Project ancient acoustics part 3 of 4 : Influence of geometrical and material assumptions on ray-based acoustic simulations of two ancient theatres

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PROJECT ANCIENT ACOUSTICS PART 3 OF 4: INFLUENCE OF GEOMETRICAL AND MATERIAL ASSUMPTIONS ON RAY-BASED ACOUSTIC SIMULATIONS OF TWO ANCIENT THEATRES

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Acoustic models of ancient theatres found in literature are often based on assumptions, both for geometrical and material properties. The influences of these assumptions on modelling results have been assessed in this paper, which is part of the Ancient Acoustics project. Acoustical measurements were conducted in the Odeon of Herodes Atticus, the theatre of Epidaurus and the theatre of Argos, resulting in a large amount of high quality impulse responses per theatre. As part of the Ancient Acoustics project, 3D models were realised of the Odeon of Herodes Atticus and the theatre of Epidaurus to be used in the ray-based room acoustic simulation software 'Odeon'. To ensure the geometric accuracy of our models, measurements were performed with a Total Station theodolite in both theatres. A stepwise evaluation on the influence of the absorption and scattering coefficients is presented for the most accurate geometry using various plausible literature data. Next, the model material settings, for which the trends of simulated result were closest to the acoustic measurements, have been applied to both our own and literature based 3D models with various geometrical accuracies. The run-to-run deviations were taken into account and optimized settings were used, such as the number of rays and the transition order. Finally, the influence of the geometric deviations on selected acoustical parameters are evaluated and presented.

1. Introduction

Acoustic models are used to investigate the acoustic quality of an existing space, of a space yet to be realized, or of spaces that no longer are as they once were. Greek and Roman open air theatres and odeons are spaces that fall into the latter category. The models of these theatres found in literature are often based on assumptions, both for geometrical and for material properties [1-2], resulting in models with uncertainties and estimations for the geometrical properties and material settings. The input properties of these acoustic models are often modified for the model output to fit results of available measurements. This process is referred to as calibration. The fitting of the results is in most cases based on a limited number of source receiver (SR) combinations. However, it is uncertain if deviations from measurements are due to incorrect model input, or to an incorrect modeling approach itself.

This paper is part of the Ancient Acoustics project [3-5]. During this project, impulse response (IR) measurements were conducted in the Odeon of Herodes Atticus, the theatre of Epidaurus and the theatre of Argos resulting in a large amount of high quality IR's per theatre. As part of this project, geometrical acoustic models of the Odeon of Herodes Atticus and the theatre of Epidaurus were constructed. The theatre of Argos was excluded from this study as only the first rows are preserved. Surveying measurements with an automated theodolite were performed in both theatres to aid in the design of the acoustic models. In this article a parametric study on the influence of the material and of the geometrical properties is presented.

2. Method

Detailed geometric models of both theatres have been constructed, resulting in a model with 5394 surfaces for the Odeon of Herodes Atticus (denoted Herodes) and 15022 surfaces for the theatre of Epidaurus (denoted Epidaurus). Simplified models are made, substituting the seating areas and the stairs in the detailed models with flat surfaces, modelled as fractional surfaces type to avoid edge scattering, resulting in models with 1874 and 924 surfaces respectively. Furthermore, two models based on literature [6] were realised with 3168 and 5887 surfaces. In Fig. 1 and 2 the wireframe visualization of the geometrical models are depicted.

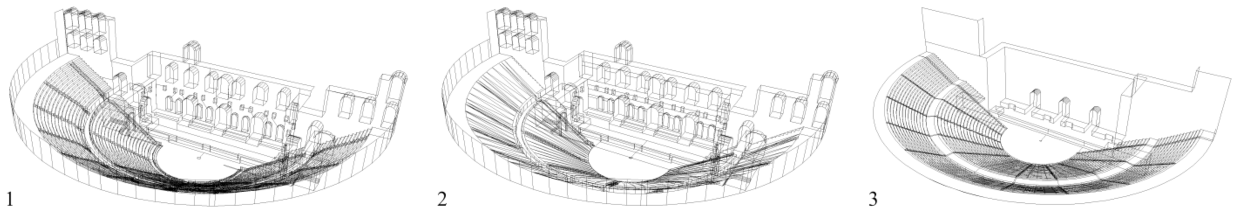

Figure 1: Wireframes visualizations of the Odeon of Herodes Atticus as obtained by Odeon (software). From left to right, the detailed model (1), the simplified model (2), and the model recreated from literature [6] (3).

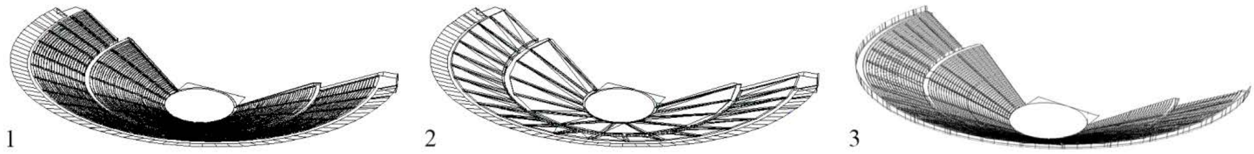

Figure 2: Wireframes visualizations of the theatre of Epidaurus as obtained by Odeon (software). From left to right, the detailed model (1), the simplified model (2), and the model recreated from literature [6] (3).

The geometrical models are imported in the room acoustics software Odeon 12.12, that uses a combination of the image source method and ray tracing. The numbers of rays used for the simulations are between 1/10 and 1 times the number of rays needed to create a stable decay curve with Global Estimation [7]. For Herodes the number of rays used is 1 million. For Epidaurus the number of rays used is 5 million. A sensitivity study has been conducted on the transition order (TO), using either a transition order 2 (TO 2), as suggested by the Odeon manual [7], or 0 (TO 0) as suggested by literature [8]. The TO describes the number of reflections that are determined by the use of the early image source method instead of the ray-radiosity method [7]. The measured positions used are as mentioned in project part 1 [3] with only source S1. The source is modeled as an omnidirectional source with a sound power of 100 dB, and an impulse response length of 5000 ms is used. Equal to the measurement conditions, the temperature is 15 °C with a 70 % relative humidity for Herodes and 14 °C and 86 % for Epidaurus [3].

Material properties are assigned to the two detailed models. All models are enclosed with walls and roof modeled with α=1. Initial absorption (α) and scattering coefficients (s) as mentioned in literature [2] and [9] are used; see setting 1 in Table 1. To evaluate the influence of these coefficients on the model output, only the absorption coefficient of the seating area is adjusted, as this is the largest area of the model assumed to result in the most noticeable effects. Values are chosen to get a stepwise evaluation with values higher and lower than the literature value. Afterwards a sensitivity study on the scattering coefficient of the seating area is conducted. The choice for these sensitivity studies results in the material settings as depicted in Table 1.

Table 1: Settings of used absorption and scattering coefficients. Setting 1 obtained from literature [2, 9].

Setting No	Elements	Material	Absorption Coefficient	Scattering Coefficient
1	Seating area	Marble	0.013	0.55
2			0.100	0.55
3			0.200	0.55
4			0.005	0.55
5			0.013	0.90
6			0.013	0.10
1-6	Scene wall	Porous stone	0.200	0.40
	Orchestra	Mosaic	0.030	0.55
	Stage	Earth	0.420	0.40

The averaged values for the full octave bands 500-1000 Hz of the acoustical parameters T_{20}, EDT, and C_{80} are evaluated in accordance with ISO 3382. T_{20} was chosen instead of T_{30} because of the available decay range in the measurements [4]. No run-to-run variation [10,11] was found in the detailed model's parameter results. The cumulative root-mean-square deviation (RMSD) between the measured values and simulation was used to choose the setting of material properties to apply to the simplified models and the literature models. The IR of the first and the last receiver position of line E (Herodes) and F (Epidaurus) [4] were calculated separately and compared with the IR's to gain insight in the calculated energy decay. The T_{20}, EDT, and C_{80} for the detailed, simplified, and literature model were assessed to evaluate the influence of the geometry.

3. Results

In this chapter, the results of both theatres are presented without the discussion. Per theatre, the parametric study on the material settings is presented, then the RMSD of the simulated parameters to the measured values are mentioned, and finally, the influence of the geometry is denoted.

3.1 Odeon of Herodes Atticus

The Herodes modelling results of material settings 1 to 6 are compared with the measured results of all 200 receiver positions. The cumulative distribution of the simulations and the measurements are displayed in Fig. 3. The modelled values display a similar trend with the measured values for all three investigated parameters. However, an underestimation of the T_{20} appears for the entire field while EDT and C_{80} are more in range with the measured values.

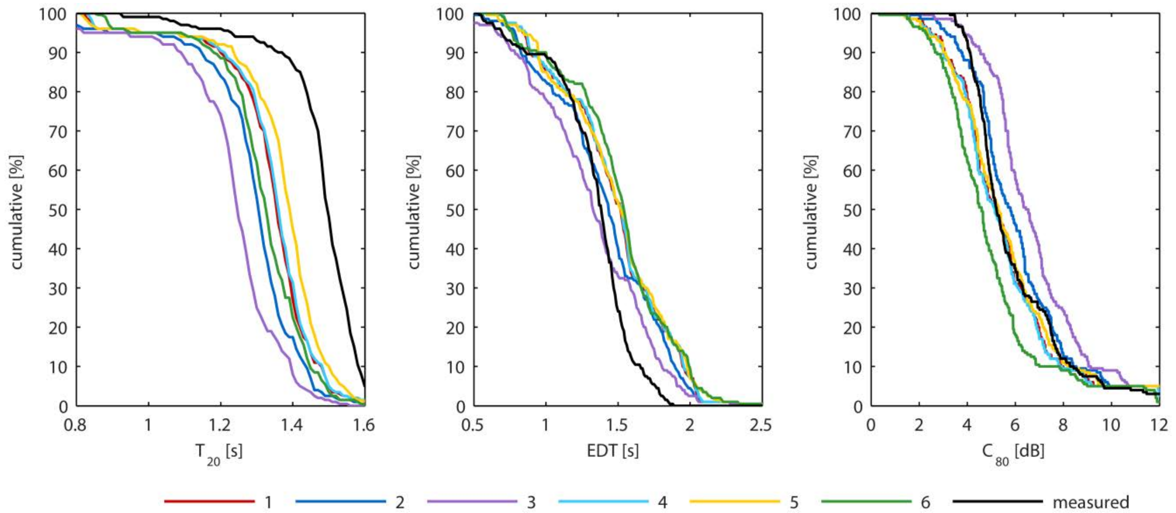

Figure 3: Cumulative distribution functions for the T_{20}, EDT, and C_{80} as obtained for the material settings of Table 1 applied to the detailed model of the Odeon of Herodes Atticus with TO 2.

Table 2: The influence of material settings for the Odeon of Herodes Atticus expressed in JND between measured and modelled values of the T_{20}, EDT, and C_{80} for material settings 1 to6.

		1	**2**	**3**	**4**	**5**	**6**
TO 0	T_{20}	3	3	4	3	2	3
	EDT	6	7	8	8	6	6
	C_{80}	1	2	2	2	1	1
TO 2	T_{20}	2	3	3	2	2	2
	EDT	4	4	4	4	5	4
	C_{80}	1	1	2	1	1	2

As shown in Table 2, none of the average differences are within the Just Noticeable Difference (JND). An increased absorption coefficient for the seating area results for both TO's in a larger deviation between the measured and simulated results. A decreased absorption coefficient appears to have limited effect.

The distribution of the results of all 200 receiver positions are displayed in Fig. 4. In Fig. 5 the decay curves for two receiver positions as obtained by the measurements and the simulations of the detailed model are depicted. The measured values are an average of the five equal-angular source rotations of S1.

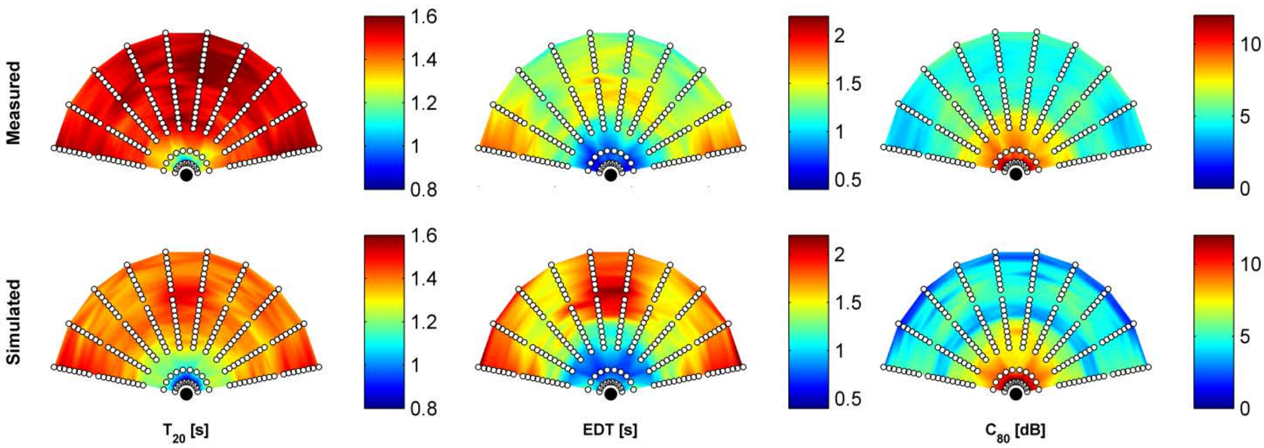

Figure 4: Contour plots of the T_{20}, EDT, and C_{80} as obtained for material setting 1 applied to the detailed acoustic model of the Odeon of Herodes Atticus with TO 2. Measured: above, modelled: below.

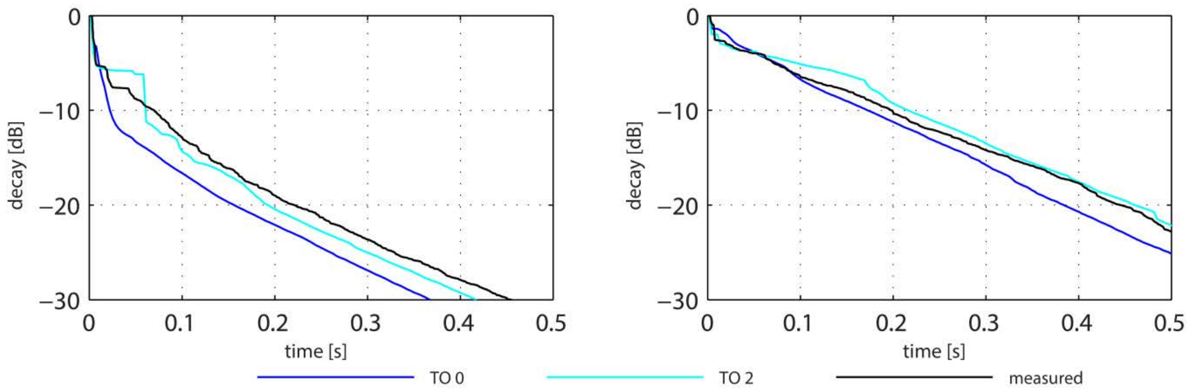

Figure 5: Decay curve for receiver position R1 and R20 on line E for the Odeon of Herodes Atticus (the simulated values are modelled with material setting 1)

Based on the cumulative RMSD as depicted in Table 2, setting 1 (literature based) modeled with TO 2 was the option with the least deviation from the measurements. This setting has been applied to the simple geometry and the geometry as obtained from literature. The results of the different geometries are depicted in Fig. 6 and Table 3. The ratio of the seating area to the total surface area is 25 % for the detailed model, 21 % for the simplified model, and 28 % for the literature model.

Table 3: The influence of geometry for the Odeon of Herodes Atticus expressed in JND between measured and modelled values of the T_{20}, EDT, and C_{80} for all geometrical models.

		Detailed model	Simplified model	Literature model
TO 2	T_{20}	2	4	1
	EDT	4	5	7
	C_{80}	2	2	2

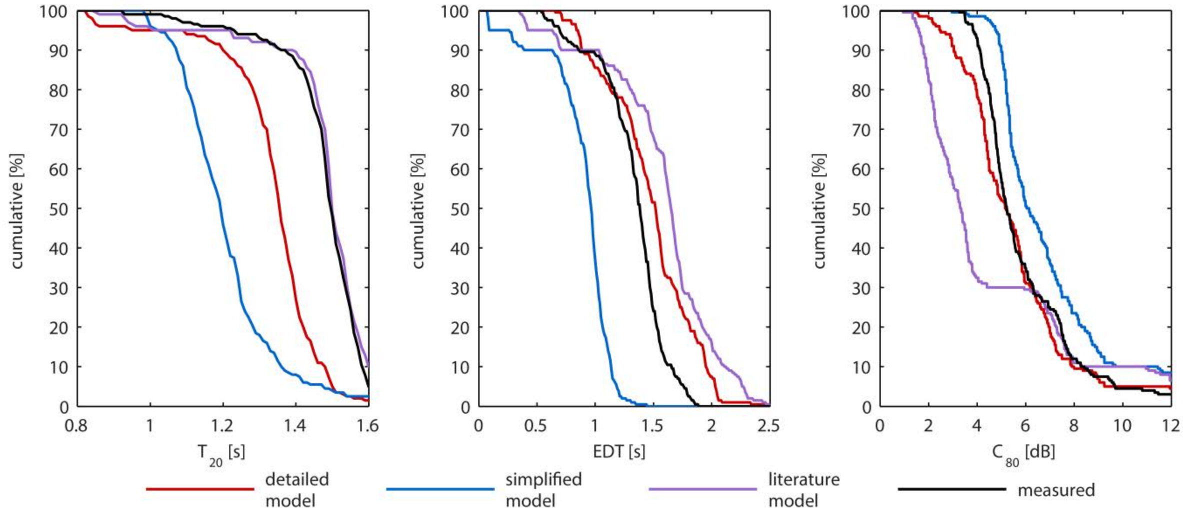

Figure 6: Cumulative distribution functions of parameters T_{20}, EDT, and C_{80} depicting the influence of the geometry for the Odeon of Herodes Atticus

3.2 Theatre of Epidaurus

The modelling results, of material settings 1 to 6, of Epidaurus are compared with the measured results of all 228 receiver positions. The cumulative distribution of both the simulations and measurements are displayed in Fig. 7. The modelled values display a similar trend with the measured values for the reverberation time T_{20}. However an overall underestimation of the T_{20} appears. The trend of the EDT and the C_{80} do not follow the measured trend.

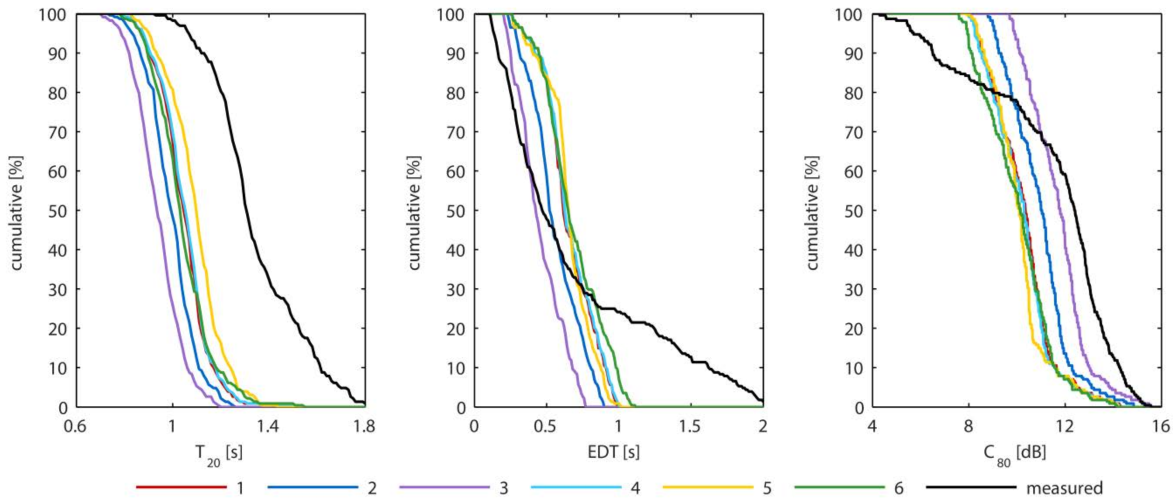

Figure 7: Cumulative distribution functions of the T_{20}, EDT, and C_{80} as obtained for all the material settings of Table 1 applied to the detailed model of the theatre of Epidaurus with TO 0.

Table 4: The influence of material settings for the theatre of Epidaurus expressed in JND between measured and modelled values of the T_{20}, EDT, and C_{80} for material settings 1 to 6.

		1	2	3	4	5	6
TO0	T_{20}	5	6	6	5	4	5
	EDT	13	14	15	13	13	12
	C_{80}	2	2	2	2	2	2
TO2	T_{20}	9	9	8	9	8	9
	EDT	38	33	15	13	13	45
	C_{80}	4	4	2	2	2	4

None of the average differences are within the JND. An increased absorption coefficient for the seating area results for both TO's in a larger deviation between the measured and simulated results. The decreased absorption coefficient appears to have limited effect.

Measured and simulated contour plots of the three acoustical parameters can be seen in Fig. 8. The simulated values show the same trend; different values are found on the edges of the theatre compared to the middle section. However, the differences are much larger in the measured results. Note that a different range has been applied for the measured and simulated contour plots. In Fig. 9 the decay curves for two receiver positions as obtained by the measurements and the detailed model are depicted. The measured values are an average of the five rotations of S1.

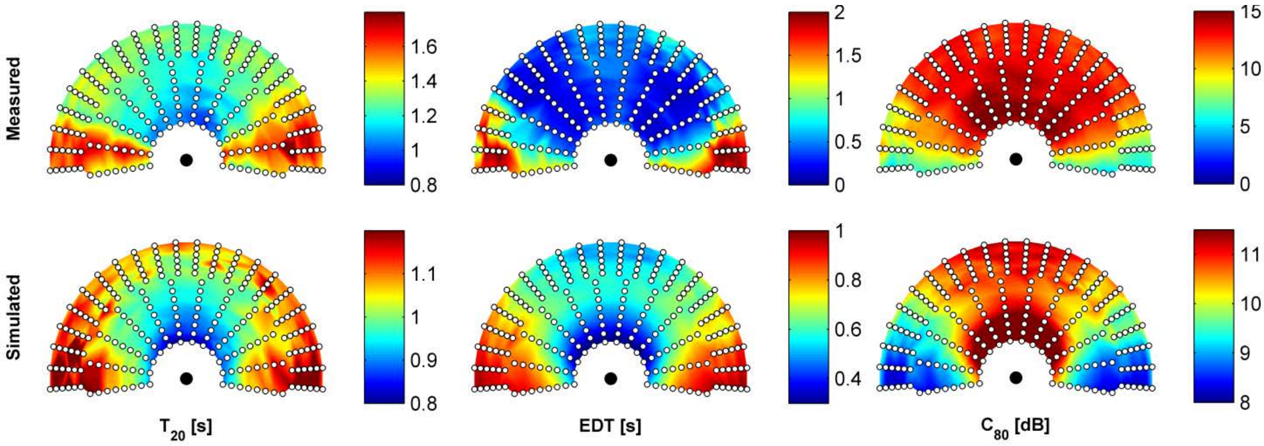

Figure 8: Contour plots of the T_{20}, EDT, and C_{80} as obtained for material setting 6 applied to the detailed acoustic model of the theatre of Epidaurus with TO 0. Measured: above, modelled: below.

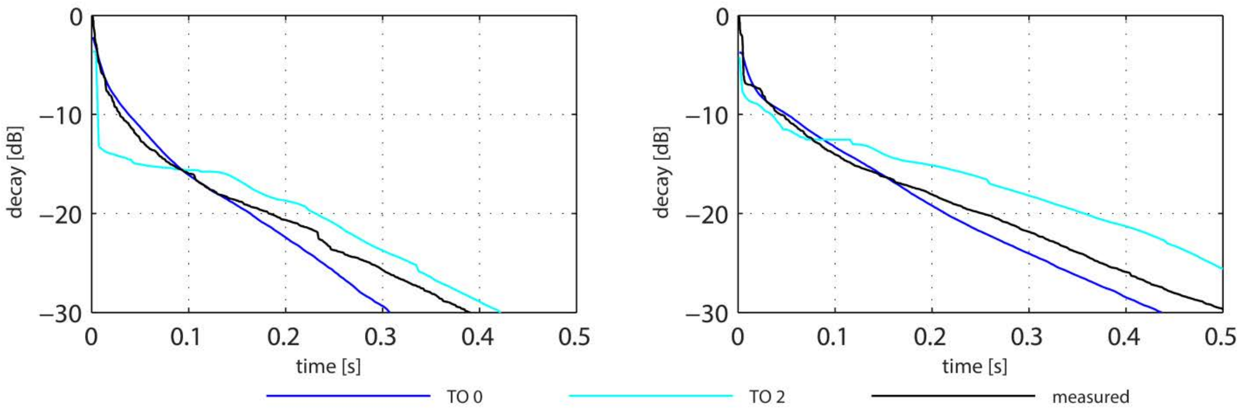

Figure 9: Decay curve for receiver position R1 and R20 on line F for the theatre of Epidaurus (simulated values are modelled with material setting 6)

Based on the cumulative RMSD as depicted in Table 4, setting 6 (low scattering) with TO 0 is the setting with the least deviation from the measurements. This setting has been applied to the simplified geometry and the literature geometry. The results for the different geometries are depicted in Fig. 10 and Table 5. The ratio of the seating area to the total surface area is 43 % for the detailed model, 39 % for the simplified model, and 46 % for the literature model. The simplified model has also been simulated with material setting 5 (high scattering). This was done to check if the higher scattering could compensate for the lack of detail.

Table 5: The influence of geometry for the theatre of Epidaurus expressed in JND between measured and modelled values of the T_{20}, EDT, and C_{80} for all geometrical models.

		Detailed model	**Simplified model**	**Literature model**
TO 0	T_{20}	5	15	7
	EDT	12	23	13
	C_{80}	2	10	2

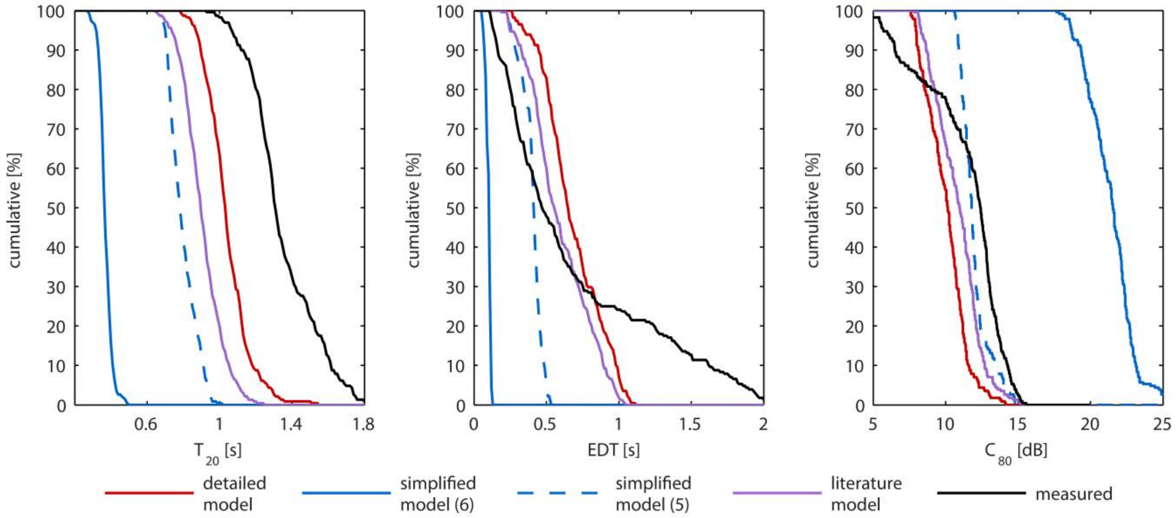

Figure 10: Cumulative distribution functions for the T_{20}, EDT, and C_{80} showing the influence of the geometry for the theatre of Epidaurus. The simplified model is included twice; once modeled with material setting 6 (low scattering) and once with material setting 5 (high scattering)

4. Discussion and conclusions

For the most accurate geometry based on on-site theodolite measurements, the T_{20} results from the calculations are lower than the measurements for all studied material properties studied for both theatres. However, the distribution of the variation in T_{20} results show similar trends. Further reduction in absorption of materials does not lead to a better prediction. In addition, the scattering coefficient does not have a considerable effect on the outcome of the detailed models. The EDT and C_{80} predictions also show errors larger than the JND. It seems that predictions within one JND from the measured results are not possible with the settings used.

Using a Transition Order of 2 gives predicted results closest to the measured values for all parameters studied in Herodes. However, in the decay curve, a plateau or change in decay rate can be observed caused by the 1st and 2nd order reflections calculated by the image source method. This effect was not found in the measured decay curves and is likely erroneous. Thus, the closer match of predicted parameter results using a TO of 2 is not a more accurate prediction. For Epidaurus, the decay curves also contain a plateau when using a TO of 2. For this theatre, the average predicted parameter results is closer to the measured results when using TO of 0.

Even though the absolute results and variations over positions deviate, the detailed model does reproduce some trends measured in the theatres. For Epidaurus, the measured reverberation time is higher and clarity lower for the outer lines compared to the middle section. The model also predicts this effect, but with a more subtle variation in parameter results. This explains the deviation in cumulative distribution presented in Fig. 7. A similar trend is found for the EDT of Herodes, where it seems that the outer and middle lines (at 0 and 90 degrees angle) show a slightly higher EDT than the lines in between them (at 45 degrees angle). Possibly, this effect is caused by sound being reflected back and forth when the seating area are opposite to another seating area or opposite to a reflective wall.

For both theatres, the simplified model shows the biggest deviation from the measurements. For Epidaurus, a high scattering coefficient of the flat audience area brings the results much closer to the detailed model. For Herodes, the model based on literature has higher values for T_{20} than the detailed model and as a result a higher agreement with the measurements. This is most likely caused by less openings in the scene than in the detailed model, due to the limited information on the scene wall design in the literature source. This reduction in ‘absorption’ is the reason for higher T_{20} values.

In general, we can conclude that it was not possible to obtain accurate modelled results using the geometrical modelling approach for the two theatres. Changing material properties or more detailed geometry input did not improve the model outcome sufficiently. Nonetheless, trends found in the measurements could be reproduced using the model showing the value of geometrical acoustics modelling.

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