most famous theatres, Epidaurus, from the viewpoint of a room acoustician. In particular, a wave-based room acoustics modelling method, 3D finite-difference time domain (FDTD), is applied to study acoustic phenomena, which contribute to the impulse response of such a theatre.

This study concentrates on simulation and analysis of sound propagation in an Epidaurus model within the first 200 ms after the direct sound. It is well know that human hearing integrates early energy after the direct sound of speech due to the Haas effect [2]. Therefore, it is assumed that the early reflections and the early scattered energy are among the most important reasons for the strength of sound and high speech intelligibility in the Epidaurus theatre. First, measured data [3] from Epidaurus are analyzed to understand how the sound energy is built up in time. Then, several simulations with both wave-based and ray-based techniques are presented to understand how the geometry of an ancient theatre amplifies speech.

2. Background

The most extensive, but unfortunately not very well known, study of the acoustics of the ancient theatres has been presented by Canac [4]. In many respects his book has made a prominent contribution, especially considering that the book was published in the 1960s. He studied different geometries with image sources and showed how the direct sound and early reflections from the orchestra and the back wall of the stage are important to amplify the voices of ancient actors. Moreover, he proposed that sound waves might travel along the circular seating rows, i.e., by bending along the curved surfaces. However, he misunderstood the contribution of lateral reflections by proposing that they should be suppressed and he did not discuss the backscattering of sound from the seating rows at all.

Perhaps the most well-known explanation of the acoustics of ancient theatres has been published by Declercq and Dekeyser [5]. They performed acoustic simulations on an Epidaurus model using a geometric 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, not only 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. 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.

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Such low frequency attenuation is important for reducing the wind noise as well. However, Declercq and Dekeyser did not show any time domain data or frequency responses, but only their own non-traditional visualizations of modelling results.

Farnetani *et al.* [6] 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 the theatres with similar construction the reverberation time is around 1.0 second. Based on sound strength values Farnetani et al. proposed that the sound energy is mainly concentrated on the first part of the impulse response, including the direct sound and the two outstanding reflections from the floor and the 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, Farnetani *et al.* could not exactly correlate the wave theory of scattering [5] with the experimental results.

Chourmouziadou and Kang [7] studied the evolution of the acoustics for theatres constructed in different eras. With computer modelling they simulated impulse responses and show the results with room acoustic 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. It might be questionable whether the room acoustics parameters [8] can really be used to judge the acoustics of the ancient theatres. The parameters are developed to describe acoustics of enclosed spaces, not open outdoor venues.

3. Analysis of the measured data

According to the knowledge of the authors Vassilantonopoulos *et al.* [3] are the only ones who have shared the measured impulse response data from Epidaurus. The data consists of normalized impulse responses from one source position, in the center of the orchestra (see Figure 1 in [3]), to 10 receiver positions.

Here, four of these responses are analyzed to see how the sound energy evolves in time in Epidaurus. Figure 1 shows the wide band energy responses. The direct sound is followed by a few reflections, but it is indeed quite hard to see the backscattered reflections, which are clearly visible in the scale model measurements by Farnetani *et al.* [6]. Figure 1 also reveals that the wide band energy is vanishing very fast after the direct sound. Figure 2 plots the frequency responses in each position. The frequency responses are computed with a window from the initial direct sound up to 20, 50, and 1000 ms. This method is explained in more detail by Pätynen *et al.* [9].

Figures 1 and 2 reveal that almost all energy contributing to the total sound power at every seat in Epidaurus arrives very soon after the direct sound. Therefore, to understand the acoustics of Epidaurus, it is quite reasonable to study only the first 100–200 ms after the direct sound.

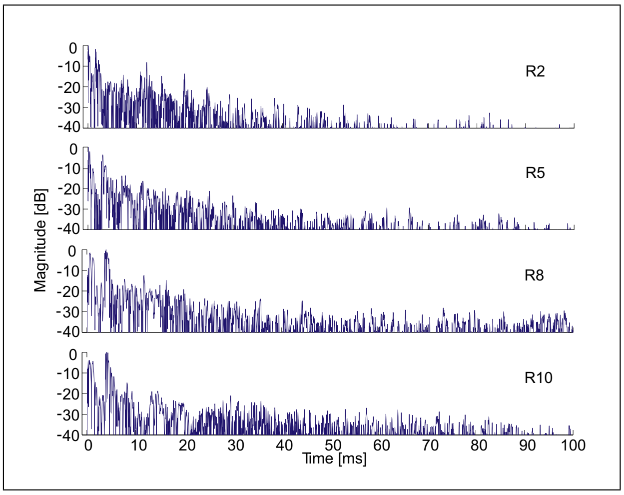

Figure 1. Normalized measured energy responses at distances 15.6, 29.6, 47.6, and 57.6 m (R2, R5, R8, and R10, respectively, see Figure 1 in [3]).

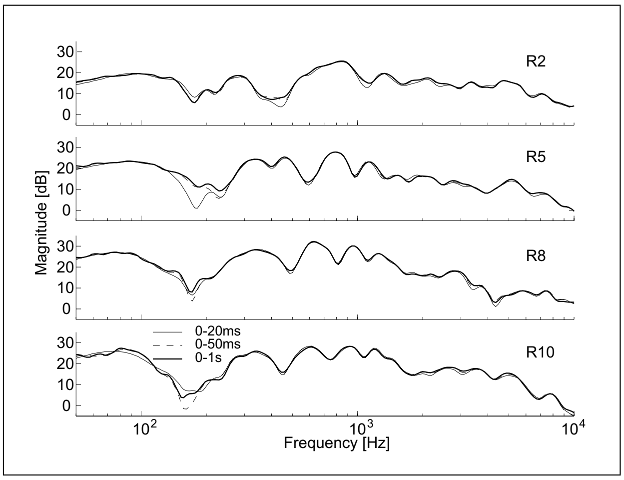

Figure 2. Frequency responses at positions R2, R5, R8, and R10, smoothed at 1/3 octave bands. Four responses are computed within a time window from the initial direct sound up to 20, 50, and 1000 ms.

Another interesting fact is that the measurement results do not support the findings in simulations of Declercq and Dekeyser [5]. Frequency responses in Figure 2 do not show any considerable attenuation of the frequencies below 500 Hz. Instead, the low frequencies below 150 Hz are emphasized. The dip seen at approximately 180 Hz, both here and in the original paper (see Figure 4 in [3]), is probably due to the backscattered sound from the seating rows, as the dip is present at all receiver positions.

The measurements [3] were done with an omnidirectional microphone and thus it is impossible to analyze in which direction the sound energy reaches the microphone. However, the theory of backscattered reflections from the upper seating rows [5, 6] is supported by the measurements of Odeon at Patras as presented in Figure 7 in [10]. In the directional analysis it can be seen that most of the

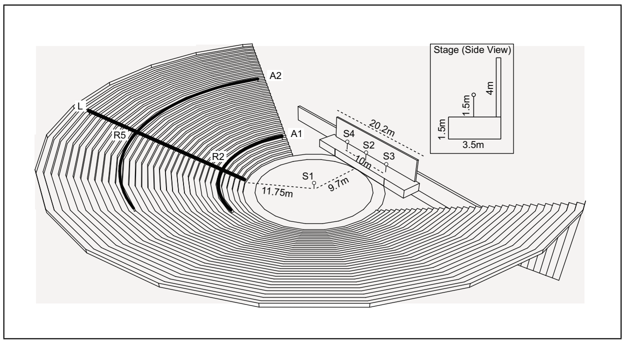

Figure 3. The model of Epidaurus used in the simulations. The model has only the lower cavea consisting of 31 seat rows. Source position S1 is the same as in the measurements [3] and sources S2, S3, and S4 are on the stage. Simulations were done for 123 receiver positions as follows: receivers 1–31 were one on each seat row on line L, Arc A1 had 46 receivers, and Arc A2 had 46 receivers.

energy after the direct sound is coming from behind the recording microphone.

4. Simulations

The lower cavea of Epidaurus was simulated using a 3D finite-difference time domain (FDTD) method and a beam tracing method. The additional 21 seating rows in the upper cavea were omitted in order to reduce the computational load. The model was designed with Google Sketchup with the measures collected from various sources [11, 5, 3]. The low frequency simulation was implemented as the standard rectilinear (SRL) FDTD scheme [12, 13]. The method provides a discrete approximation of a bounded and continuous wave propagating system that inherently models wave diffraction effects. This approximation leads to well documented, but manageable, frequency dependent numerical error called dispersion error. Dispersion error arises because wave speed is observed to be both frequency and directionally dependent, as opposed to constant. The dispersion error is most apparent as frequency increases, meaning that low frequencies typically smaller than $0.196{*}f_s$ suffer from dispersion error by a negligible amount [13]. Some preliminary work also quantified dispersion error in terms of perceptual limits [14, 15]. The model of Epidaurus, presented in Figure 3, is so large that the sampling frequency of the mesh was limited to $f_s = 7\,\text{kHz}$ in the proprietary modelling software. Therefore band limiting the virtual microphones to less than 1 kHz ensures the effects of dispersion error do not affect any subsequent results. The internodal distance was 8.5 cm, resulting in a 3D mesh of almost 34 million nodes. The boundaries of the model had a uniform wall impedance weighting of $\alpha = 0.001$, representing a hard material. The open-air free field conditions were approximated by setting a bounding box around Epidaurus to have $\alpha = 0.99$, i.e., highly absorbing boundaries.

The high frequency sound wave propagation was simulated with a beam tracing implementation [16], an efficient algorithm for identifying valid image sources. The image sources were searched up to the fourth order. No diffraction or scattering phenomena were included in the beam tracer modeling, and thus the results show only the specular reflection paths. However, the specular reflection paths help to interpret the low frequency simulations because it is sometimes quite hard to clearly see individual reflections from the low pass filtered impulse responses. Together with the low frequency simulations the specular paths allow us also to explain how sound propagates over the corrugated audience seating area in the Epidaurus model.

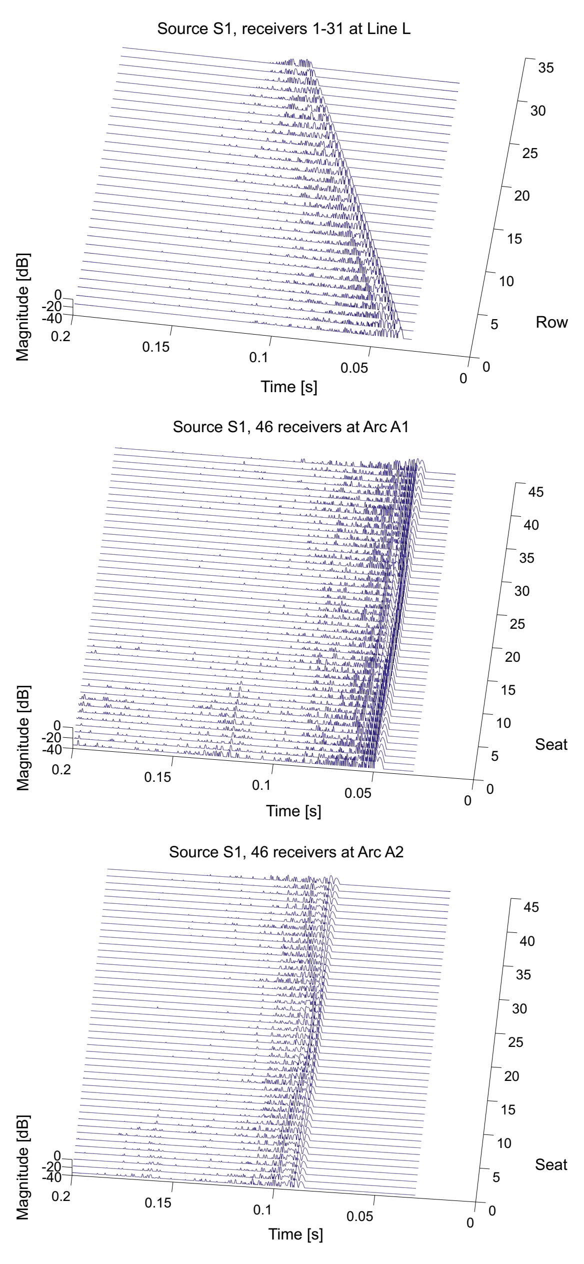

Figure 4. Simulations in the time domain without a stage. Sound source S1 is in the center of the orchestra at height of 1.5 meter.

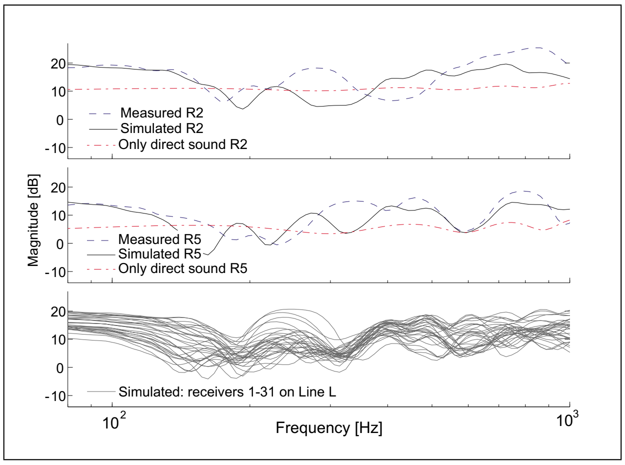

Figure 5. Comparison of the frequency responses (smoothed at 1/3 octave bands) with measurements and simulations. Bottom figure plots simulated frequency responses at each receiver position on Line L.

5. Comparison of measurements and 3D FDTD simulations

Even though all the details of the measurement equipment [3] are not available, it is worthwhile to compare the simulation results with the measurements. In the simulations, the sound source S1, see Figure 3, was at a height of 1.5 meter and all receiver positions 0.8 meter above the seats. In addition, the model used in these simulations did not have the stage structure because it is ruined and the effects are not present in the measurements. Figure 4 illustrates all simulated responses in the time domain. The wavefronts can be seen quite clearly by plotting low pass filtered (cut off frequency at 700 Hz) responses side by side from adjacent seats. The simulations show that there are several wavefronts after the direct sound, most of them possibly from the seating rows behind the measurement positions. The line at rows 22 to 31 is due to a non-perfect absorbing boundary and it does not correspond to real reflected impulses. The middle figure interestingly illustrates that in the centre of the cavea (first 10 receivers) a lot of reflections are coming between 60 and 90 ms after the direct sound. The Epidaurus seating rows cover the angle of 210 degrees. Based on the arrival times the reflections are from the seats closest to the outer edge, i.e., lateral reflections from the seats, which are at a wider angle than the semicircle.

Figure 5 compares the frequency responses in receiver positions R2 and R5. It can be seen that the simulations are not so far away from the measurements, although some differences exist. It is not easy to guess the reasons for this slight mismatch, but the absorption coefficients of the materials certainly differ.

The comparison of the simulated response with the frequency response of the simulated direct sound in a free field shows interestingly that low frequencies up to 170 Hz are emphasized. It is quite evident that the ground reflection and some scattered energy from seat rows make the bass stronger, almost 10 dB. Again, this conflicts with the results presented earlier by Declercq and Dekeyser [5], but the simulations are in line with the measured data, see Figure 2. The lowest figure in Figure 5 plots the frequency responses at all 31 rows of the lower cavea. It is seen that the dip between 180 and 200 Hz is present in all responses. The same dip is clearly visible in the measured data, see Figure 2. A recent study [17] attributes this dip due to the scattering from the seat rows. In addition, on average, the theatre amplifies the higher frequencies above 500 Hz more. Unfortunately, the computational resources limit the

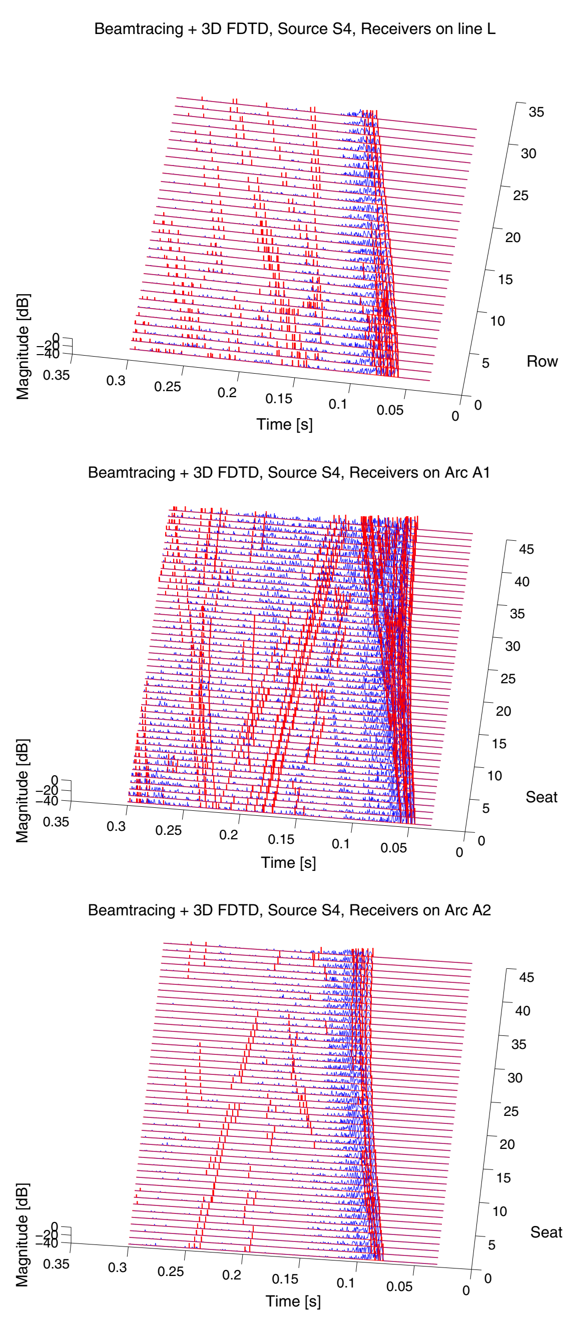

Figure 6. Simulations in the time domain from source S4. The sharp peaks are beam tracing results and wider bumps are low passed 3D FDTD results.

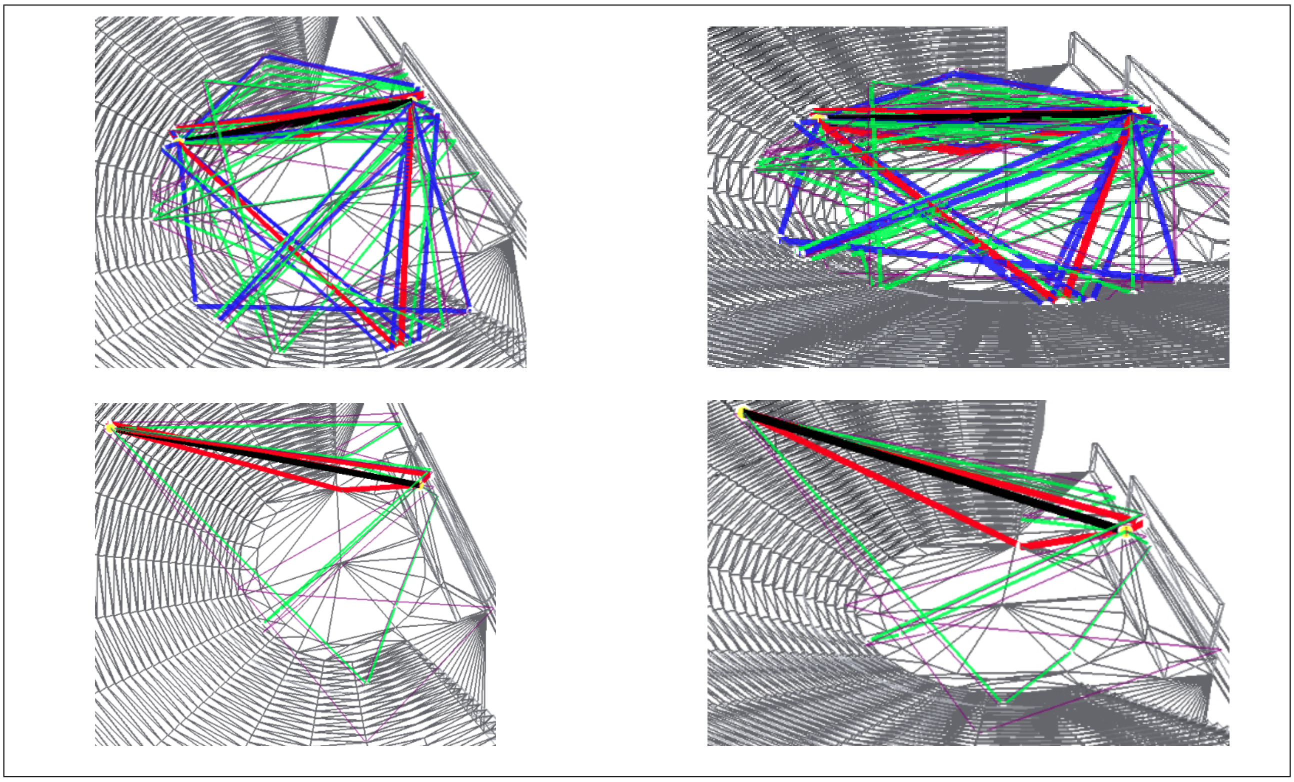

Figure 7. Beam tracing visualizations up to 4th order specular reflections from source S4 to R2 (upper figures) and to R5 (lower figures).

highest reliable results to 1 kHz and higher frequencies can not be simulated with the employed 3D FDTD method without introducing significant dispersion error.

6. Simulation with the stage

In ancient times Greek drama was performed with only as many as three male actors standing on the stage. Sometimes the drama was enhanced with a small chorus who were standing and acting on the orchestra, i.e., on the round area in front of the stage [1]. The actors were never in the focal point of the orchestra, the position in which modern measurements are often done (source S1, see Figure 3). To study how well the speech was conveyed to the audience it is reasonable to simulate the acoustics with sound sources on the stage at the head height of a male actor. Even though there are no measurements of Epidaurus with the stage to compare with, the simulations would reveal how the speech was amplified in the real act.

In this study, the source positions S2, S3, and S4 were 1.5 m above the stage, i.e., 3 meters above the ground level, see Figure 3. Figure 6 illustrates both the FDTD and the beam tracing results from source S4 to all 123 receiver positions. First, as the source is now higher, the beam tracing finds a good number of specular paths immediately after the direct sound, confirming the finding of backscattering from successive seating rows. In addition, later in time there are many first and higher order specular reflections from seating rows, as illustrated with ray paths to receivers R2 and R5 in Figure 7. Some of the higher order ray paths hint that sound energy could be conveyed along curved seating rows the same way as in “whispering galleries” in some cathedrals. Indeed, Canac suggested such an idea in his book [4] and even in the occupied situation there is room for sound between the sitting listener and the next step.

The FDTD simulation results show that there is more low frequency energy than in Figure 4 because of the stage wall and ground reflections. Moreover, the backscattering is also clearly visible. Interestingly, for receivers at Arc A1, the low frequency simulation finds a clear reflection path (middle figure in Figure 6, diagonal line starting at 100 ms at seat 1) that the beam tracing, modelling only the specular paths, does not find. Based on arrival times ihis reflection is diffracted and reflected from the lowest seating rows on the opposite side of the orchestra.

Figure 8 shows the frequency responses from all three simulated source positions to receivers on Line L. Again, the dip close to 200 Hz is visible with another dip almost one octave higher. But most importantly, the frequency responses are more uniform than in the measurements and simulations with the source in the center of the orchestra (S1). When the frequency responses are compared to the corresponding direct sounds in a free field it can be seen that, in the lower part of the cavea (R2), the theatre amplifies the sound up to 15 dB, depending on the frequency. Further away (R5), the amplification is more modest at low frequencies, but above 500 Hz it is 10 dB on average.

The amplification of the sound can also be studied by computing sound Strength (G) [8]. Figure 9 shows G values at all seats on Line L at octave bands. The values are on average 10 dB higher at all octave bands than in the free

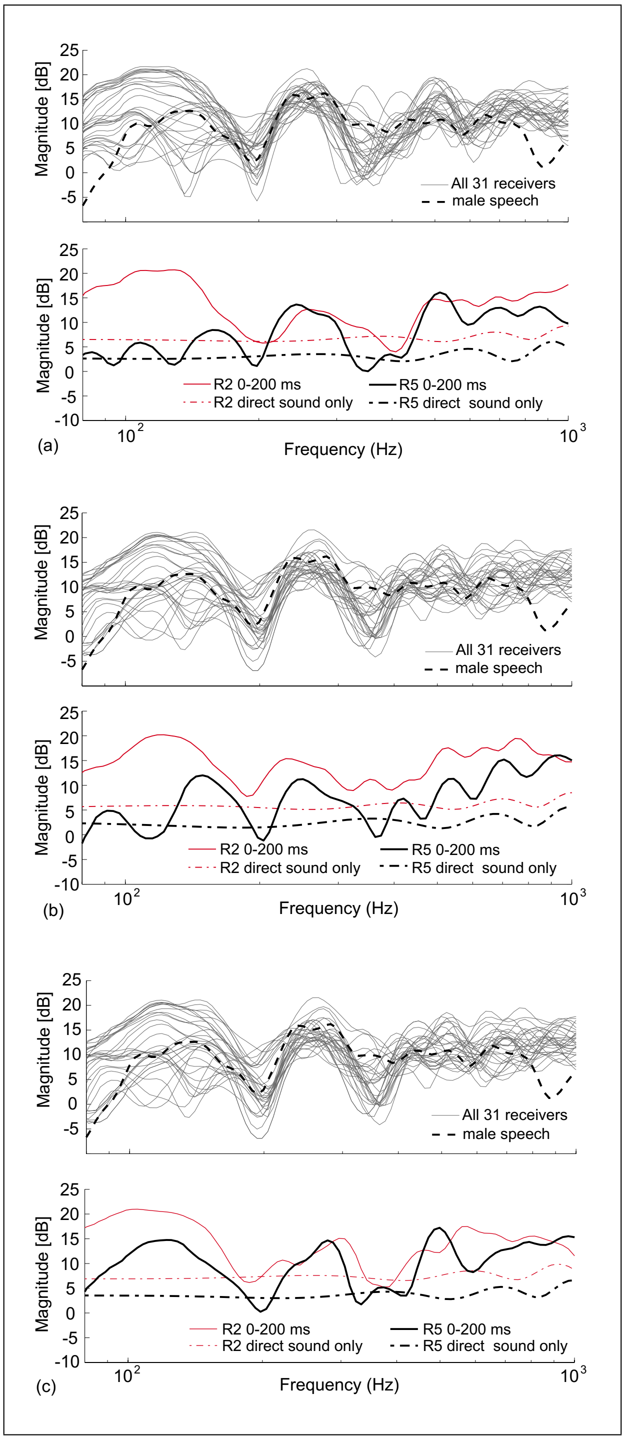

Figure 8. Frequency responses (smoothed at 1/3 octave bands) at receiver positions 1 to 31 on Line L from source positions S2, S3, and S4 on the stage. The average frequency response of male speech is shown for reference.

field (straight line in each subplot) from source positions on stage (S2, S3, and S4). In addition, the G values are reasonably high even at row 31, which is at the distance of over 40 m from the source positions on stage. The predicted G values are indeed very high as Farnetani *et al.* [6] reported values of about 5 dB more than in free field to be expected in ancient theatres.

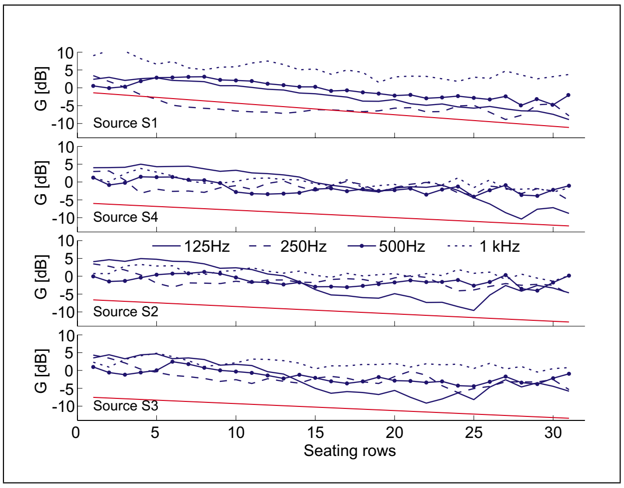

Figure 9. Strength (G) values at octave bands at every receiver on Line L from all four source positions. Simulation with S1 does not have the stage, see Figure 3. The straight lines show G values in free field.

7. The acoustics of Epidaurus

Based on the analysis of the in-situ measurements, visits, and simulations of this study, the great acoustics for speech, the acoustics of Epidaurus, can be explained as follows.

The strong sound and high speech intelligibility requires a high enough signal to noise ratio. Epidaurus is located at the peaceful countryside in Greece. Therefore, the background noise in the venue is considerably low and signal to noise ratio is reasonably high, in particular at ancient times when the stage building blocked the excess noise from the valley.

In addition to unobstructed direct sound, the early reflections are very important for good speech intelligibility [18]. The reflections from stage wall, orchestra, seating rows and backscattering of the seating rows arrive to the listener considerably fast after the direct sound. In addition, they are all from hard and reasonably flat surfaces, thus they are well fused to the direct sound, resulting in much stronger and louder sound [2, 19]. A visualization from a 2D FDTD simulation is showing all these sound field components in Figure 10. The visualization clearly shows the direct sound, ground reflection, stage back wall reflection and its ground reflection, and finally backscattering from the seating rows. Furthermore all these components of the sound field are even visible in the upper cavea.

The sound power in speech is carried by the vowels, which are harmonic signals. Figure 8 shows the comparison of the frequency responses from the stage to all seat rows with an average spectrum of 10 s of anechoic male speech. Below 500 Hz, due to backscattering and early reflections, Epidaurus amplifies the power carrying frequencies for vowels in male speech, i.e., fundamental frequency $F0$ (125-140 Hz) and first harmonics (250–290 Hz and 375–420 Hz) [20]. The information in vowels is in three main formant regions. For all vowels they

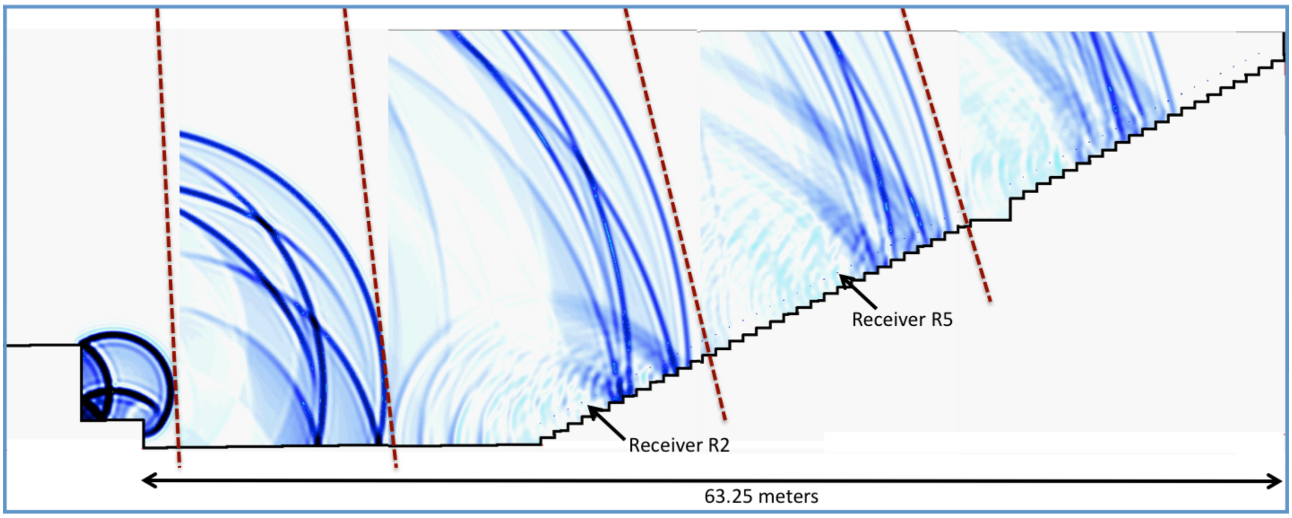

Figure 10. Visualization of 2D FDTD simulations at five different time moments. The 2D model consists of both the lower and upper cavea and the stage building.

are between 300 and 3000 Hz [20], i.e., the highly amplified frequency region in Epidaurus due to backscattering from higher seating rows. The seating rows are 0.367 m high, i.e., effectively reflecting frequencies higher than $f = 340/(2 * 0.367) = 463$ Hz (at least half of the wavelength).

The late reverberation is detrimental for speech intelligibility [18], because reverberation masks and blurs transients and consonants in speech. The Epidaurus has short late reverberation and it is at low level, mainly because the venue is not an enclosed space. Moreover, there is hardly any reverberation at low frequencies, which can be clearly heard from a video of an impulse response measurement[1]. The video also reveals that, when this impulse response measurement is listened to in the orchestra area, the Epidaurus clearly has a ringing sound on musical note A, i.e. 220 Hz and its harmonics (440, 660, 880, etc.). Indeed, the depth of one seat row is 0.746 m, thus $f = 340/(2 * 0.746) = 227$ Hz and when the impulse has to diffract-reflect-diffract at higher seating rows the distance is a bit longer, resulting in approximately 220 Hz. Again, this frequency matches well with the fundamentals in human speech. Similar tone color was heard all over the audience area during the impulse response measurements (when the video was shot), although the ringing was considerable shorter.

To summarize, the early reflections fuse to direct sound and raise the overall sound power level. However, at low frequencies, periodic seating rows filter out the frequencies with no excitation in speech but amplify the fundamental and first harmonics of male speech, thus raising signal to noise ratio. In addition, there is hardly any late reverberation to muddy sound at low frequencies. At higher frequencies, from 500 to 4000 Hz, the seating rows considerably amplify the sound, resulting in high speech intelligibility all over the audience area.

8. Conclusions

The acoustics of Epidaurus was studied with a 3D FDTD method and a beam tracing method. The simulations were shown to be reasonably well in line with the measured data, thus allowing the simulations with the stage. Unfortunately it does not exist anymore. The simulations with the source positions on the stage showed that the voices of the male actors were considerably amplified due to the geometry of the theatre. The results revealed that, during ancient times, at every seat of the audience the unobstructed direct sound was heard well and was supported with considerably many early reflections. Those reflections strengthen only the frequencies important for male speech, optimizing the signal to noise ratio and resulting in powerful sound with remarkably high speech intelligibility. To verify the presented findings a temporary stage structure should be constructed on site for measurements.

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