

Effect of Dome-Shape on the Reverberation Time of the Mosque - A Case Study

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Abstract Acoustic performance of worship places has been a focus of extensive research. Mosques are traditionally featured by domes, but there is a lack of adequate scientific studies on the effect of dome-shape on their acoustic performance. In order to address this issue, the present study has performed a case study on a typical mosque located at Imam Abdulrahman Bin Faisal University campus in Saudi Arabia. Simulations were performed with four different dome-shapes namely Saucer, Drum, Onion and Pointed [1], which represent typical forms and architectural features, by using ODEON Room Acoustics Program. The results were validated by in-situ measurements (with DIRAC room acoustic system) and statistical analysis (by Microsoft Excel tools). In each case, the acoustic characteristics were evaluated, by considering Imam (prayer leader) position as the sound source. The results establish that selecting the appropriate dome-shape is crucial, as it can have a direct positive or negative impact on the reverberation time of mosques. According to the dome-shape, both Saucer and Pointed domes have the optimum acoustic performance for both T30 and EDT. Both domes meet the theoretical standards to maintain the acoustical comfort. As the results would vary according to the size and architectural features of the building, a case-specific analysis is important at the early design stage.

Keywords Dome-shape, Mosque, Acoustic Performance, Acoustic Characteristics, ODEON Program, DIRAC Room Acoustic System

1. Introduction

Mosques (known as 'Masjid' in Arabic) are important public spaces used by millions of Muslims around the world for a variety of worship activities. Because of their international ubiquity and various modes of use, their acoustical properties should be well understood and regularly optimized. Acoustic performance of worship places in general, and of mosques in particular, has been a topic of extensive research. A brief review of the pertinent literature is presented here to provide a background of the current study.

El-Khateeb and Ismail [2] performed field measurements and simulation to study speech transmission index (STI) in the main hall of the madrasa and mosque of Sultan Hassan Cairo, Egypt. Sü and Yilmazer [3] studied the acoustical characteristics of Kocatepe Mosque, in Ankara, Turkey; they found that the acoustical quality of the mosque was not optimal when it was empty, but was close to optimal when fully occupied. Ghaffari and Mofidi [4] conducted a comparative analysis of mosques and churches in terms of their acoustic characteristics. Khabiri *et al.* [5] presented a method for evaluating acoustic performance in a mosque's main prayer hall by using computer simulation. Similar studies were also reported by Inoue *et al.* [6], Eldien and Al Qahtani [7], Carvalho and Freitas [8], Al Shimemeri *et al.* [9], Eldien and Al Qahtani [7], Putra *et al.* [10], Gul and Caliskan [11], Din *et al.* [12], Abdullah and Zulkefli [13], Kassim *et al.* [14], Elkhateeb *et al.* [15], Othman *et al.* [16], Karaman and Güzel [17], and Suárez *et al.* [18].

Abdou [19] performed in-situ measurements in 21 typical contemporary mosques of different sizes and architectural features in order to characterize their acoustical quality and to identify the impact of air conditioning (AC), ceiling fans, and sound reinforcement systems on their acoustics. It was found that the reverberation time (RT) of these mosques was close to or within optimal only when they were fully or partly (two-thirds) occupied; this was attributed to the relation of RT with the absorption coefficient of the occupants. In another study [19], he focused on the effect of mosque geometry (form) on the acoustic performance. Though significant effect was not observed, performance of the mosque with a rectangular shape was comparatively better in terms of STI, while the octagonal shape showed the least performance. Oldham and Elkhateeb [20] studied the acoustical characteristics of four historical patterns of mosques in Cairo: semi-closed Rewaq, semi-closed Iwan, closed Iwan, and closed simple. Iwan is a rectangular hall with three sides walled and one side entirely open, while Rewaq is an arcade or portico with at least one side open [21]. The architectural parameters considered were: room area, volume, shape, form, finishing materials, roof-type, and room aspect ratio. It was shown that the semi-closed Iwan pattern had the best performance while the semi-closed Rewaq pattern showed the worst. In a study on the effect of prayer hall geometry and finishing materials on the acoustic performance of mosques, Ismail [22] reported that prayer halls with large hemispherical domes had low surface area-to-volume ratio, which caused a reduction of total sound absorption of the space. Also, the commonly used finishing materials in the studied mosques were found to be warranting adequate acoustic treatment. Kavraz [23] assessed the impact of materials on wall surfaces and the density of worshippers on the acoustic performance of mosque's prayer hall. It was observed that these factors could influence the performance, especially at low frequencies. In a similar study, Hafizah et al. [24] focused on the effect of using kenaf fibers and micro perforated panels as sound absorbers, which could effectively reduce the reverberation time.

Ahmad et al. [25] focused on the acoustic performance of Mihrab (place where the leader of prayer stands) in Mosques, by conducting case studies on typical mosques in Malaysia. Din et al. [26] studied the effect of Mihrab geometry on the acoustic performance of mosque, by considering pyramidal and dome roof-styles. It was found that Mihrab's geometry had only little influence on the performance of speech intelligibility. Harun [27] developed speech intelligibility (SI) prediction models for

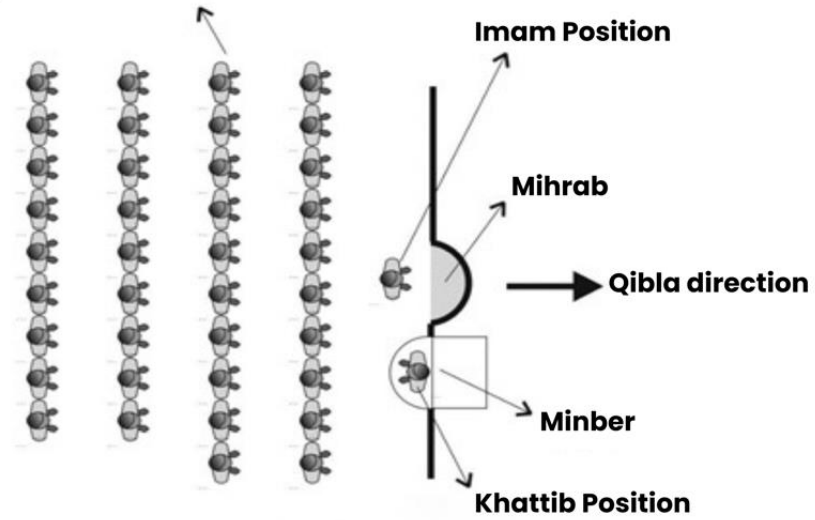
rooms with reflective domes, which were validated by case studies conducted in 32 mosques with domes in Malaysia. Utami [28] studied the acoustical performance of a typical mosque in Indonesia with two types (curved and pointed) of hemispherical domes. He concluded that these domes did not produce a significant impact on the speech quality inside the prayer hall, as the geometrical proportion of the dome was small compared to the larger rectangular hall. Kassim et al. [29] investigated the effect of angle and height of the dome on the acoustical parameters, and observed that a pyramidal dome with a steeper angle contributed to poor sound clarity.

The review of previous studies reveals that the literature on acoustical performance of mosques largely dealt with field measurements and computer simulations to identify issues and provide guidelines for proper acoustic design. Few works focused on the effects of various factors such as architectural design, size, shape, materials, mihrab-form and roof-geometry. However, a detailed study on the impact of dome-shape on the acoustic performance of a mosque is still lacking. Domes are often built by considering the aesthetics and heritages, while the acoustic performance criteria are not properly incorporated in the design. Accordingly, the present study examines the impact of dome-shape by considering a typical mosque inside a university campus in the Kingdom of Saudi Arabia.

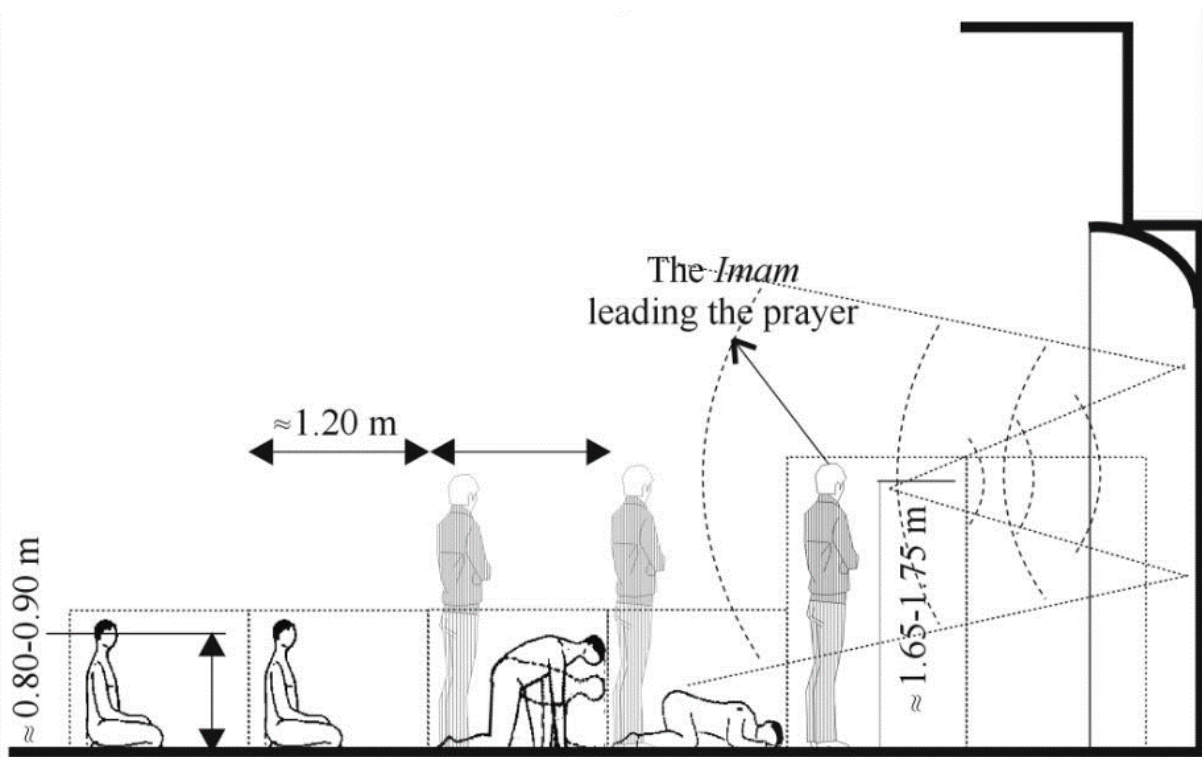
2. Design Features and Functions of Mosque

Mosques have basic common design features as spaces for worship. They typically have a simple rectangular form, walled enclosure with a roofed prayer-hall. The long side of the rectangle is always oriented towards the holy mosque in Makkah which is known as 'Qibla'. The place of prayer leader (Imam) is known as 'Miharb' which is usually built as a projection at the center of the front wall facing Qibla. The pulpit for preaching is known as 'Minbar' which is built on the right side of Mihrab. The preacher who delivers sermons on Fridays is known as 'Khatib'. Figure 1 illustrates Mihrab, Mimbar, Imam position, Khatib position, prayer rows, and congregation (worshippers) performing daily individual or group prayers. The wall wainscots are sometimes covered with marble tiles or wooden boards or panels tongued and grooved to compose a vertical pattern. The floor area is mostly carpeted, and the ceilings are finished with painted concrete. Depending on the climatic conditions, mosques are air-conditioned or provided with fans [19].

Congregation aligned in rows parallel to Qibla wall



a)



b)

Figure 1. Illustration of basic worship terminology in a mosque: (a) Mihrab, Mimbar, Imam position, Khatib position and prayer rows, (b) Congregation performing individual or group prayers [19]

3. Dome-shapes and Their Acoustic Performance

A dome is a hemispherical architectural structure, which symbolizes the Islamic architectural style of most mosques. Though the importance of domes in worship buildings has been recognized since ancient times, their acoustic performance has not been given the deserving of research attention. The dome-geometry is one of the most inconvenient forms in acoustics. Due to the concave form of the domes, the incident sound energy does not go out without reflecting several times in the dome. Consequently, the reflected sound energy from the dome reaches back to the room with a time delay, leading to echoes or noise and a reduction on STI. The behavior of sound energy in a dome in both plan and cross sections is shown in Figure 2. As can be seen, the reflected sound energy that is increasingly delayed, especially in large domes, is a cause of echoes [22]. The use of cavity resonators can prevent the reflection of sound energy and reradiate it throughout the room. Besides getting a diffused field, the sound coming from the dome shortly after the direct sound creates a divine effect in the atmosphere of worship. In addition to the detrimental effects of late reflections and echoes, more

complicated behavior can be expected due to the coupling of the dome volume to the rest of the room. Thus, a proper understanding of the acoustic behavior of different types of domes is vital in choosing the appropriate dome-shape for a particular mosque-design.

4. Methodology

4.1. The Mosque and Dome-shapes Description

The mosque under study was a typical mid-size mosque situated inside a university campus in Saudi Arabia. Figure 3 illustrates the architectural features of the mosque. It has a prayer hall area of 23 m × 23 m and a ceiling height of 4.8 m. The interior surface materials consist of carpet and marble tiles for the main floor, painted plaster walls, glass with metal frames for windows, and painted plaster for the ceiling. All walls are covered with marble of 1m height. Mihrab's wall is covered with wood. Figure 4 shows the four typical dome-shapes namely (a) Saucer dome, (b) Drum dome, (c) Onion dome, and (d) Pointed dome, considered for the present study.

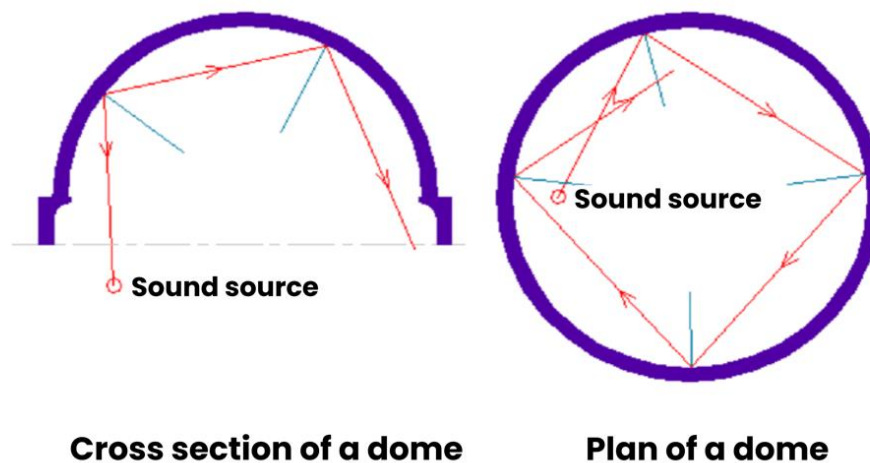


Figure 2. Sound propagation in a dome [22]

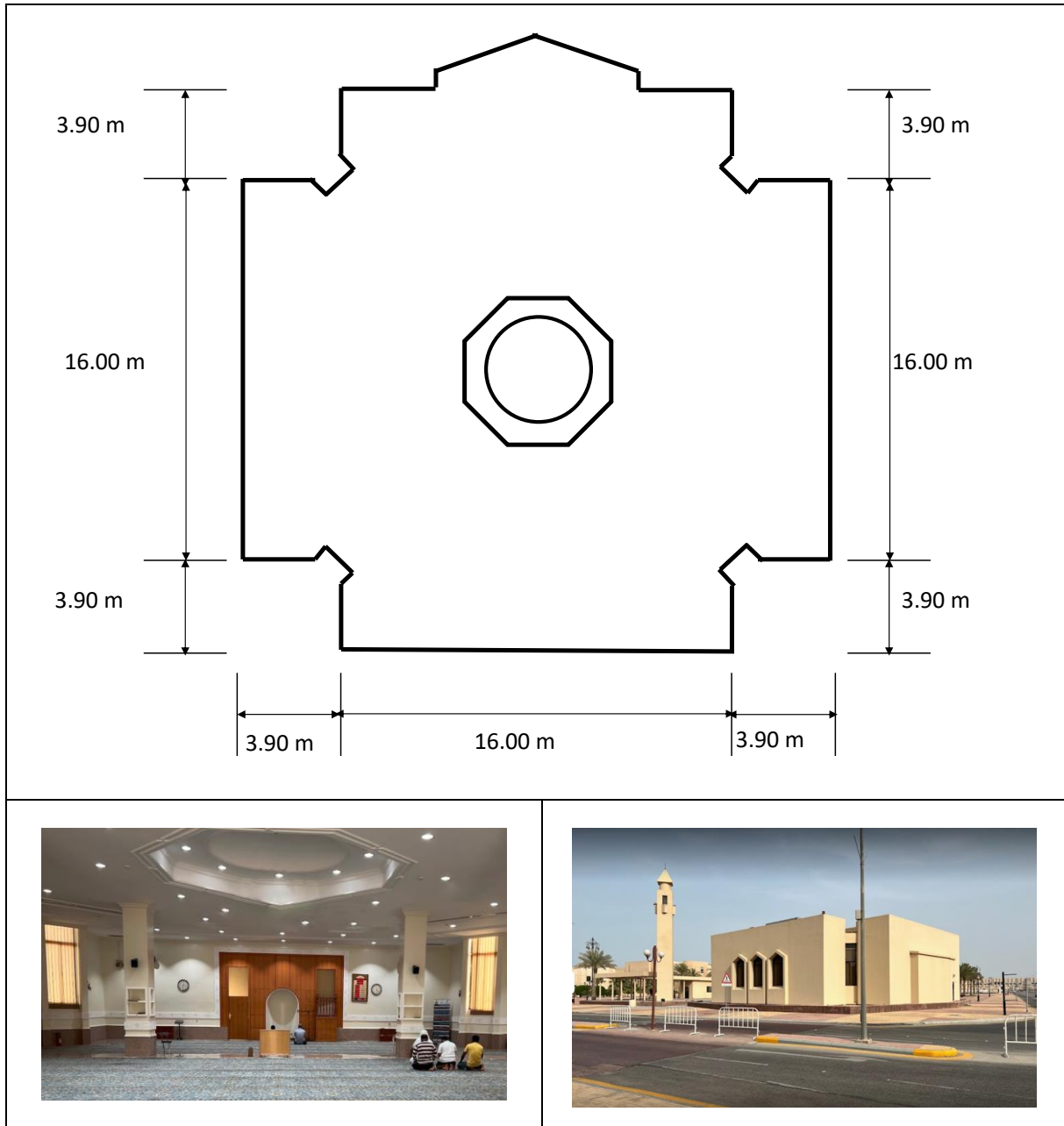


Figure 3. Architectural details of the mosque under study

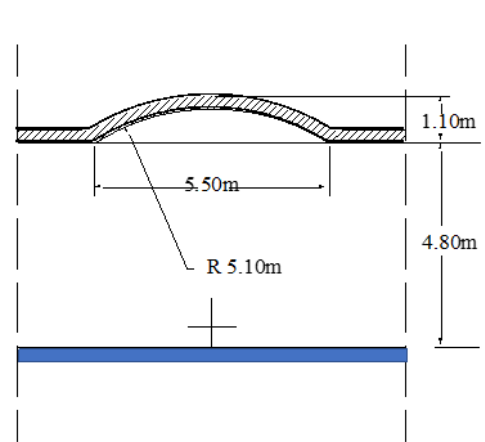
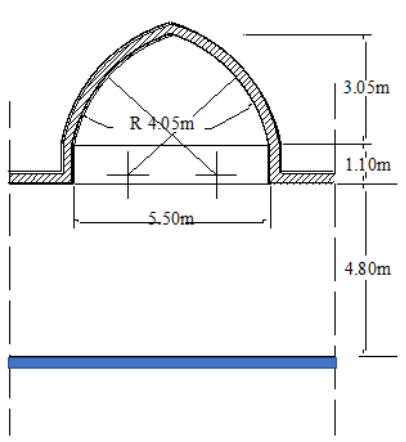
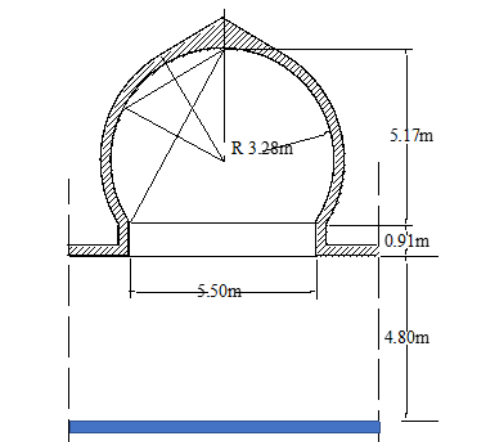
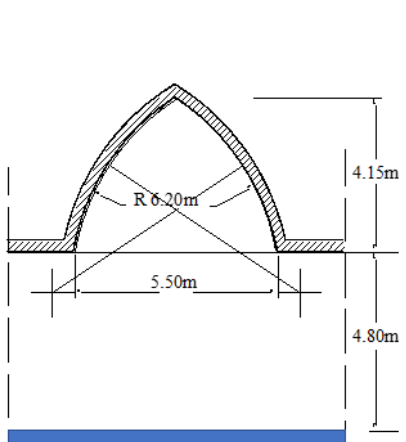
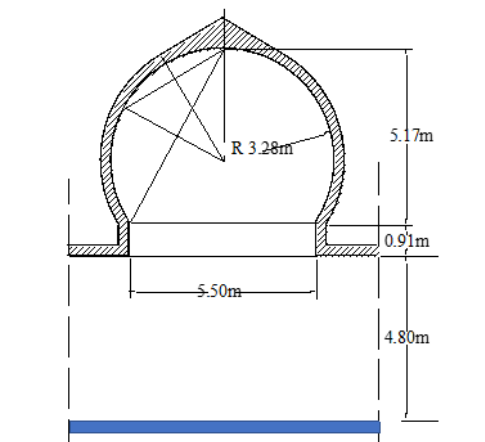
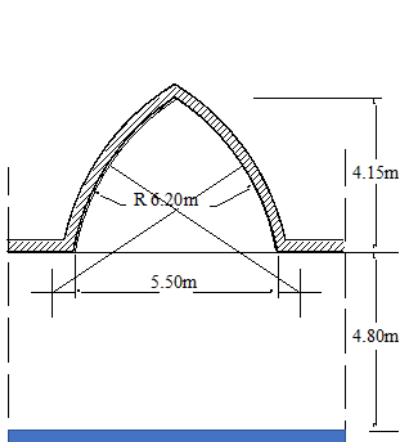
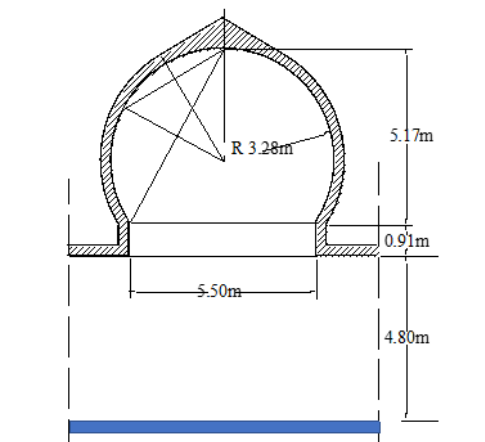
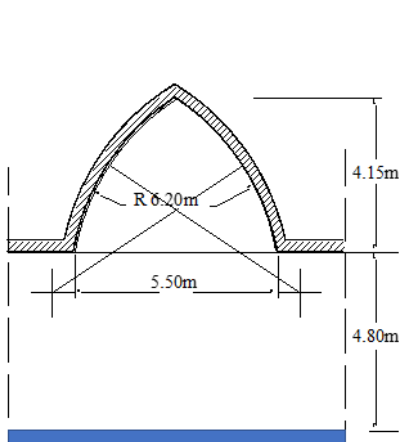
Saucer Dome		Drum Dome	
	Surface Area (m ²)		Surface Area (m ²)
	25.77		60.71
	Volume (m ³)		Volume (m ³)
	9.81		74.40
Onion Dome		Pointed Dome	
	Surface Area (m ²)		Surface Area (m ²)
	122.17		53.41
	Volume (m ³)		Volume (m ³)
	152.85		49.67

Figure 4. Types and dimensions of the studied dome-shapes

4.2. Modeling and Simulation

A 3D Model of the mosque was built using AUTOCAD, and simulations were carried out by ODEON (version 11) which is a GA (geometrical acoustics)-based software extensively used for room acoustics simulations. ODEON uses a hybrid calculation method, which combines image source method and ray-radiosity method for early reflections, and radiosity method for late reflections [30]. Different materials were assigned for different sections of the mosque with different sound absorption coefficients, as summarized in Table 1. ODEON considers the scattering coefficient as the roughness of the material at mid-frequencies (707 Hz). As recommended in the software’s user manual, the scattering coefficient for general smooth surfaces and smooth painted concrete must be within 0.02–0.05 and 0.005–0.02 respectively. In our case, all materials

have smooth surfaces, so a common scattering coefficient of 0.02 was assumed. The number of rays was estimated as recommended by the software, according to the size and number of surfaces in the mosque geometry. The minimum number of rays was 220K rays (with saucer dome), while the maximum was 390K rays (with onion dome) which was chosen for all models. In all models, the maximum reflection order was set to 20K with a transition order equal to 8.

After fixing the calculation parameters, the selected receiver surfaces were divided into grids assigning 0.96 m² for each worshiper [19]. Reverberation Time (T30) and Early Decay were measured. These characteristics were measured by assuming the mosque as empty, which is justifiable as the focus of the current study was to study the influence of dome-shape only.

Table 1. Sound absorption coefficient in octave bands [31], [32].

Surface	Material	125Hz	250 Hz	500 Hz	1kHz	2 kHz	4 kHz
Walls	Marble tiles cladding	0.01	0.01	0.01	0.01	0.02	0.02
Walls	Painted plaster on brick	0.013	0.015	0.02	0.03	0.04	0.05
Mihrab Wall	8mm wood veneer	0.28	0.22	0.17	0.09	0.1	0.11
Ceiling	Plasterboard (12mm, 1/2") in suspended ceiling grid)	0.15	0.11	0.04	0.04	0.07	0.08
Dome surface	Smooth painted concrete	0.01	0.05	0.06	0.07	0.09	0.08
Floor	Carpet on concrete	0.02	0.06	0.14	0.37	0.60	0.65
Corridors	Marble	0.01	0.01	0.01	0.01	0.02	0.02
Windows	Ordinary glass	0.35	0.25	0.18	0.12	0.07	0.04

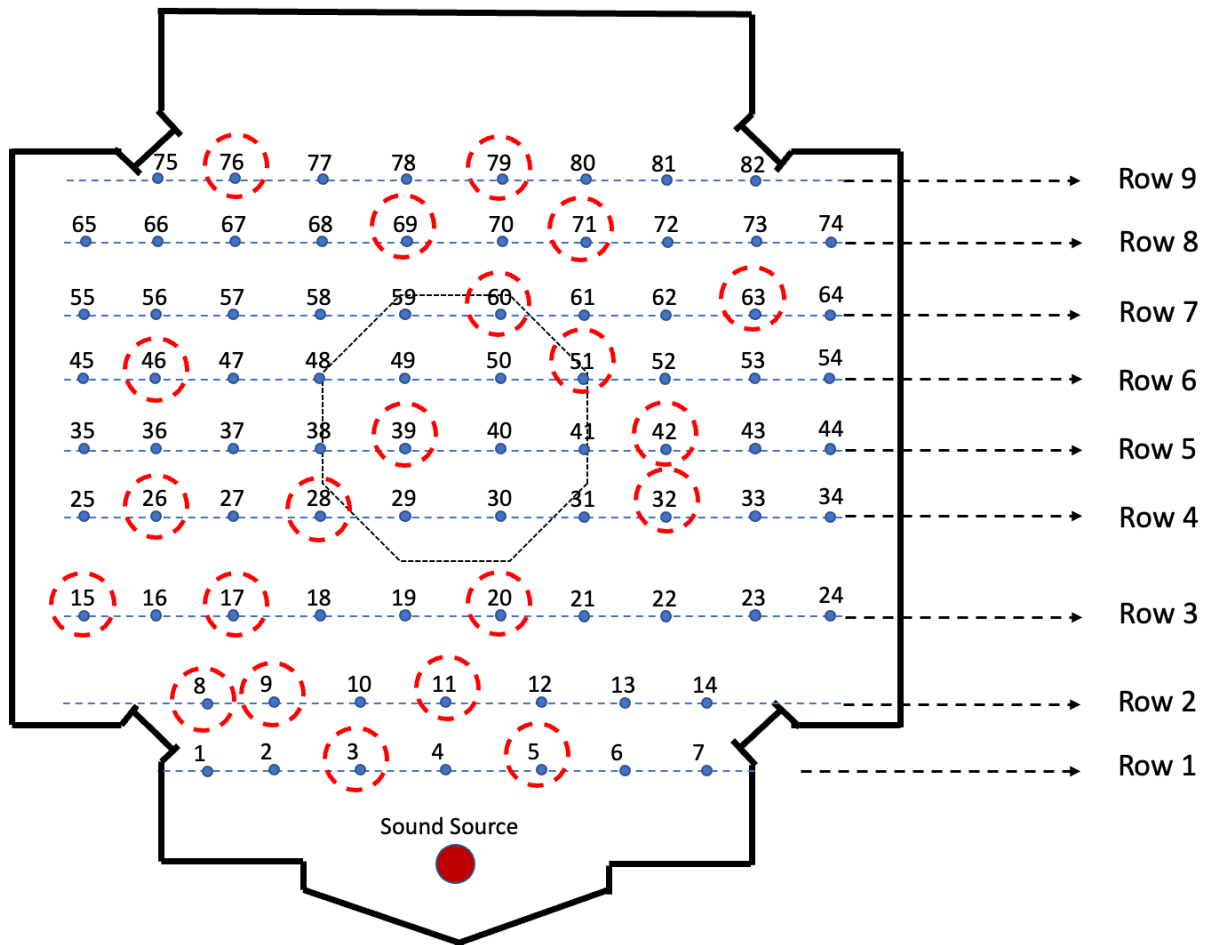


Figure 5. Sound source, simulated receiver points, and prayer rows (red circles represent the 22 measurement points)

The worshippers (hereafter termed as receivers) perform the prayer by listening to the loud recitation of Imam. As presented in Figure 5, there are 82 receiver points that represent the receivers who are aligned in 9 parallel rows. The receiver points 1-7 make prayer Row 1, and 8-4, 15-24, 25-34, 35-44, 45-54, 55-64, 65-74, and 75-82 make Row 2, Row 3, Row 4, Row 5, Row 6, Row 7, Row 8, and Row 9 respectively. For the measurements, 22 receiver

points were selected randomly (2 to 3 points from each row) to cover the whole mosque area.

The background noise levels in the mosque were measured using analyzer type B&K 2250, in two minutes interval, which was used for the simulation (Figure 6). The HVAC (heating, ventilation, and air-conditioning) system is the major source of background noise. The ear height of the receivers was taken to be 1.65 m from the floor.

4.3. In-Situ Measurements

For the purpose of validating the simulation results, in-situ measurements were performed on the study mosque. The experimental setup (Figure 7) consisted of DIRAC room acoustics system, an analyzer type 2250, a B&K power amplifier type 2734, a reference Omni Power Sound Source Types 4292, and ½ inch B&K microphone type 4134. The B&K Echo Speech Source Type 4720 was used for the speech intelligibility measurements. Measurements were carried out according to ISO 3382-2:2008 (Measurement of room acoustic parameters-Part 2) and in octave bands for the frequency range from 125Hz to 8 kHz.

The loudspeaker source was positioned at Imam position (at the center of Mihrab) at 1.65m height. Subsequently, the sound level meter was moved to each measurement position (receiver points). The DIRAC PC-based program instantly calculates the speech intelligibility and other room acoustics parameters from the sound level meter’s microphone signal.

The acoustical parameters to be assessed (T30, EDT), the octave bands used to calculate multi-octave bands’ average of acoustic parameters, the recommended ranges, and the corresponding just noticeable differences (JNDs) are presented in Table 2.

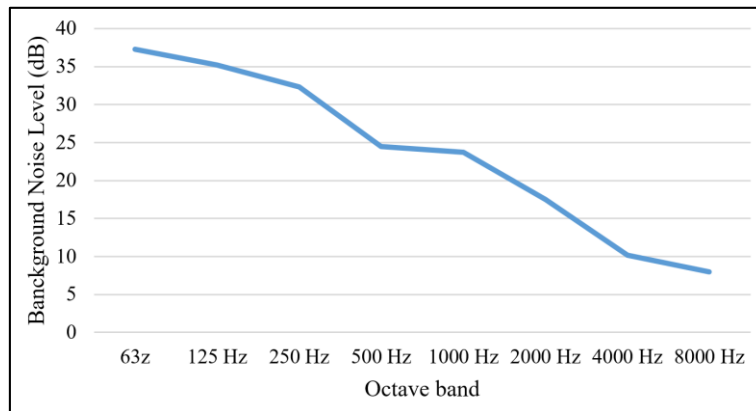


Figure 6. Measured background noise levels in octave bands

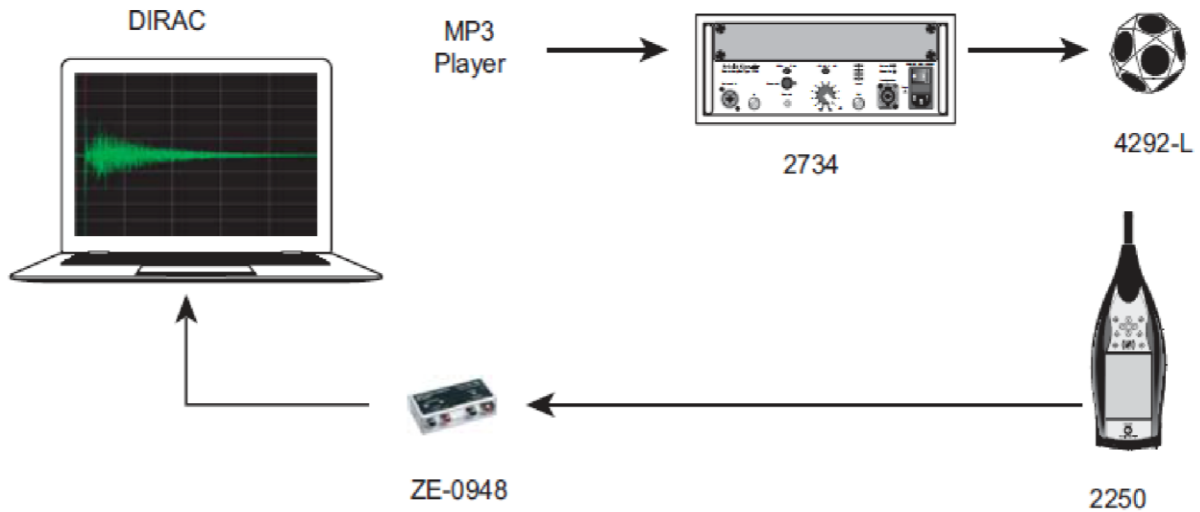


Figure 7. In-situ measurement system

Table 2. Acoustical parameters and allowable limits [33], [34], and [35]

Parameter	Recommended range (for given volume)	Just noticeable difference (JND)
T30 (for 500–1000 Hz)	From 0.9s to 1.9s	5% (lowest value)
EDT (for 500–1000 Hz)	From 0.8s and 2.1s	5% (lowest value)

5. Results and Discussion

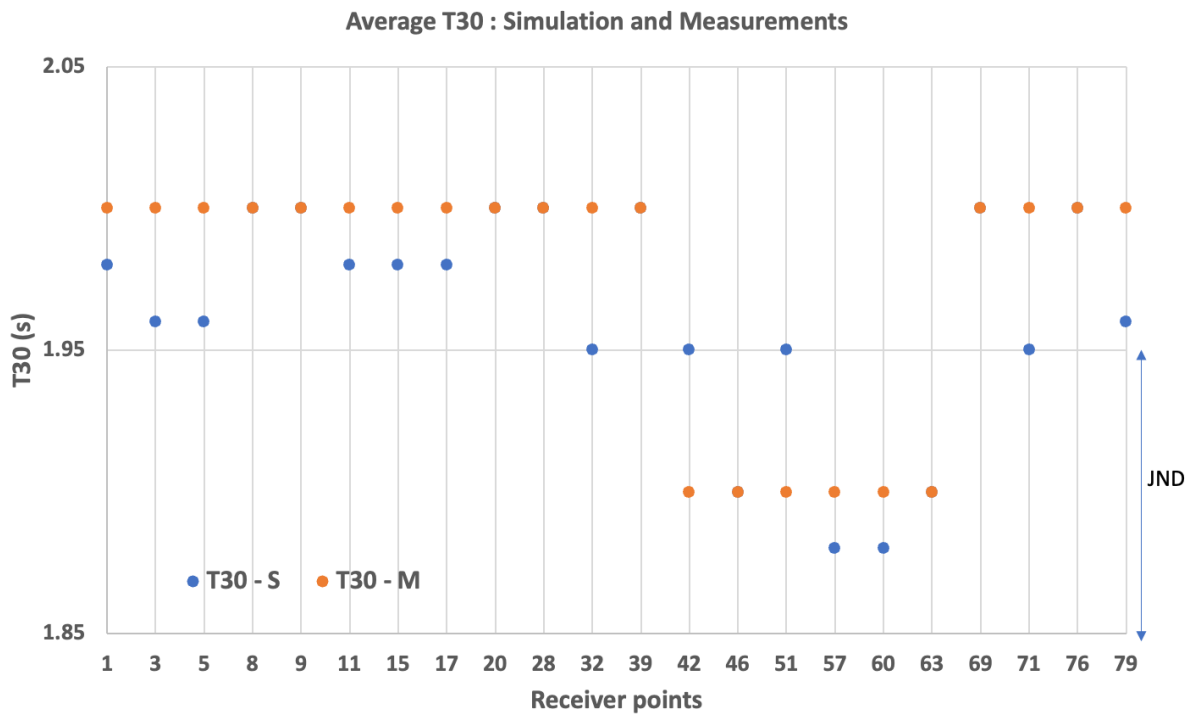
5.1. Validation

In-situ measurements were conducted inside the study mosque with Saucer dome (base case) for the 22 selected receiver points. The comparison between the simulated and measured values of T30 and EDT are presented in Figure 8. The average, minimum, and maximum values and the corresponding correlation coefficients (R^2) of the acoustic

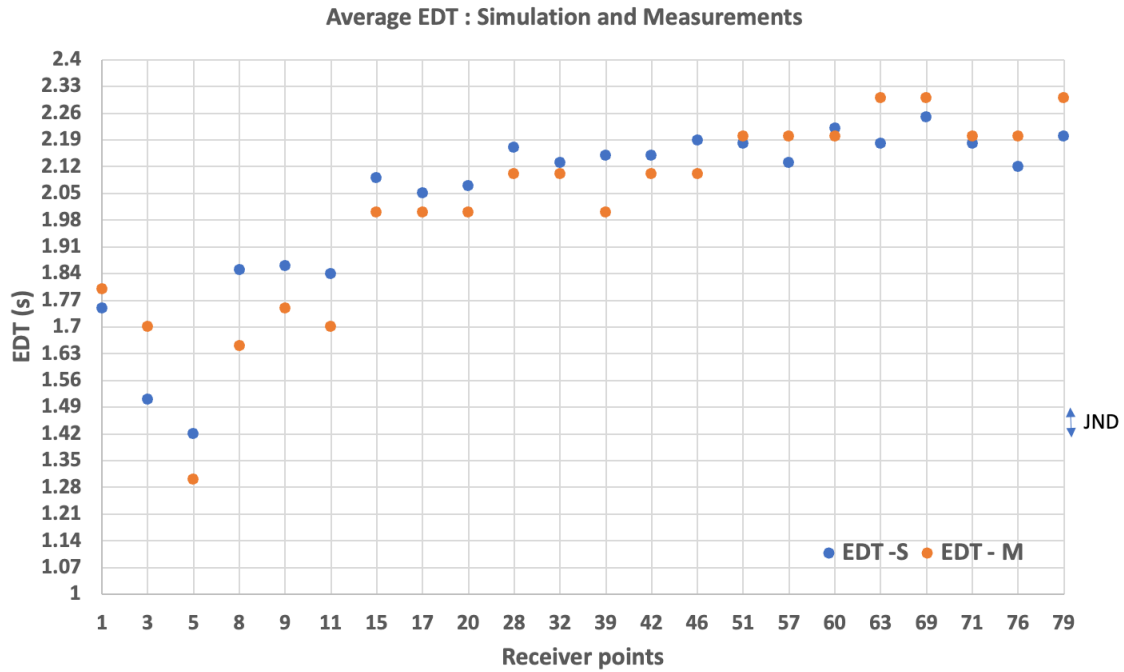
parameters (measured and simulated) are given in Table 3. The JNDs were calculated for all parameters according to the values presented in Table 2. The simulation results could be calibrated when the difference between simulation and measurement is less than the JND of each acoustical parameter [30]; thus, the calibration was realized by comparing the simulated values with the measured ones in real conditions. Table 4 summarizes the differences between simulated and measured values of all parameters, and comparison with their JNDs, which shows a good match between the simulated and measured values.

Table 3. Minimum, maximum, average, and the correlation coefficients, of simulated and measured values

Parameters	T30 (s)		EDT (s)	
	S	M	S	M
Min	1.88	1.90	1.42	1.30
Max.	2.00	2.00	2.25	2.30
Average	1.96	1.97	2.03	2.02
Correlation coefficients (R^2)	0.83		0.75	



a) T30



b) EDT

Figure 8. Comparison of simulated (blue points) and measured (red points) values for Both EDT and T30

Table 4. Differences between the simulated and measured values of the acoustic parameters, and their JNDs (differences higher than one JND are highlighted in bold)

Receivers	Diff-T30 (s)	Diff-EDT (s)
1	0.02	0.05
3	0.04	0.1
5	0.04	0.12
8	0	0.2
9	0	0.11
11	0.02	0.11
15	0.02	0.07
17	0.02	0.05
20	0	0.07
28	0	0.07
32	0.05	0.03
39	0	0.05
42	0.05	0.05
46	0	0.05
51	0.05	0.02
57	0.02	0.07
60	0.02	0.02
63	0	0.1
69	0	0.05
71	0.05	0
76	0	0.1
79	0.04	0.1
JND	0.1s	0.07s

5.2. Reverberation Time (T30)

Figure 9 presents the T30 values with different dome-shapes as a function of source-receiver distance. Previous studies have established that the optimum T30 for mosques ranges from 0.9s to 1.9s (Abdou, 2003a; Eldien and Al Qahtani, 2012; Imam et al., 2009). T30 was calculated as the average of T30 at 500Hz and 1000Hz. It can be observed that all receiver points for Saucer and Pointed domes have T30 near the optimal value, while for the Onion and Drum shapes it is greater than optimal (between 2.25s and 2.45s); this is due to the higher volume and surface area of Onion and Drum domes compared to the other domes. Homogenous T30 values are observed in all points for both Onion and Drum forms, but with Saucer, T30 increases at points near the dome and decreases at points located at the sides of prayer rows.

Reflection from the dome-surfaces was visualized by 'Reflector coverage' which is one of the ODEON tools. The 5th order reflector coverage of all dome surfaces is presented in Figure 10. We can observe that sound reflection of the Onion dome surfaces covers the area around the dome and near the Mihrab. Therefore, T30 values increase in the first rows. The impact of the Drum dome on the back area of the mosque is not strong, so T30 values on the back area of the mosque are lower than the values on the front area. The effect of Saucer dome appears clearly on the back area of the mosque, where T30 values increase. The Pointed dome surfaces reflect the sound energy randomly to cover the whole area of the mosque with a slight increase at the left side of the mosque hall. For this reason, the majority of receiver points have the same T30 value.

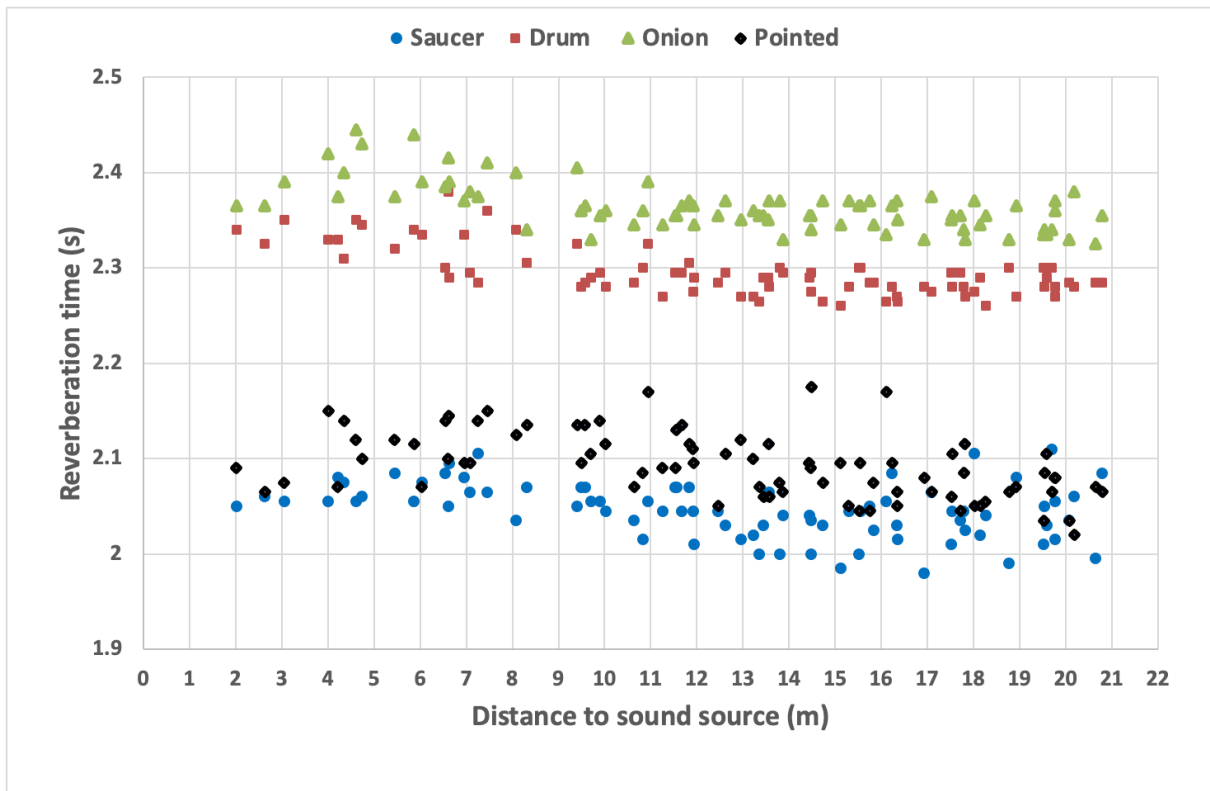


Figure 9. T30 values at all receiver points with different dome-shapes

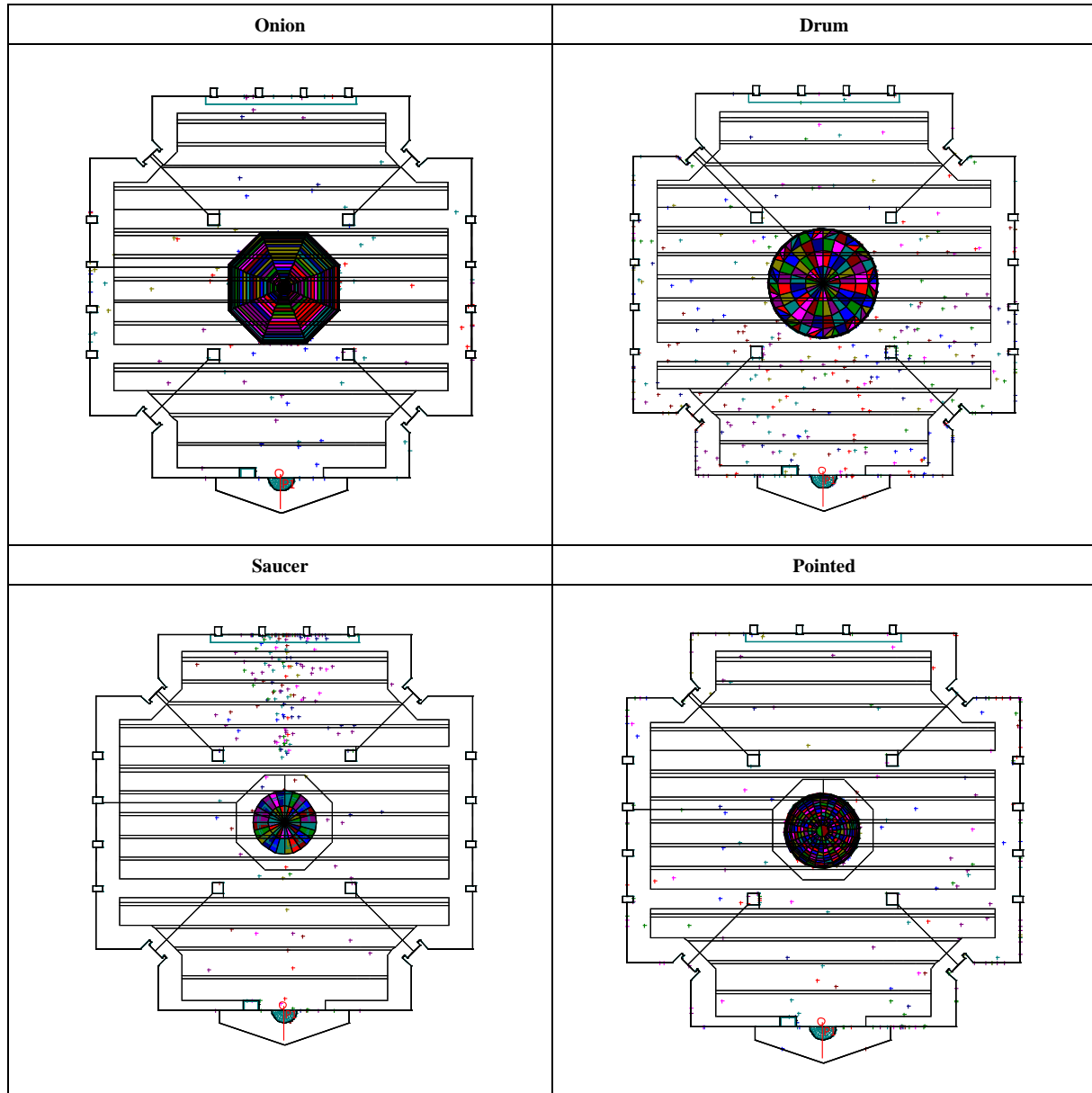


Figure 10. 5th order reflector coverage of all domes

The warmth or the bass ratio (BR) is the relation between T30 in the frequency range 125Hz -250Hz to the frequency range 500Hz -1000Hz, which is expressed as:

$$BR = \frac{RT_{125Hz} + RT_{250Hz}}{RT_{500Hz} + RT_{1000Hz}}$$

For music, BR should be between 1.0 and 1.3, while it should be between 0.9 and 1.0 for speech (Ballou, 2008). As known, speech is the main activity in mosques. The spiritual context of the male Imam's voice proves different from the normal speech. Hence, we can consider it to have BR closer to the optimal BR value for music. As shown in

Figure 11, mosques with saucers and pointed domes achieve good BR values while mosques with drum and onion domes have low BR values.

The difference of T30 average values in octave bands between the base case (Saucer dome) and the other cases is calculated. As evident from Figure 12, with the Drum and Onion domes, T30 increases at medium and high frequencies and decreases at low frequencies. This explains the decrease in BR values in these two cases. Adding materials in the space which absorb energy at high frequencies can increase the warmth. On the other hand, Pointed dome has the same effect as the Saucer dome where the difference in T30 average values is negligible.

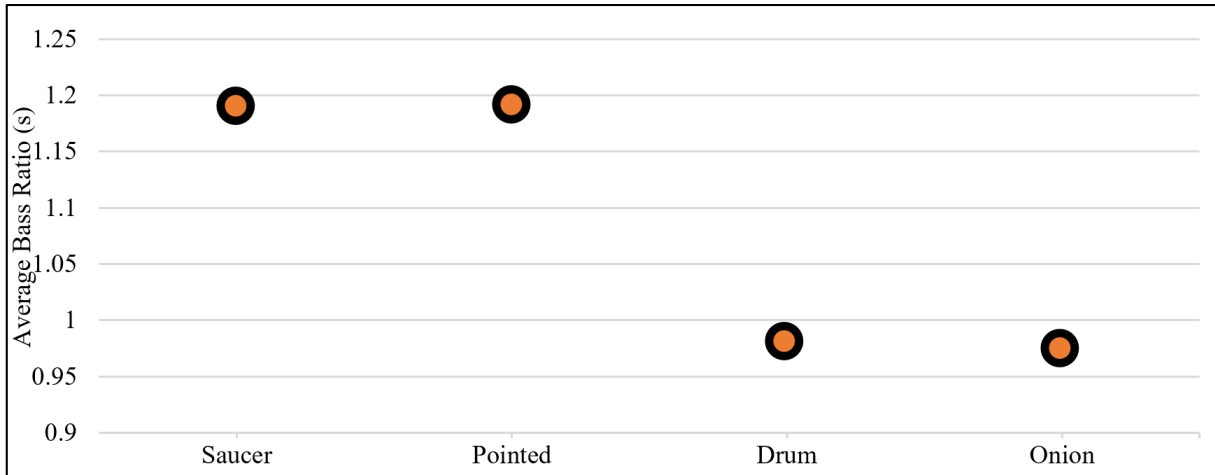


Figure 11. Average BR for various domes

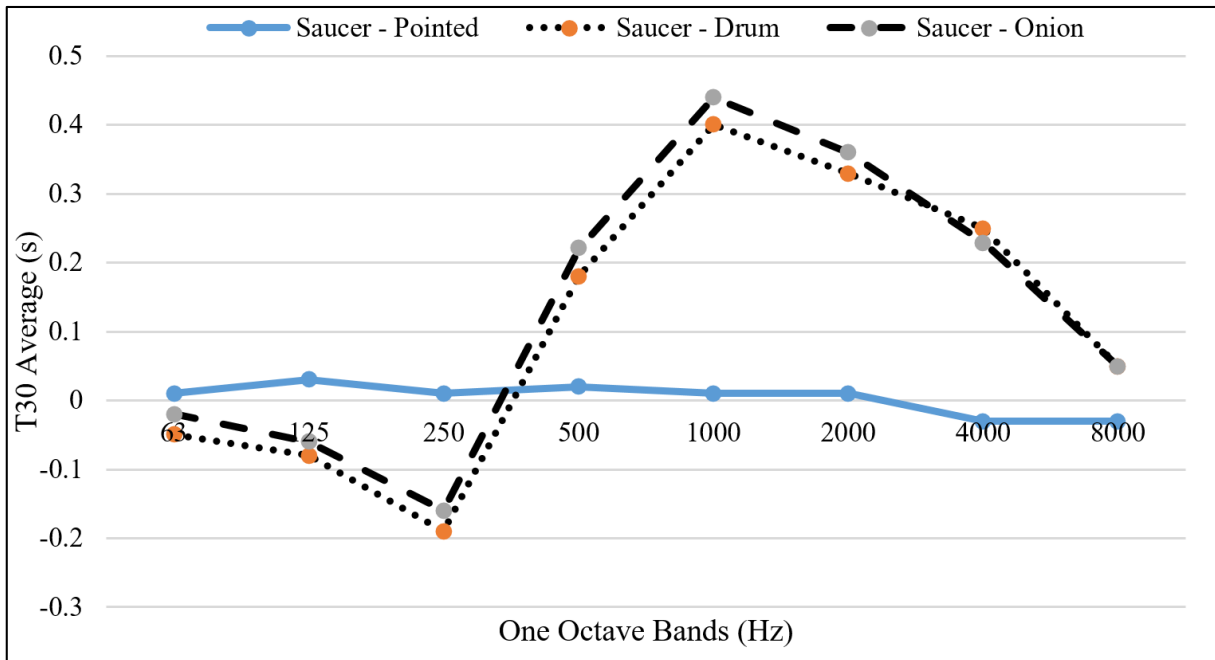
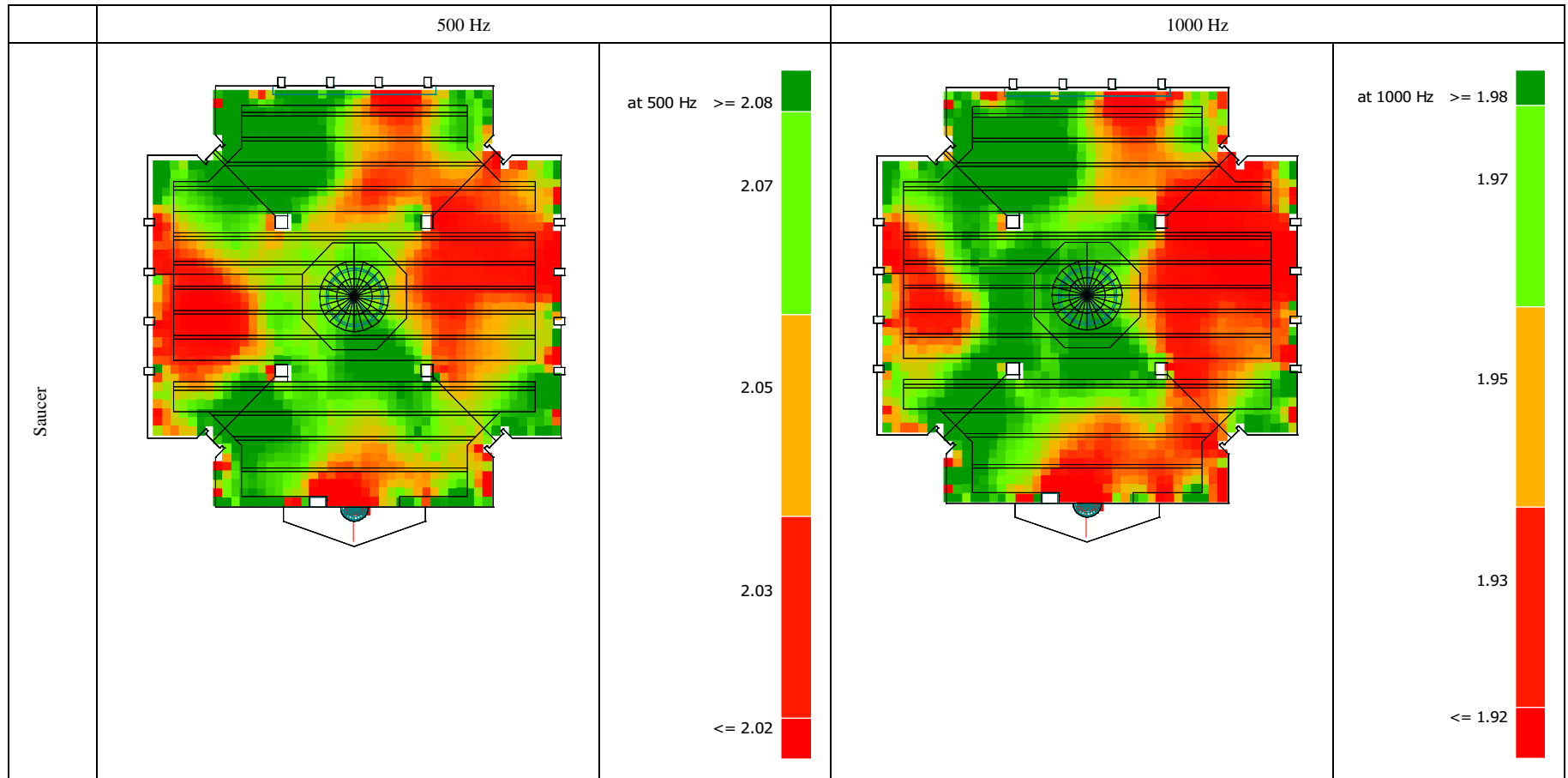


Figure 12. Difference of T30 average between the base case and other cases

The T30 distribution maps of Saucer and Pointed domes for 500 Hz and 1000 Hz are presented in Figure 13. In the base case (Saucer dome), at 500 Hz, the minimum and maximum T30 values are 2.02s and 2.08s respectively, and the corresponding values at 1000 Hz are 1.82s and 1.98s. The T30 distribution map of Pointed dome shows a great similarity with the Saucer dome. The maximum T30 value is 2.10s at 500 Hz and 1.98s at 1000 Hz, while the

minimum value is 2.04s at 500 Hz and 1.92s at 1000 Hz. The positive effect of the Saucer shape can be seen on the half left side of the mosque hall, whereas the positive effect of the Pointed shape appears clearly around the dome. For the Pointed dome, the maximum T30 values are situated on the left side of the mosque hall. This is due to the multiple repeating sound reflections between the dome surface and the Mimbar (located on the left side of Mihrab).



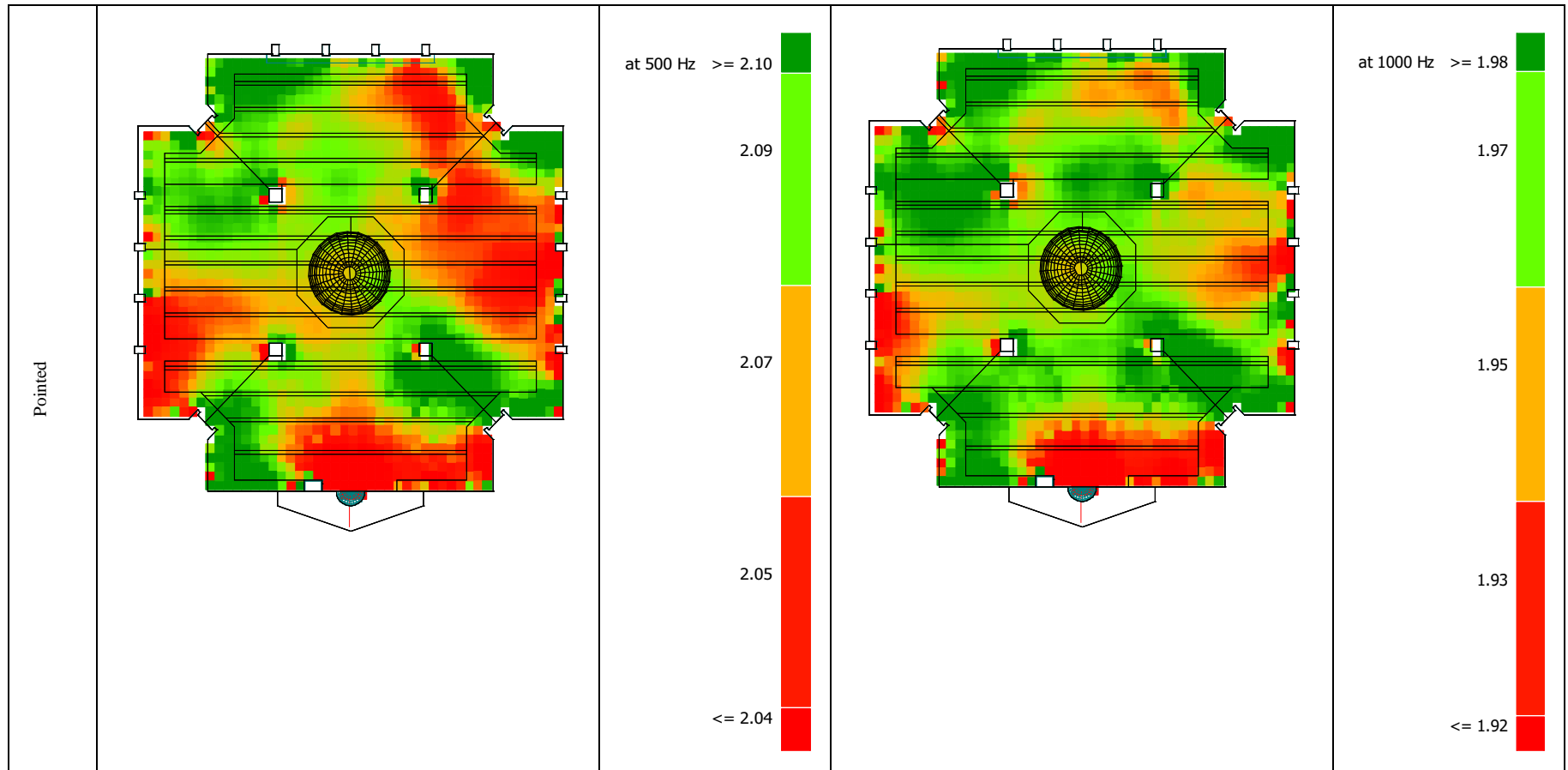
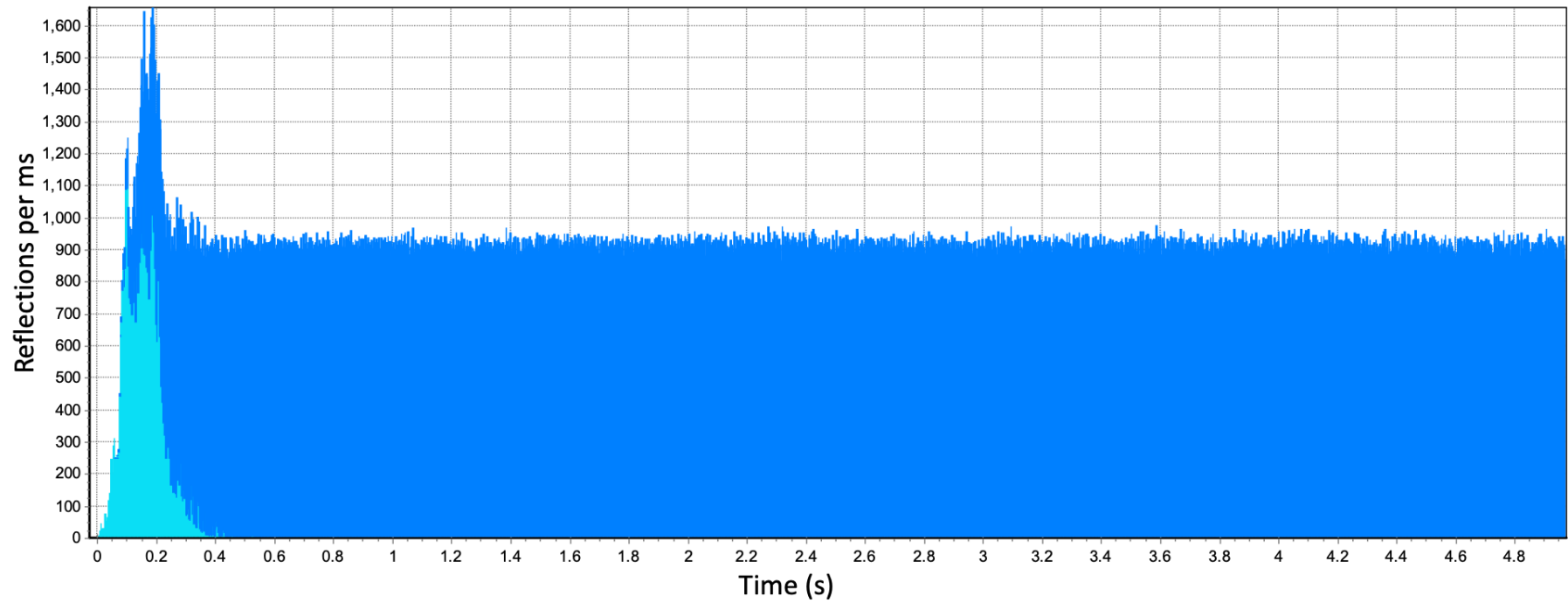


Figure 13. T30 distribution maps for Saucer and Pointed domes at 500 Hz and 1000 Hz



(a)

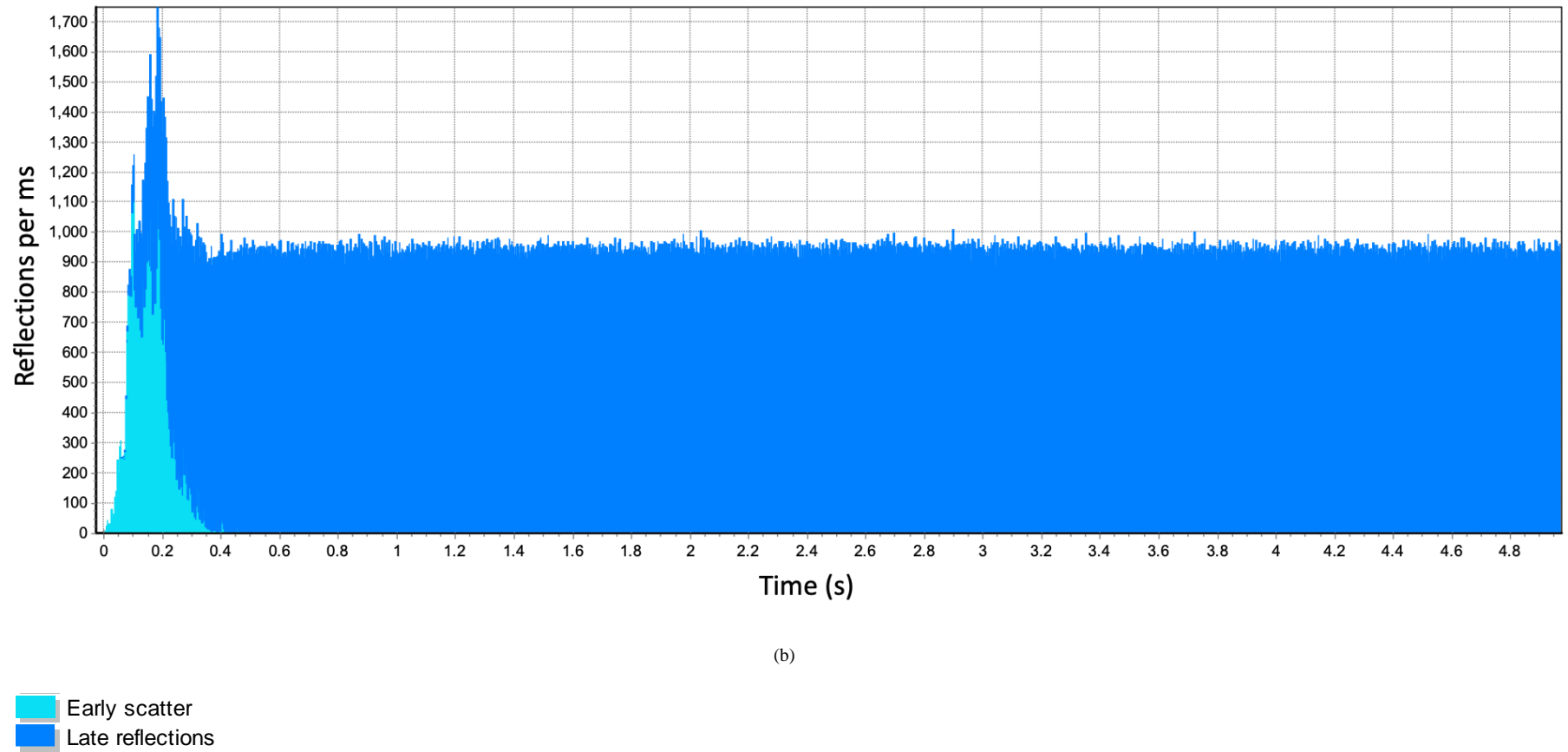
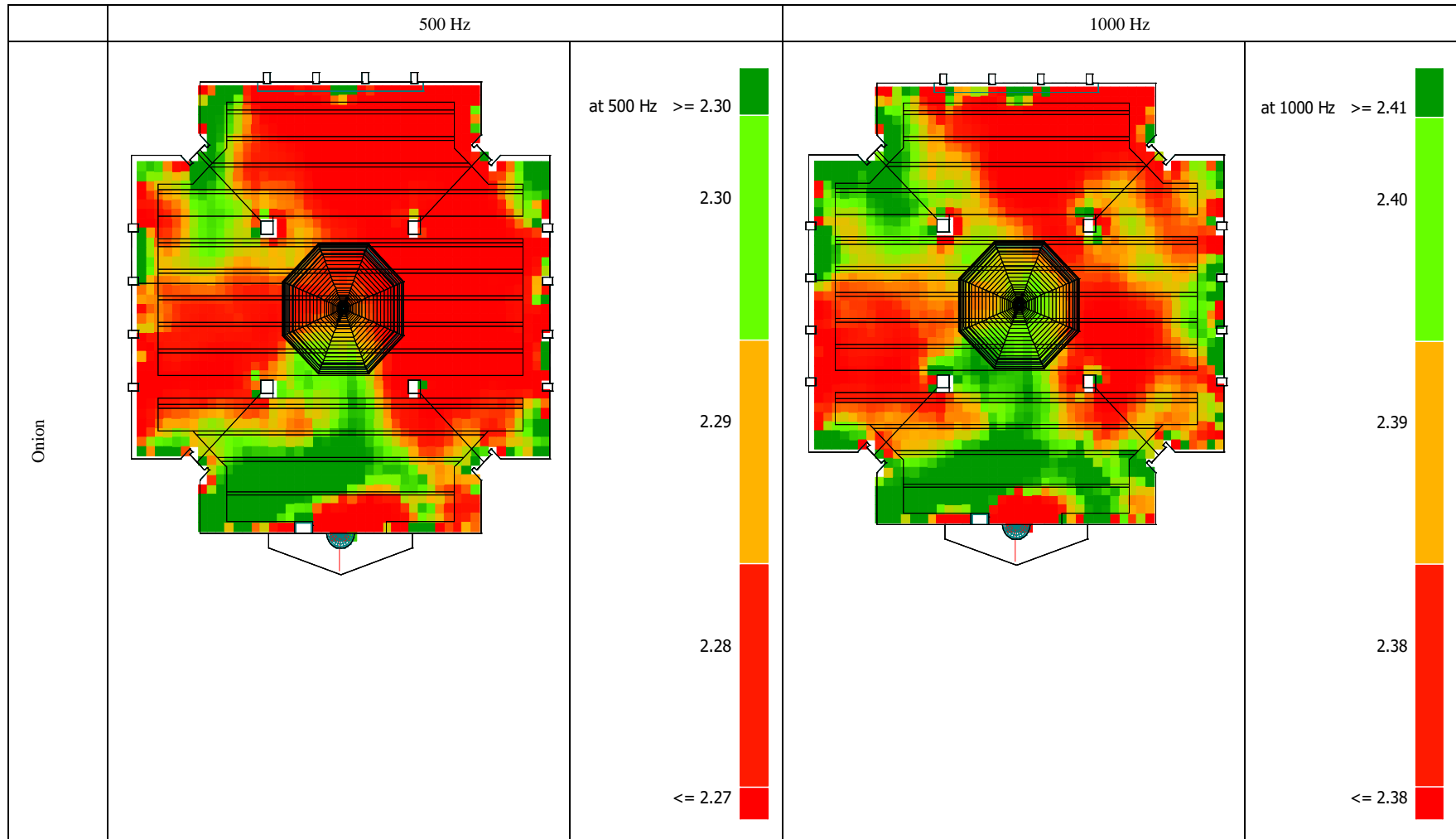


Figure 14. Reflection density produced by Saucer dome (a) and Pointed dome (b) at receiver point 16



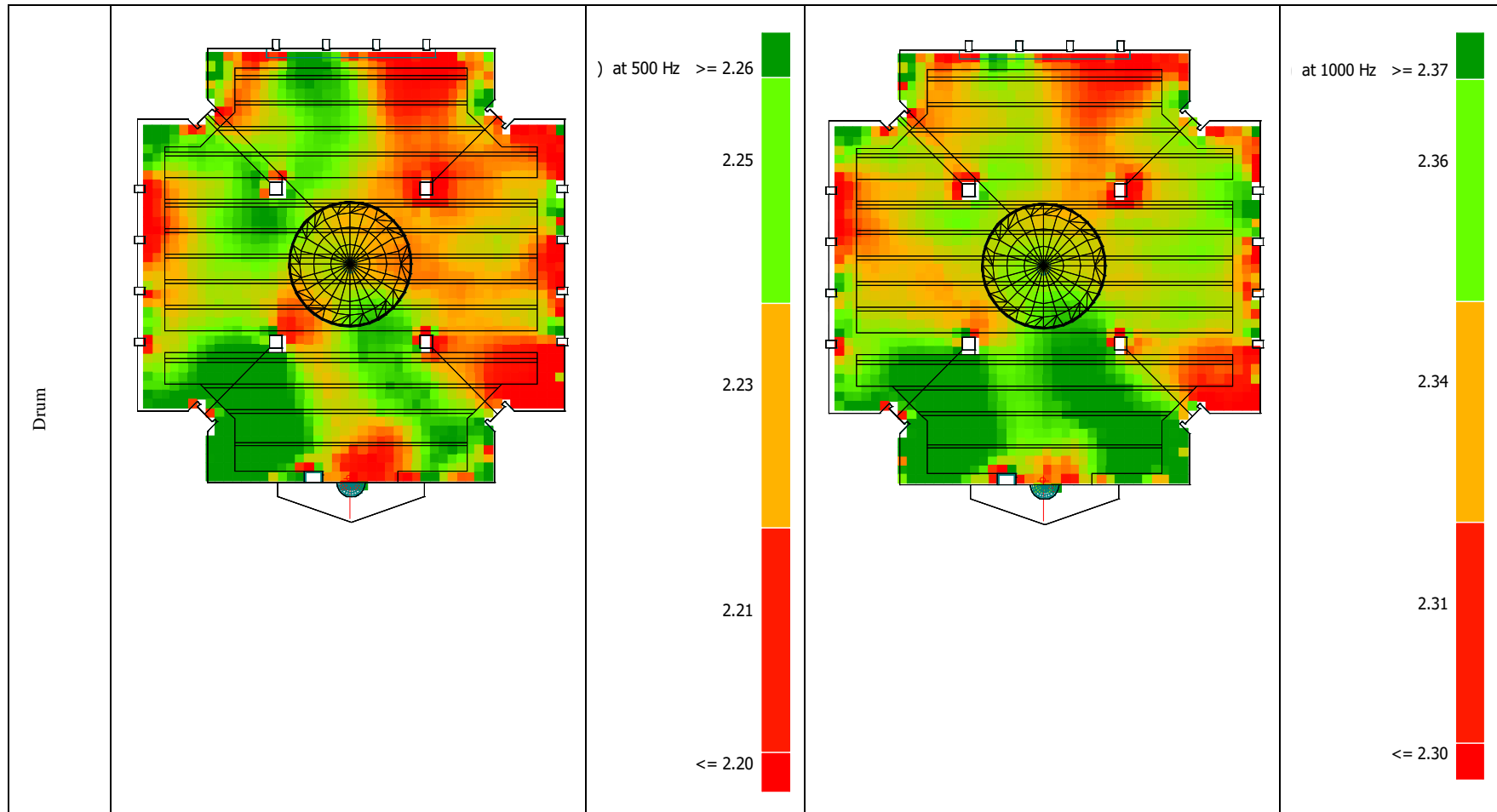


Figure 15. T30 distribution maps of Onion and Drum domes for 500 Hz and 1000 Hz

Figure 14 presents the reflection density for both Saucer and Pointed domes at receiver point 16 located at the left side of the mosque hall. We can observe the similarity of the early reflection for two types of domes, while the late reflection produced by the Pointed dome is greater than that produced by the Saucer dome.

The T30 distribution maps for Onion and Drum domes at 500 Hz and 1000 Hz are presented in Figure 15. In the case of Onion dome, minimum and maximum T30 values at 500 Hz are 2.27s and 2.30s respectively, while these are 2.38s and 2.41s, at 1000 Hz. The T30 distribution pattern of Drum dome is almost similar to that of Onion dome, with minimum and maximum T30 values of 2.20s and 2.26s respectively at 500 Hz, while these are 2.30s and 2.37s, at

1000 Hz. The negative effect of Onion shape appears clearly at the back, left, and right areas of the mosque hall, while the Drum shape caused an increase of T30 in the right an area of the mosque hall. The positive effect of both types can be observed in the front area of the mosque hall and near Mihrab.

The coefficient of variation (CV) and standard deviation/mean (SD) of RT values are calculated for all receiver points. As shown in Figure 16, CV indicates a relatively high variation in the case of Saucer and Drum domes, while it can be considered low in the case of Pointed and Onion domes. This means that Pointed and Onion domes achieve good distribution of RT values.

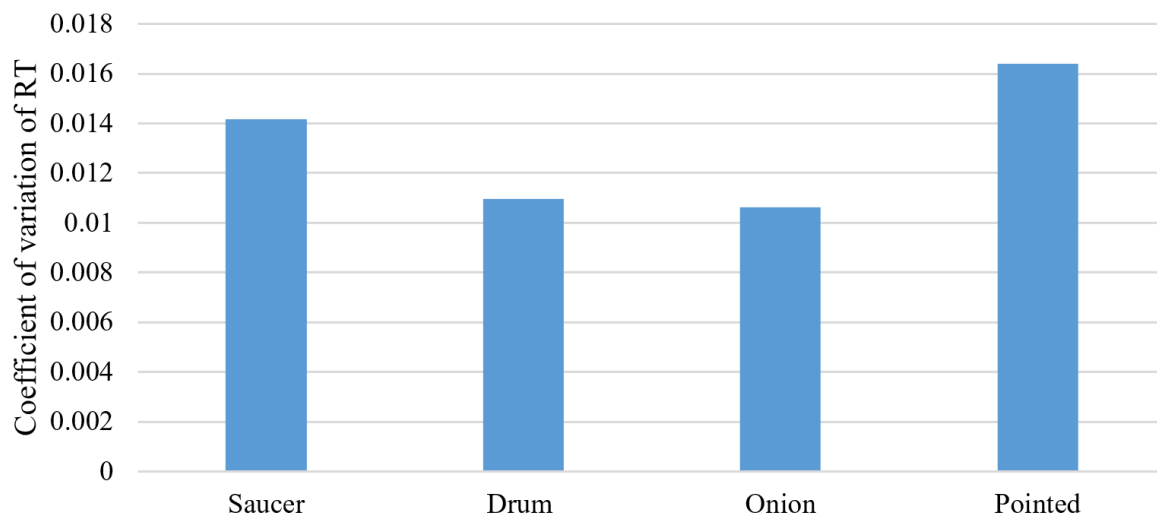


Figure 16. Coefficient of variation of RT values

5.3. Early Decay Time (EDT)

The initial rate of decay of a reverberant sound is more important than the total reverberation time. A rapid initial decay is interpreted by the human ear as a short reverberation time. The Early Decay Time (EDT) is defined as 6 times the time interval from 0dB to -10dB on the decay curve after the source has stopped emitting. If we take into consideration the definitions of EDT and T30, we will realize that they must have the same value. EDT should not be higher than $\pm 10\%$ of T30 for good acoustics (Beranek, 2008); in the present case, it should be between 0.8s and 2.1s (see recommended values in Table 2). EDT is calculated as the average at 500Hz and 1000Hz. Figure 17 presents the EDT values obtained with different dome-shapes at all receiver points. The minimum EDT value could be obtained by Saucer and Pointed domes where the EDT is 1.2s at the 1st row. This short EDT value keeps the early sound strong and clear. This is due to the reflection effect of the Mihrab wall. EDT value increases with the distance from the sound source and the maximum EDT

(2.2s) is found in the 8th row. On the other hand, the Drum and Onion shapes show an increase of EDT values in all prayer rows where EDT values are longer (1.9s to 2.6s). It is known that short EDT is an important indicator of speech clarity. In this case, the early reflected sound rays that reach to human ear within the first 50ms integrate with the direct sound rays. In general, the best EDT values are obtained by the Saucer and Pointed domes.

The difference of EDT average values in octave bands between the base case (saucer dome) and the other cases is presented in Figure 18. We can note that Drum and onion domes cause an increase of EDT values in the medium and high frequencies and a decrease of EDT values in the low frequencies. The pointed dome has approximately the same EDT values as the Saucer dome where the difference of T30 average values is negligible for all frequency ranges. For Saucer and Pointed domes, the receiver points located at the 1st and the 2nd rows have an optimal value, while for Drum and Onion domes, the optimal value is obtained only at the 1st row, as shown in Figure 19.

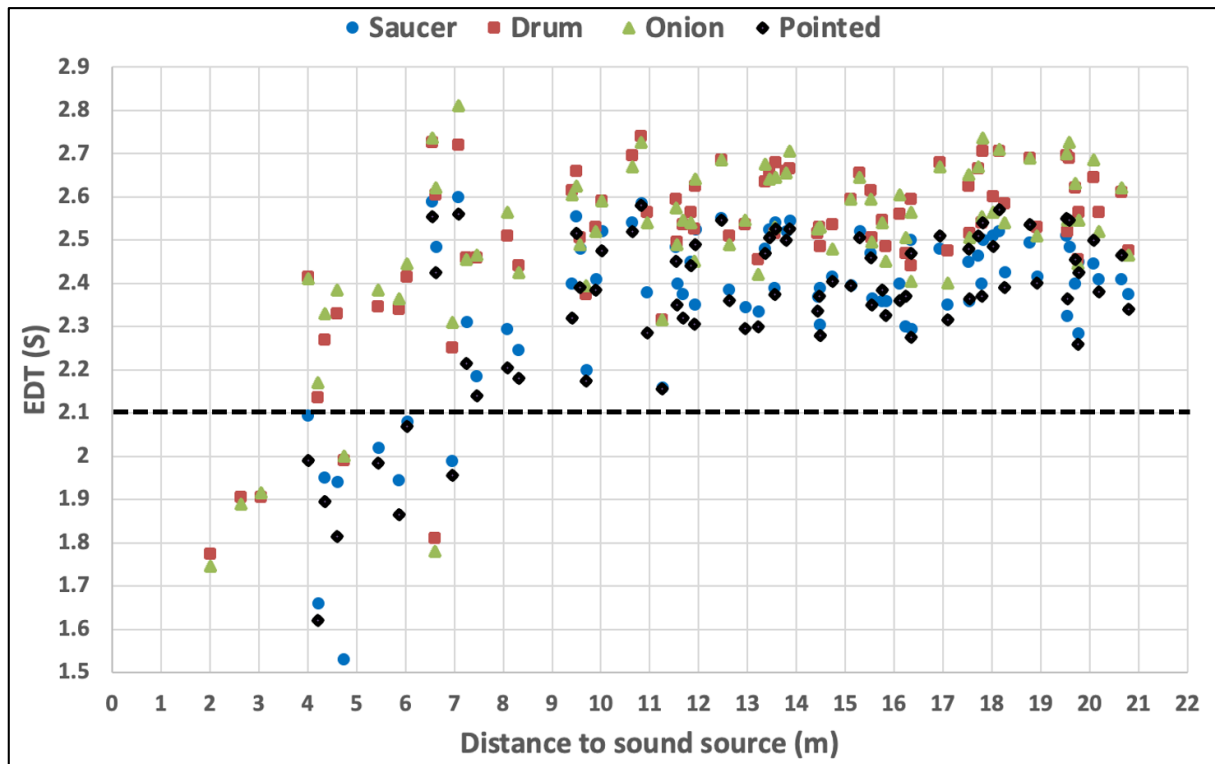


Figure 17. EDT average values at receiver points with different dome-shapes

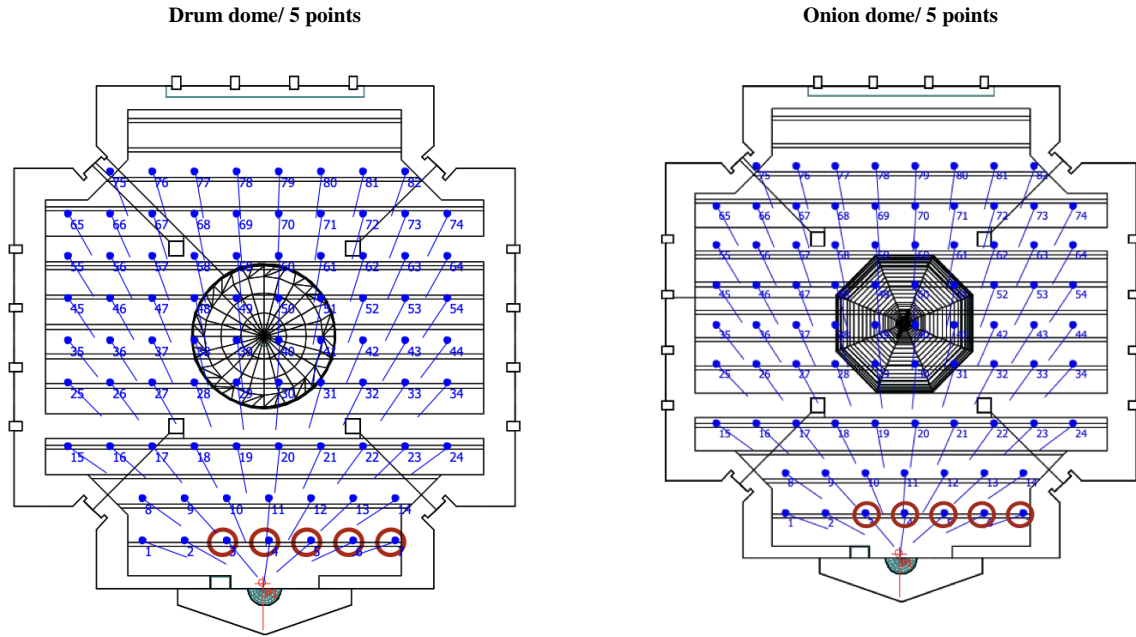


Figure 19. Location of receiver points achieved the optimal EDT

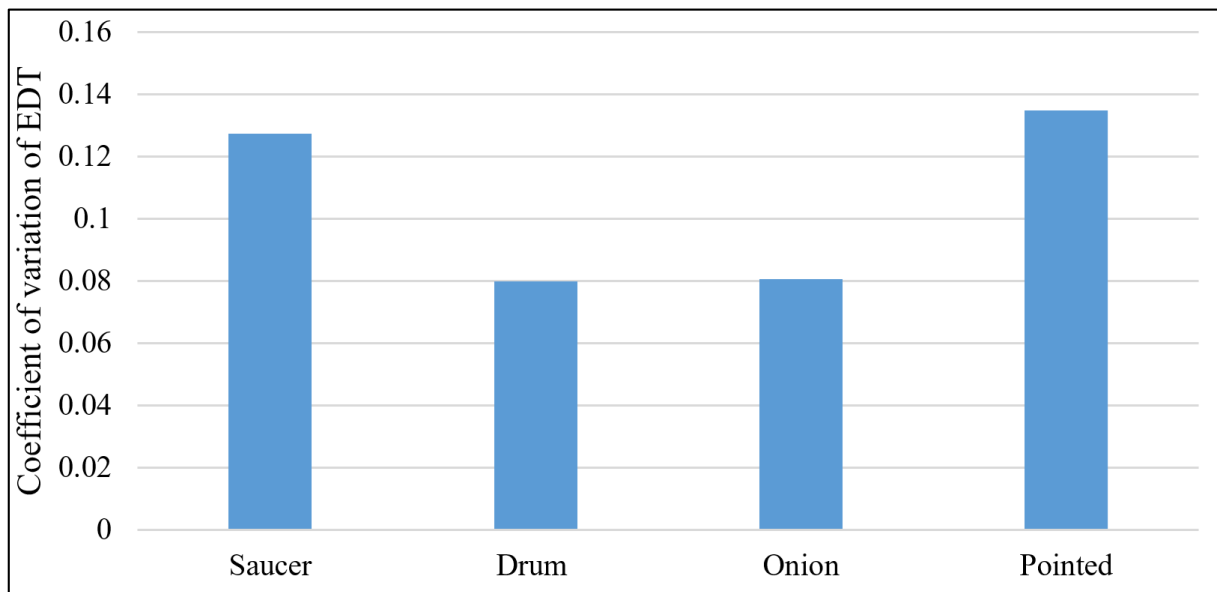
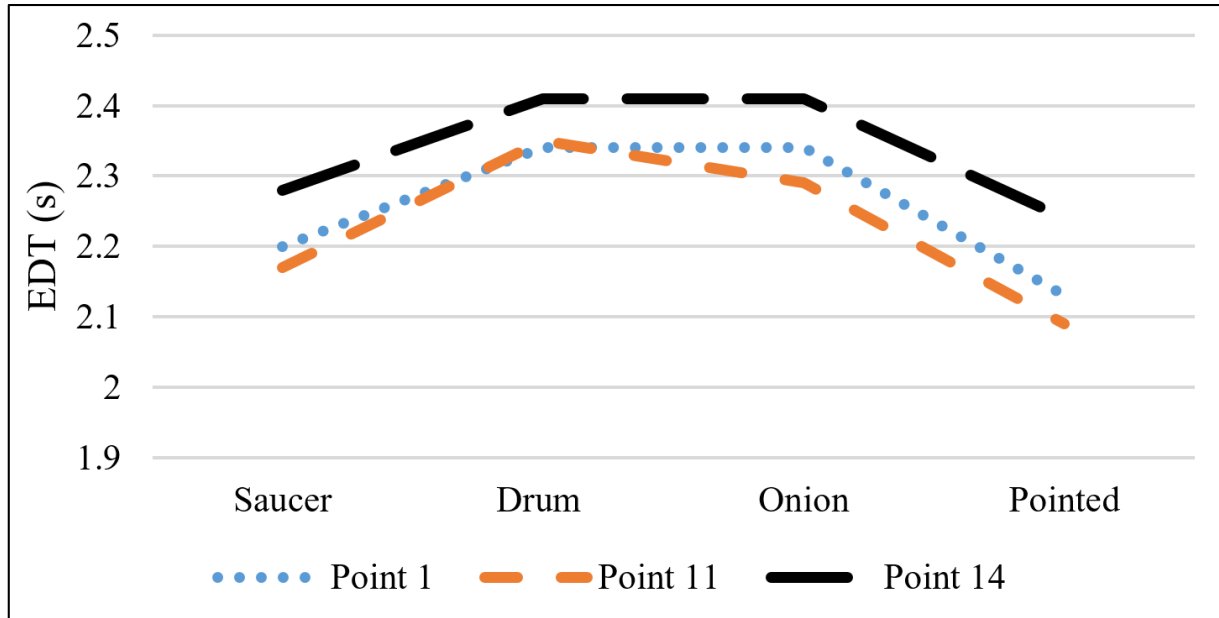


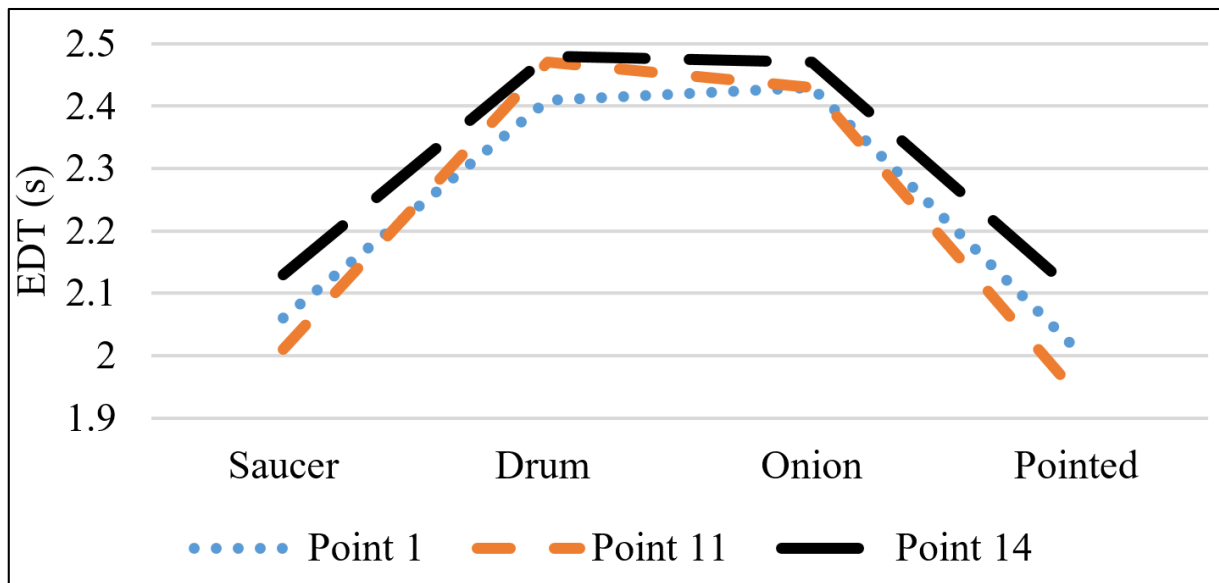
Figure 20. Coefficient of variation of EDT values

The optimal acoustic performance (short EDT) was obtained in the first and second rows for Saucer and Pointed domes, and in the first row for Onion and Drum domes. To determine the cause of variation in EDT, three points (1, 11, and 14) were selected for all the domes and compared at 500Hz and 1000Hz, as presented in Figure 21. The Drum and Onion domes caused EDT to increase at 500Hz and 1000Hz, which can be explained by the number

of reflections per second arrived at each point. Schroeder (1962) suggested that 1000 echoes per second was sufficient for the sound to be indistinguishable from diffuse reverberation. In the case of Saucer and Pointed domes, the maximum EDT values were obtained at point 14 at 500 and 1000 Hz. Thus, point 14 did not achieve the recommended EDT value.



a) EDT at 500 Hz



b) EDT at 1000 Hz

Figure 21. EDT at points 1, 11, and 14

Figure 22 demonstrates the reflection density (RD) at the selected points. It is known that RD is inversely proportional to the room volume (Schroeder, 1962). Owing to the architectural proportions, the Onion and Drum domes have greater volumes compared to Saucer and Pointed domes. Furthermore, the shape of Onion and Drum

domes causes multi-reflections inside the dome, thereby delaying the arrival of reflected sound from the dome surfaces to the receiver points, as shown in Figure 23. For the previous reasons, Onion and Drum domes caused an increase of EDT and T30.

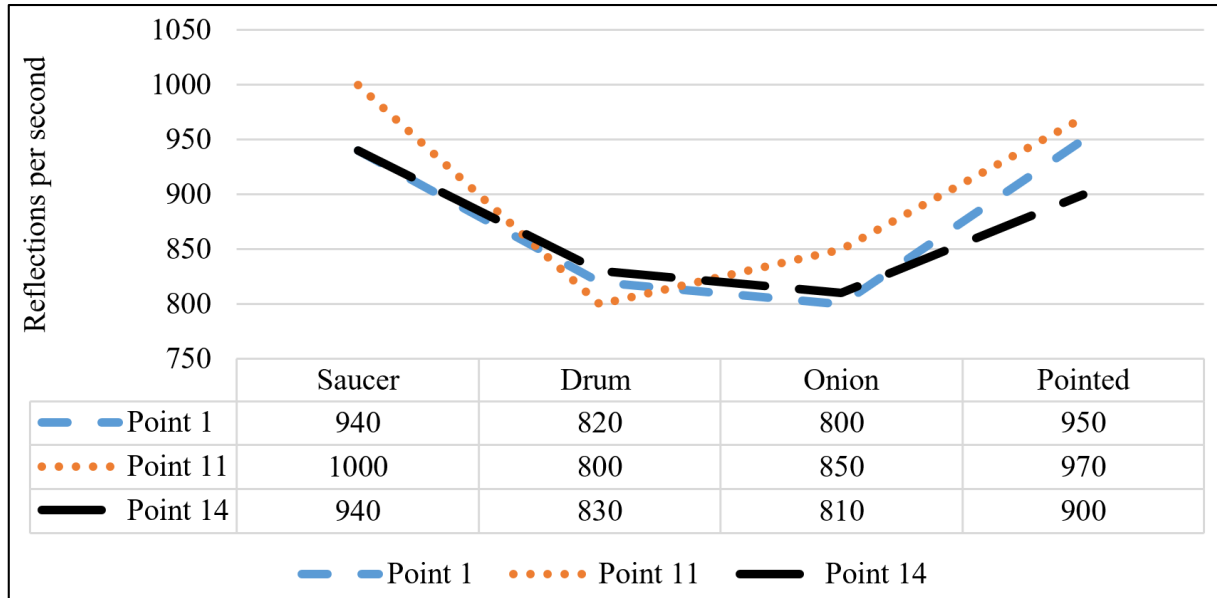


Figure 22. Reflection Density at points 1, 11 and 14

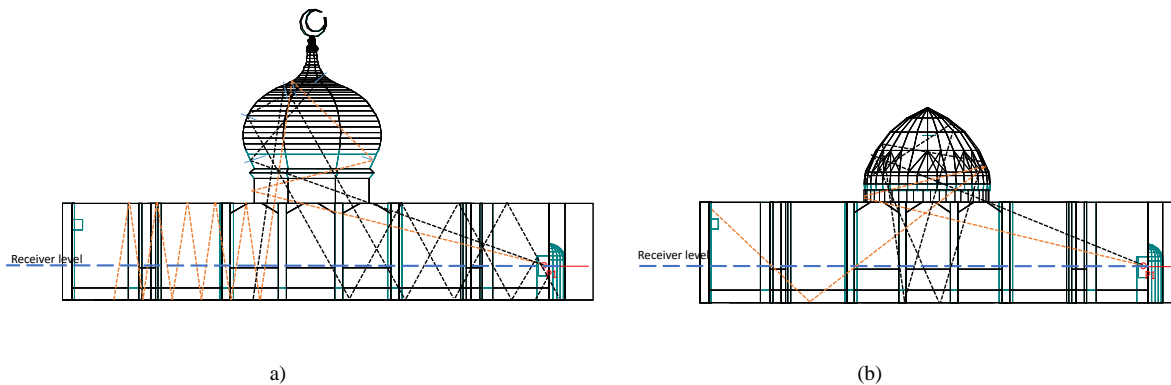


Figure 23. Reflected rays by (a) Onion Dome, (b) Drum Dome

6. Conclusions

This is the first study on the impact of dome-shape on the acoustic performance of mosques. A real mosque located in the Eastern Province of Saudi Arabia has been chosen for the simulation and in-situ measurements. The simulations were performed using ODEON (version 11s) for four typical dome-shapes, namely Saucer, Drum, Onion, and Pointed. The acoustic parameters studied were Reverberation Time (T30) and Early Decay Time (EDT). The acoustic characteristics were measured by considering Imam position as the sound source. The simulation models were calibrated on the basis of the best match between the simulated and measured parameter values. The majority of simulated and measured results were found to be within the acceptable limits of the Just Noticeable Differences (JNDs). The main findings are summarized as follows:

- Saucer and Pointed domes achieved optimal and homogenous T30 and EDT values, while the Onion

and Drum domes yielded T30 values greater than the optimal. This is due to its volume and the shape of its curved surfaces, where it focuses and amplify sound waves in certain directions, which results in a longer T30 and EDT.

- Saucer and Pointed domes achieved better BR values compared to the other domes.
- Saucer and Pointed domes achieved short EDT values and kept the early sound strong and clear.

In general, the results indicate that the optimum acoustic performance could be achieved by Saucer and Pointed domes as they meet the recommended values. The coefficient of variation was used for comparing the variations between the results and to study their distributions; the Drum and Onion domes achieve better distributions of all the acoustic parameters.

It could thus be deduced that domes can have a direct positive or negative impact on the acoustic performance of

mosques, which would vary according to the size and architectural features of the mosque. Therefore, the impact of dome-shape on the acoustical performance should be studied at the early design stage of a mosque.

The present study has been done by considering imam position as the sound source, and the findings might be different if the Khatib position would be the sound source. Therefore, considering the Khatib position as the sound source is important if the mosque's function includes the congregational Friday prayer, which is being considered in the author's future work.

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