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DISCRETISATION OF CURVED SURFACES AND CHOICE OF SIMULATION PARAMETERS IN ACOUSTIC MODELING OF RELIGIOUS SPACES

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A common characteristic of religious spaces in Eastern and Western Mediterranean cultures is the existence of large curved surfaces, usually in form of domes at the ceiling. Modeling of such spaces using geometrical acoustic algorithms typically requires discretisation of curved surfaces into planar elements. The degree of discretisation plays a crucial role in the quality of results, and simulation of several acoustic phenomena such as focusing. In this paper an investigation of the size of discretized elements is performed using the ODEON Room Acoustics Software, version 13. For this investigation a model of the mosque "Selimiye" has been used. Impulse responses of this space were recorded in many positions as part of the CAHRISMA project (Conservation of Acoustical Heritage by the Revival and Identification of the Sinan's Mosques Acoustics) in 2000 - 2003. The model has a big central dome and several other surrounding curved surfaces. Measured room acoustic parameters are compared with simulated ones while varying the discretisation of curved surfaces and several simulation parameters for the best possible agreement. The advantages and disadvantages of very high discretisation are discussed, and the question whether there is an optimum degree of discretisation or not is addressed.

1. Introduction

One of the most common questions when using algorithms of geometrical acoustics is "How many subdivisions should I use to model a curved surface?". In geometrical acoustics sound waves are represented by sound rays, so that various complex phenomena are simplified into geometrical mathematical tasks. Sound rays can be understood as series of lines connecting a source and a receiver. Reflections can be represented by rays or image and secondary sources where still the sound to the receiver can be seen as a line from the source[1]. These simplifications make it possible to calculate the acoustic response in large spaces, while maintaining a short computation time. One of the most usual assumptions in geometrical acoustics is that surfaces should be planar. This implies that curved geometries need to be discretized into planar elements. Moreover, for the purpose of calculating how much energy is reflected, all surfaces are considered to be infinitely large in comparison to the wavelength. For practical room models surfaces cannot not be infinitely large, but they should be kept as large as possible. Taking into account that the wavelength at 1000 Hz is approximately 0.34 metres, a reasonable assumption is to keep surface dimensions no smaller than 0.34 meters[1].

These two aforementioned restrictions have a direct impact on modeling curved surfaces using typical geometrical acoustic methods, such as image source method[2], ray tracing[3], acoustic

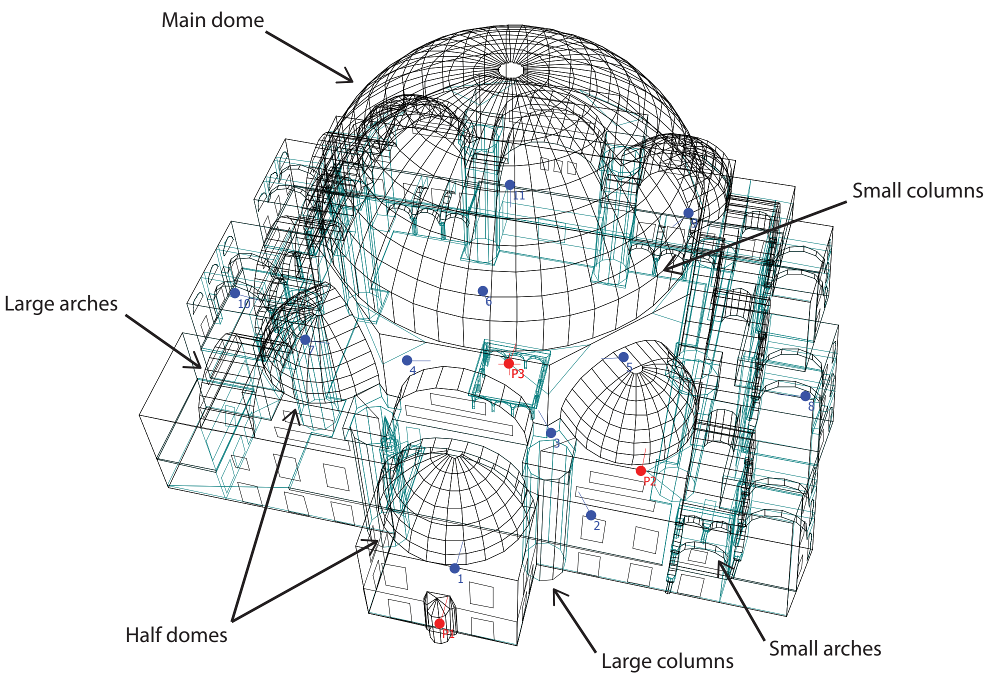


Figure 1: Wireframe of the model of the Selimiye mosque, as it looks inside ODEON when the main dome has been discretized by 50 elements. Sources are indicated in red color and receivers are indicated in blue.

radiosity[4] and combinations of these methods such as ray radiosity[1], beam tracing and radiant exchange[5], as well as Combined acoustical radiosity and image source method[6]. Curved surfaces have to be subdivided into planar sections, but the size of subdivision remains uknown in many cases.

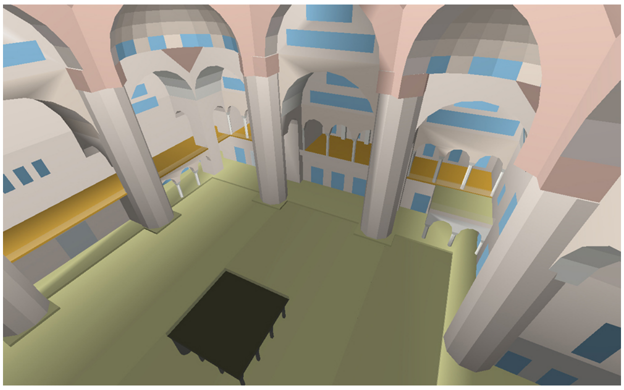
In this paper the influence of subdivision of curved surfaces in a rather diffuse space is investigated. Several simulations of a mosque equipped with domes are performed in ODEON Room Acoustic Software, version 13, for varying geometrical representation. The software uses a combination of the image source method (at the early part of the response) and ray radiosity (at the late part of the response). The simulated results are compared with measurements and the behavior of the error is analyzed.

2. Room Model

The model chosen for the present paper is the Selimiye Mosque (Turkish: Selimiye Camii), an Ottoman imperial mosque, located in the city of Edirne, Turkey. The space was measured as part of the CAHRISMA project (Conservation of the Acoustical Heritage by the Revival and Identification of the Sinan's Mosques Acoustics), between 2000 and 2003 [7, 8].

The Selimiye Mosque is a huge worship space of about 43 m height, with a dome of about 31 m diameter. The volume is approximately 68606 m^3. Apart from the main dome, the building consists of 5 half domes, more than 40 small and big arches, and more than 35 cylindrical columns. For typical room acoustic simulations all of these curved surfaces have to be discretized into planar elements. Fig.1 shows a wireframe of the geometry as it looks inside ODEON, when the main elements of the model have been discretized as follows: • *Main dome*: 50 sections in 360°. • *Half domes*: 13 sections in 180°. • *Large columns*: 10 strips in 360°. • *Small columns*: 6 strips in 360°. • *Large arches*: 13 strips in 180°. • *Small arches*: 6 strips in 180°.

In Fig. 2a the same model is shown in 3D view, with materials displayed by colors according to their absorption at the frequency range from 63 Hz to 8000 Hz [9]. According to this procedure



(a) Material overview of the Selimiye mosque in a 3D rendering in ODEON. Colors are displayed according to absorption [9].

(b) Photo of the mosque. Marble and stone walls are equipped with decorative elements, that increase absorption and scattering.

Figure 2: 3D rendering and photos of the Selimiye mosque.

surfaces that are hard at low frequencies appear in cool color, while surfaces that are absorptive at high frequencies appear in warm color. As can be seen in Fig. 2a and 2b most of the surfaces are made out of hard stone and marble materials. During the CAHRISMA project, observation and information from technicians at the moaque had led to an initial estimation of materials as shown in Table 1. The scattering coefficient varies from 1%, for very hard surfaces, to 40%, for highly rough surfaces with many decorative elements.

2.1 Measurements

Impulse responses were measured in the room for 3 source and 10 receiver positions, which gave a total of 30 combinations. An omnidirectional dodecahedron type of source was used, together with an omni-directional microphone and a custom measurement MATLAB® script. The impulse responses were obtained in .WAV format, which makes it possible to load them in measurement processing software and derive all relevant room acoustic parameters. For this paper the measurement facilities in ODEON Room Acoustic Software are used to process the impulse responses. The tool *Load impulse response* allows importing and processing of impulse responses in .WAV format, while it automatically detects the onset and truncation time at the noise floor[10, 1]. A clear impulse response is then obtained for extracting common or customized room acoustic parameters.

2.2 Calibrating the PC model using a Genetic Material Optimizer

An initial comparison between simulations and measurements is performed for the list of absorption coefficients displayed in Table 1. All 30 source-receiver combinations are used and the average error between seven simulated and measured room acoustic parameters is derived.The parameters taken into consideration are EDT (Early Decay Time), T_{15} (Reverberation Time), T_{30} (Reverberation Time), T_S (Gravity/Center Time), SPL (Sound Pressure Level), D_{50} (Definition) and C_{80} (Clarity) [11]. Since different units are used to express each parameter, the differences between simulations and measurements are normalized in JND (Just Noticeable Difference) (e.g. 5% for T_{30} and 1 dB for C_{80}). As a result, the average error is expressed in a single JND value per frequency. Differences less than 1 JND cannot be perceived by humans, hence such results are considered fairly accurate. The average error can be expressed by the formula:

$$\epsilon[JND] = \frac{\sum_{k=1}^{K}\sum_{i=1}^{I} |[Par_i^k]_{Sim} - [Par_i^k]_{Meas}|}{K \cdot I}, \tag{1}$$

where $[Par_i^k]_{Sim}$, $[Par_i^k]_{Meas}$ represent the simulated and measured acoustic parameter i for the source-receiver combination k. K is the total number of source-receiver combinations, while I is the total number of used acoustic parameters. The comparison is performed using ODEON's tool *Investigation of simulation parameters* which shows the $\epsilon[JND]$ as a function of different number of rays in simulations. The tool helps to set two of the most important simulation parameters in ODEON: 1)The transition order and 2) The number of late rays. The transition order controls the shift from the image source model to ray radiosity, while the number of late rays determines how many rays are used for the calculation of the late part of the response, during the ray radiosity method. A transition order of 2, with 10000 late rays seemed to be a good combination for minimizing the average JND error between simulations and measurements.

A calculation with the *Investigation of simulation parameters* tool showed an average error well above 1 JND; meaning that it was worth trying to optimize the initial set of absorption coefficients (Table 1) in order to reduce this error. The *Genetic Material Optimizer* tool in ODEON [12] offers a fast way to tune the absorption coefficients of selected materials in order for $\epsilon[JND]$ to be minimized. For the optimization process the list of room acoustic parameters used for the initial comparison is now modified. Two parameters, EDT and T_{30} are still used, but the rest five are defined as variations of the D_{50} parameter, in order to directly compare the energy content at different parts of the impulse response. ODEON offers the facility to add custom parameters by typing the corresponding formula in the *Room Acoustic Parameter List* tool. We define the equation: $D_{x,y} = \int_x^y p^2(t) / \int_0^\infty p^2(t)$, where $p^2(t)$ is the instantaneous pressure of the impulse response at the receiver position. By varying the time variables x and y (in ms) the parameters $D_{0,35}$, $D_{35,80}$, $D_{80,120}$, $D_{180,280}$, $D_{280,\infty}$ are obtained. These particular time intervals are chosen with respect to the space and the time it takes for the impulse response to develop. Especially, the parameter $D_{180,280}$ corresponds to a time interval that includes the sound energy arriving at the floor as a first order reflection from the main dome, when a source is placed underneath (eg. source P3 in Fig. 1).

Table 1: Materials used in the model with initial (*Init.*) and optimized (*Opt.*) absorption coefficients.

		Frequency (Hz)								
Material		**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**Area (m^2)**
Stone and plaster with painting - main dome	*Init.*	0.010	0.020	0.020	0.050	0.070	0.100	0.110	0.110	1049
	Opt.	0.009	0.017	0.039	0.069	0.110	0.170	0.193	0.128	
Stone and plaster with painting - small half domes	*Init.*	0.010	0.020	0.020	0.050	0.070	0.100	0.110	0.110	242
	Opt.	0.022	0.011	0.037	0.082	0.670	0.114	0.107	0.083	
Stone and plaster with painting - half dome Mihrab	*Init.*	0.010	0.020	0.020	0.050	0.070	0.100	0.110	0.110	112
	Opt.	0.030	0.030	0.010	0.039	0.096	0.071	0.075	0.118	
Windows, stone and plaster - window area domes	*Init.*	0.180	0.185	0.135	0.115	0.095	0.085	0.075	0.075	404
	Opt.	0.185	0.131	0.208	0.163	0.108	0.08	0.108	0.040	
Marble - walls, columns and flat ceilings	*Init.*	0.010	0.010	0.010	0.010	0.010	0.030	0.040	0.040	7612
	Opt.	0.011	0.013	0.007	0.014	0.008	0.035	0.050	0.029	
Marble , mix of painted and unpainted - arches	*Init.*	0.010	0.010	0.010	0.010	0.010	0.025	0.035	0.035	1185
	Opt.	0.010	0.007	0.010	0.011	0.011	0.020	0.034	0.032	
Marble Mukarnas Pandantif	*Init.*	0.020	0.020	0.080	0.150	0.160	0.180	0.200	0.200	724
	Opt.	0.025	0.017	0.101	0.125	0.156	0.227	0.260	0.149	
Window glass	*Init.*	0.350	0.350	0.250	0.180	0.120	0.070	0.040	0.040	535
	Opt.	0.416	0.246	0.321	0.154	0.151	0.060	0.036	0.037	
Boarded floor + carpet	*Init.*	0.120	0.140	0.120	0.150	0.350	0.570	0.600	0.600	6490
	Opt.	0.109	0.160	0.183	0.164	0.261	0.467	0.597	0.259	
Marble Special Door	*Init.*	0.010	0.010	0.010	0.010	0.010	0.030	0.040	0.040	17.2
	Opt.	0.008	0.013	0.007	0.009	0.013	0.032	0.045	0.030	

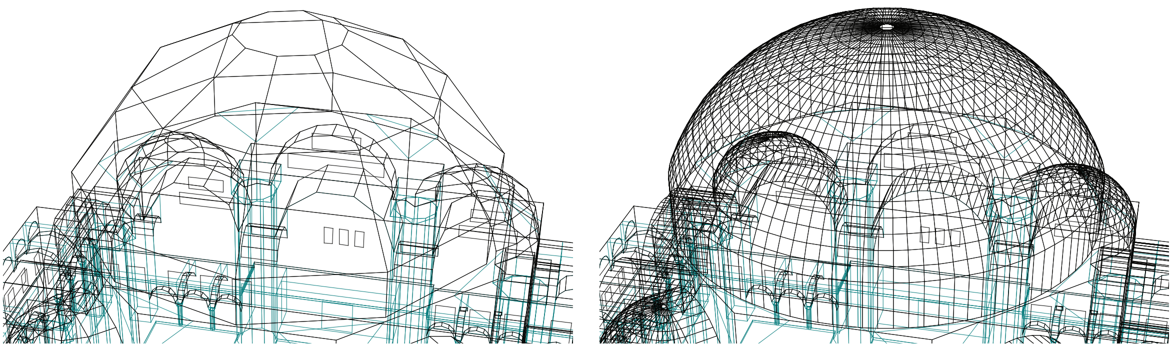
The *Genetic Material Optimizer* performs several rounds of optimization which are called generations. The starting point is the initial set of materials (absorption coefficients for each frequency). At each generation, lists of improved absorption coefficients are derived. Details on how the tool works can be found in [12] and [1]. For the model under investigation a great number of tests was carried out with the *Genetic Material Optimizer* using different settings. Finally the algorithm was run for 10 generations and provided the optimized absorption coefficients shown in Table 1. Table 2 shows the improvement in $\epsilon[JND]$ for the set of parameters as was modified for use during the optimization, as well as the improvement in $\epsilon[JND]$ for the original set of common room acoustic parameters. The error for this set is less than 1 JND for four out of eight octave bands, while it remains below 2 for the rest.

Table 2: Average error per frequency before/after optimization of materials, for the modified set of parameters: EDT, T_{30}, $D_{0,35}$, $D_{35,80}$, $D_{80,120}$, $D_{180,280}$, and $D_{280,\infty}$ and the initial set of parameters: EDT, T_{15}, T_{30}, T_S, SPL, D_{50} and C_{80}.

	Frequency (Hz)	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Modified set	$\epsilon[JND]$ (initial)	0.898	0.902	2.733	0.908	1.081	0.932	1.132	2.197
	$\epsilon[JND]$ (optimized)	0.886	0.843	0.687	0.496	0.630	0.693	0.913	1.323
Initial set	$\epsilon[JND]$ (initial)	1.815	1.883	5.453	1.582	1.748	1.469	1.722	3.625
	$\epsilon[JND]$ (optimized)	1.709	1.792	0.996	0.754	0.943	0.944	1.341	1.692

3. Simulations for varying surface discretisation

Simulations of the optimized Selimilye mosque model were performed for 14 degrees of discretisation of three types of curved surfaces: The main dome, the half domes and the large arches (see Fig. 3). Denoting the number of sections that make the main dome by M and the number of sections that make the half domes and the large arches by N, the discretisations can be described as: $(M,N) = (10,5),(20,7),(30,9),(10+10*k, 5+2*k)\dots$, where $k = 3,4,5\dots$. One extra pair $(M,N) = (5,3)$ was introduced as an extreme case of geometry simplification.

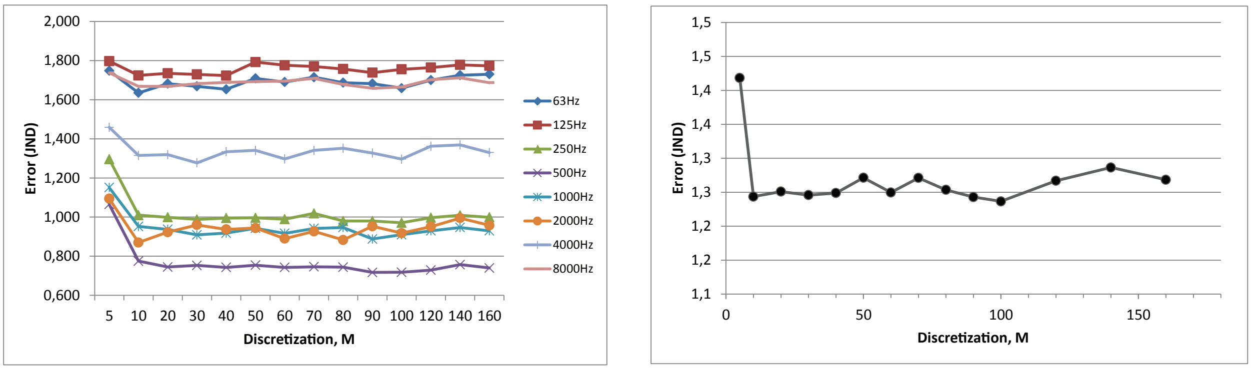


(a) $(M,N) = (10,5)$. (b) $(M,N) = (100,23)$.

Figure 3: Two examples of discretisations of the Selimilye mosque model.

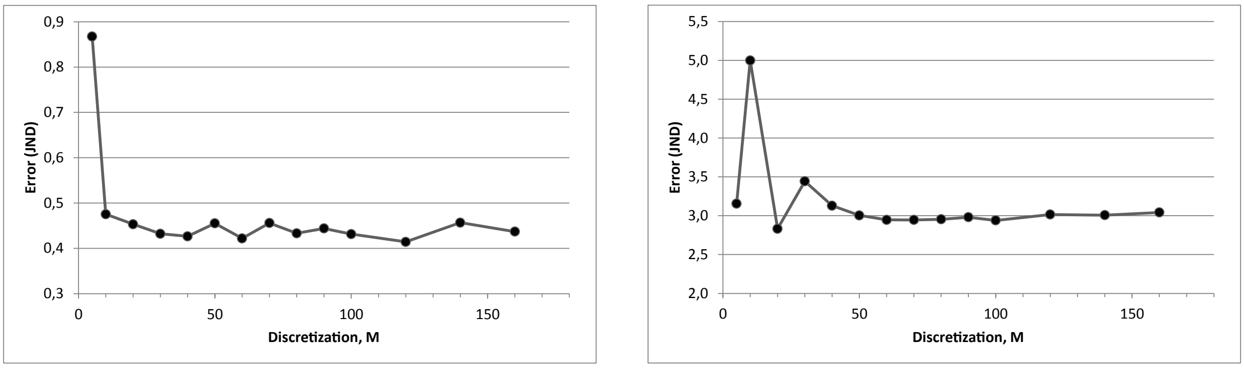
4. Results

The graphs in Fig. 4 show the average error for the parameters EDT, T_{15}, T_{30}, T_S, SPL, D_{50} and C_{80} among all 30 source-receiver combinations. It can be seen that apart from the most simplified pair $(M,N) = (5,3)$, all other discretisations provide a virtually stable error. Similar behaviour is



(a) Octave bands from 63 Hz to 8000 Hz. (b) Average of all octave bands from 63 Hz to 8000 Hz.

Figure 4: Error in JND, averaged for all parameters EDT, T_{15}, T_{30}, T_S, SPL, D_{50} and C_{80} for all source - receiver combinations.



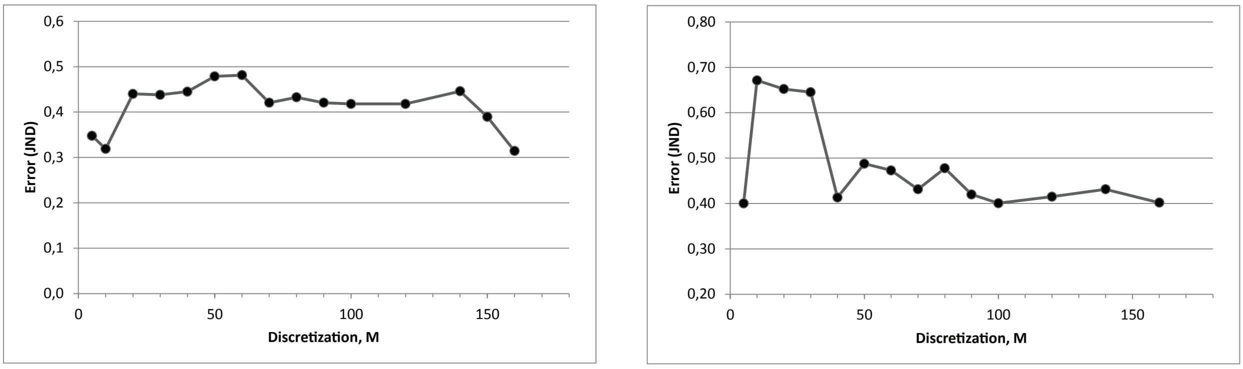
(a) T_{30} parameter. (b) T_S parameter.

Figure 5: Error in JND, averaged for all source - receiver combinations and all octave bands from 63 Hz to 8000 Hz.

observed in Fig. 5 where the global error for specific parameters, such as T_{30} and T_S, does not seem to be affected with discretisation. This apparently simple result leads to the important conclusion that for such a big and diffuse space curved surfaces do not need to be discretized in a high degree for predictions within 1 JND. Even for a combination $(M, N) = (10, 5)$ (main dome consisting of 10 sections) the predictions are accurate enough. An explanation for this outcome is that as long as the volume of the domes approximate the real volume, the behaviour of the sound field will not be affected from the actual geometry when the receiver is far away from such surfaces.

4.1 Echo parameter

One of the most important phenomena that can be observed in rooms with curved surfaces is focusing and echo [1]. The echo criterion suggested by Dietsch & Kraak [13] has been implemented in ODEON, since version 11, to help locating positions with echo problems. According to this criterion, echo values above 1 can cause annoyance due to echo to more than 50% of people and values above 1.5 can cause annoyance to more than 90%. The error in echo between measurements and simulations for the whole group of 14 discretisations for source P3 and receiver R3 is shown in Fig.6a. It can be seen that again increasing the discretisation does not improve the accuracy of the predictions significantly. In Fig.6b the error for the custom parameter $D_{180,280}$ for the same source-receiver combination is shown. The parameter was introduced to represent the energy arriving at the floor due to first order focused reflections from the main dome. Although the change is lower than 1 JND, some fluctuation



(a) Echo (Dietsch) parameter.

(b) $D_{180,280}$ parameter.

Figure 6: Error between measurements and simulations for different discretisations (P3 - R3).

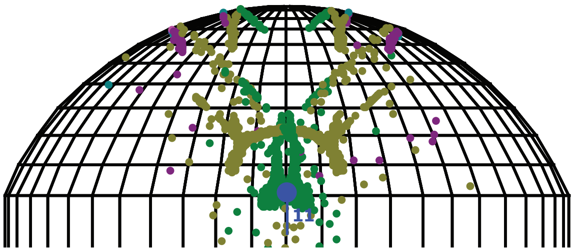
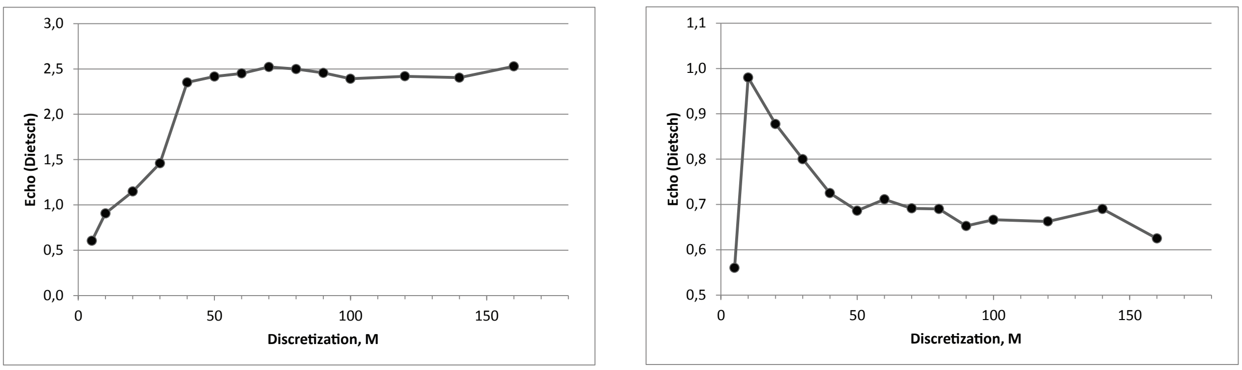


Figure 7: Introducing a new receiver inside the main dome.

occurs for discretisations lower than $(M, N) = (50, 13)$. After that, the error seems to stabilize.

In order to examine the direct impact on the main dome at possible echoes, due to focusing, a dummy receiver is placed at an ideal location: inside the main dome (Fig. 7). The 3DBilliard tool in ODEON helps to determine the position where maximum focusing is expected to occur. This location was not part of the measurement program during the CAHRISMA project. However, simulations for this special position reveal useful conclusions that can be extended to cases where the radius of the dome is equal or smaller than the height of the ceiling. Figure 8 shows the strength of the echo as a function of the discretisation at receiver R11, when source P2 or P3 are active at a time. It can be seen that the predictions stabilize after about 50 discretisations, meaning surfaces every $7.2°$. It is interesting to observe that in these two cases the predictions converge towards different directions: in Fig. 8a the echo is maximized, while in 8b it is minimized.



(a) Source P2 is active.

(b) Source P3 is active.

Figure 8: Echo (Dietcsh) values at receiver R11 for different discretisations, when source P2 and source P3 are active respectively.

5. Conclusions

Via simulations the correlation between discretisations of domes and many acoustical parameters has been studied, in the case of the Selimiye Mosque. The study has been done using the ODEON simulation software. It is shown that for domes far away from the source and receiver positions, the discretisation (when above a extremely rough approximation) has little effect on the parameters under investigation: EDT, T_{15}, T_{30}, T_S, SPL, D_{50} and C_{80}. It seems that in such a large and diffuse space the sound field is not affected by small changes in the geometry of curved, concave surfaces.

The investigations for the dummy receiver in the dome shows that in the focusing region the discretisations have much larger effect on the results, and that the prediction stabilizes near 50 sections for the main dome (500 surfaces for the whole dome). This could provide a general empirical rule for discretisations, according to which concave cylindrical surfaces and domes may be subdivided every 7 to 8°. Smaller subdivisions would only increase computation times without improving the predictions. However, no measurements are available for that receiver location to evaluate simulations. The study also shows that using surfaces much smaller than the wavelength at 1000 Hz does not deteriorate the predictions, even though the assumption of infinite plane surfaces in the image source method and other geometrical approaches tends to be violated.

The results of this study provide an initiation for further investigation in less diffuse rooms, with uneven absorption and for a series of measurements at the focusing region of domes.

REFERENCES

1. Christensen, C. L., Koutsouris G., Gil J., *ODEON Room Acoustics Software, User's Manual*, Odeon A/S, Denmark (2016).
2. Allen, J. B. and Berkley, D. A., Image method for efficiently simulating small-room acoustics, *J. Acoust. Soc. Am.*, **65**, 943-950 (1979).
3. Krokstad, A., Strøm, S., and Sørsdal, S., Calculating the acoustical room response by the use of a ray tracing technique, *J. Sound Vib.*, **8**, 118-125 (1968).
4. Nosal, E. M., Hodgson, M., and Ashdown, I., Improved algorithms and methods for room sound-field prediction by acoustical radiosity in arbitrary polyhedral rooms, *J. Acoust. Soc. Am.*, **116**, 970-980 (2004).
5. Lewers, T., Strøm, S., and Sørsdal, S., A combined beam tracing and radiant exchange computer model of room acoustics, *J. Appl. Acoust.*, **38**, 161-178 (1993).
6. Koutsouris, G., Brunskog, J., Jeong, C. and Jacobsen, F., Combination of the acoustical radiosity and the image source method, *J. Acoust. Soc. Am.*, **133**, 3963-3974 (2013).
7. Weitze, C. A., Rindel, J. H., Christensen, C. L., Anders Christian Gade, The acoustical history of hagia sophia revived through computer simulation, *Proceedings of the 18th International Congress on Sound and Vibration*, Rio de Janeiro, Brazil (2011).
8. Weitze, C. A., Rindel, J. H., Christensen, C. L., Gade, A. C., Comparison between In-situ recordings and Auralizations for Mosques and Byzantine Churches, *Joint Baltic - Nordic Acoustical meeting*, Copenhagen, Denmark (2002).
9. Rindel, J. H., Christensen, C. L., The use of colors, animations and auralizations in room acoustics, *Internoise*, Innsbruck, Austria, (2013).
10. Christensen, C. L., Koutsouris, G., Rindel, J. H., The ISO 3382 parameters. Can we measure them? Can we simulate them?, *International Symposium on Room Acoustics*, Toronto, Canada (2013).
11. ISO 3382-1, *Acoustics - Measurement of room acoustic parameters - Part 1: Performance spaces*, 2009.
12. Christensen, C. L., Koutsouris, G., Rindel, J. H., Estimating absorption of materials to match room model against existing room using a genetic algorithm, *Forum Acusticum*, Krakow, Poland (2014).
13. Dietsch, L., Kraak, W., Ein objektives Kriterium zur Erfassung von Echostörungen bei Musik- und Sprachdarbietungen, *Acustica*, **60**, 205-216 (1986).