


Acoustical simulation and optimization in Mosques

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Abstract: This article discusses the assessment and optimization of speech intelligibility in the Grand Mosque in Makkah. It is the most iconic Islamic site in the world. Most of the surface material used is marble, which is considered to be a highly sound reflective material. Acoustic measurement of the current conditions (with a surface area of 85,000 m²) was conducted. A virtual model was used to obtain an optimum acoustical solution. The measurement and inspection of ambient acoustical data were conducted using the EASERA measuring tool, and as a result, late energy arrival (after 100 ms) was noticed; this forms echoes and decreases intelligibility. It was also noticed that the measured background noise levels were as high as 90 dB (A). High temperature and humidity degrade the quality of the ambient acoustical environment. A virtual model for the targeted areas (Massa roof and adjacent perimeter) was created using EASE simulation software. Mapping results showed a high level of intelligibility (0.6) and homogenous distribution of the sound pressure level (SPL) (max. variation 9 dB). Loudspeaker columns minimized late energy arrival. The “active” approach improved the ambient acoustical environment in the targeted area and eliminated the necessity of an expensive “passive treatment”.

Keywords: acoustic performance; electro-acoustic; architectural acoustic; mosque acoustic; acoustic simulation

1. Introduction

There is no doubt that designing the acoustics and sound systems inside mosques is considered to be a difficult task facing acousticians and sound reinforcement system (SRS) experts. This can be attributed to the presence of important design criteria related to different worshipping modes [1]. Mosques are places of worship used for prayer, public speaking, preaching, lecturing, and Quran recitations. Therefore, acoustic comfort is essential because it allows for maintaining an acceptable level of the delivered sound [2]. All modes of worship in mosques are related to speech intelligibility. Furthermore, the prayer call (adhan) is announced through the sound system. Hence, the design of any mosque’s acoustic-related architectural elements and features must involve careful attention if a good listening experience is to be attained.

Many sound systems that are designed to propagate sound waves over large distances exhibit major problems when listeners are located close by. The sound waves received at a closer proximity may damage the human ear since the high amplitude of acoustic vibration can damage the human eardrum, inner ear, and even the Eustachian tube in extreme cases. However, if the propagated sound levels are reduced, they cannot

be heard over long distances as intended. To obtain an applicable system, the acoustic SRS must be well designed. One of the problems that must be considered is the large areas of holy sites and the sound reflections from the surrounding surfaces. Reflections from highly reflective surfaces lead to irregular and prolonged reflections and degrade speech intelligibility. Additionally, architectural elements such as columns, domes, and “muqarnasat” (ornamental shapes) may lead to unpleasant perceptions from the ambient acoustic environment [1,3]. There are a number of papers that discuss acoustic characterization in mosques, but very few of these papers deal with acoustics in large open-air structure mosques [4,5].

The Holy Haram in Makkah is the most inspiring holy place for Muslims. It is an essential site of pilgrimage in the Hajj ceremony, which every Muslim worshipper must perform at least once in their life (if they are able). Upon the expansion of Massa and the adjacent piazza areas, the local authorities requested an update of the SRS. The local authorities aimed to achieve the most pleasant acoustical environment and to overcome the reduction in sound quality on the Massa roof and the adjacent areas. The newly proposed loudspeaker arrangement on the Massa roof and the areas of interest are presented in this study. No similar research has been performed in the Grand Mosque. The current study concerning this prestigious site is the first of its kind to be published.

The Holy Haram in Makkah is large in size, and its architectural structure is very complex. It contains closed and widespread open-air areas as well as semi-open-air areas. The main worshipper areas of interest are “Sahan Al Mattaf”, the Massa building roof, piazza area (I), and piazza area (II). The Massa roof and adjacent piazza area (II) are considered in this study. To achieve a pleasant acoustic experience in mosques, predefined criteria regarding room acoustics and sound system design inside mosques should be considered [6]. In this study, the ambient acoustic environment in the areas of interest is evaluated using the existing SRS. Subsequently, a virtual model with the newly proposed sound system is developed using the software EASE for the areas under consideration. Furthermore, a comparison between the measured and simulated results at particular testing points is presented and discussed in this study.

Although further measurements were not possible due to site security sensitivities and high visitor volume, this article provides a detailed description of the current measurement procedures using the EASERA software [7], employing a ray tracing method with over one million beams to ensure the accuracy of the results. Accordingly, the audience was positioned within the model at a standard ear height of 1.7 m. The article also details the absorption coefficients of the marble used in the Great Mosque and the audience. Furthermore, it addresses the unique challenges of large, exposed structures, noting the scarcity of such studies. The results are placed within the context of the Great Mosque’s specific environmental challenges, such as delayed reflections from the surrounding high-rise buildings and mountains, and are compared to the controlled “active” approach of digitally oriented loudspeaker columns.

2. Area targeted by the design and the surrounding landscape

The Grand Mosque in Makkah (called the Holy Haram in the Arabic literature) is located in a valley and surrounded by high-rise buildings and mountains, which has a

major influence on the ambient acoustic environment. **Figure 1** shows a sky view of Haram's main structures, the surrounding area, and the area targeted by the design.

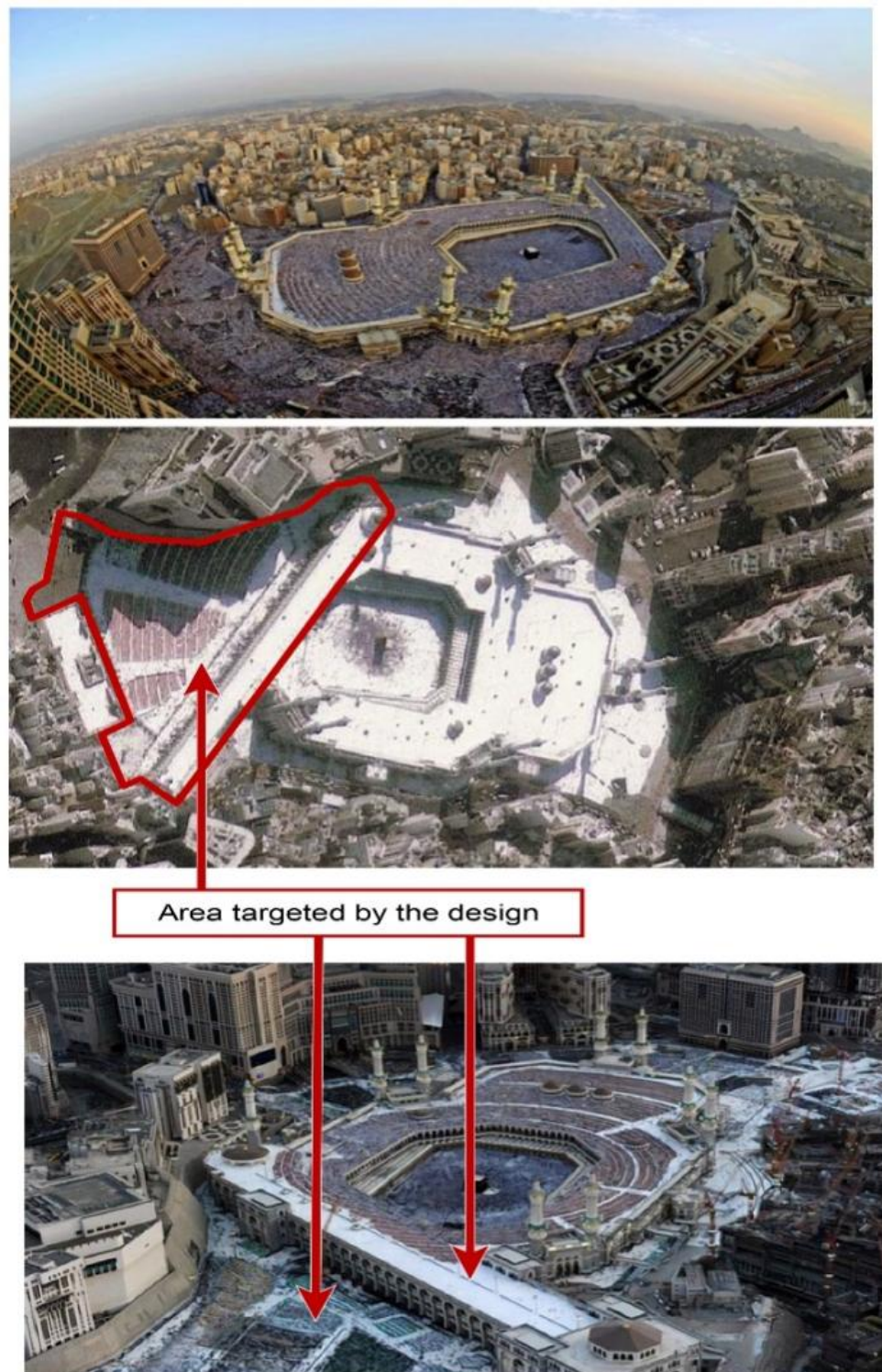


Figure 1. The occupied Holy Haram in Makkah and the surrounding area, the main structures, and the area targeted by the design.

The roof of the Massa building (a three-story building) and the adjacent piazza area have floor spaces of approximately 20,000 m² and 64,000 m², respectively. The audience floor surface area is made of highly reflective marble. All audience areas under consideration are exposed to open air and consequently to high noise levels and

echoes from nearby buildings, the valley, and the mountains. A computer model was made to investigate the acoustics of the Massa roof and the adjacent perimeter after the installation of a suitable sound system. As a first step, an evaluation of the current situation of the ambient acoustical environment was conducted using Prober software. **Table 1** shows the absorption coefficients for a standing audience and marble used on all areas considered in this investigation [8,9]. The absorption coefficients are calculated for two standing persons in an area of 2.7 m² which is the approximate area needed for two worshippers during standing worship in mosques.

Table 1. Absorption coefficients of a standing audience and marble.

Frequency (Hz)	Audience (2.7 per s/m ²), α	Marble, α
63	0.26	0.01
125	0.22	0.01
250	0.42	0.01
500	0.88	0.01
1000	1.2	0.01
2.0	1.2	0.02
4000	1.18	0.02

Note: α , absorption coefficient.

3. Measurement procedure

This part of the paper describes the basic theoretical principles necessary for understanding the measuring techniques. The software EASERA developed by Ahnert Feistel Media Group (AFMG) utilizes a pink noise excitation in the measuring process. A two-port measuring diagram is shown in **Figure 2a**. As an input signal, an excitation signal generated by a signal generator is fed into the Grand Mosque sound system by using an external high-quality AD/DA hardware converter (AUBION X.8), as shown in **Figure 2b** [10].

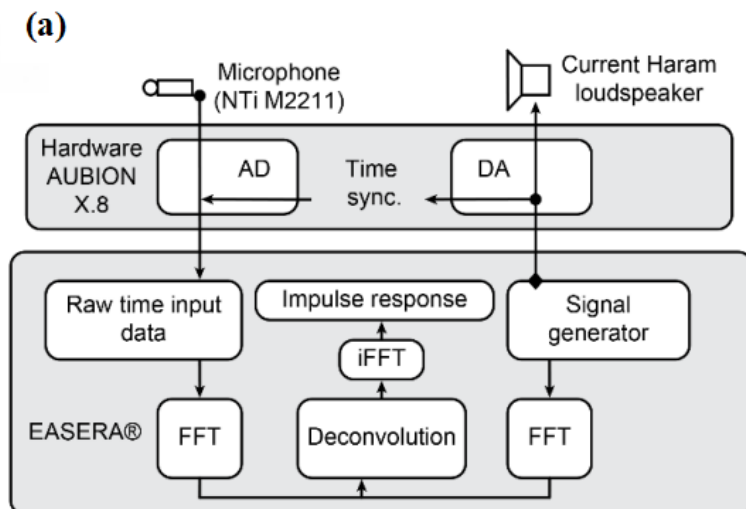


Figure 2. Cont.

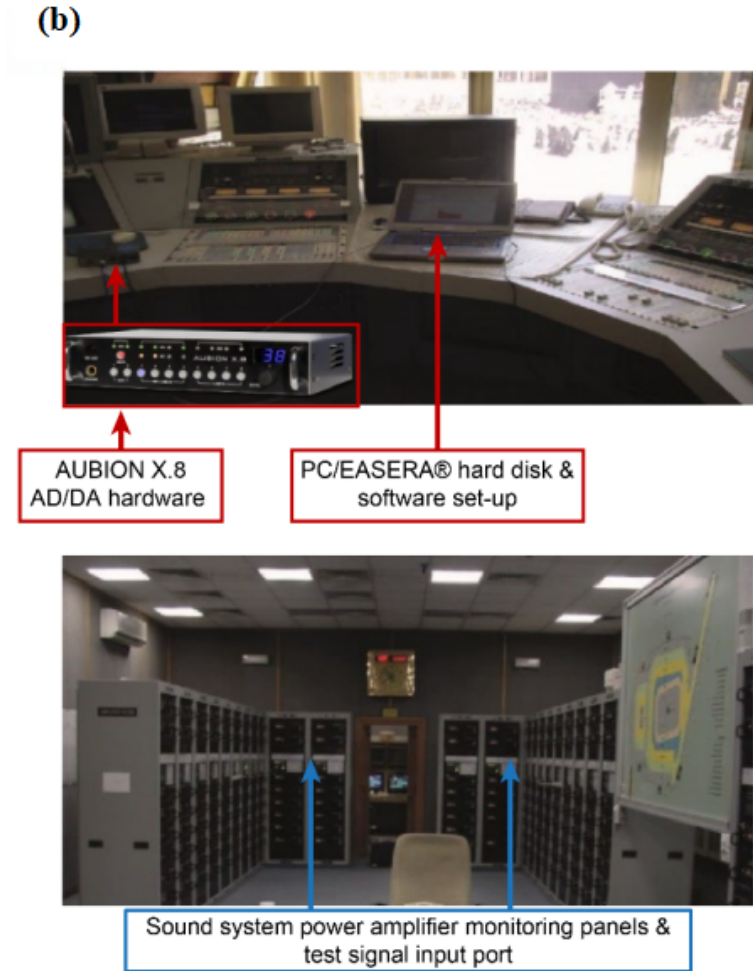


Figure 2. (a) Basic block diagram of EASERA software and hardware; (b) Control room containing the current loudspeaker power amplifier monitoring panels and testing setup.

Such an AD/DA converter is needed to ensure the quality of the test tone conversion and the data gathering needed for the postprocessing stage. The area tested is covered with hundreds of different kinds of loudspeakers mounted on the Massa wall and roof, and the adjacent piazza area. Unfortunately, photos of the different kinds of loudspeakers are not allowed to be taken or released to the public.

First, the unprocessed output signal (raw data) is recorded and stored on a PC hard disk. EASERA allows the influence of the background noise to be eliminated (this is not represented for simplicity). If $E(f)$ is the input signal and $A(f)$ is the output signal (refer to **Figure 3**), then $H(f)$ is the transfer function [11].

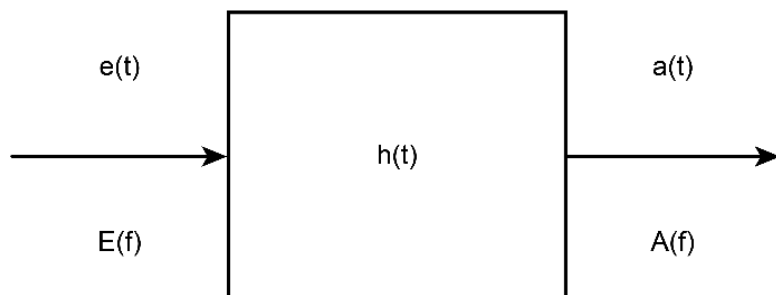


Figure 3. Signal representation for an LTI system in the frequency and time domains using the Fourier transform.

The impulse response $h(t)$ can then be computed by using the inverse Fourier transform. The energy time curve is simply the square of the impulse response.

4. Description of field measurements

Measurements were performed on the Massa roof and the adjacent piazza area while these areas were occupied by worshippers (high background noise). It is not expected that occupancy will affect the background noise level [12]. Two types of measurements were made: **relative measurements** of impulse responses using EASERA, and **absolute measurements**, performed using a sound pressure level (SPL) Meter (Type CEL-593) after the necessary calibration of the measuring equipment to measure sound pressure levels at predetermined points [13]. All measuring attempts were made while the minaret (a tower-like building) sound system was functioning, using **pink noise** excitation signals. This was done to detect any late-arriving energy (because of the height and late reflections from the surrounding towers and buildings) at the testing point's position, as this causes echoes and consequently decreases intelligibility.

Measurements of the SPL were conducted in the worst-case conditions for sound radiation in open air; i.e., high temperature, low humidity, and high background noise from large numbers of worshippers, all of which result in degraded values of speech intelligibility [14]. The signal-to-noise ratio (S/N) was kept at over 40 dB in most of the testing positions by increasing the signal output level. As a result, better postprocessed results were acquired, and the elimination of high background noise (sometimes as high as 65 dB) was possible. These conditions were applied to the currently used sound system so that a system could be designed that could operate in the worst-case conditions of sound propagation. Testing positions were selected that covered a cross-section of the Holy Haram that was as representative as possible and included acoustically critical listener positions.

4.1. Case study

At point (X) in the piazza area, several kinds of measurements were taken (refer to **Figure 4**). These measurements were done in the worst-case conditions possible: hot weather, low humidity, high levels of background noise, and a considerable number of worshippers [14].

Point X was chosen because it is exposed to remote surface late energy reflections. At this location, a high level of background noise (high level of pedestrian traffic) and extensive late arrival of sound energy is detected compared to other locations. This can be explained by the late reflections from the surrounding towers facing the minaret SRS. The results at point X are the only ones shown among the numerous measurement results from places in the audience areas. The results acquired at point X (worst-case scenario) are used to set the necessary noise floor during the simulation runs. A higher noise floor necessitates greater efforts in selecting the number, position, and settings of the participating arrays to achieve usable speech transmission index values of >0.5 in all audience areas [1, 6]. Calculations are made over all audience areas (shown as mapping files), but with the same noise floor as that at point X, regarded as the highest

value that may occur. Thus, we conservatively consider the highest possible noise floor value and hence avoid degraded intelligibility [11].

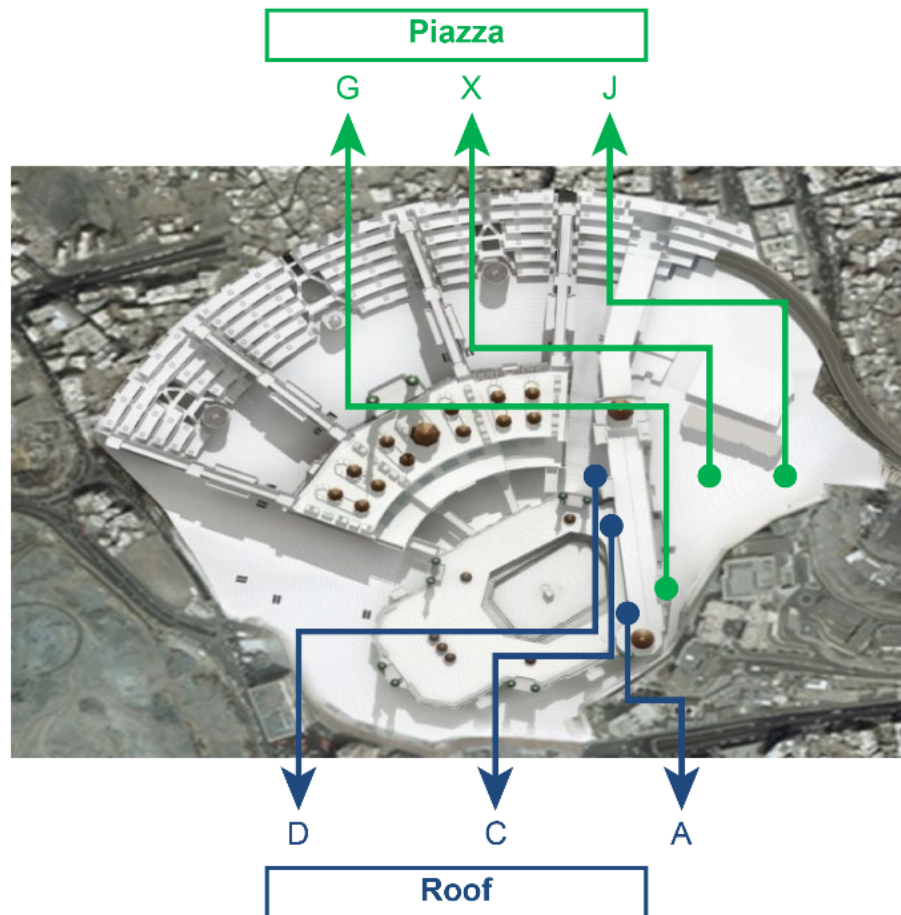


Figure 4. Testing point positions on the Massa roof and the perimeter.

It should also be highlighted that because of the given religious value of the place and particular local authority procedures concerning presenting testing results to the public, the presentation of the sound measurement results at only specific points is permitted. These measurements are as follows.

4.1.1. Impulse response

This measurement was taken first to evaluate the ambient acoustical environment using the current classical SRS. A depth inspection of late sound energy arrival from the minarets and late sound reflection from the buildings and towers surrounding the Haram was conducted to evaluate the effects on sound quality. **Figure 5** shows the impulse response recorded at position (X) in the piazza.

The direct sound was measured with a delay of approximately 210 ms, and short-time reflections arrived 40 ms later, but strong late reflections were noticed approximately 100 ms and nearly 160 ms after the direct sound. These late reflections formed echoes and hence decreased sound intelligibility [15]. Additionally, relatively strong early reflections from the area surrounding Haram were noticed. In ideal cases, early reflections coming after the initial time delay gap (ITDG) should have a lower strength level [15]. The following reflections arriving after the ITDG should not be discrete on the time scale to prevent echoes [15,16]. This was not noticed in the shown

impulse response. Additionally, high levels of background noise were found, which plays a major role in reducing the intelligibility of the emitted sound [11]. Section 5.3.3 shows a simulated energy-time curve at point (X) after using the proposed loudspeaker columns as a form of demonstrating sound quality improvement.

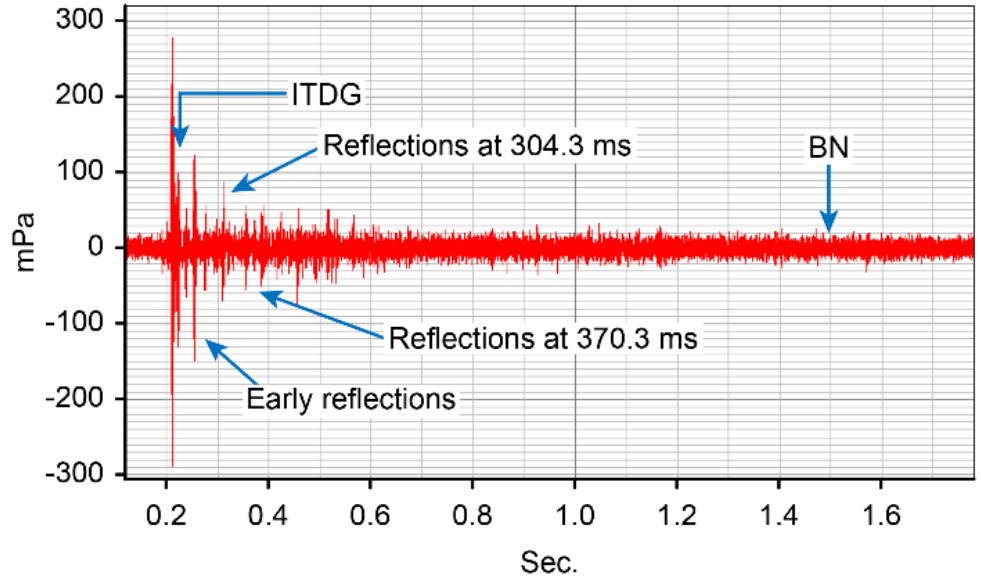


Figure 5. Impulse response recorded at point (X) on the Massa roof and adjacent perimeter.

4.1.2. Sound pressure level measurements

Sound pressure level measurements at point (X) in the piazza area were taken using a CEL-593 meter. Additionally, at the same point, the background noise was measured. These measurements aimed to obtain a better view of the A-weighted strength of the sound in a frequency range from 16 Hz to 16,000 Hz. The results of the two measurements are provided in **Figures 6 and 7**.

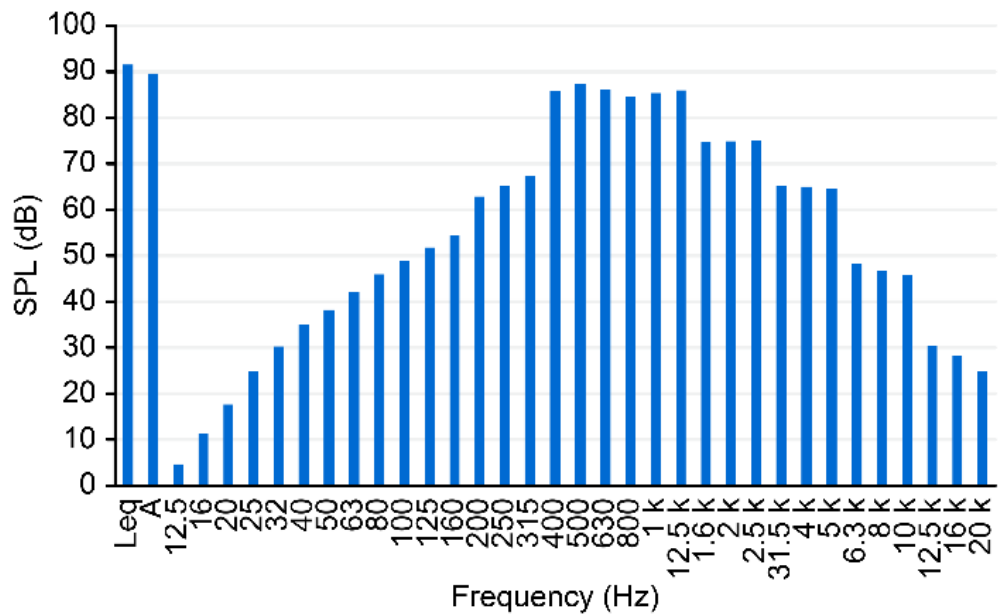


Figure 6. Sound pressure level (A-weighted) at point X during the adhan (call for prayers).

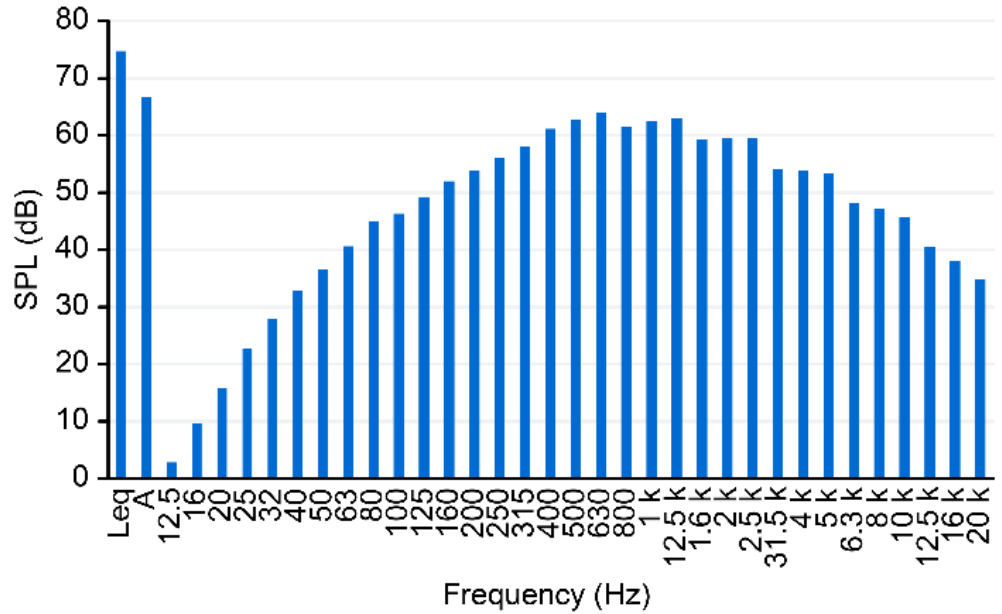


Figure 7. The noise level in the Massa adjacent perimeter.

Figure 6 shows that the peak SPL was recorded at 500 Hz with a maximum of 89 dB. **Figure 7** illustrates that the maximum value of the noise level at 630 Hz was 65 dB.

5. Virtual model

A computer model was built using the acoustical simulation program EASE. **Figure 8** represents the rendered EASE model of Massa’s roof and the adjacent piazza area. To make a virtual model in this computer program (EASE), dimension values of the place, i.e., the length, width, and height, including the fine structure of all walls, floor, and ceiling parts, must be known. The needed absorption and scattering properties of partial surface areas must be input to the virtual model. Importantly, this model performs as a closed volume. Difficulties arise when making a model for open areas. Most of the time here, a ceiling and some wall parts do not exist (open structure). In this case, to close the spaces in EASE, the missing surface parts of the model must be substituted with artificial surface parts with 100% absorption. This modeling technique ensures that rays exiting the structure do not erroneously contribute to the calculated sound field in the audience area, accurately reflecting the open-air nature of the site [17].

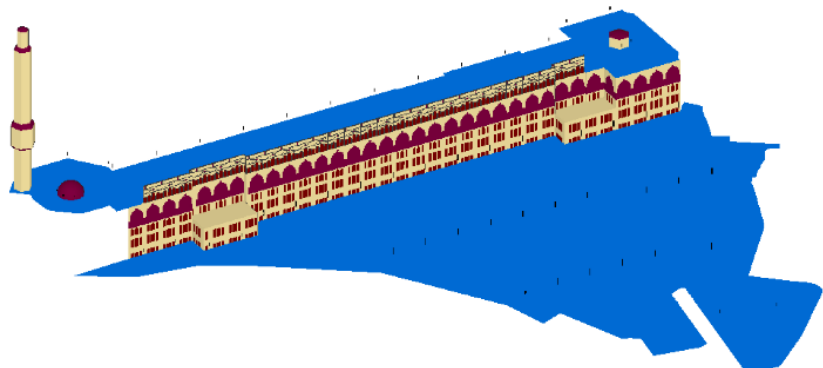


Figure 8. Rendered EASE model of the Massa roof and the adjacent piazza area.

Additionally, **Figure 9** shows the positions of the “audience areas” in the model (marked in blue). In these audience areas, the simulation results for the acoustical concept are obtained.

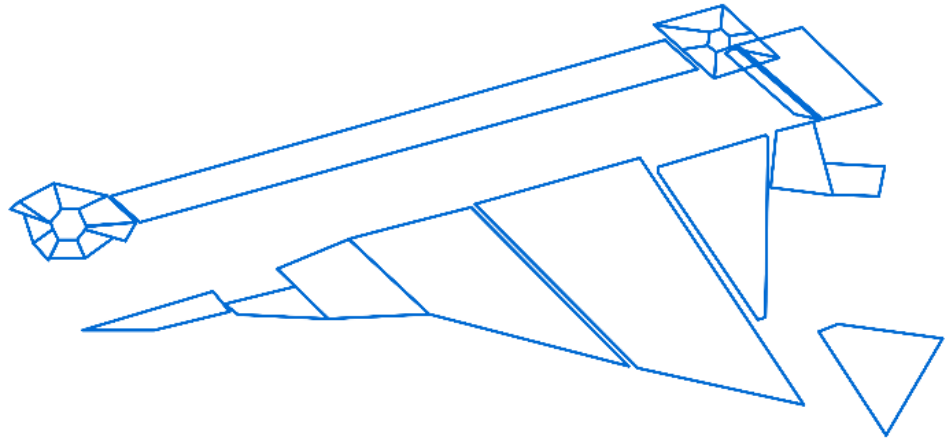


Figure 9. Audience areas.

The audience is positioned at ear height (1.7 m) in the model. The acoustical concept is optimized throughout these audience areas at the ear height level. In the EASE simulation, a special ray tracing method based on geometrical acoustics is used to calculate the sound distribution inside the model in specific, predetermined areas, the so-called audience areas (in mosques, these are areas where worshippers are praying). All rays are radiated more or less randomly from a source (loudspeaker) and meet partially in the audience area. Here, more than one million rays are needed to obtain reasonable results. However, all rays that intersect the artificial surface parts (here, for instance, the open sky) are 100% absorbed and do not contribute to the calculation results in the audience area. The calculation results show the sound level distribution with the selected new speaker arrays under open-air conditions. Experience with the EASE simulation program has shown that the simulated results will match the real results after the new system is installed very well.

5.1. Sound reinforcement system design

The acoustical aim of the newly developed computer model sound system is to ensure a homogeneous distribution of the sound pressure level in overall audience areas and hence to overcome the challenges of background noise and late reflections. As per standard acoustic principles, a signal must match or exceed the noise floor in such high-density environments to achieve a functional Signal-to-Noise (S/N) ratio [18]. Additionally, a good level of intelligibility and sound audibility is essential. While peak levels reach 100 dB to overcome ambient noise, these levels are transient. The system is designed to comply with WHO/OSHA exposure limits by utilizing digital steering to focus energy only on occupied areas, thereby reducing the overall noise dose for worshippers.

The loudspeaker arrays used exhibit wide and almost constant coverage behavior in the horizontal domain and directed radiation properties in the vertical domain [19]. Their beams can be steered and controlled digitally. Furthermore, they have a fixed

directivity pattern at the different frequencies. This is done by changing the active physical length of the loudspeaker column according to the radiated frequencies by electronic means [20]. The directivity patterns of one sample of different loudspeaker arrays proposed in this work are shown in **Figure 10**.

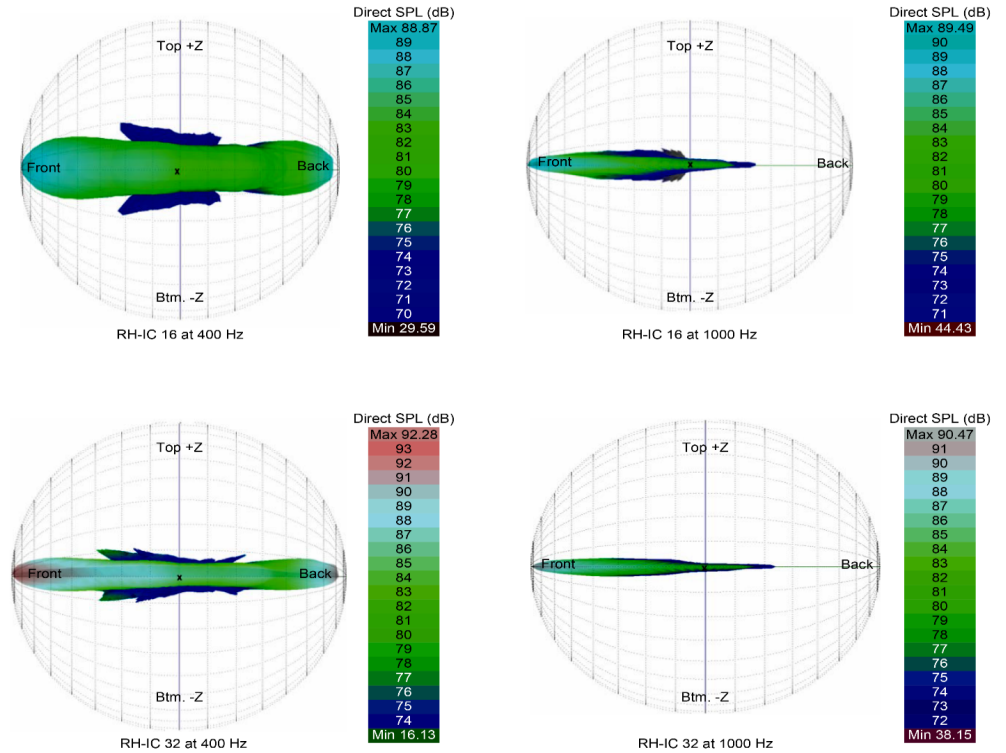


Figure 10. Samples of directivity pattern at different frequencies for IC16 and IC32, ICONYX loudspeaker column (from Renkus Heinz).

The ICONYX 16 loudspeaker column, manufactured by RENKUS-HEINZ, has high-performance amplifiers that drive 16 coaxial transducers and is referred to as IC16 [19]. There are four different types, IC8, IC16, IC24, and IC32, where the attached number refers to the number of coaxial transducers in each unit. The loudspeaker arrays show a very concentrated directivity pattern even at low frequencies of 400 Hz. Recently, many design methods and techniques have emerged that improve the performance of speakers and direct sound towards a determined location or spot. Examples of such methods include combining the least-squares and acoustic contrast criteria method or using multiple sources for the same reason [21,22]

5.2. Setting specifications of the arrays

The worshipper areas and positions of all loudspeaker columns on the Massa roof and the adjacent piazza are shown in **Figure 11**. Here, the locations of the loudspeaker arrays and their types are shown. The angles, internal settings, and the total number of needed loudspeakers are adjusted to obtain the targeted SPL and STI measures. The target STI and SPL values of the design are more than 0.5 and ≥ 90 dB (A), respectively [1].

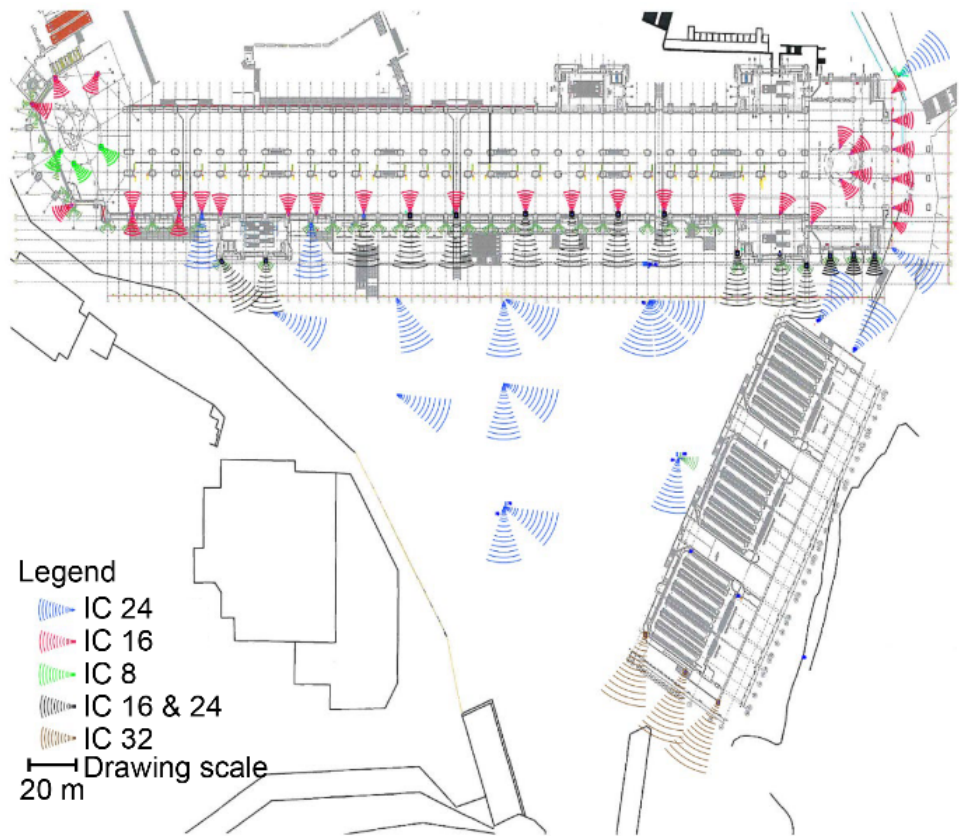


Figure 11. Top view of the Massa showing the locations, types, and directions of the loudspeaker arrays.

Figure 12 shows samples of the internal settings of IC16 and IC32 loudspeaker columns using the program BeamWare. BeamWare is internal setting software devoted to simulating and adjusting loudspeaker array radiation patterns based on the geometry of the space. The radiation pattern (simulated at 1000 Hz) shows reduced scattered radiation and side energy loops emitting sound toward adjacent areas and remote surfaces.

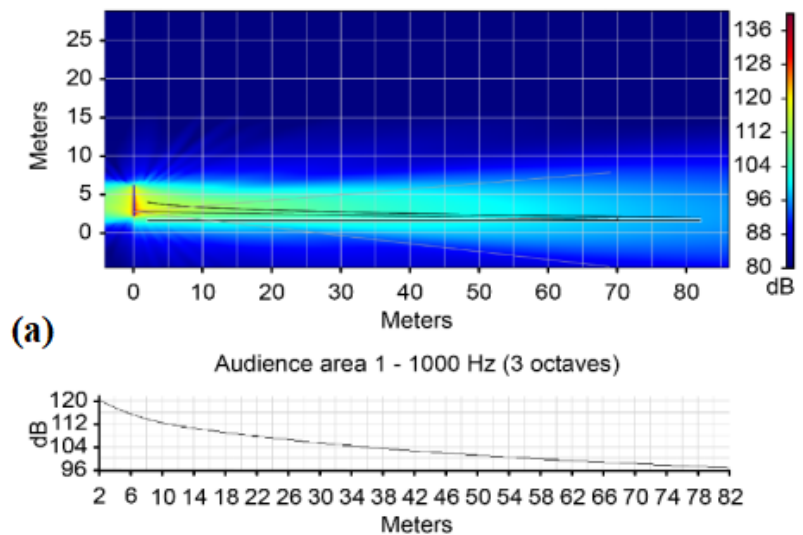


Figure 12. Cont.

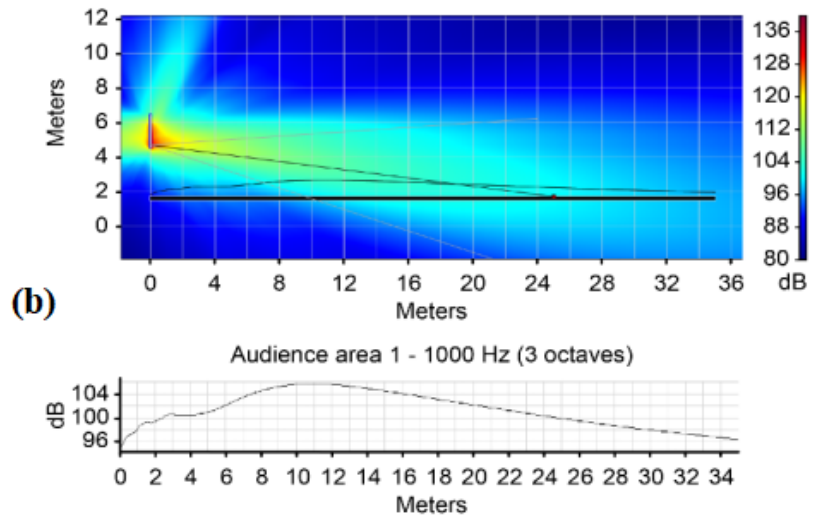


Figure 12. Samples of the internal settings of loudspeaker arrays IC32 (a) and IC16 (b).

5.3. Simulation results

5.3.1. Sound pressure level

In the following, the calculation results for the sound pressure levels in the Massa roof and the adjacent piazza area are shown. The levels are demonstrated with the design illustrated in **Figure 11**. The mapping data in **Figures 13–18** show the total and direct sound pressure levels (at 250 Hz and 1000 Hz) throughout the targeted audience areas. The simulations are performed assuming an occupied roof to demonstrate the effect of the worshippers absorbing the direct sound (even though this effect is not expected to be strong, as the acoustical center in the line arrays is moved approximately 1.5 m above the height of hearing for standing worshippers). In the piazza area, mappings are shown for two kinds of line arrays located on the Massa wall at height levels of 6.5 m and 9 m. A homogenous distribution of total and direct sound pressure levels is maintained throughout the audience areas, with an acceptable maximum variation of 9 dB. This is due to the sustained radiation behavior of the loudspeaker columns used, which are described in Section 5.2.

The homogeneity of the sound pressure level distribution is quite evident. Most of the values are above 100 dB, which exceeds the background noise in the area. Such values must be lowered to prevent harm to the health of worshippers [23]. The direct sound mapping simulation at 250 Hz and 1000 Hz shows sustained direct SPL for the investigated frequencies despite the widespread area of the Massa roof and adjacent piazza area (approximately 20,000 m² and 64,000 m², respectively). The internal setting programming capabilities and electronic aiming of the acoustical center of each loudspeaker result in an even distribution of direct sound pressure levels within a maximum variation of 9 dB.

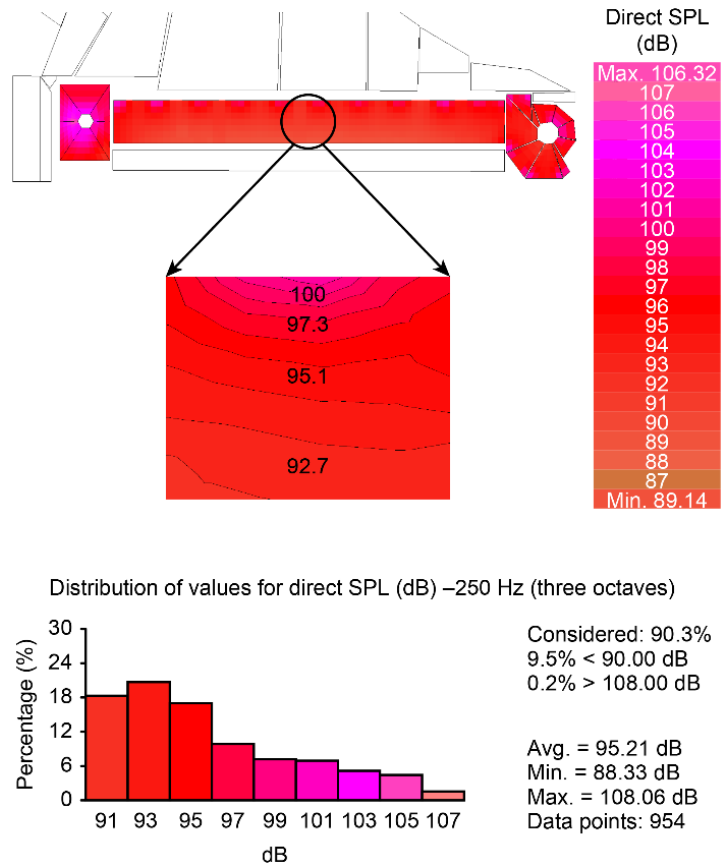


Figure 13. Direct SPL on the Massa roof at 250 Hz.

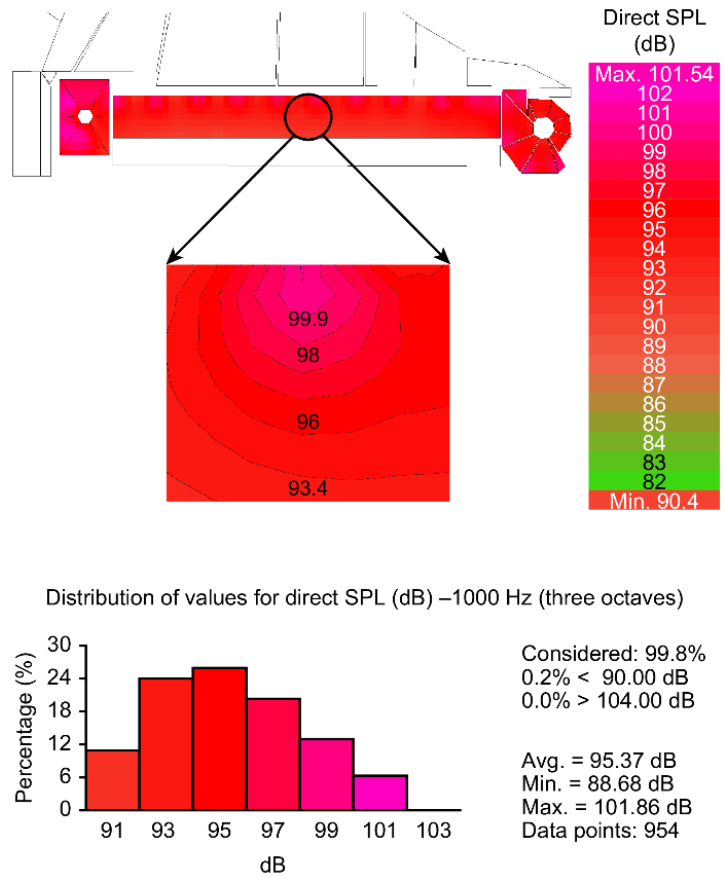


Figure 14. Direct SPL on the Massa roof at 1000 Hz.

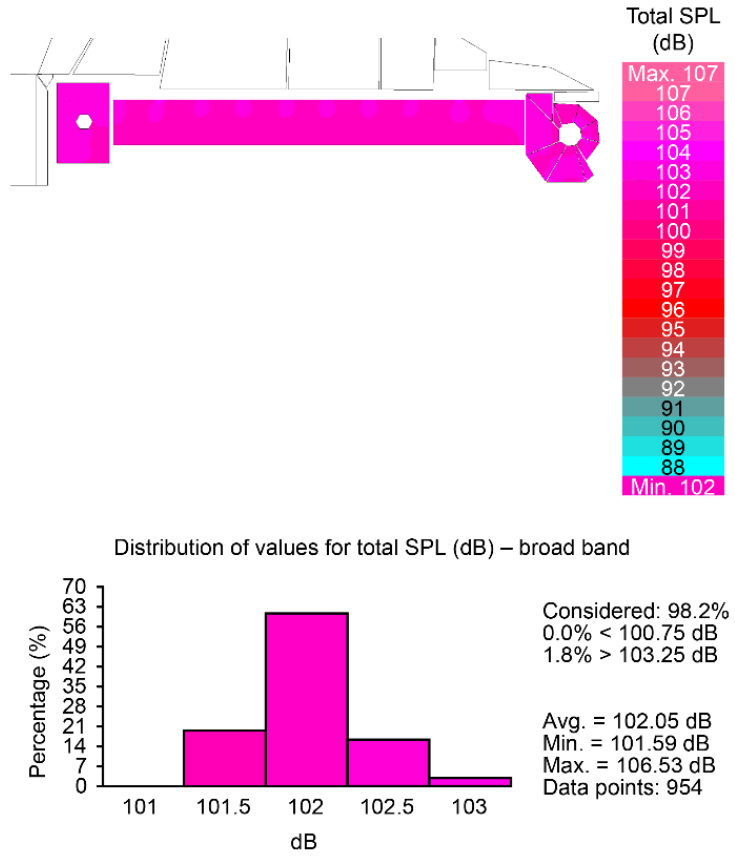


Figure 15. Total SPL (125–8000 Hz) on the Massa roof (broadband).

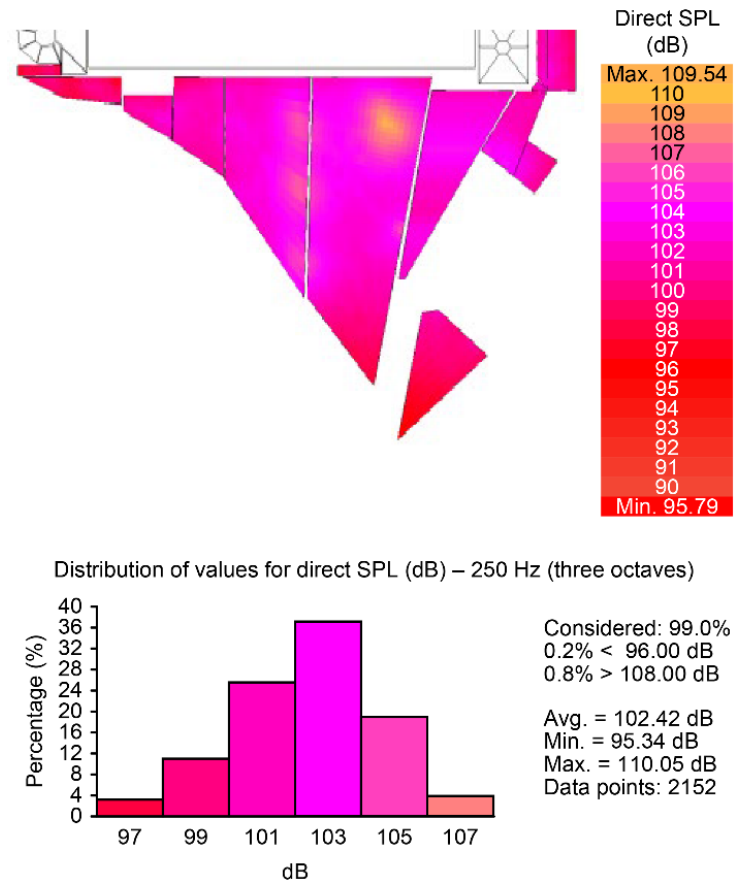


Figure 16. Direct SPL in the Massa adjacent piazza at 250 Hz.

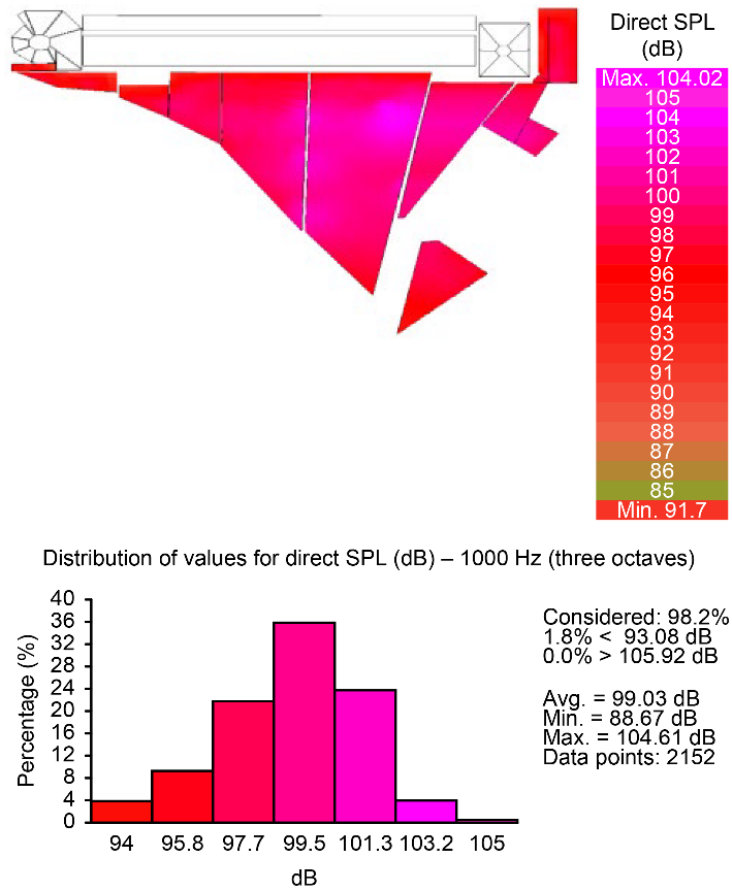


Figure 17. Direct SPL in the Massa adjacent piazza at 1000 Hz.

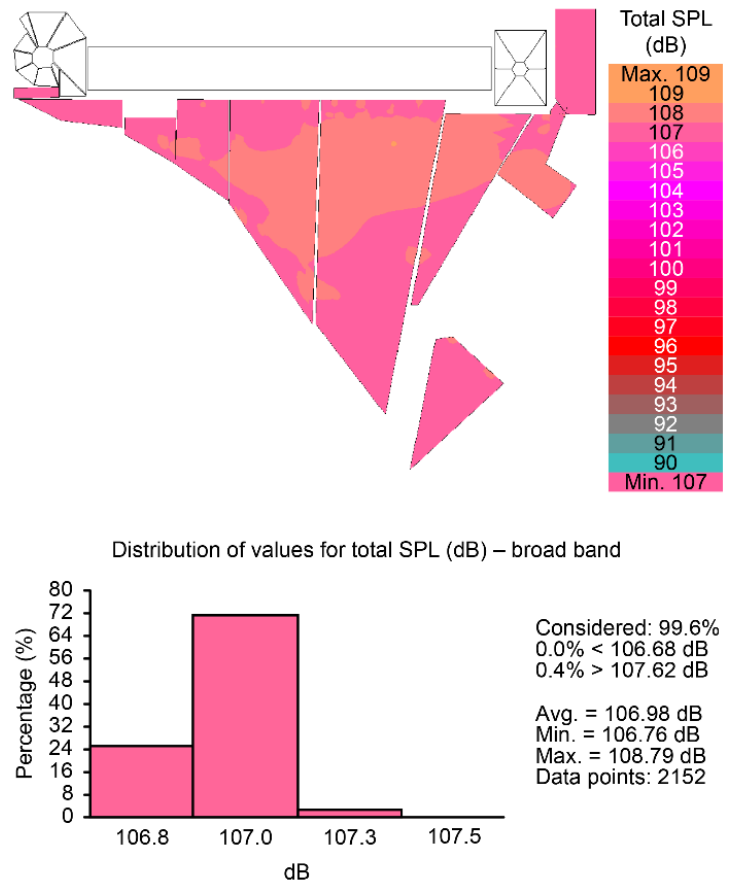
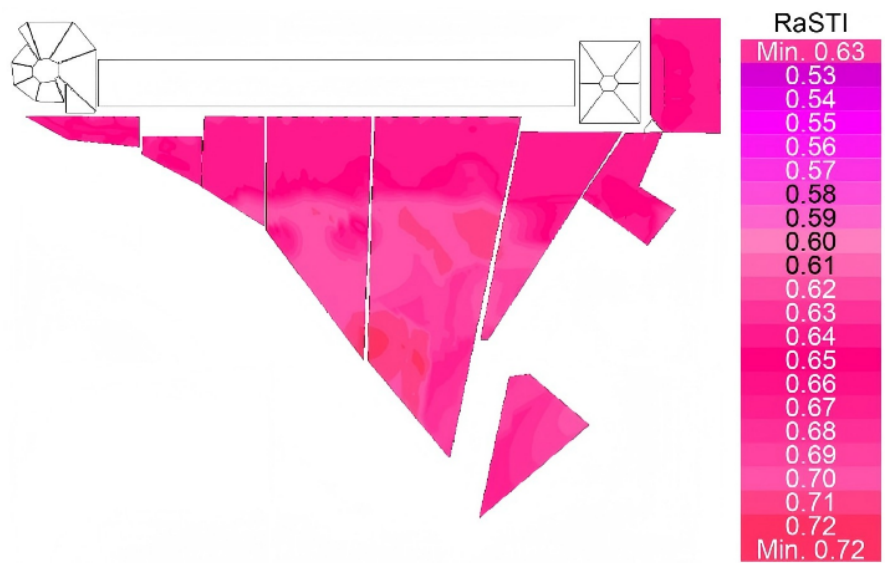


Figure 18. Total SPL (125–8000 Hz) in the Massa adjacent piazza (broadband).

A high level of direct sound and early reflection from near surfaces and loudspeakers (arriving within the first 50 ms after the direct sound) has been proven to enhance good conditions for speech [11]. The addition of early reflections increases the effective signal-to-noise ratio and related speech intelligibility scores, as discussed below [16]. Additionally, the total SPL is simulated to demonstrate the results within the important frequency range of speech (125–8000 Hz); only a small variation of max 3 dB is noticed.

5.3.2. Speech intelligibility

Figure 19 shows the rapid STI (RaSTI) mapping results for the Massa roof and the adjacent piazza from EASE (considering noise level). All values were above 0.6. This is a good or fair indicator of a high level of intelligibility of sound. Although the average background noise levels are as high as 70 dB (A), good RaSTI values are obtained. This is because the line arrays are highly directed toward worshippers. Array speakers are capable of producing consistent sound levels from the front to the back of the listening space and direct sound energy in the direction of targeted areas, hence enhancing the early energy arrival (during the first 50 ms) and improving sound intelligibility [16].



Distribution of values for RaSTI – 1000 Hz (three octaves)

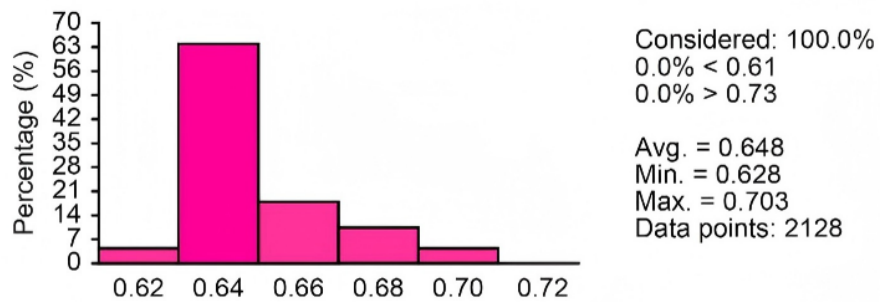


Figure 19. *Cont.*

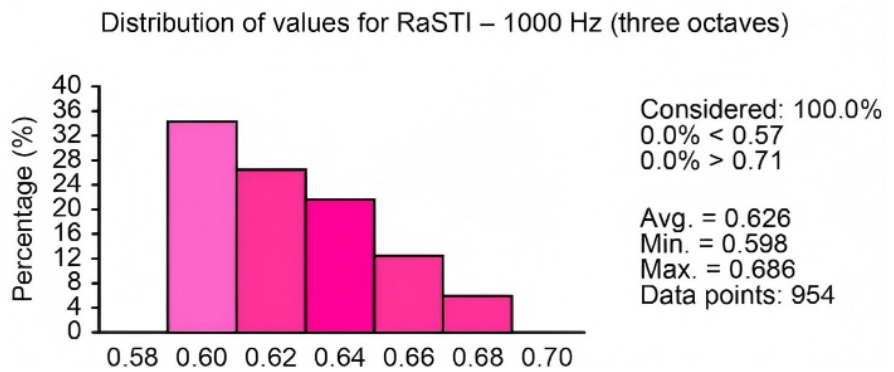
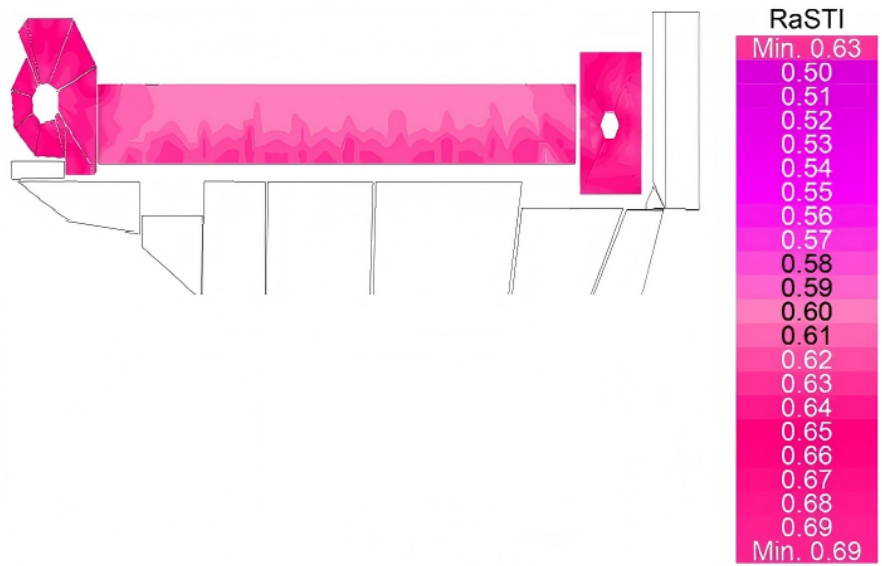


Figure 19. RaSTI mapping results for the perimeter area and Massa roof with noise.

Additionally, representative locations are chosen on the Massa roof and in a wide spread of the piazza area to investigate the intelligibility values by means of the modulation transfer function (MTF). **Figure 20** shows the MTF values and associated STI values. The lower the MTF values are, the worse the intelligibility of sound (lower STI). In this case, all STI values in the piazza area are above 0.6.

The simulated results for the speech intelligibility (STI) at the preselected marked points in **Figure 4** on the Massa roof and adjacent piazza are shown in **Table 2**.

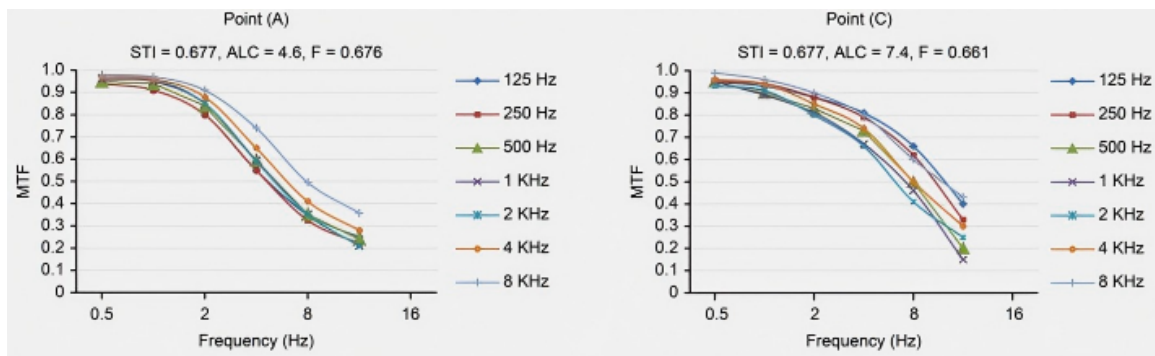


Figure 20. Cont.

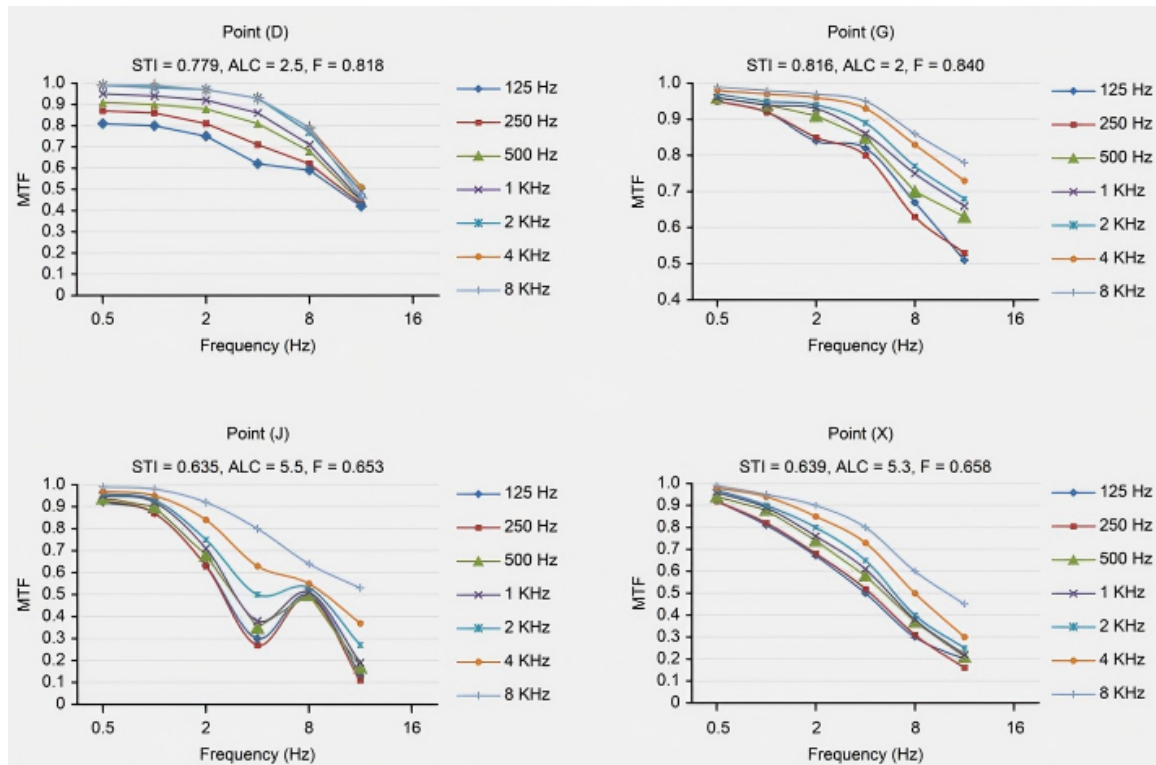


Figure 20. MTF at the preselected location and associated STI values on the Massa roof and adjacent piazza.

Table 2. STI values on the Massa roof and the adjacent piazza.

Position	Simulated STI
A	0.677
C	0.661
D	0.779
G	0.816
X	0.639
J	0.635

5.3.3. SPL vs. delay

Figures 21–23 show the SPL vs. delay curves as simulated in the piazza and above the Massa. The simulation is conducted at the location mentioned in the previous section. It is noticeable that classical behavior (the SPL decreases with time) is exhibited and that no strong reflections or accumulations of late energy arrival occur [24,25]. The behavior exhibited in the measurements at position (X), as shown in Figure 5, no longer occurs in the simulated values (compare Figure 5 to the results for point X provided in Figure 21). Figures 21–23 show that there are no stronger reflections after a subsequent weaker reflection, in contrast to Figure 5. The old design caused echoes and decreased intelligibility dramatically.

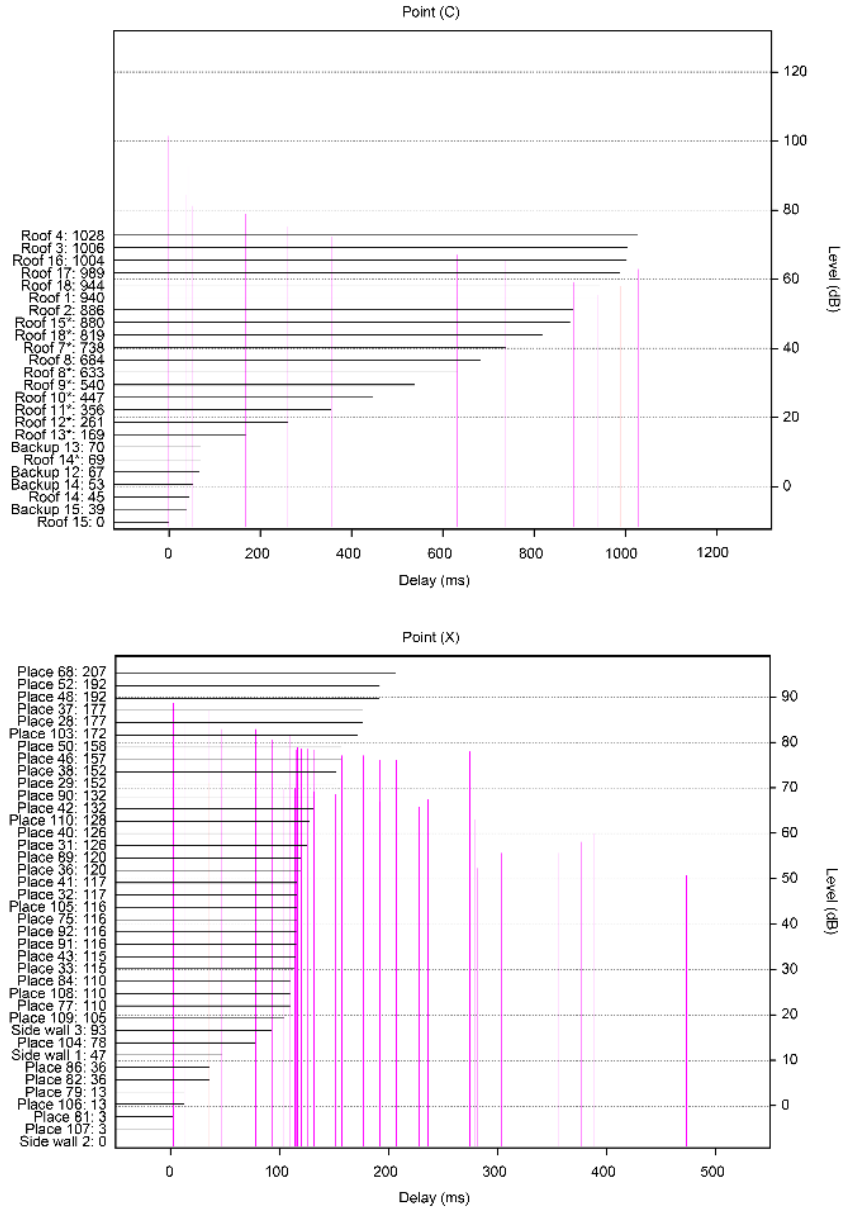


Figure 21. Simulated SPL vs. delay curves at testing points (C) and (X) on the Massa roof and Piazza.

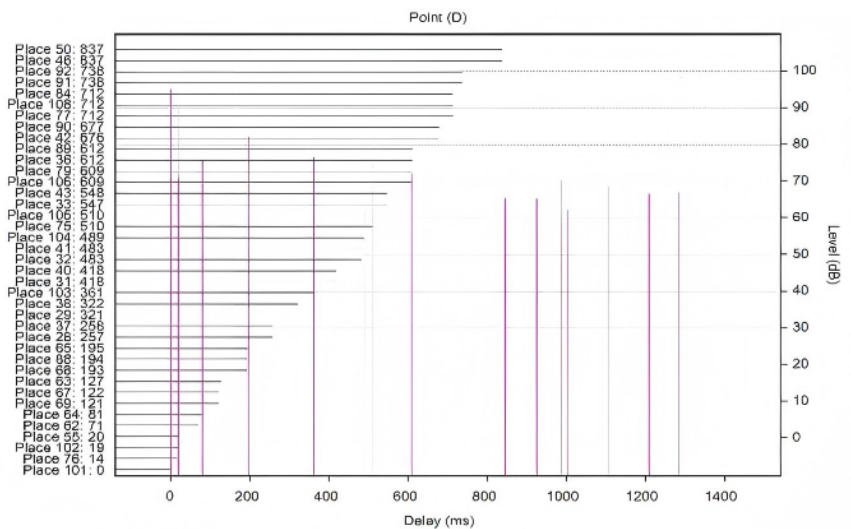


Figure 22. Cont.

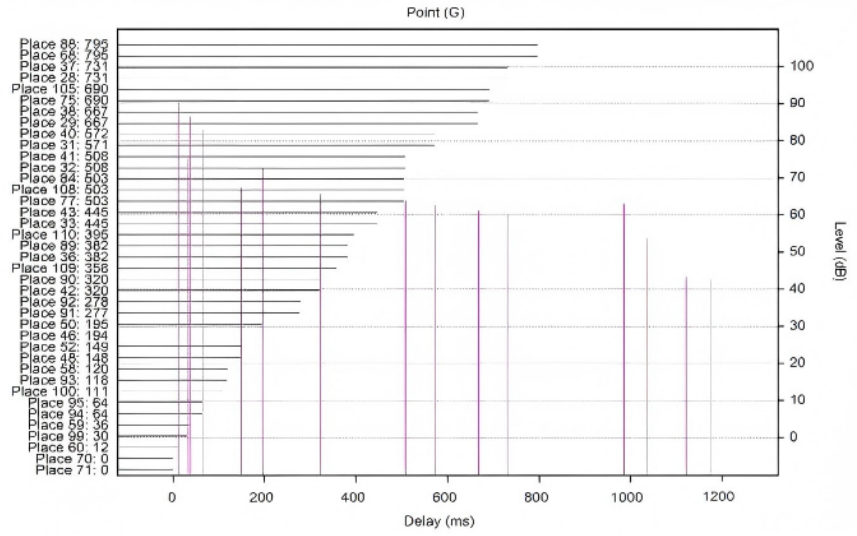


Figure 22. Simulated SPL vs. delay curves at testing points (D) and (G) on the Massa roof and Piazza.

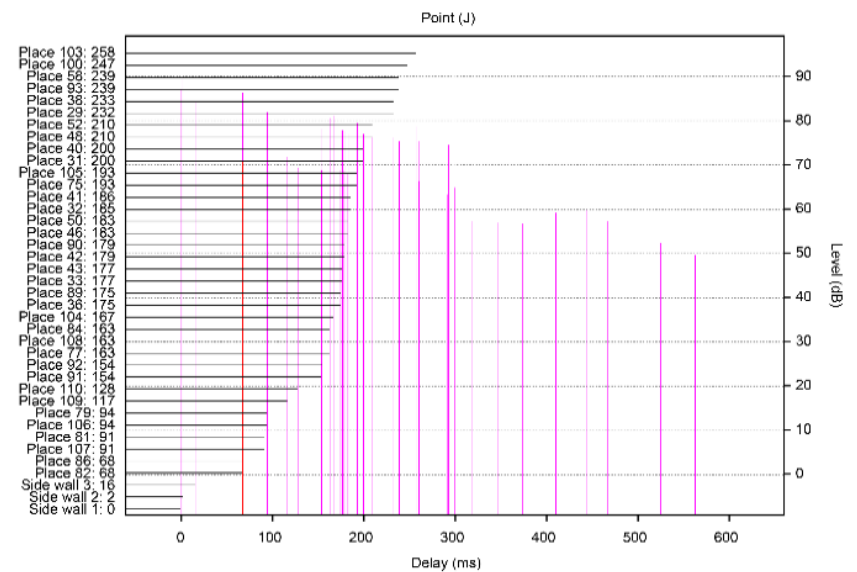
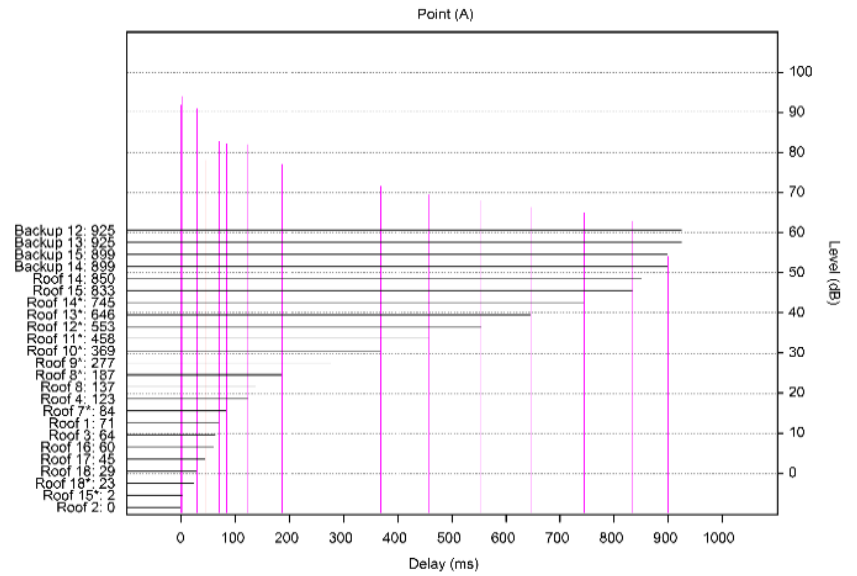


Figure 23. Simulated SPL vs. delay curves at testing points (A) and (J) on the Massa roof and Piazza.

The simulation results shown in **Figure 19** demonstrate that despite average background noise levels of 70 dB (A), the proposed system maintains acceptable RaSTI values for mosques above 0.6 [26]. This is achieved because the line arrays are highly directional, concentrating sound energy on the worshippers and minimizing the impact of ambient noise.

6. Discussion

The open-air area under consideration has a large total surface area of approximately 85,000 m². It represents a particular part of the whole Grand Mosque area (refer to **Figure 1**). Conducting field measurements and constructing computer-aided virtual models for such an area was not an easy task. Even though the area under consideration is not a closed structure, the acoustic measurements of the current condition characteristics of the Massa roof and Piazza show late reflections arriving 100 ms after direct sound. These reflections form echoes and contribute significantly to decreasing speech intelligibility [11]. Additionally, relatively strong early reflections caused by surrounding buildings and mountains are noticed. The successive time delay between early reflections is identified; this delay is caused by high-rise buildings in the area. Additionally, a maximum high level of background noise (70 dB(A)) is recorded, which critically contributes to reducing the intelligibility of the emitted sound [11]. Conducting passive treatment (surface treatment) in such an environment would be costly and unreliable, as it would impact the architecture of all reflecting surfaces in such a large open area.

Decreasing the sound energy emitted toward neighboring buildings and remote surfaces is a practical and cost-effective solution for tackling this issue. The loudspeaker arrays used have almost constant coverage toward the audience (even at low frequencies, such as 400 Hz) and hence reduce the scattered radiation and side energy beams emitting sound toward adjacent areas and remote surfaces [20].

An almost homogeneous distribution throughout the audience area on the Massa Roof and the piazza area is found in simulations, with an acceptable maximum variation of 9 dB. In the virtual model, simulated total sound pressure levels recorded at some locations have a level of difference of over 40 dB from the measured background noise. Additionally, the simulated results of the direct sound level are maintained as low as 90 dB in all areas (20 dB more than the measured background noise).

Further, a good level of intelligibility and sound audibility (between 0.6 and 0.7) is found in simulations of this large open space structure. Other measures are taken to ensure that the designed SRS achieves a high level of intelligibility and reduces remote reflections. STI values are simulated by means of the MTF at the predefined location. Lower MTF values are correlated with worse sound intelligibility (lower STI) [15]. In this case, all STI values in the piazza area and above the Massa are greater than 0.6. Inspecting the SPL vs. delay curves shows that the SPL decreases with time, and no late energy arrivals are noticed. On the other hand, the measured impulse response at position (X) shows that some strong reflection occurs in the form of a late energy arrival, which causes echoes and accordingly decreases intelligibility [11]. This is not the case in the simulated results with the proposed sound system.

The acoustical assessment of a site as significant and complex as the Grand Mosque involves inherent limitations. First, the vast spatial volume requires high computational resources; to maintain accuracy, the study focused on segmented representative sections rather than a single massive calculation. Second, data collection was constrained by stringent security requirements and the continuous flow of worshippers, which restricted the duration of field tests. Third, the surrounding urban environment in Makkah is highly dynamic; reflections from newly completed high-rise towers can alter field results over time. Future work will focus on post-installation field verification once the surrounding construction is complete to ensure performance within a stable urban environment.

7. Conclusion

This article addressed many aspects of the acoustics and sound system of the holiest worship place on Earth for Muslim people, known as the Grand Mosque of Makkah Al-Haram. It, perhaps, consists of one of the largest sound systems in any worship place. This article also discusses the challenges, sound quality, and acoustic system scheme. The improvement of the acoustic situation on the Massa (area shown in **Figure 8**) addresses the ambient acoustical environment on the roof of Massa and on the adjacent piazza and contributes to providing the most pleasant hearing experience for worshippers. Echoes and sound reflections from adjacent high-rise buildings and valley mountains degrade the sound intelligibility in the area under investigation. Hot weather conditions, dry weather, and high levels of ambient noise contribute to decreasing sound intelligibility and audibility [11].

The proposed “active treatment” of the acoustical environment in the Grand Mosque in Makkah succeeded in maintaining a good level of sound intelligibility by electronic means. “Passive treatment” of reflecting surfaces would not be reliable and can be extremely expensive. Avoiding exciting remote surfaces with sound energy using directed loudspeakers improved sound intelligibility and the worshippers’ experience. The newly adapted SRS design provided a standardized distribution of sound levels throughout the targeted audience area with a maximum SPL variation of 9 dB. Additionally, the simulated STI values on the Massa roof and the adjacent piazza were more than 0.6. Using loudspeaker arrays with electronically steerable radiation beams would concentrate the sound energy toward the audience and decrease acoustical deficiencies resulting from remote reflections. Adopting such methods in future mosques will shape and improve the worshiper’s experience, especially in structures such as mosques where speech intelligibility and audibility are a necessity [1].

This article addresses many aspects of the acoustic/sound system of the Grand Mosque, which makes this article very unique in this field, as few articles have been published on the acoustic systems of mosques or other Muslim gathering places. It also addresses many aspects of sound quality and the characteristics of the surface regarding sound reflection. Furthermore, it addresses the unique challenges of large open-air structures, noting the rarity of such studies. The findings are contextualized by the specific environmental challenges of the Grand Mosque, such as late reflections from surrounding high-rise buildings and mountains, which are compared to the controlled

“active” approach of digitally steered loudspeaker columns.

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Abbreviation

EASERA	electronic and acoustic system evaluation and response analysis
EASE	enhanced acoustic simulator for engineers
SPL	sound pressure level
AFMG	Ahnert Feistel Media Group
ITDG	initial time delay gap
S/N	signal-to-noise ratio
LTI	linear time-invariant
AD/DA	analog to digital/digital to analog
STI	speech transmission index
RaSTI	rapid speech transmission index
MTF	modulation transfer function
ADA	Acoustic Design Ahnert

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