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# ACOUSTICAL FEATURES OF THE ÜÇ ŞEREFELİ MOSQUE IN EDIRNE (THE MOSQUE WITH THREE BALCONIES)

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## ABSTRACT

This study focuses on the acoustical characteristics of Üç Şerefeli Mosque, built in between 1437and 1447 during the reign of Sultan Murad II in Edirne, which was the second capital city of the Ottoman Empire before conquest of İstanbul. The Mosque was utterly damaged by fire in 1732 and by an earthquake in 1748, then restored in 1764. At its time of construction Üç Şerefeli Mosque was the grandest of Edirne mosques, specifically its dome, and the greatest architectural achievement of the Ottoman architects. It had become a prototype for its successors, representing the transitional architectural style of typical Seljuk mosques towards to the Ottoman style. Within the scope of this study, initially the field tests were carried out in its unoccupied condition, in order to archive the current acoustical conditions. Basic room acoustics parameters are evaluated, including T30, C80 and STI. Acoustical simulations are utilized to investigate the occupied conditions of the mosque. Ray-tracing and diffusion equation model (DEM) computations are applied to comparatively analyze the modeling techniques of posture positions. DEM is also used to visualize the contribution of the dome in energy fragmentation within the mosque, through energy flow vectors and volumetric sound energy distribution maps.

**Keywords:** *mosque acoustics, historical acoustics, Üç Şerefeli Mosque, ray tracing, diffusion equation model, occupant absorption*

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## 1. INTRODUCTION

Sacred spaces in historical context are significant subjects of archaeoacoustic in regards to preservation of acoustical footprint of existing or partly ruined sites as part of intangible cultural heritage. There is numerous research on church acoustics from different parts of the world including churches of Portuguese [1], basilicas of Italy [2] cathedrals in Spain [3] and in France [4]. Europe-centered studies occupy the majority of research on historical Christian worship spaces, while in South America and rest of the world the investigations are mostly on contemporary churches as detailed in Giron et al.'s study [5]. Comparatively a smaller number of studies focus on mosque acoustics, in historical sites. Some of those sites are in Jordan [6], Saudi Arabia [7], Egypt [8], in Algiers [9], and in Türkiye [10]. There are also some specific investigations on the acoustical modifications of historical Chirstian worship spaces that are partially [11] or totally [12] converted to mosques in their time span.

This study contributes to the literature on archeacoustics of sacred spaces with an Islamic worship space from 15$^{th}$ century Ottoman architecture; Üç Şerefeli Mosque (the Mosque with Three Balconies) in Edirne. The methodology includes field tests to archive the existing conditions and later to tune acoustical models for further analysis of occupancy, as to highlight its original in-use conditions. Ray-tracing and diffusion equation model (DEM) are applied in search of the effects of modeling occupant postures and its variations among different geometrical acoustics computation techniques. The study utilizes data from recent research on occupant posture modeling in worship spaces [9, 13].

## 2. ÜÇ ŞEREFELİ MOSQUE, EDİRNE

Üç Şerefeli Mosque (the Mosque with Three Balconies), was built in between 1437 and 1447 during the reign of

Sultan Murad II in Edirne city, which was the second capital city of the Ottoman Empire before conquest of İstanbul. The Mosque was utterly damaged by fire in 1732 and by an earthquake in 1748, then restored in 1764. The name of the mosque is inspired from its minaret at southern corner (67 m high), which has three small balconies and was the highest minaret of Ottoman Empire at its time of erection [14]. In addition, the four-minaret typology was first realized in Üç Şerefeli Mosque, as previously the Ottoman Mosques had only two minarets.

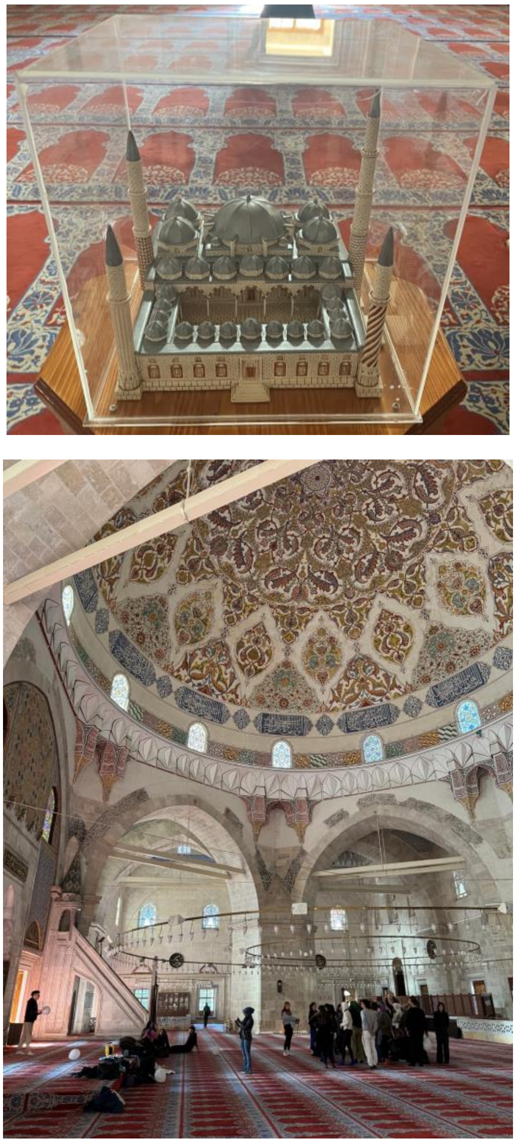

**Figure 1**. 3D Scale-model (above) and interior view (below) of Üç Şerefeli Mosque

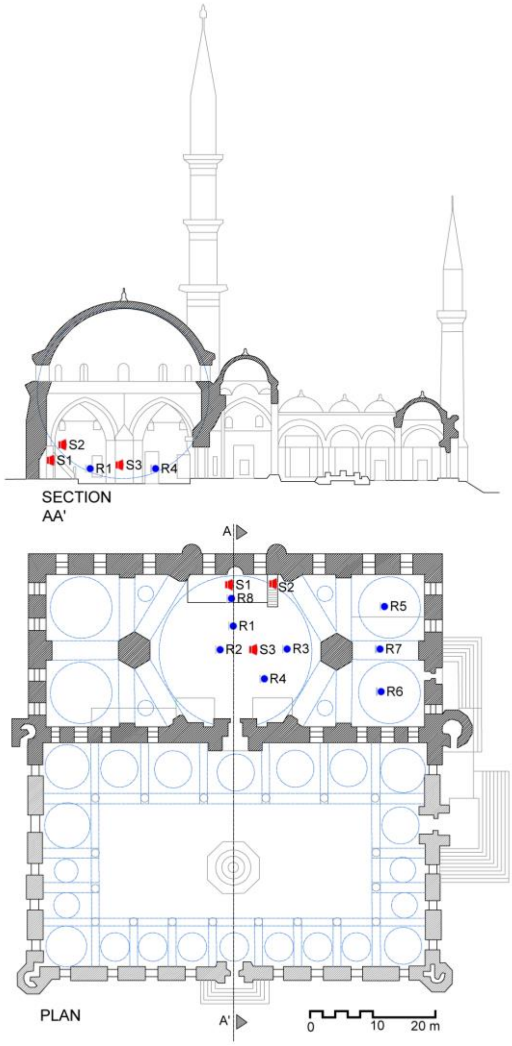


**Figure 2**. Plan and section views of Üç Şerefeli Mosque with source (in red: S1-S3)) and receiver positions (in blue: R1-R8), (plan and section reproduced by the author)

The particular significance of Üç Şerefeli Mosque is that, at its time of construction it was the grandest of Edirne mosques, specifically its dome (see Fig. 1), and the greatest architectural achievement of the Ottoman architects. It had become a prototype for its successors, representing the transitional architectural style of typical Seljuk mosques towards to the Ottoman style. The multi-equal domed mosque typology had left its place a tectonic style of a central dome supported with smaller domes on sides, which symbolizes the start of classical period and the end of early classical period in Ottoman architecture [15].

The mosque has a rectangular plan measuring approximately 24 m by 60 m. The central dome is 24 meters in diameter, and the height of the peak point of the dome from interior is also almost 24 meters. This is one significant architectural feature, as the full virtual circle of the dome is tangent to the floor (see Fig. 2). This causes the prayer plane to fall within the focal zone of the dome, producing particular acoustical phenomena as discussed in later sections. The central dome is supported internally by six piers, and completed on the two sides by two smaller domes (in total four), apart from four seat domes at the corners of central dome [15]. The mosque is mainly of limestone masonry. Columns and their capitals, mihrab, minbar and portals, are made of marble.

## 3. METHODOLOGY

### 3.1 Field Measurements

The Field tests were held on 19th of October 2025, right after morning prayer with very few visitors inside the mosque. The tests are held as part of a field trip with 3rd year architectural design students, of TED University. Within the limited time of unoccupied condition of the mosque, the tests were held with balloon pops as a sound source, at three different source positions; one in front of mihrab (S1), one at müezzin mahfili (S2) and one underneath the central dome (S3) (see Fig. 2). The first two represents regular activity patterns, *imam* in front of mihrab (daily prayers) and *imam* at the minbar (preaching). The third source position is selected specifically to record the audible echo formation underneath the central dome to analyze RIR further. In total eight different receiver positions (R1-R8) are coupled with three different source configurations. The measurement system includes B&K (Type 4190ZC-0032) microphone covering the frequency interval in between 100 Hz to 8000 Hz. Sampling frequency of the recorded multi-spectrum impulse is 48 kHz. DIRAC Room Acoustics Software Type 7841 v.4.1 and ODEON v.18 are used for post-processing RIRs.

### 3.2 Ray-Tracing and Diffusion Equation Model

The acoustical simulations of the mosque are carried out by two geometrical acoustics methods that are ray-tracing and diffusion equation model (DEM) analysis in a finite element scheme. The objective of acoustical simulations is to test the effect of occupancy within the mosque, in the case of in-use condition. For applying different estimation methods, the acoustical models of the structure are generated as 3D- surfaces for ray-tracing and as a solid model for DEM using archived drawings. Materials are assigned in accordance with field observations, as well as relevant references [14,15]. Simplified graphical model used in ray-tracing comprises 2,572 plane surfaces with a total surface area of 9,000 m² (see Fig. 3). The acoustical volume of the model is approximately 24,000 $m^3$. This model is then imported into ODEON 18.00 Room Acoustics Software. The acoustic simulation settings include an impulse response length of 10,000 ms. Applied number of late rays is 6,000. Maximum reflection order is 10,000 and impulse response resolution is set to 1 ms.

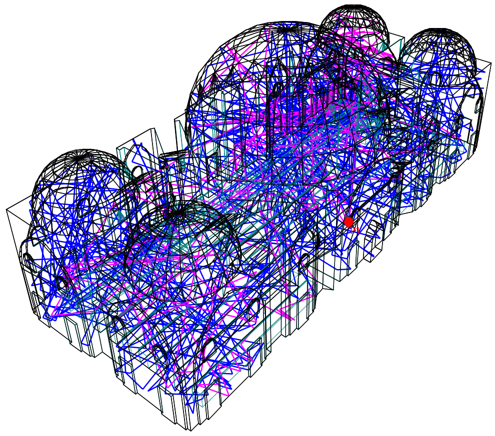

**Figure 3.** Ray tracing model of Üç Şerefeli Mosque

Applied DEM equations are briefly presented in the following, while detailed information can be found at Valeau et al. and Jing & Xiang's work [16,17]. The time-dependent sound energy density *w*, in a unit time (t) and position (r), in the presence of an omni-directional sound source, *q (r,t)* can be estimated by [16]:

$$(\partial w(r,t)/\partial t) - D\nabla 2w(r,t) + cmw(r,t) = q(r,t), \in V \quad (1)$$

where *D* is the diffusion coefficient, which takes into account the room morphology via its mean free path (D=λ*c/3). The term *cmw(r, t)* accounts for atmospheric attenuation within the room, with *m* being the absorption coefficient of air (which is effective after 2000 Hz). The boundary equation is as follows [17]:

$$-D\frac{\partial w(r,t)}{\partial n} = \frac{c\alpha}{4(1-\alpha/2)} w(r,t), \text{ on } S \quad (2)$$

where α is the absorption coefficient of the specific surface or boundary. The energy flow level is then defined as:

$$J_L(r,t)=10\log_{10}\left\{\left[\frac{\partial w(r,t)}{\partial x}\right]^2+\left[\frac{\partial w(r,t)}{\partial y}\right]^2+\left[\frac{\partial w(r,t)}{\partial z}\right]^2\right\}^{1/2} \quad (3)$$

The DEM model is meshed by making sure that the maximum mesh size of each entity is smaller than the mean-free-path (MFP) of the volume. MFP of the mosques solid model is 10.67 m and accordingly diffusion coefficient (D) is 1,223. Complete mesh consists of 70,194 domain elements, 20,546 boundary elements, and 5,299 edge elements (see Fig. 4).

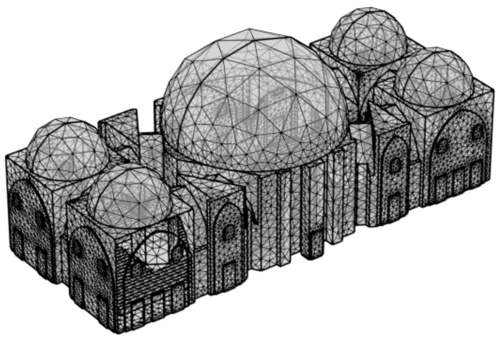

**Figure 4.** Meshed model of Üç Şerefeli Mosque (mesh size; max: 6.13 m, min: 1.1 m)

This study utilizes acoustical simulations in order to test the effect of occupancy conditions on sound energy decay patterns within the mosque. There are different approaches to model prayers in worship spaces. In the case of mosques, the prayers have different postures including sitting on carpet and standing in daily prayer, and sitting in Friday's sermon. In this study sitting position is studied to check the acoustical parameter results of different modeling techniques. Standing position is excluded as it is momentary and intelligibility of the orders of imam is not a critical issue. Moreover, the prayers already now different steps of the prayer activity and have a sense of what is being said. Intelligibility is more critical during sermons, while the prayers sit and listen for a long duration of time. Also, listening or joining in the ritual recitals reflect this pattern of posture. In previous research, Sabbagh and Elkhateeb [13] tested different postures of prayers in a reverberation room for bare and carpeted floor conditions. This study utilizes their laboratory measurements for comparing prayers at sitting position in the cases of floor absorptive and reflective conditions over field-tuned acoustical model of Üç Şerefeli Mosque. The applicability of these absorption coefficients to acoustical simulations are further discussed. Modeling occupancy as a whole surface floor, as baffles or blocks is also assessed by Martellotta et al. [9]. Oldham and Elkhateeb [18], previously modeled prayers as boxes to be applied in a ray-tracing simulation.

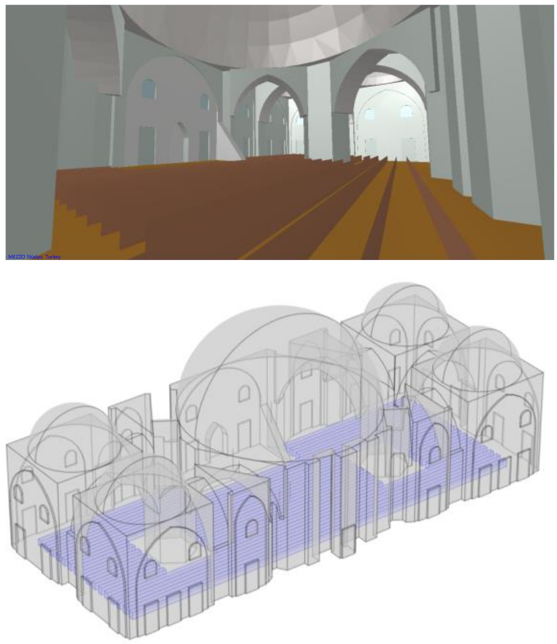

**Figure 5.** 3D-open Gl view from ray-tracing in the baffles modeled as sitting prayers (above), solid model with box surfaces modeled as sitting occupants (below)

This study applies sitting posture in three ways, first the whole floor surface is used as a prayer plane by attaining absorption coefficients from Sabbagh and Elkhateeb's [13] study, as well as scattering coefficients (see Table 1), considering the density is around 1.5 pers/m$^2$. Second, the baffle surfaces are modeled at a height of 1 m and with a width of 1.25 m in between rows. Third, the sitting prayers are modeled as boxes with a height of 0.91 m and width of 0.63 m [8] (see Fig 5). The absorption and scattering coefficients of surfaces with different materials applied in ray-tracing and DEM are given in Table 1. Minor adjustments over alpha values have been necessary, when ray-tracing and DEM obtained acoustical parameter values are tuned to field test results for different source and receiver positions.

**Table 1.** Specifications of different materials assigned in ray-tracing simulations and DEM models of Üç Şerefeli Mosque; sound absorption coefficients over 1/1 octave bands, and applied scattering coefficients

| Material | Sound Absorption Coefficients over 1/1 Octave Bands (Hz) | | | | | | Scattering coefficient |
|---|---|---|---|---|---|---|---|
| | 125 | 250 | 500 | 1000 | 2000 | 4000 | |
| Lime cement plaster (dome and ceiling surfaces) | 0.02 | 0.02 | 0.03 | 0.04 | 0.05 | 0.05 | 0.10 / 0.40 (muqarnas) |
| Stone piers arches (R-for raytracing, D-for DEM) | 0.12 (R) 0.10 (D) | 0.11 (R) 0.10 (D) | 0.03 | 0.02 | 0.05 | 0.07 | 0.20 |
| Marbled surfaces (mihrab wall, minbar) | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.20 |
| Solid wooden door and wooden furniture | 0.14 | 0.10 | 0.06 | 0.08 | 0.10 | 0.10 | 0.20 |
| Large pane of glass | 0.18 | 0.06 | 0.04 | 0.03 | 0.02 | 0.02 | 0.10 |
| Carpet | 0.085 | 0.11 | 0.26 | 0.40 | 0.61 | 0.65 | 0.20 |
| Prayers sitting on carpet - $A_{Obj}$ ($m^2$) [13] | 0.12 | 0.34 | 0.57 | 0.68 | 0.81 | 0.88 | 0.70 (flat floor) / 0.50 (baffle) / 0.20 (box) |
| Prayers sitting on bare floor - $A_{Obj}$ ($m^2$) [13] | 0.08 | 0.20 | 0.35 | 0.51 | 0.59 | 0.67 | |
| Vinyl for the bare floor | 0.02 | 0.03 | 0.03 | 0.03 | 0.03 | 0.02 | 0.10 |

Wherever there is a difference in between ray-tracing and DEM alpha coefficients, it is indicated accordingly in Table 1 (R for ray-tracing, D for DEM), otherwise the coefficients apply for both. The absorption coefficients per $m^2$ obtained in reverberation chamber (prayers on carpet and prayers on bare floor data) are adjusted according to the total area of baffle (considering both sides for ray-tracing, single-side for DEM) and box surfaces, when they are applied to ray-tracing and DEM models.

## 4. RESULTS AND DISCUSSION

### 4.1 Acoustical field measurements

This section initially provides the acoustical parameter results gathered from RIRs collected at acoustical field tests within the mosque. Fig. 6 presents T30 values over octave bands averaged for different source-receiver positions excluding S3, which is right underneath the main dome and demonstrating a strong echo formation (see Fig. 7). Fig. 6 also provides the field-test tuned acoustical simulation results of ray-tracing and DEM models; including average, maximum and minimum values of T30 at measured positions. Fig. 8 presents C80 values over octave bands averaged for different source-receiver positions similarly. Together with maximum and minimum values. S1 and S2 averages for measured receiver positions are also presented in Fig. 8. This is to check if different positions of preacher (*imam*) change the clarity of sound, which more relates to intelligibility. According to Fig. 6, T30 average is 6.68 s for low frequencies, 5.72 s for mid frequencies, and 2.40 s for high frequencies. This indicates a bass ratio of 1.17, which helps augmenting the male voice, so that is suitable for a mosque function. The difference between S1 and S2 measured receiver positions do not deviate much in regards to T30, so not plotted separately.

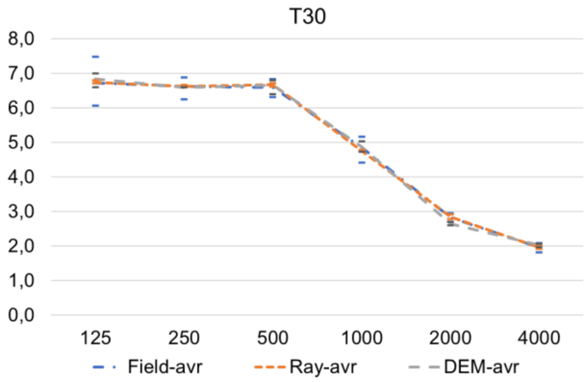


**Figure 6.** T30, in seconds, values for source-receiver configurations over 1/1 octave bands, in Hz; average, min. and max values for field tests, ray-tracing simulations and DEM computations, unoccupied state of the mosque

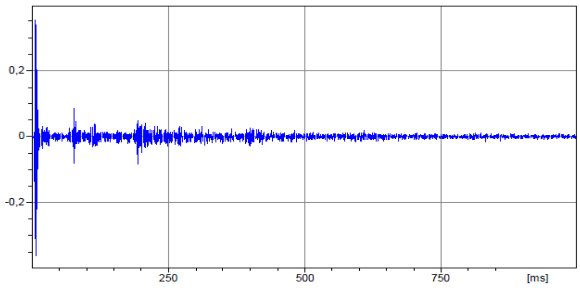


**Figure 7.** RIR recorded at $S_3R_2$ configuration, unoccupied state of the mosque

C80 values indicate that only after 1 kHz, the values fall in between -2 and +2 range, to be optimum for both speech and music related activities (see Fig. 8). The variation per receiver position is diverse as expected. The highest values observed at the closest position to the source that is $S_1R_1$ and the lowest values are at $S_1R_5$ and $S_2R_5$. While not included in the average value the source and receiver position right underneath the dome ($S_3R_2$) shows even higher C80 values then $S_1R_1$. This particular position has a strong echo formation, which may influence and dominate the early energy portion of the decay. As shown in Fig. 7, the audible echo or the first strong reflection after the direct sound, occurs around 78 ms. The secondary strong reflections occur after about 192 ms. Similar to the C80 result the STI value is highest at $S_3R_2$, indicating a rating of 0.80. This result may be biased with the high energy of first early reflection once again. Among the other measured source-receiver configurations, which are included in averages, $S_1R_1$, $S_1R_2$ exhibits STI 0.60 meaning that the prayer positions closer to the mihrab and minbar have *Good* intelligibility ratings, whereas the rest have Fair. The tuning of ray-tracing and DEM models to field test results are carried out, focusing initially on the T30. The process has continued as 1 JND difference is satisfied for all octaves and most source-receiver configurations. The deviation of T30 in between different receiver positions, especially for mid frequencies and below is higher at the field tests when it is compared to ray-tracing and DEM. The T30 difference between measured source-receiver positions is greatest at 125 Hz, and the deviation is not larger than 2-3 JNDs.

Fig. 9 presents volumetric sound energy distribution and energy flow vectors obtained from DEM solutions at time instant 2 s for the empty state of the mosque, which highlights sound energy concentration underneath the central dome. Being an instant in a time-dependent solution, as the sound energy distribution reaches to the steady state, the deviation measured in dB is not high in between different positions of the mosque. While, the energy flow vectors highlight the energy separation underneath different virtually separated volumes of the mosque. In Fig. 9, it can easily be observed that the main dome generates a focal zone feeding back the sound energy from the center of the dome towards the floor and prayer zones underneath the side semi-domes.

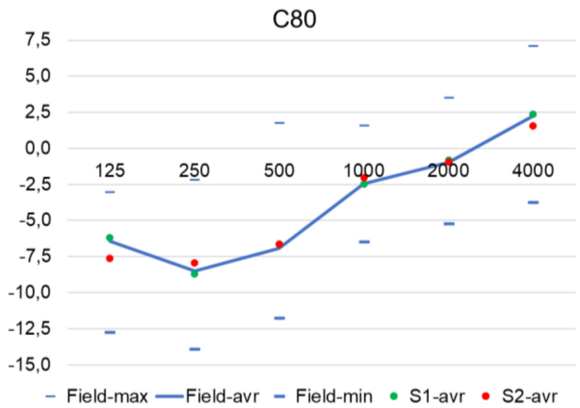


**Figure 8.** Field test results of C80, in dB, values for source-receiver configurations over 1/1 octave bands, in Hz; average, min. and max values, average of S1 and S2 tested receiver positions, unoccupied state of the mosque

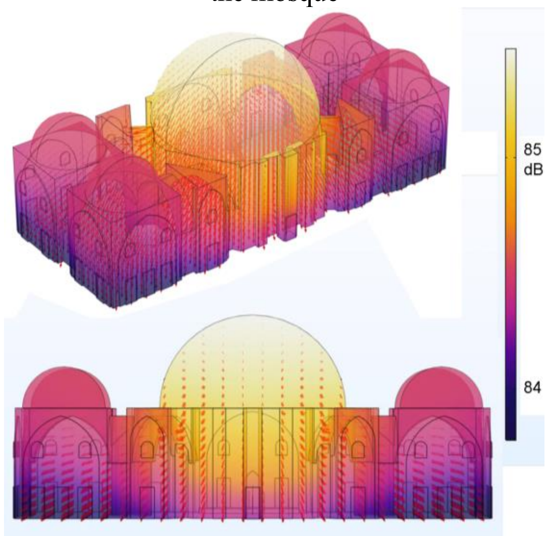


**Figure 9**. Volumetric sound energy distribution and energy flow vectors obtained from DEM solutions at 500 Hz, time instant 2 s for unoccupied state of the mosque, axonometric view (above), section looking towards mihrab wall (below)

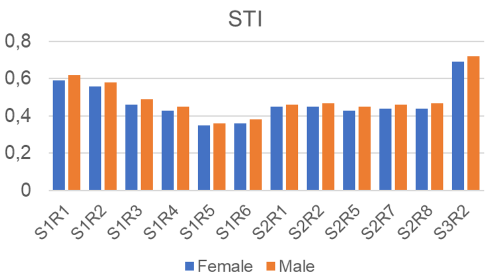


**Figure 10.** Field test results of average STI values for tested source-receiver configurations, empty state of the mosque

### 4.2 Occupant posture simulations

This section presents outcomes of modeling techniques of occupant postures in the mosque with a focus on sitting condition, as being a typical position for both daily prayers and listening sermons in the mosques. As also discussed in Martellotta et. al.'s study [9] baffle and box configurations together with flat surface is tested. This study simply compares ray-tracing and DEM results without a correction factor on estimated T30 values. As given in Table 1, absorption coefficients are gathered from previous literature of sitting prayers over bare and carpeted floor [13]. The results of three different occupant posture models for carpeted floor are given in Fig. 11 and bare floor are given in Fig. 12 for ray-tracing and DEM solutions. In both simulations the absorption coefficients attained to surfaces of different materials are identical. The masking effects are currently not considered to reduce complexity and to make pure comparisons of ray-tracing and DEM models possible.

According to Fig. 11 and Fig. 12 in overall scenarios modeling the surface flat and attaining scattering to the overall floor as given in Table 1 (for ray-tracing) results in the lowest T30 values both in ray-tracing and DEM. When the results of two methods are compared, they are mostly within 1 JND over octave bands. In flat floor case the sitting-prayer alpha values are attained to the whole floor surface, for practicality. Whereas in both baffle and box configurations at least 1 m is left in between aisles and the closest walls or piers. So, this can be the reason for the lowest values, in flat floor models. Baffle and box comparison is more critical, as which one to apply especially in the case of DEM application is an open question. In the case of bare floor, meaning the floor is reflective, Ray-baffle results are slightly higher than DEM-baffle results after 500 Hz (2-3 JND), whereas the difference for 125 Hz and 250 Hz is less than 1 JND. For box-scenario, in overall the difference between ray and DEM models are around 1 to 2 JND in overall octave bands. The greatest deviation among the data group is for the case of box model and carpet floor in ray tracing versus the others. T30 values of Ray-Box model for the absorptive floor case are 2-3 JND higher than Ray-Baffle results after 250 Hz. For the carpet floor scenario, the closest data group is for Ray-Baffle and DEM-Box results for overall octave bands following flat models.

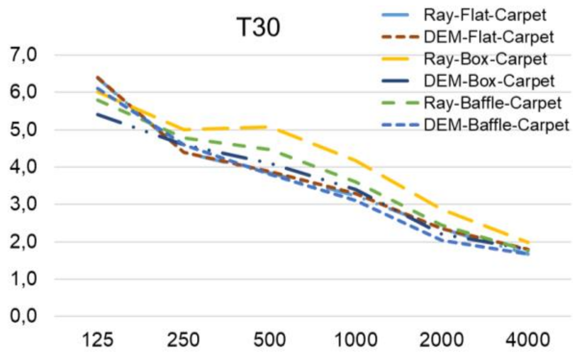


**Figure 11.** Average T30, in seconds, values over 1/1 octave bands, in Hz; sitting occupants within the mosque modeled as a flat surface, as baffles and as boxes over carpet floor; ray-tracing and DEM results

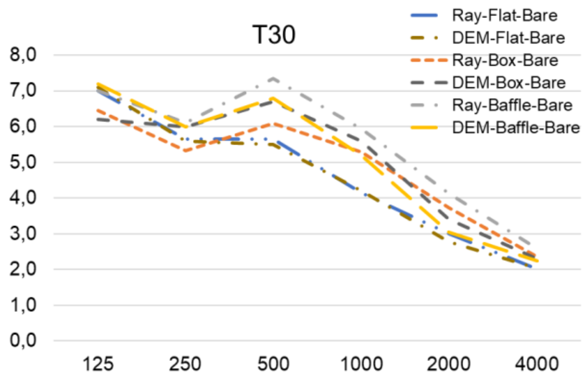


**Figure 12.** Average T30, in seconds, values over 1/1 octave bands, in Hz; sitting occupants within the mosque modeled as a flat surface, as baffles and as boxes over bare floor; ray-tracing and DEM results

It should be noted that a robust comparison and validation of estimated results can only be through field-tested data in the occupied condition of the mosque. Another validation can be through field measurements that were previously held in unoccupied and occupied conditions of auditoriums, where more comparable data can be available. Accordingly, correction factors can be studied in detail as future steps of this study.

## 5. CONCLUSION

This study for the first time investigates the acoustical characteristics of Üç Şerefeli Mosque in Edirne, which is a significant piece of cultural heritage representing a transition period of Ottoman Mosque architecture. Results of field tests are discussed over basic room acoustic parameters. Ray-tracing simulations and DEM computations are applied to further assess the effect of occupancy, focusing on sitting prayer posture. Different posture modeling approaches are tested and compared. Field measurements in occupied spaces as a future research step are found necessary to validate and tune results gathered from geometrical acoustics methods.

## 6. ACKNOWLEDGMENTS

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